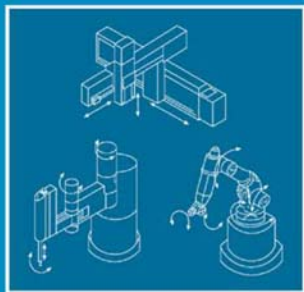


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Advanced welding processes

Technologies and process control

John Norrish

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Advanced welding processes

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John Norrish

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Contents

	<i>Preface</i>	<i>ix</i>
	<i>Acknowledgements</i>	<i>xi</i>
1	An introduction to welding processes	1
1.1	Introduction	1
1.2	Conventional welding processes	2
1.3	Summary	15
2	Advanced process development trends	16
2.1	Introduction	16
2.2	Safety and environmental factors	21
2.3	Skill and training requirements	21
2.4	Areas for development	21
2.5	Process application trends	22
2.6	Summary	25
3	Welding power source technology	26
3.1	Introduction	26
3.2	Basic power source requirements	26
3.3	Conventional power source designs	27
3.4	Electronic power regulation systems	31
3.5	Output level, sequence and function control	39
3.6	Practical implications of electronic power regulation and control	42
3.7	Summary	43
4	Filler materials for arc welding	44
4.1	Introduction	44
4.2	MMAW consumables	44
4.3	Submerged arc welding consumables	46

vi	Contents	
4.4	Filler wires for GMAW and FCAW	47
4.5	Summary	57
5	Gases for advanced welding processes	58
5.1	Introduction	58
5.2	Shielding gases for arc welding processes	58
5.3	Gases for laser welding	71
5.4	Summary	72
6	Advanced gas tungsten arc welding	74
6.1	Introduction	74
6.2	Process developments	74
6.3	Process variants	79
6.4	Control of GTAW and related processes	91
6.5	Summary	98
7	Gas metal arc welding	100
7.1	Introduction	100
7.2	Metal transfer in GMAW	100
7.3	The physics of metal transfer	110
7.4	Summary: metal transfer phenomena	113
7.5	Control of conventional GMAW	113
7.6	Summary: process control	120
7.7	Recent developments in the GMAW process	120
7.8	Summary	134
8	High-energy density processes	136
8.1	Introduction	136
8.2	Plasma keyhole welding	138
8.3	Laser welding	144
8.4	Electron beam welding	157
8.5	Summary	164
9	Narrow-gap welding techniques	165
9.1	Introduction	165
9.2	Principles and features of narrow-gap welding	165
9.3	Narrow-gap welding processes	166
9.4	Summary and implications	177
10	Monitoring and control of welding processes	179
10.1	Introduction	179
10.2	Manual control techniques	180
10.3	Monitoring	188

10.4	Automated control techniques	203
10.5	Summary and implications	216
11	Welding automation and robotics	218
11.1	Introduction	218
11.2	Automation options	219
11.3	Simple mechanization	219
11.4	Dedicated and special-purpose automation	223
11.5	Robotic welding	225
11.6	Modular automation	236
11.7	Programmable control	236
11.8	Remote-control slave and automated systems	237
11.9	Advances in welding automation	238
11.10	Evaluation of and justification for automated welding	242
11.11	Summary	246
	Appendices	247
	Appendix 1: Welding processes classification	249
	Appendix 2: Shielded metal arc welding (SMAW) electrode classification	250
	Appendix 3: Burn-off characteristics	254
	Appendix 4: American, Australian and European FCAW classification systems	257
	Appendix 5: Flux-cored wire for surfacing and wear resistance	260
	Appendix 6: Plasma keyhole welding parameters	262
	Appendix 7: Plasma keyhole welding of titanium	263
	References	265
	<i>Index</i>	279

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Preface

Welding has traditionally been regarded as a craft rather than a technological manufacturing process. This reputation has not been helped by the dependence of conventional joining techniques on highly skilled manual operators and the relatively high cost and poor reproducibility associated with many welding processes. These attributes led to the ‘Special Process’ classification of welding in international quality standards. In fact, although it may be a complex multi-disciplinary subject, a great deal of high-quality research has been conducted into the fundamentals of welding processes and the basic principles are now well understood. This research has provided a scientific basis for significant developments in the technology.

Early developments in welding technology were focused largely on weldability and metallurgical research, which enabled a wide range of materials to be joined, adequate joint properties to be maintained and the integrity of welded joints to be controlled. Whilst further work is still required in the materials research area, in particular to enable advanced materials to be joined effectively, much of the recent effort has been devoted to improved understanding of the basic processes, consumable and equipment development and control and automation.

John Norrish
University of Wollongong

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I would like to acknowledge the continued help, advice, encouragement and goading which have been generously provided by many friends and colleagues in the welding industry around the world, also my students, who have taught me much and whose work is reported widely in the following pages.

Last, but by no means least, I would like to thank my long-suffering family for their forbearance during the protracted gestation of this work.

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1.1 Introduction

Welding and joining are essential for the manufacture of a range of engineering components, which may vary from very large structures such as ships and bridges, to very complex structures such as aircraft engines or miniature components for micro-electronic applications.

1.1.1 Joining processes

The basic joining processes may be subdivided into:

- mechanical joining;
- adhesive bonding;
- brazing and soldering;
- welding.

A large number of joining techniques are available and, in recent years, significant developments have taken place, particularly in the adhesive bonding and welding areas. Existing welding processes have been improved and new methods of joining have been introduced. The proliferation of techniques which have resulted makes process selection difficult and may limit their effective exploitation. The aim of this book is to provide an objective assessment of the most recent developments in welding process technology in an attempt to ensure that the most appropriate welding process is selected for a given application.

This chapter will introduce some of the basic concepts which need to be considered and highlight some of the features of traditional welding methods.

1.1.2 Classification of welding processes

Several alternative definitions are used to describe a weld, for example:

A union between two pieces of metal rendered plastic or liquid by heat or pressure or both. A filler metal with a melting temperature of the same order as that of the parent metal may or may not be used. [1]

or alternatively:

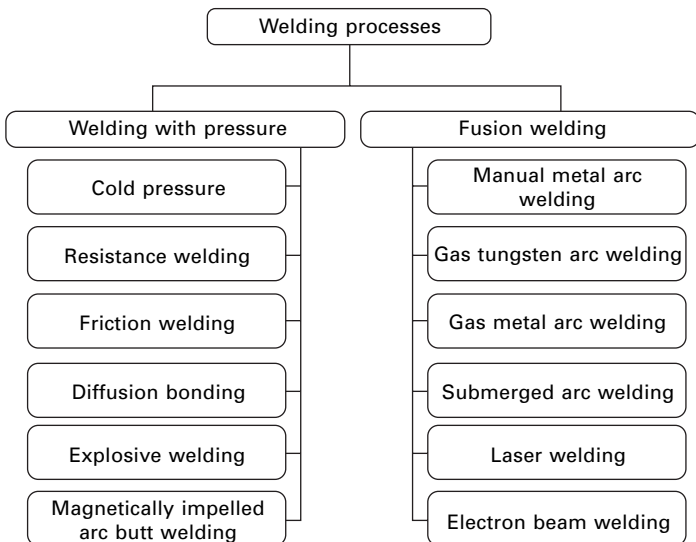
A localized coalescence of metals or non-metals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone, with or without the use of a filler metal. [2]

Many different processes have been developed, but for simplicity these may be classified in two groups; namely ‘fusion’ and ‘pressure’ welding as shown in Fig. 1.1, which summarises some of the key processes. A more extensive list of processes is reproduced in Appendix 1. [1]

1.2 Conventional welding processes

A brief description of the most common processes, their applications and limitations is given below. The more advanced processes and their developments are dealt with in more detail in the remaining chapters.

An international standard ISO 4063 [3] identifies processes by a numeric code. The first digit of this code specifies the main process grouping whilst the second and third digit indicate sub-groups. The main groups and some



1.1 Some important welding processes.

Table 1.1 Examples of numbering system from ISO 4063

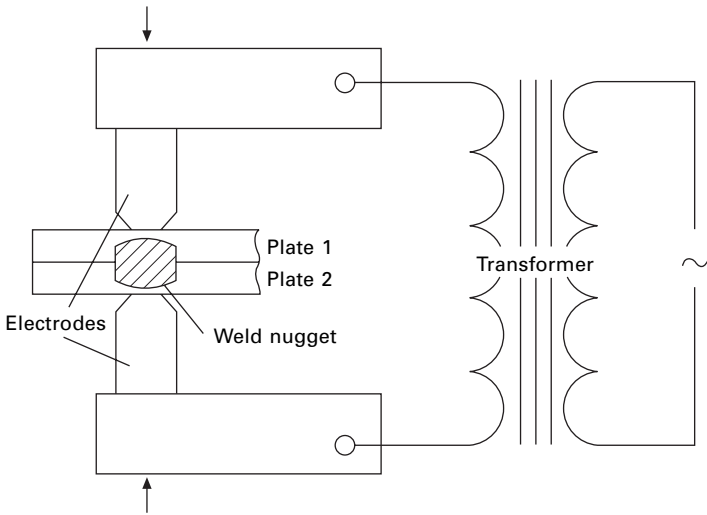
Main group	Secondary group	Sub-group
{1} Arc welding	{12} Submerged arc welding {13} Gas shielded metal arc welding {15} Plasma arc welding	{111} Manual metal arc welding {131} Metal inert gas welding {141} Tungsten inert gas welding
{2} Resistance welding	{21} Resistance spot {22} Resistance seam {23} Projection welding	{222} Mash seam welding {291} High frequency resistance welding
{3} Gas welding	{31} Oxy-fuel gas welding	{311} Oxy acetylene welding
{4} Welding with pressure	{42} Friction welding {48} Cold pressure welding	{441} Explosive welding
{5} Beam welding	{51} Electron beam welding {52} Laser beam welding	{511} Electron beam welding in vacuum {521} Solid state laser welding {522} Gas laser welding
{7} Other welding processes	{71} Aluminothermic welding {75} Light radiation welding	{753} Infrared welding
{8} Cutting and gouging	{81} Flame cutting {82} Arc cutting {83} Plasma cutting {84} Laser cutting	{821} Air arc cutting
{9} Brazing and soldering	{91} Brazing {94} Soldering	{912} Flame brazing {944} Dip soldering

examples of sub-groups are shown in Table 1.1 and where appropriate the classification code is given in { }brackets in Sections 1.2.1 and 1.2.2.

1.2.1 Welding with pressure

Resistance welding {2}

The resistance welding processes are commonly classified as pressure welding processes although they involve fusion at the interface of the material being joined. Resistance spot {21}, seam {22} and projection welding {23} rely on a similar mechanism. The material to be joined is clamped between two electrodes and a high current is applied (Fig. 1.2). Resistance heating at the contact surfaces causes local melting and fusion. High currents (typically



1.2 Resistance welding system.

10000 A) are applied for short durations and pressure is applied to the electrodes before the application of current and for a short time after the current has ceased to flow.

Accurate control of current amplitude, pressure and weld cycle time are required to ensure that consistent weld quality is achieved, but some variation may occur due to changes in the contact resistance of the material, electrode wear, magnetic losses or shunting of the current through previously formed spots. These ‘unpredictable’ variations in process performance have led to the practice of increasing the number of welds from the design requirement to give some measure of protection against poor individual weld quality. To improve this situation significant developments have been made in resistance monitoring and control; these allow more efficient use of the process and some of the techniques available are described in Chapter 10.

Features of the basic resistance welding process include:

- the process requires relatively simple equipment;
- it is easily and normally automated;
- once the welding parameters are established it should be possible to produce repeatable welds for relatively long production runs.

The major applications of the process have been in the joining of sheet steel in the automotive and white-goods manufacturing industries.

Cold pressure welding {48}

If sufficient pressure is applied to the cleaned mating surfaces to cause substantial plastic deformation, the surface layers of the material are disrupted,

metallic bonds form across the interface and a cold pressure weld is formed. [4] The main characteristics of cold pressure welding are:

- the simplicity and low cost of the equipment;
- the avoidance of thermal damage to the material;
- it is most suitable for low-strength (soft) materials.

The pressure and deformation may be applied by rolling, indentation, butt welding, drawing or shear welding techniques. In general, the more ductile materials are more easily welded.

This process has been used for electrical connections between small-diameter copper and aluminium conductors using butt and indentation techniques. Roll bonding is used to produce bimetallic sheets such as Cu/Al for cooking utensils, Al/Zn for printing plates and precious-metal contact springs for electrical applications.

Friction welding [42]

In friction welding, a high temperature is developed at the joint by the relative motion of the contact surfaces. When the surfaces are softened, a forging pressure is applied and the relative motion is stopped (Fig. 1.3). Material is extruded from the joint to form an upset.

The process may be divided into several operating modes in terms of the means of supplying the energy:

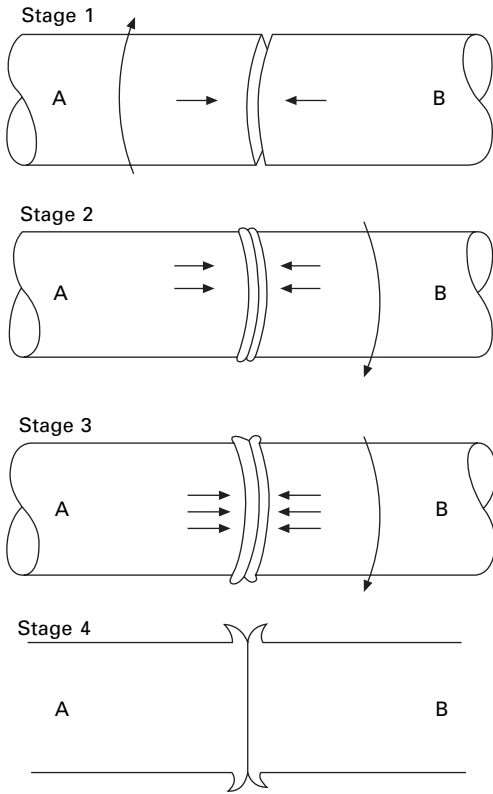
- (1) Continuous drive: in which the relative motion is generated by direct coupling to the energy source. The drive maintains a constant speed during the heating phase.
- (2) Stored energy: in which the relative motion is supplied by a flywheel which is disconnected from the drive during the heating phase.

Rotational motion is the most commonly used, mainly for round components where angular alignment of the two parts is not critical (Fig. 1.4). If it is required to achieve a fixed relationship between the mating parts, angular oscillation may be used and for non-circular components the linear and orbital techniques may be employed. Features of the process include:

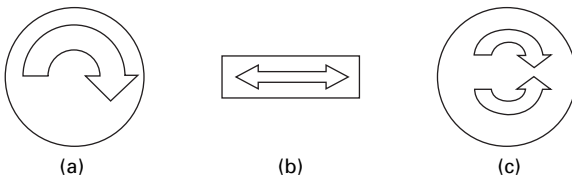
- one-shot process for butt welding sections;
- suitable for dissimilar metals;
- short cycle time;
- most suited to circular sections;
- robust and costly equipment may be required.

The process is commonly applied to circular sections, particularly in steel, but it may also be applied to dissimilar metal joints such as aluminium to steel or even ceramic materials to metals. Early applications of the process

6 Advanced welding processes



1.3 Friction welding. Stage 1: A fixed, B rotated and moved into contact with A. Stage 2: A fixed, B rotated under pressure, interface heating. Stage 3: A fixed, forge pressure applied. Stage 4: relative motion stopped, weld formed.



1.4 Friction welding variants: (a) normal rotational motion, (b) linear oscillation, (c) angular oscillation.

included the welding of automotive stub axles, but the process has also been applied to the fabrication of high-quality aero-engine parts, [5] duplex stainless steel pipe for offshore applications [6] and nuclear components. [7]

Recent developments of the process include the joining of metal to ceramics, [8] the use of the process for stud welding in normal ambient conditions and underwater, and the use of the process for surfacing. [9] The linear technique

has recently been successfully demonstrated on titanium alloy welds having a weld area of 250 mm^2 using an oscillation frequency of 25 kHz, 110 N mm^{-2} axial force and an oscillation amplitude of $\pm 2 \text{ mm}$. [10]

Diffusion bonding or diffusion welding {45}

In diffusion bonding the mating surfaces are cleaned and heated in an inert atmosphere. Pressure is applied to the joint and local plastic deformation is followed by diffusion during which the surface voids are eliminated. [11] Features of the process include:

- it is suitable for joining a wide range of materials;
- it is a one-shot process;
- complex sections may be joined;
- a vacuum or controlled atmosphere is required;
- a prolonged cycle time may be necessary.

The process can, however, be used for the joining of complex structures which require many simultaneous welds to be made.

Explosive welding {441}

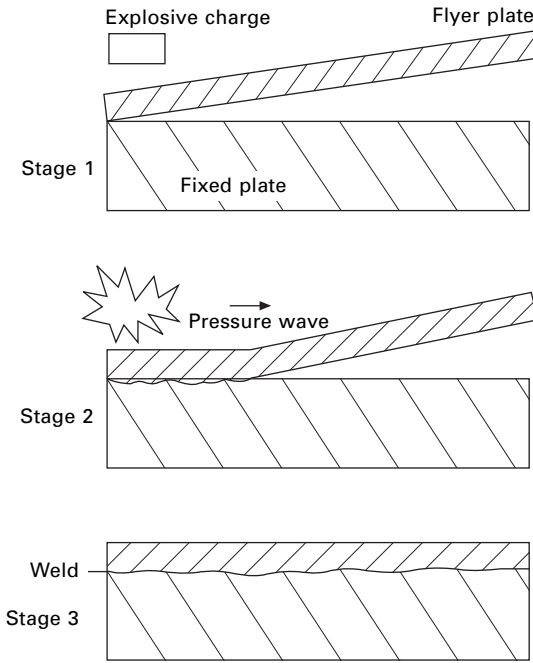
In explosive welding, the force required to deform the interface is generated by an explosive charge. In the most common application of the process, two flat plates are joined to form a bimetallic structure. An explosive charge is used to force the upper or 'flier' plate on to the baseplate in such a way that a wave of plastic material at the interface is extruded forward as the plates join (Fig. 1.5). For large workpieces, considerable force is involved and care is required to ensure the safe operation of the process. Features of the process include:

- it is a one-shot process;
- it offers a short welding time;
- it is suitable for joining large surface areas;
- it is suitable for dissimilar thickness and metals joining;
- careful preparation is required for large workpieces;
- safety is an issue.

The process may also be applied for welding heat exchanger tubes to tube plates or for plugging redundant or damaged tubes.

Magnetically impelled arc butt (MIAB) welding {185}

In MIAB welding a magnetic field generated by an electromagnet is used to move an arc across the joint surfaces before the application of pressure [12]



1.5 Explosive welding.

(Fig. 1.6). Although the process produces a weld similar to that of friction welding, it is possible to achieve shorter cycle times and relative motion of the parts to be joined is avoided. Features of the process are:

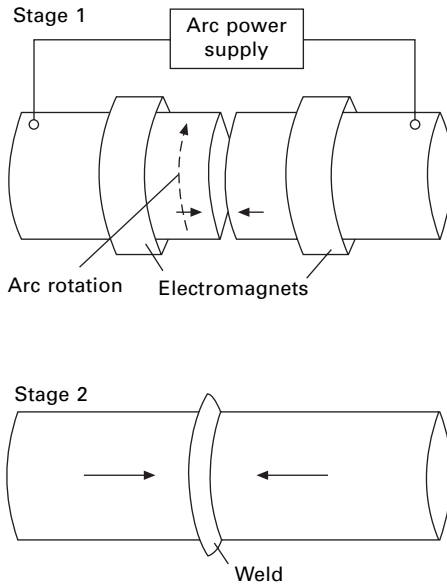
- it is a one-shot process;
- it is suitable for butt welding complex sections;
- it offers a shorter cycle time than friction welding.

The process has been applied fairly widely in the automotive industry for the fabrication of axle cases and shock absorber housings in tube diameters from 10 to 300 mm and thicknesses from 0.7 to 13 mm. [13] It is also being developed for transmission pipeline welding, particularly for small diameter thin wall pipe.

1.2.2 Fusion welding

Gas tungsten arc welding (GTAW) [141]

In the gas tungsten arc welding process [also known as tungsten inert gas (TIG) in most of Europe, WIG (wolfram inert gas) in Germany, and still referred to by the original trade names Argonarc or Heliarc welding in some countries], the heat generated by an arc which is maintained between the



1.6 Magnetically impelled arc butt (MIAB) welding. Stage 1: rotating arc heats end faces. Stage 2: forge pressure applied.

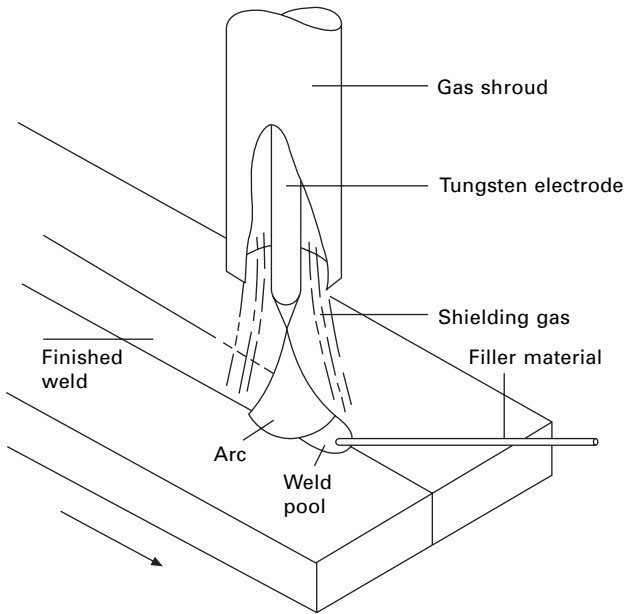
workpiece and a non-consumable tungsten electrode is used to fuse the joint area. The arc is sustained in an inert gas which serves to protect the weld pool and the electrode from atmospheric contamination (Fig. 1.7). The process has the following features:

- it is conducted in a chemically inert atmosphere;
- the arc energy density is relatively high;
- the process is very controllable;
- joint quality is usually high;
- deposition rates and joint completion rates are low.

The process may be applied to the joining of a wide range of engineering materials, including stainless steel, aluminium alloys and reactive metals such as titanium. These features of the process lead to its widespread application in the aerospace, nuclear reprocessing and power generation industries as well as in the fabrication of chemical process plant, food processing and brewing equipment.

Shielded metal arc welding (SMAW) – Manual metal arc welding (MMAW) {111}

Shielded metal arc welding [also known as MMAW (manual metal arc welding) in Europe and Australia and still referred to as ‘Stick’ welding in many parts



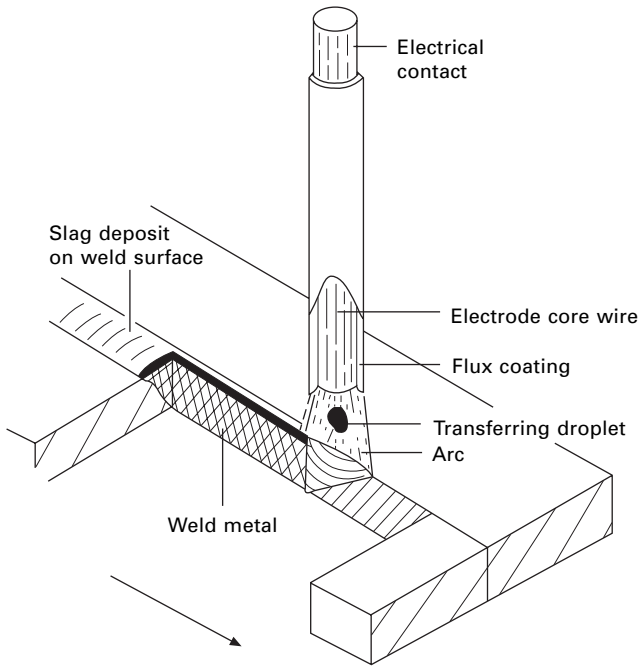
1.7 The gas tungsten arc welding (GTAW) process.

of the world] has for many years been one of the most common techniques used in the fabrication of steels. The process involves an arc as the heat source with shielding provided by gases generated by the decomposition of the electrode coating material and by the slag produced by the melting of mineral constituents of the coating (Fig. 1.8). This slag may also be chemically active; providing for example, an additional method of controlling impurities or dissolved gases in the weld pool. In addition to heating and melting the parent material, the arc also melts the core of the electrode and, thereby, provides filler material for the joint. The electrode coating may also be used as a source of alloying elements and additional filler material. The flux and electrode chemistry may be formulated to deposit wear- and corrosion-resistant layers for surface protection.

Significant features of the process are:

- the equipment requirements are simple;
- a large range of consumables are available;
- the process is extremely portable;
- the operating efficiency is low;
- it is a labour intensive process.

For these reasons, the process has been traditionally used in structural steel fabrication, shipbuilding and heavy engineering as well as for small batch production and maintenance.



1.8 Shielded metal arc welding [or manual metal arc welding (MMAW)].

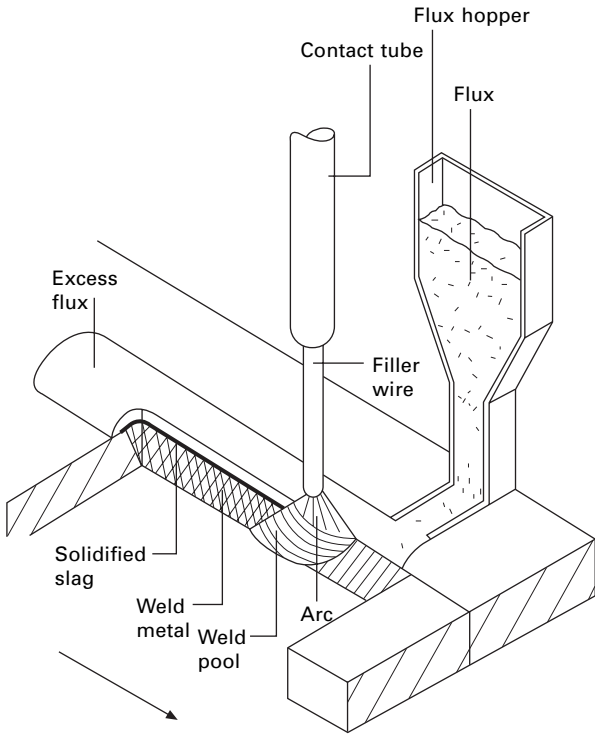
Submerged arc welding (SAW) [12]

Submerged arc welding is a consumable electrode arc welding process in which the arc is shielded by a molten slag and the arc atmosphere is generated by decomposition of certain slag constituents (Fig. 1.9). The filler material is a continuously fed wire and very high melting and deposition rates are achieved by using high currents (e.g. 1000 A) with relatively small-diameter wires (e.g. 4 mm).

The significant features of the process are:

- high deposition rates;
- automatic operation;
- no visible arc radiation;
- flexible range of flux/wire combinations;
- difficult to use positionally;
- normally used for thicknesses above 6 mm.

The main applications of submerged arc welding are on thick section plain carbon and low-alloy steels and it has been used on power generation plant, nuclear containment, heavy structural steelwork, offshore structures and shipbuilding. The process is also used for high-speed welding of simple



1.9 Submerged arc welding.

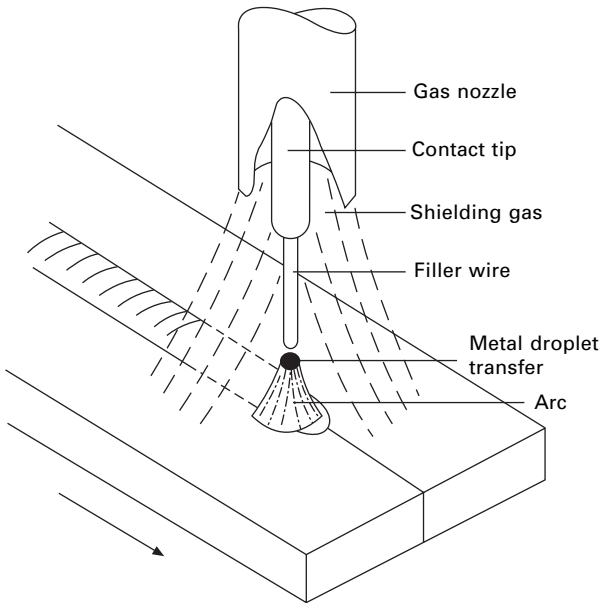
geometric seams in thinner sections, for example in the fabrication of pressure containers for liquefied petroleum gas. Like shielded metal arc welding, with suitable wire/flux combinations, the process may also be used for surfacing.

Gas metal arc welding (GMAW) {13}

In gas metal arc welding [also known as metal inert gas (MIG) or metal active gas (MAG) welding in Europe; the terms semi-automatic or CO₂ welding are sometimes used but are less acceptable] the heat generated by an electric arc is used to fuse the joint area. The arc is formed between the tip of a consumable, continuously fed filler wire and the workpiece, and the entire arc area is shielded by an inert gas. The principle of operation is illustrated in Fig. 1.10.

Some of the more important features of the process are summarized below:

- low heat input (compared with SMAW and SAW);
- continuous operation;
- high deposition rate;



1.10 Gas metal arc welding (GMAW) or metal inert gas (MIG) welding.

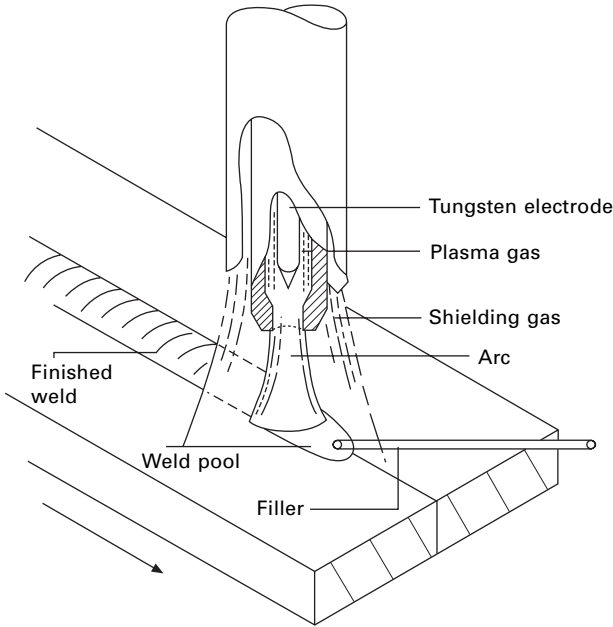
- no heavy slag – reduced post-weld cleaning;
- low hydrogen – reduces risk of cold cracking.

Depending on the operating mode of the process, it may be used at low currents for thin sheet or positional welding.

The process is used for joining plain carbon steel sheet from 0.5 to 2.0 mm thick in the following applications: automobile bodies, exhaust systems, storage tanks, tubular steel furniture, and heating and ventilating ducts. The process is applied to positional welding of thicker plain carbon and low alloy steels in the following areas: oil pipelines, marine structures and earth-moving equipment. At higher currents, high deposition rates may be obtained and the process is used for downhand and horizontal-vertical welds in a wide range of materials. Applications include earth-moving equipment, structural steelwork (e.g. I-beam prefabrication), weld surfacing with nickel or chromium alloys, aluminium alloy cryogenic vessels and military vehicles.

Plasma welding {15}

In plasma welding, the heat generated by a constricted arc is used to fuse the joint area, the arc being formed between the tip of a non-consumable electrode and either the workpiece or the constricting nozzle (Fig. 1.11). A wide range of shielding and cutting gases are used depending on the mode of operation



1.11 Plasma welding.

and the application. In the normal transferred arc mode, the arc is maintained between the electrode and the workpiece; the electrode is usually the cathode and the workpiece is connected to the positive side of the power supply. In this mode, a high energy density is achieved and the process may be used effectively for welding and cutting.

The features of the process depend on the operating mode and the current and will be described further in Chapters 5 and 7, but, in summary, the plasma process has the following characteristics:

- good low-current arc stability;
- improved directionality compared with TIG;
- improved melting efficiency compared with TIG;
- possibility of keyhole welding.

These features of the process make it suitable for a range of applications including the joining of very thin materials, the encapsulation of electronic components and sensors, and high-speed longitudinal welds on strip and pipe.

Electron beam welding {51}

A beam of electrons may be accelerated by a high voltage to provide a high-energy heat source for welding (see Chapter 8). The power density of electron

beams is high (10^{10} to 10^{12} W m⁻²) and keyhole welding is the normal operating mode. The problem of power dissipation when the electrons collide with atmospheric gas molecules is usually overcome by carrying out the welding operation in a vacuum. Features of the process include:

- very high energy density;
- confined heat source;
- high depth-to-width ratio of welds;
- normally requires a vacuum;
- high equipment cost.

Applications of electron beam welding have traditionally included welding of aerospace engine components and instrumentation, but it may be used on a wide range of materials when high precision and very deep penetration welds are required.

Laser welding [52]

The laser may be used as an alternative heat source for fusion welding (see Chapter 7). The focused power density of the laser can reach 10^{10} or 10^{12} W m⁻² and welding is often carried out using the 'keyhole' technique. Significant features of laser welding are:

- very confined heat source at low power;
- deep penetration at high power;
- reduced distortion and thermal damage;
- out-of-vacuum technique;
- high equipment cost.

These features have led to the application of lasers for microjoining of electronic components, but the process is also being applied to the fabrication of automotive components and precision machine tool parts in heavy section steel.

1.3 Summary

A wide range of welding processes is available and their suitability for a given application is determined by the inherent features of the process. Specific process developments and advances in automation and process monitoring, which may be used to enhance most welding systems, will be described in Chapters 2–11.

2.1 Introduction

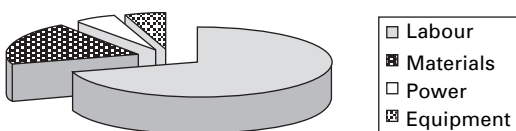
The primary incentive for welding process development is the need to improve the total cost effectiveness of joining operations in fabrication and manufacturing industries. Other factors may, however, influence the requirement for new processes. Concern over the safety of the welding environment and the potential shortage of skilled technicians and operators in many countries have become significant research considerations.

Many of the traditional welding techniques described in Chapter 1 are regarded as costly and hazardous, but it is possible to improve both of these aspects significantly by employing some of the advanced process developments described in the following chapters. The background to the development of some of the more significant developments and current trends in the application of advanced processes are discussed below.

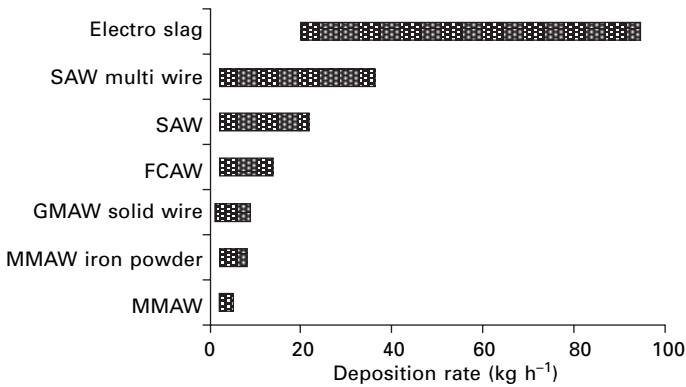
2.1.1 Cost effectiveness

The cost of producing a welded joint is the sum of costs associated with labour, materials, power and capital plant depreciation. The total cost of welding operations in western economies is largely governed by the cost of labour and, in many traditional welding processes, this can account for 70 to 80% of the total. This is illustrated schematically in Fig. 2.1.

In the past, it seems to have been assumed that the cost effectiveness of welding processes was totally dependent on deposition rate. Processes which



2.1 Welding costs.



2.2 Indication of deposition rates for a range of consumable electrode processes. [14]

gave increased deposition rate were sought and a comparison of the common consumable electrode processes is given in Fig. 2.2. [14]

In general, the higher the deposition rate, the shorter the weld cycle time and the lower the labour cost. Some of the more recent developments in processes with high deposition rates are discussed in the following chapters. Deposition rate may, however, give a misleading indication of cost effectiveness if, for example, quality is sacrificed and higher repair rates are required. Deposition rate is also an inappropriate way of describing 'single shot' high joint-completion rate autogenous processes such as explosive welding and laser welding.

For a more complete assessment of cost effectiveness, it is clear that the following additional factors should be considered:

- control of joint quality;
- joint design;
- operating efficiency;
- equipment and consumable cost.

Control of joint quality

Traditional welding processes are controlled by a large number of interrelated operating parameters and the joint quality often depends on the optimization of these parameters as well as the careful control of pre-weld and post-weld treatments. In order to ensure repeatable joint quality, the operating parameters derived from a combination of established 'rules' and welding trials are defined for each joint in the form of a welding procedure. [15] For critical structural joints, this welding procedure and the operator may require formal approval by a certifying authority. This process of procedure generation and

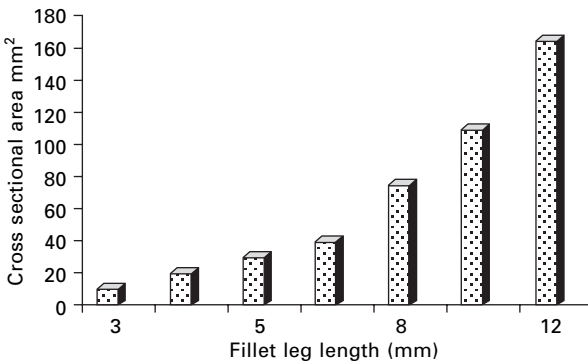
qualification is both time consuming and costly and, once a procedure has been established, the additional cost involved in adopting a new process may be prohibitive unless the cost of re-qualification can be recovered from the potential savings.

The success of this control technique also depends on ensuring that the predetermined procedure is actually followed in production; this in turn means monitoring the performance of the equipment used and ensuring that the operator adheres to the original technique. Unfortunately this is not always the case and additional costs are often incurred in post-weld inspection and weld repair. The development of techniques which enable the welding process to be controlled more effectively should have a significant impact on costs. The use of more tolerant consumables, more repeatable equipment and processes, automation, on-line monitoring and real-time control systems all contribute to improved overall process control. In addition, there is renewed interest in the use of modelling and parameter prediction techniques to enable the optimum welding parameters to be established for a given welding situation.

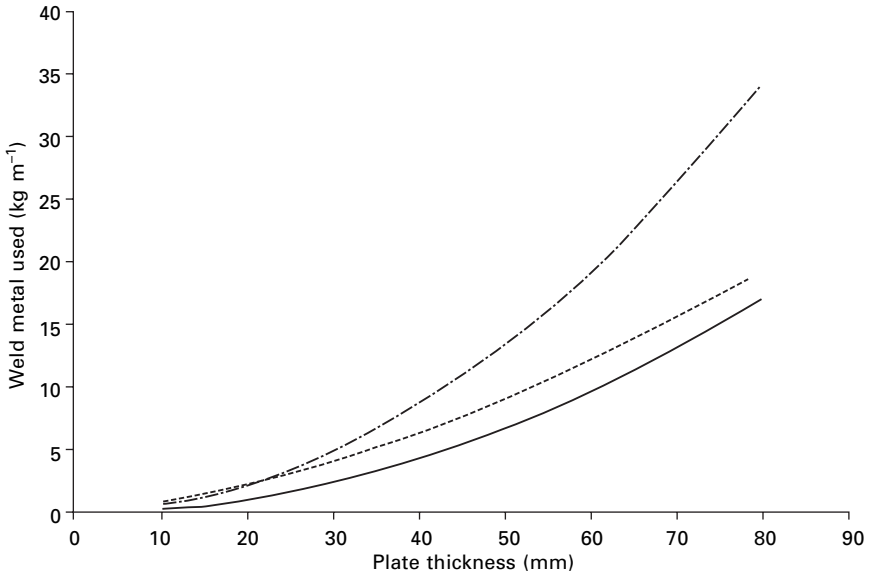
Joint design

Over-specifying the joint requirements has a marked effect on the cost of welding; in the case of a simple fillet weld, a 1 mm increase in the specified leg length can increase the cost by 45% as shown in Fig. 2.3.

The choice of a specific joint design can automatically preclude the use of the most cost-effective process; for example, limited access or complex joint profiles may limit the process choice and it is important for the designer to understand the limitations of the joining process to avoid these restrictions. Conversely, the selection of an appropriate process may reduce both joint preparation costs and joint completion time. In general, the joint completion time is related to the required weld metal volume and it can be seen from



2.3 Effect of joint design (fillet leg length) on weld metal requirements.



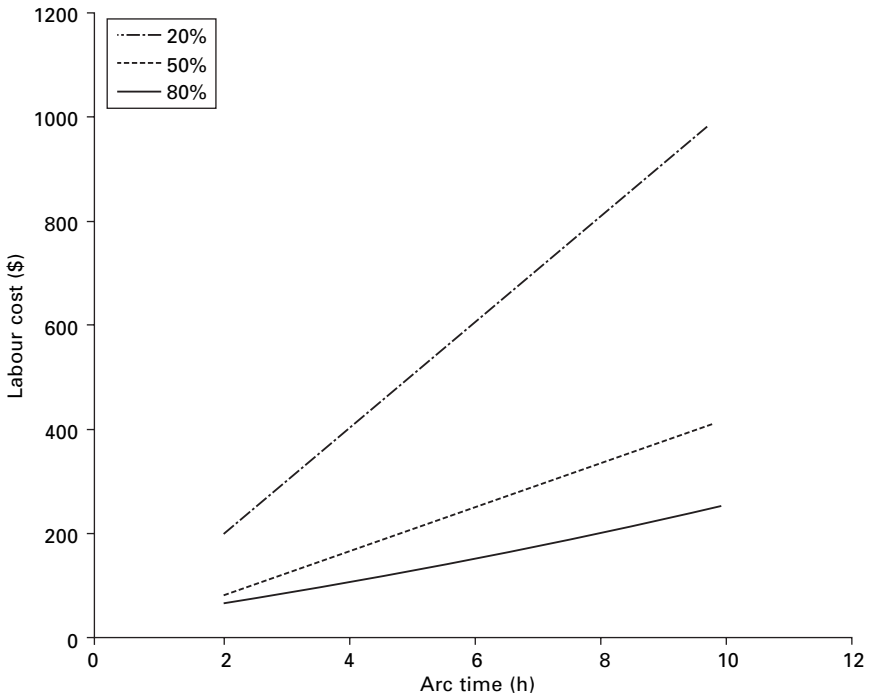
2.4 Effect of weld preparation design on consumable consumption in kg m^{-1} . The welds are all but welds with (a) ... single 60° V preparation, (b) - - - single V 20° preparation, (c) — double V 60° preparation.

Fig. 2.4 that this will vary significantly depending on the joint design. For example, using the electron beam process, a butt joint in 20 mm thick steel will be completed more quickly than the equivalent GMAW weld which will require a 50° to 60° included angle to enable satisfactory access. Process developments which require low weld metal volume and limited joint preparation are therefore likely to be more cost effective.

Operating efficiency

The operating efficiency of welding processes is usually expressed as the 'operating factor'¹ which is the ratio of welding time to non-welding time expressed as a percentage. Values of operating factor of 15 to 20% are not uncommon for MMAW welding whilst figures of 30 to 50% may be achieved with manual GMAW. [16,17] Improvements in operating factor have a major influence on costs since they directly influence the labour element. The influence of operating factor on the labour cost is shown in Fig. 2.5.

¹The operating factor is sometimes referred to as the 'duty cycle'; this is, however, liable to be confused with the duty cycle terminology which is used to describe the output rating of equipment.



2.5 Effect of operating factor on costs (for a labour rate of \$50 per hour).

Post-weld operations

The welding process may generate problems which need to be rectified after welding. The most common problems of this type are distortion and residual stresses, although metallurgical problems such as grain growth and hydrogen-induced cold cracking and cosmetic problems such as damage to surface coatings and spatter deposits must also be considered. The need to carry out additional mechanical or thermal operations after welding will obviously increase the cost of fabrication and process developments that reduce this requirement are desirable.

The risk of defects often generates a requirement for costly post-weld inspection and non-destructive examination and, although recent codes of practice allow the significance of defects to be related to the service conditions, if rectification is required, this involves increasing the value of work in progress, causes delays in production and is often labour intensive. Early identification of potential quality problems is therefore both desirable and cost effective.

Table 2.1 Some examples of common welding safety hazards

Hazard	Process
Electric shock	Arc, resistance electron beam
Radiation, visible, IR, UV ionising radiation (x-rays)	MMA, TIG, MIG, plasma, laser Electron beam
Particulate fume	Arc and power beam processes
Toxic gases (e.g. ozone)	Arc processes
High pressure and asphyxiant gases	Most welding and cutting processes
Flammable and explosive gases	Oxy fuel processes, plasma cutting
Noise	Friction, plasma

2.2 Safety and environmental factors

Some of the potential safety hazards found in welding are listed in Table 2.1. [18]

The operator is normally protected by means of protective clothing, local screening and ventilation whilst additional protection may be required to protect other workers in adjacent areas. These measures may be costly in themselves as well as having an effect on the overall efficiency of the production operation. Process developments that improve the working environment or remove the operator from the more hazardous operations are therefore desirable.

2.3 Skill and training requirements

Many of the traditional welding processes required high levels of operator skill and dexterity, which can involve costly training programmes, particularly when the procedural requirements described above need to be met. The newer processes can offer some reduction in the overall skill requirement, but this has, unfortunately, been replaced in some cases by more complex equipment and the time involved in establishing the process parameters may result in a reduction in operating factor. Developments which seek to simplify the operation of the equipment will be described below, but effective use of even the most advanced processes and equipment requires appropriate levels of operator and support staff training. The cost of this training will usually be recovered very quickly in improved productivity and quality.

2.4 Areas for development

Advances in welding processes may be justified if they offer the following:

- increased deposition rate;
- reduced cycle time;
- improved process control;

- reduced repair rates;
- reduced joint preparation time;
- removal of the operator from hazardous area;
- reduced weld size;
- reduction in post-weld operations;
- improved operating factor;
- reduction in potential safety hazards;
- simplified equipment setting.

Some or all of these requirements have been met in many of the more advanced process developments which have occurred; these will be described in detail in the following chapters, but the current trends in the application of this technology are examined below.

2.5 Process application trends

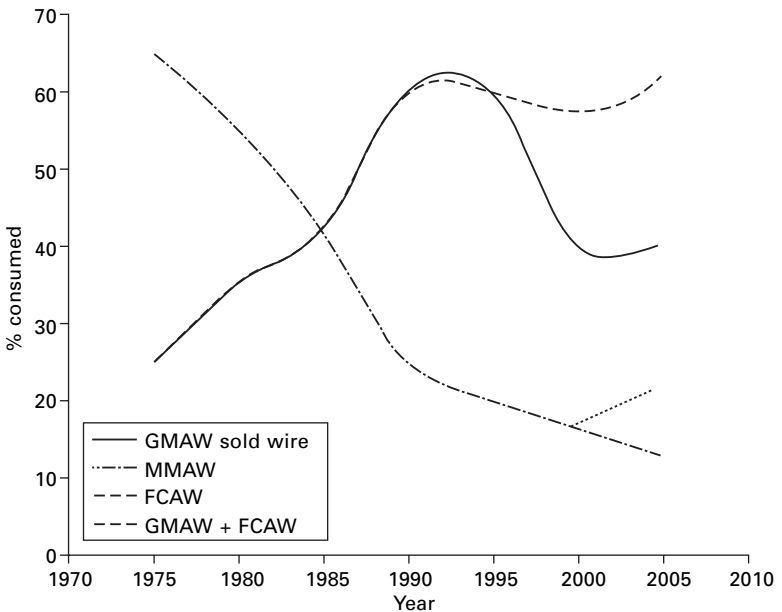
Several important trends may be identified on an international level in the application of welding processes; these are:

- process change in consumable electrode arc welding processes;
- the increased use of automation;
- increased interest in new processes (e.g. laser welding);
- the requirement to fabricate advanced materials.

2.5.1 Consumable trends

The use of GMAW and flux cored arc welding (FCAW) processes at the expense of traditional MMA welding is evident in many industrialized countries. The figures for the production and consumption of welding consumables in the UK, Japan and the USA are shown in Fig. 2.6. [19] The latest figures [20] indicate that the amount of welding performed with MMAW electrodes will stabilize at between 10 and 20% in industrialized countries, whilst slightly higher figures would be expected in the developing countries. The use of submerged arc consumables has already stabilized at around 13% of deposited weld metal. [21]

This trend illustrates the importance of establishing the overall cost of the welding operation; the flux-cored consumable is inevitably more costly to manufacture and often more than four times more expensive to purchase when compared with the solid wires used for GMAW. The increase in deposition rate, higher operating factor, improved process tolerance and enhanced joint quality can, however, result in a reduction in the overall cost of the weld in spite of the higher consumable costs. The total cost will depend on the application; it can be shown for example that for a simple 6 mm horizontal/vertical fillet GMAW welding with a solid wire gives the lowest overall cost,



2.6 Consumable consumption trends: average figures. Significant increases in the use of flux-cored wires were observed in some countries (e.g. Japan) in the 1980s and this increase has occurred at the expense of both solid wire GMAW and MMAW.

whereas, in the case of a multi-pass vertical butt weld in 20 mm thick steel a rutile flux-cored wire is a more cost-effective solution. [22]

2.5.2 Automation

The use of single-shot processes like resistance spot welding and continuous processes such as GMAW enable increased use to be made of automation. The trends for the introduction of robotics have been well reported. [23]

Many resistance welding robot applications are found in the automotive industry, whereas the use of robotic GMAW and GTAW systems is more diverse. It is also clear that the uptake of robots in Japan has exceeded that in western Europe and is also higher than the rate of application in the USA. The use of simple mechanisation and non-robotic automation in welding is less well reported, but in newer processes such as laser and electron beam welding some form of automation is an essential part of the system. Simple low-cost mechanization is recognized as a very cost-effective means of automation, particularly for GMAW and FCAW processes, and its use is expected to increase. Computer-numerical-controlled (CNC) modular automation systems have been introduced recently and these perform many

of the functions normally associated with welding robots but allow increased flexibility.

The ability to integrate welding as a well controlled process in a flexible manufacturing facility is now technically feasible, and with the aid of robot- or computer-controlled welding cells facilities such as on-line data recording, automatic component recognition, on-line quality assurance, and automatic reporting of machine malfunction and production statistics may all be provided. The capital cost of integrated fabrication facilities of this type is high, but the economic benefits must be assessed on the basis of overall productivity improvements and end-product costs.

2.5.3 New processes

The use of new joining techniques such as laser welding, MIAB and diffusion bonding appears to be increasing. The application of these processes has in the past been restricted, but with the increased recognition of the benefits of automation and the requirement for high-integrity joints in newer materials it is envisaged that the use of these techniques will grow.

As mentioned in Chapter 1, friction stir welding has been a significant development and continues to find new applications where high-speed distortion-free welding is required in ductile materials. Continued development of this process is likely to extend its application range.

Total worldwide sales of industrial lasers have been growing at a rate of around 10% per year since 1988, when sales were estimated at around 3000 units, [24] and it is expected that this growth rate will continue with CO₂ laser sales increasing at a rate of 13% per annum and 7% per annum growth in Nd:YAG. The YAG growth is expected to be dominated by high-power (3–4 kW) units. Welding applications are likely to be responsible for around 20% of this growth.

Considerable development effort has recently been devoted to hybrid (laser/GMAW) welding and the process has applications in the shipbuilding and automotive industry. More efficient diode and fibre lasers are now available with output powers of 3–20 kW and the application of these devices in welding and surface engineering is the subject of much research.

New techniques such as magnetic impulse welding have recently been introduced and are already finding application in some areas of the automotive industry. The viability of many of these processes has also been improved by equipment, consumable and process control developments, which will be discussed in the following chapters.

2.5.4 Advanced materials

There is an increasing demand to utilize more advanced materials as the service conditions of fabrications become more arduous and, in many cases,

economic and environmental pressures favour improved strength-to-weight ratios. These trends are evident in such diverse areas as aircraft construction, offshore structures and the fabrication of microcircuits. Developments in advanced materials include higher-yield-strength thermo-mechanically treated low-alloy steels, fibre-strengthened composite materials (e.g. aluminium), polymers, cermets and ceramics. The application of these materials may depend on the ease of establishing reliable joints between two components of the same material or, quite often, between dissimilar interfaces, such as metal to ceramic bonds. Methods of bonding these advanced materials are still undergoing development, but procedures for high-yield-strength steels are already available using common arc welding techniques and encouraging results have been achieved using solid-phase bonding techniques for ceramic to metal joints.

2.6 Summary

The need for development in welding processes has been generated by economic and social factors; this has led to the development of more efficient consumables and equipment and a marked increase in the use of automation. A significant trend is the use of enhanced control and monitoring in conventional welding processes.

The introduction of new processes and advanced materials has provided improved capabilities and renewed challenges in joining technology.

Examples of the advances made in some of the most important welding processes are described in subsequent chapters.

3.1 Introduction

Many of the recent developments in arc welding have been made possible by improvements in the design of the welding power supplies and, in particular, the introduction of electronic control. The basic requirements of arc welding power supplies will be examined below and the principles of both conventional and advanced power source designs, their advantages and limitations will be described.

3.2 Basic power source requirements

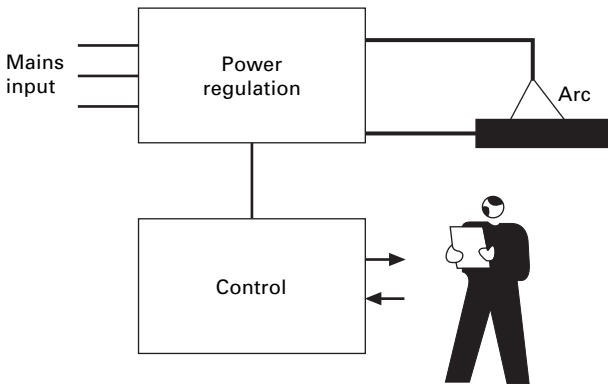
There are three basic requirements for arc welding power sources:

- to produce suitable output current and voltage characteristics for the process;
- to allow the output to be regulated to suit specific applications;
- to control the output level and sequence to suit the process and application requirements.

These requirements are illustrated in Fig. 3.1.

In order to produce suitable output levels for most arc welding processes, the normal mains power supply must be converted from high voltage–low current to relatively high current at a safer low voltage. This function may be performed by a conventional transformer and, if direct current is required, a rectifier may be added to the output. The addition of a rectifier has the added advantage that a three-phase supply may be used¹ and the loading on the supply will be more uniform with approximately equal currents being drawn

¹Although the ‘Scott connection’ system may be used to obtain a single-phase output from a three-phase supply this does not give balanced loading. Multi-operator transformers with a three-phase input and three single-phase outputs have been used, but the loading of the three-phase input is dependent on the number of arcs in use and the output current.



3.1 Functional requirements of welding power sources.

from each line. In addition, the power source design must meet the following requirements:

- conformity with prescribed codes and standards;
- safe installation and operation;
- provide satisfactory operator interface/controls;
- provide automation system interfaces, where necessary.

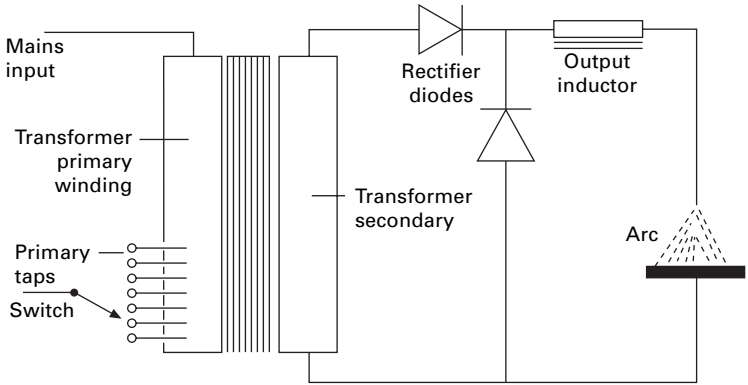
3.3 Conventional power source designs

Conventional power sources have for many years used electro-magnetic control systems to enable the output power to be adjusted; some of the more common designs employ the following control techniques:

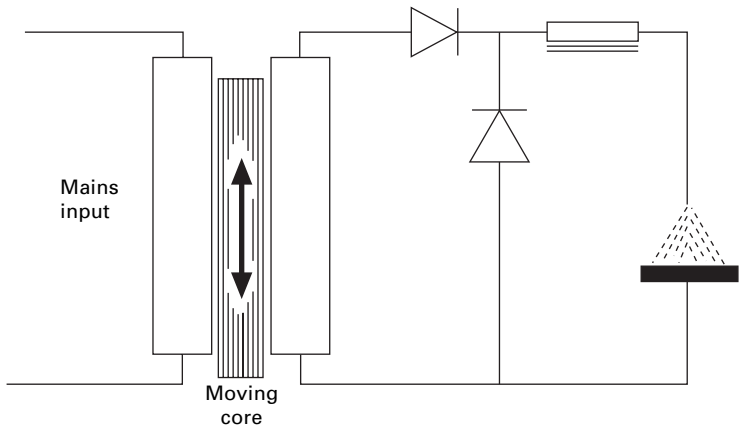
- tapped transformers;
- moving-iron control;
- variable inductor;
- magnetic amplifier.

3.3.1 Tapped transformers

By incorporating tappings in the primary coil of the welding transformer, the turns ratio of the transformer may be varied and the output regulated. It is normal to provide tappings that allow adjustment to suit a range of mains input voltages in most transformer-based designs, but when this technique is the principal method of control, additional tappings that are selected by a switch, as shown in Fig. 3.2, are provided. This type of control is simple, robust and low in cost, but it will only provide a stepped output and, unless a large number of switch settings or dual-range switching are provided, the output voltage steps tend to be coarse. Remote control or continuous regulation



3.2 Tapped transformer-rectifier. Note that for clarity a single-phase circuit is shown (most industrial units are three-phase).



3.3 Moving-iron control transformer.

of the output are not feasible with this system, but it is often used for low-cost and light duty GMAW equipment.

3.3.2 Moving-iron control

An alternative technique for modifying the output of a transformer is to vary the magnetic leakage flux with a shunt as shown in Fig. 3.3. By controlling the position of the shunt, the amount of magnetic flux linking the primary and secondary coils is changed and the output varies (the output varies inversely with the amount of shunting). This method of control gives continuous variation of the output and movement of the shunt may be motorized to allow remote operation, but it is costly, subject to mechanical wear and the

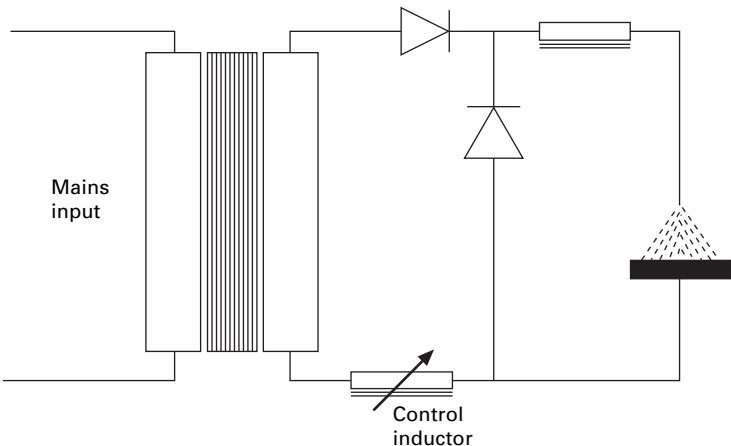
output can only be regulated slowly. The use of this type of control is now largely confined to small low-cost MMA power sources.

3.3.3 Variable inductor

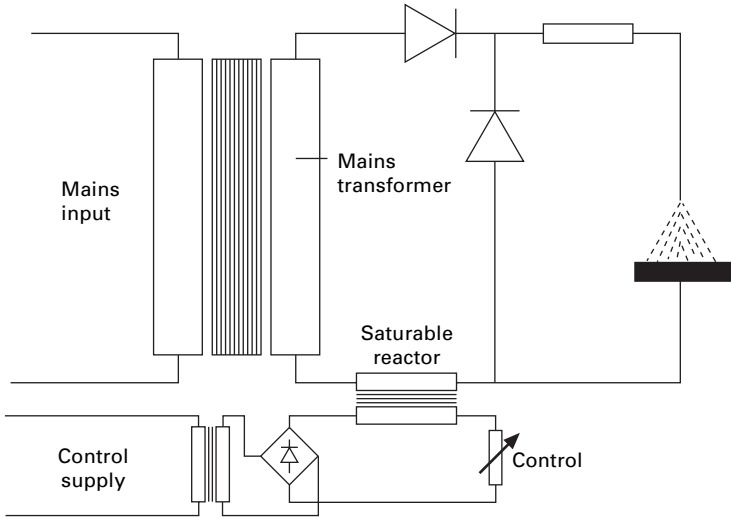
A variable or tapped inductor may be connected in the ac output circuit of the transformer to regulate arc current as shown in Fig. 3.4. Although continuous current adjustment may be achieved with this design, remote operation is not usually feasible and the high-current inductor is a large, costly item. A possible advantage of the design is that the inductance causes a phase-shift of up to 90° between AC current and voltage waveforms. This may improve arc re-ignition (with 90° phase-shift, the voltage will be at its maximum value when the current passes through zero). This design has been used in the past for MMAW and GTAW power supplies.

3.3.4 Magnetic amplifier

A magnetic amplifier or saturable reactor control is illustrated in Fig. 3.5. A coil fed with a variable DC current is wound around a magnetic core which also carries a winding from the AC output of the transformer. As the DC level in the control coil is increased, the average value of magnetic flux within the core increases towards the saturation level thus limiting the variation of the magnetic field and reducing the AC output. The technique allows continuous variation of the output, remote control and a certain amount of output waveform modification. The response rate of the system is, however, relatively slow, the DC control current can be fairly high (e.g. 10 A) and the saturable reactor is both bulky and expensive. Magnetic amplifier control has commonly been



3.4 Variable inductor control.



3.5 Magnetic amplifier control.

used for GTAW power sources although it has also been used in some GMAW equipment in order to obtain some measure of remote control.

3.3.5 Control of static and dynamic characteristics of conventional power supplies

The dynamic (e.g. rate of change of current, and instantaneous relationship between current and voltage) and the static characteristics (the relationship between the mean output current and voltage) of the power supply can have a significant effect on process performance. With conventional power sources, it is normal practice to use constant-current static characteristics for the GTAW process in order to obtain optimum striking and current stability, but constant voltage for GMAW in order to achieve self-adjustment. [25]² These characteristics are normally predetermined at the design stage and cannot be varied by the user. [26]

Dynamic characteristics can be adjusted electrically and, in GMAW welding, it is common to use a DC inductor in the power source output to control the rate of current rise during the short circuit in the dip transfer mode. Older GMAW equipment had continuously variable inductance control, but many equipment manufacturers now limit the range of adjustment by using a simple low-cost tapped inductor. The limited scope for adjustment of the dynamic

²A conventional variable slope/variable inductance unit has been developed but this is costly and complex. [25]

characteristics by the user simplifies the operation of the equipment and offers adequate control for many applications. It does, however, restrict the possibility of significant improvements in process performance.

3.4 Electronic power regulation systems

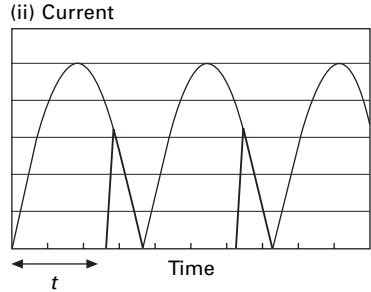
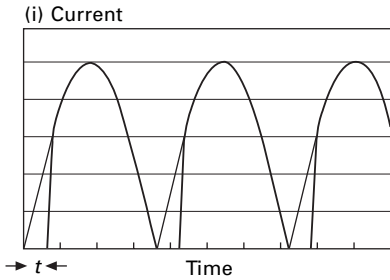
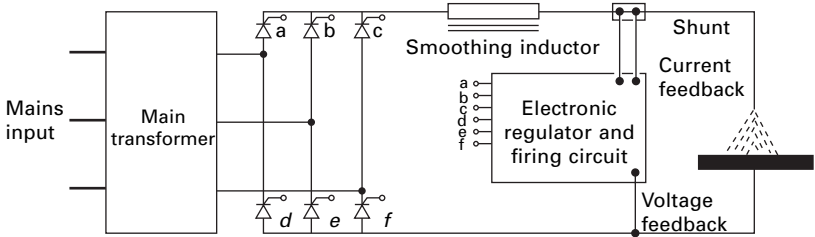
The availability of high-power semiconductors has led to the development of a range of alternative, electronic power source designs [27] which may be classified as follows:

- SCR phase control;
- transistor series regulator;
- secondary switched transistor power supplies;
- primary rectifier–inverter;
- hybrid designs.

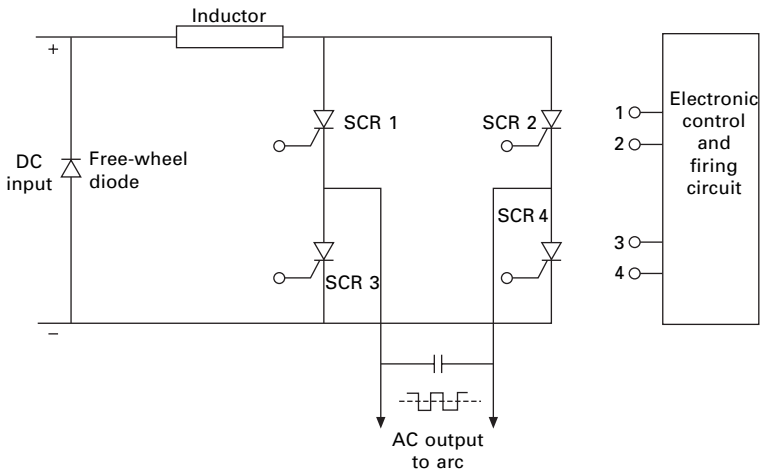
3.4.1 SCR phase control

Silicon-controlled rectifiers (SCRs) may be regarded as ‘switchable’ diodes. The device only starts to conduct in the forward direction when a signal is applied to the gate connection. Under normal circumstances the device cannot be turned off until the forward current falls to zero. These devices may be used instead of the normal diodes in the secondary circuit of a DC power supply. To regulate voltage output, the delay between the normal onset of conduction and the gate signal is varied (Fig. 3.6). If the amplitude of the voltage waveform is fixed, it is necessary to use a long firing delay to achieve low output levels and the ripple in the output waveform becomes severe. This problem may be reduced by using a three-phase SCR bridge, by using a large output inductance, or by using an inter-phase inductance. Alternatively, the SCR control may be placed in the primary of the transformer, in which case some smoothing is obtained from the transformer itself. The use of inductance in any of the forms described above is an effective means of smoothing, but it does limit the dynamic response of the power source.

An AC output may be obtained by using SCRs connected ‘back to back’, one set conducting in the positive half-cycle whilst another set conducts in the negative half-cycle. In addition, by using an inductor or an inverter circuit (Fig. 3.7), it is possible to produce a ‘square’ output waveform which offers process benefits in GTAW, MMA and SAW. The advantages of this type of control are its simplicity, robustness and the large amplification obtained that enables high output levels to be controlled by very low-level electronic signals. The speed of response of the system is limited by the necessity to cross current zero before a revised firing angle becomes effective; hence, the best response expected would be in the range of 3 to 10 ms.



3.6 SCR phase control circuit (three-phase) and controlled wave form for a single phase, a-f in the upper diagram are SCRs. The lower traces show the waveform from a single SCR: (i) small firing delay with high mean output; (ii) large firing delay with low mean output.



3.7 Simple secondary inverter for ac welding.

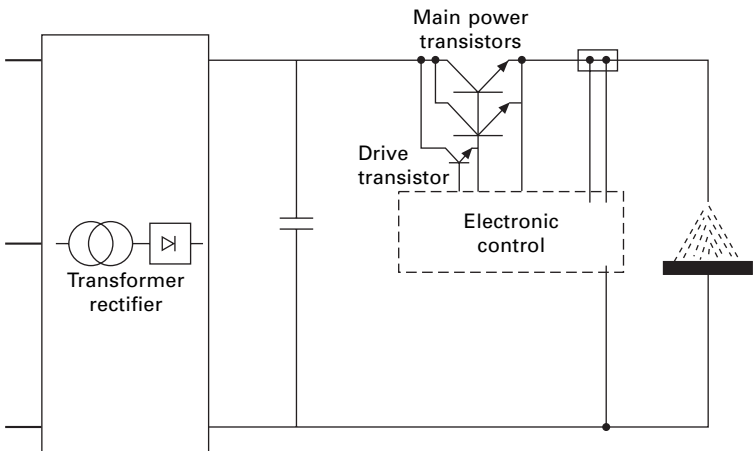
Even with the limitations of ripple and response rate, it is possible to produce power sources with significantly better performance than previous conventional designs and, in particular, it is possible to stabilize the output of the power source by means of feedback control. The SCR phase control

system has been used for DC MMA, GMAW, square-wave AC GTAW, [28, 29] GMAW and SAW power sources.

3.4.2 Transistor series regulator

The output of a transistor may be controlled by adjusting the small current flowing through its 'base' connection. The series regulator consists of a transistor in series with the DC welding supply, the output power being continuously regulated by means of the base current. It is usual to incorporate a feed-back control system to ensure output stabilization and an amplifier to supply the drive signal to the transistor (Fig. 3.8).

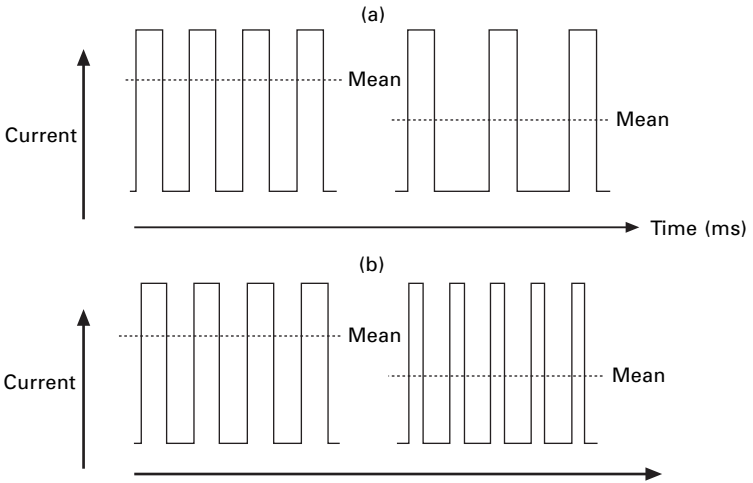
Until fairly recently, the capacity of individual transistors was limited and large banks of devices (connected in parallel) were necessary to handle typical welding currents. The recent availability of higher-power devices has, however, reduced this problem. The important characteristics of the transistor series regulator are its rapid response rate (the response time of transistors is measured in microseconds) and its 'ripple'-free output. [30] The main disadvantages of the system are the poor efficiency and high cost. The poor efficiency results from the dissipation of surplus power as heat from the devices, necessitating the use of water cooling for most applications. The equipment cost is a function of the number of devices used and the need to balance each transistor to ensure current sharing. The high response rate, accuracy and low ripple of this type of power supply make it suitable for small high-precision supplies and, particularly, for process research work. GTAW, GMAW and SAW units are available.



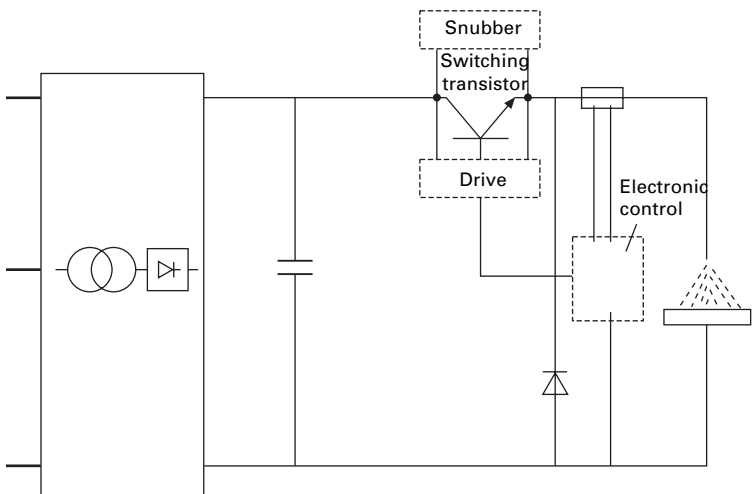
3.8 Principle of the transistor series regulator.

3.4.3 Secondary switched transistor power supplies

The high heat dissipation of the transistors in a series regulator results from their continuous operating mode. An alternative method of regulating the output is to switch the transistor on and off at a rapid rate; the mean output level is then a function of the ratio of on to off time (Fig. 3.9). Although the circuit design is very similar to that of the series regulator (Fig. 3.10) the process of switching the device in this way gives a significant improvement



3.9 Modulation techniques for control of output level: (a) frequency modulation, (b) pulsewidth control.



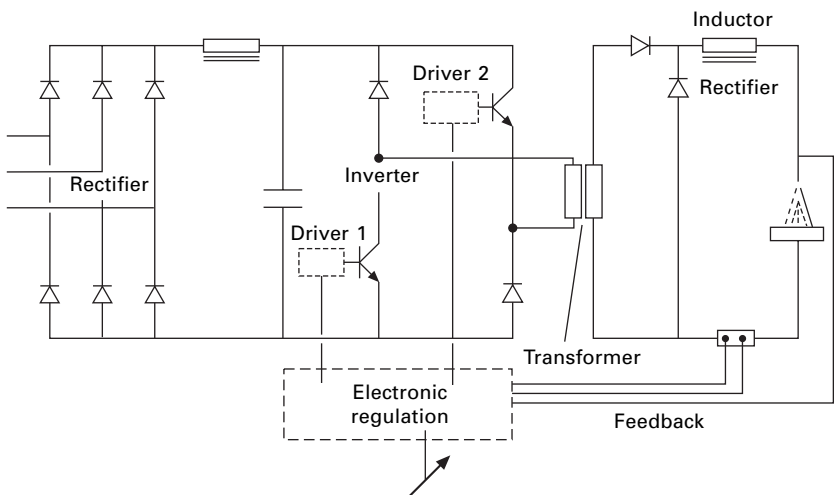
3.10 Circuit principle – switched control.

in efficiency and enables normal air cooling to be used. The chopped waveform appears at the output, but, if a sufficiently high switching rate is used, this does not have any detrimental effect on the process. Switching frequencies of 1000 to 25 000 Hz are commonly used. Response rate is also determined by the switching frequency but the higher-frequency supplies are capable of responding within a few microseconds, which is significantly faster than conventional supplies and approaching the rate achieved with series regulators. GMAW and GTAW power sources of this type are available and offer high precision at currents up to 500 A at an economical capital cost.

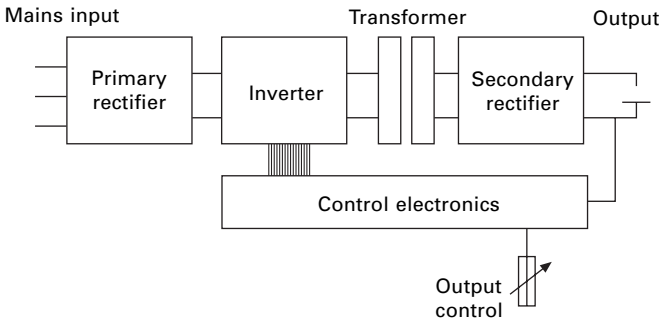
3.4.4 Primary rectifier–inverter

The methods of control outlined above use a conventional transformer to achieve the step down in voltage required for welding. This transformer operates at the incoming mains frequency of 50 Hz. The primary inverter design utilizes the fact that transformer size may be significantly reduced if its operating frequency is increased. The basic circuit is illustrated in Fig. 3.11 and the principle of operation in Fig. 3.12.

The primary AC supply is first rectified and the resultant high DC voltage is electronically converted by the inverter to high-frequency AC. Only at this stage does the supply enter the transformer. Since the frequency of operation is between 5 and 100 kHz, the transformer is small; furthermore output control is achieved by chopping or phase-shifting within the inverter and very high response rates are achieved. The transformer output must be rectified to avoid potential losses in the high-frequency AC circuit.



3.11 Typical inverter circuit.



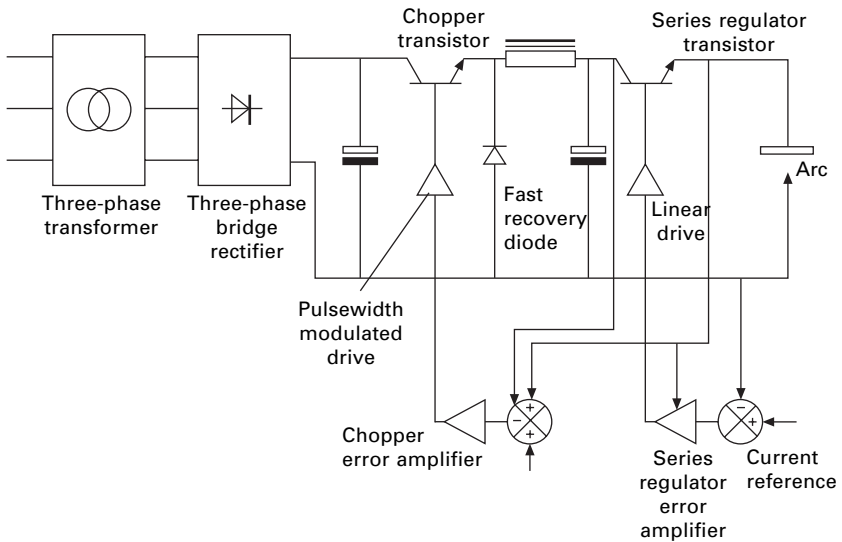
3.12 Primary rectifier–inverter.

The welding output is smoothed and stabilized and, although it is not possible to achieve the same response rates as those obtained with the series regulator, it is possible to produce the output characteristics required for recent process control developments. This type of circuit was initially used for MMA power sources, but it is now being employed for GTAW and pulsed GMAW units. It has particularly good electrical efficiency and a comparison of inverter and conventional power sources at current settings of 250 A has shown that idle power consumption is only one-tenth of that of a conventional machine and, during welding, the efficiency is around 86% compared with 52% for a conventional unit. [31, 35]

3.4.5 Hybrid designs

It is possible to combine the electronic control techniques outlined above to improve the performance and cost effectiveness of the power source. For example, the use of a secondary chopper to pre-regulate the supply followed by a small air-cooled transistor series regulator for final control of the output has been described, [32] the circuit is shown schematically in Fig. 3.13 and the advantages of this approach are summarized in Table 3.1. Hybrid designs may also be adopted to produce a square-wave AC output by adding a secondary inverter to the output of a DC phase-controlled unit. SCR phase-controlled power sources may be used in conjunction with an SCR inverter [33] or, alternatively, the system may be based on an integrated primary rectifier–inverter design. Sophisticated experimental hybrid units have been developed, for example for high-frequency AC plasma welding, [34] in order to investigate potential improvements in process control.

Alternative power devices such as asymmetrical SCRs (ASCRs) [35] or metal oxide–silicon field-effect transistors (MOSFETS) may also be used to improve the efficiency of conventional electronic and hybrid systems.



3.13 Hybrid chopper/series regulator power source for GTAW [32] (courtesy PEC Ltd).

Table 3.1 Comparison of series regulator and hybrid systems for 300A GTAW power supply

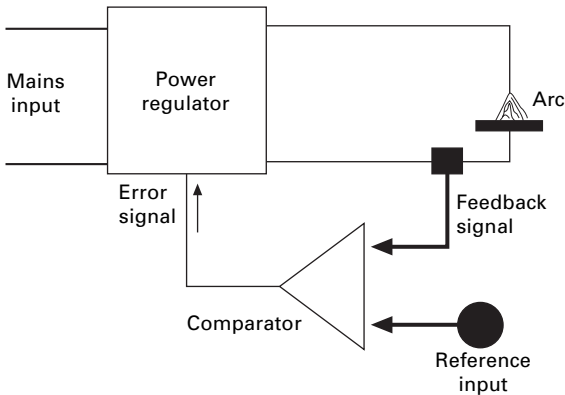
Feature	Hybrid chopper – series regulator [30]	Conventional series regulator
Maximum dissipation	2 kW	8.5 kW
Transistors	Four high current devices	>100 low current devices
Ripple	<2 A peak/peak	<1 A peak/peak
Overall cost	Low device and assembly cost	Very costly – labour-intensive construction
Response	Max 150 kHz, 1 ms rise time	Max 1 Hz, 100 μ s rise time
Accuracy	Better than 1% of maximum current	Better than 1% of maximum current
Chopping frequency	1.5 Hz	N/A

3.4.6 Features of electronic power source designs

The electronic designs all share a capability for remote control and are easily interfaced with system controllers within the power supply or from an external source. The output response, accuracy and repeatability are generally considerably better than those achieved with conventional electromagnetic control systems, and the features of the various designs are summarized in Table 3.2.

Table 3.2 Features of various power source designs

Power source type	Output characteristics	Electrical efficiency	Physical characteristics	Relative cost	Applications
Conventional tapped transformer–rectifier, moving iron, variable inductor, magnetic amplifier etc.	Fixed at design stage, slow response rate, no mains voltage stabilisation	Fair – but magnetising current and thermal losses in transformer	Relatively heavy and industrial duty units are large but robust and reliable	1	Manual GMAW, MMAW, GTAW. Hobby units and general purpose fabrication
SCR phase control	Electronically variable within response limits of switching system. Mains stabilised but high ripple especially at low output	Fair	May be more compact than conventional design due to reduction of magnetic (wound) components	4	Manual and mechanised GMAW/GTAW and manual MMAW. Medium to high quality fabrications
Transistor series regulator	Very fast response, flexible control, waveform control, accurate, ripple free, repeatable	Poor	Fairly large, may be water cooled	6	High quality mechanised and automated GMAW and GTAW. Precision engineering and R&D
Primary rectifier–inverter	Fast response, variable output, stable and repeatable	Very good	Compact – electronically complex	3	Medium to high quality manual and automated, multiprocess
Hybrid and secondary chopper	Fast response, variable output, stable and repeatable	Very good	Medium size, air cooled	4	Medium to high quality manual and automated, multiprocess



3.14 Principle of feedback control.

It is not possible to select an ideal design from this list, but series regulator designs are often only justified for very-high-precision and research applications, whilst primary inverter-based designs are cost effective and suitable for a wide range of production tasks. One important characteristic that all of these systems share is the use of feedback control.

Feedback control

Feedback control is a useful technique which can be applied most effectively with electronic power sources. The basis of the technique is illustrated in Fig. 3.14; the output of the system is measured and compared with the desired output parameters, any difference between the two values will cause an 'error' signal to be generated and the feedback system then adjusts the output to correct the imbalance. Although this type of control may be applied to conventional power source designs, it is usually costly, complicated and too slow. Hence, most conventional power sources have 'open-loop' control, i.e. if the input varies, the output changes by a proportional amount. The higher response rates and low signal levels available from electronic control systems make 'closed-loop' or feedback control effective and economical and give inbuilt stabilization of output.

3.5 Output level, sequence and function control

For most welding processes, a prescribed sequence must be followed when initiating or terminating the process. In addition, it may be necessary to control the rate of current rise or decay and modulate the output during welding. The extent to which these features could be provided has in the past been limited by conventional power source design technology and the use of

relay logic and electrical control techniques. Two new approaches have now been adopted in order to improve the flexibility and accuracy of sequence control, these are:

- the use of discrete electronic control;
- microprocessor control.

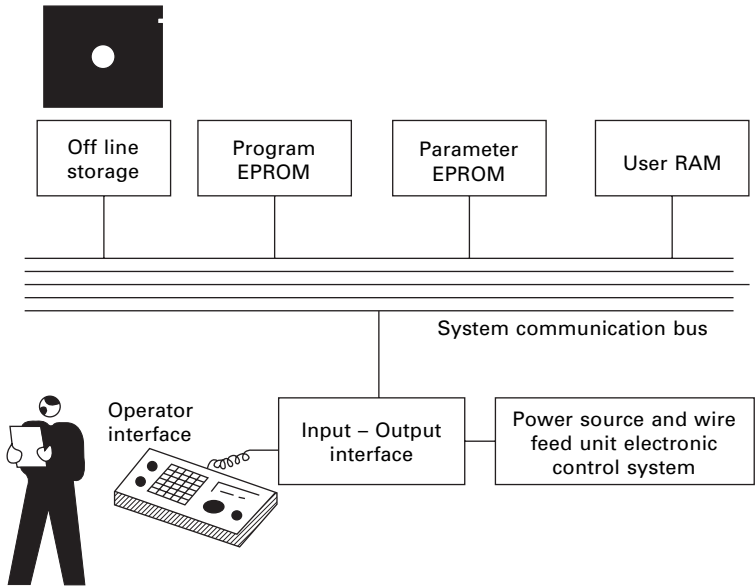
3.5.1 Discrete component electronic control

The control signal levels required to 'drive' the electronic power regulation circuits described above are usually small and may be derived from electronic logic circuits. These circuits may be configured to perform the most complex tasks using standard analogue and digital components (such as timers, programmable logic arrays, power regulators, operational amplifiers and comparator circuits) which are packaged in single chips. The performance of these systems is far better in terms of cost, speed, accuracy and long-term reliability than the previous relay logic designs. In general, however, discrete electronic control circuits are custom designed for a specific power source and the facilities and range of operation are fixed at the design stage. The flexibility of discrete electronic circuit designs has been increased by the storage of welding control parameters on electrically programmable read only memory (EPROM) chips, which may be easily programmed by the manufacturer of the equipment and replaced when improved process parameters are developed or new facilities are added.

3.5.2 Microprocessor and digital signal processor control

The alternative approach, using microprocessor control, can allow much more flexibility and many additional facilities may be provided. A single microprocessor chip can control both the sequence of welding and regulation of the output power.

The schematic design for a microprocessor control system is illustrated in Fig. 3.15. The microprocessor carries out a series of instructions and calculations sequentially, but certain important tasks may be given priority over less important tasks, for example it may be required to check the output current level once every 0.3 ms when welding is in progress, but the status of certain front-panel controls may be ignored unless welding ceases. The effectiveness of this type of system for real-time control of the output depends on the resolution of the analogue-to-digital converters, the operating speed of the microprocessor (the clock rate) and the design of the software. A typical system using a clock rate of 12 MHz and 10-bit analogue-to-digital converters is able to check and correct any deviations in output every 0.3 ms and maintain the current within 1 % of the desired level.



3.15 Microprocessor control system.

It is common now to use a particular form of microprocessor which is known as a digital signal processor (DSP). The specifications of these devices vary, but often include all the peripherals required for monitoring and control as well as communication facilities for external interrogation of the system as discussed in Chapter 2. They provide a reliable and cost effective means of achieving sophisticated control and facilitate the synergic control systems mentioned later in Chapter 7.

Although the dedicated microprocessor control approach does not allow complete design flexibility (the software will often represent a significant investment and revisions may be costly), the designer can build in the ability to change certain parameters based on a knowledge of the welding process requirements. This may be used to simplify the operation of the equipment or to provide the user with the ability to reprogramme key process variables.

3.5.3 Programming and one-knob control

The concept of a single adjustment knob for 'complex' parameter setting, for example in the GMAW process, is not new and power sources using preset wire feed and voltage controls and a single condition selector switch were available in the mid 1970s. However, without electronic feedback control, novel, but unreliable, methods of mains voltage stabilization had to be employed. With electronic power regulation and feedback control power sources may be programmed by the supplier or the user with reliable 'optimum'

welding conditions. Programming and storage of welding parameters is made even easier if microprocessor control systems are used as described above.

3.5.4 External computer control

Control of electronic power sources by means of an external micro-computer has also been used. This has mainly been for research applications where a wide range of process variables are under investigation, but many microprocessor-controlled power sources now have the facility to communicate with a host computer using standard serial communications protocols (RS232, RS423, USB, CAN, etc). This allows welding parameters to be ‘downloaded’ to the equipment as well as facilitating remote control and monitoring. This technique may also be used in production applications and the robotic system being developed for remote-controlled repair welding of turbine runners is a good example of this approach.

3.6 Practical implications of electronic power regulation and control

The changes in the technology of welding power sources described above have some significant practical implications: the power sources can be manufactured using modern electronic assembly techniques and the dependence of these designs on expensive raw materials, such as iron for transformer cores and copper for the windings, is reduced. This should enable the manufacturers of these more advanced power sources to offer them at costs similar to those of conventional designs. These designs also offer the user the following advantages:

- improved repeatability;
- increased ease of setting;
- enhanced process capabilities.

Improved repeatability has a direct impact on the quality of the welded joint and the ability to maintain welding parameters within the range specified in the welding procedure, and is likely to reduce the repair and rework costs discussed in Chapter 2. The increased ease of setting should improve the operating efficiency and reduce the risk of operator error. The enhanced process capabilities result from the ability to change various process output parameters of an electronic power supply during welding. The output characteristics are not predetermined and may be varied (within the limits of the transformer output) to produce beneficial effects. For example, in the case of GMAW, constant-current output characteristics may be used for improved control and the output may be modified dynamically to provide self-adjustment. In MMA welding systems, the current may be increased

instantaneously at low voltages to prevent electrode 'sticking'. These characteristics will be discussed in more detail in the following chapters. In order to make effective use of electronic power supplies the user will, however, need to consider service support and training. The skills required for repairing and maintaining this type of equipment are not the same as those needed for conventional electromagnetic power sources.

3.7 Summary

Conventional power source designs continue to be viable for simple, robust low-cost applications. A tapped transformer/rectifier GMAW machine is, for example, approximately 60% cheaper than an electronic unit of the same current rating. However, the electronic power source designs usually offer improved capabilities in terms of output consistency and flexibility as well as providing the possibility of enhanced process control. [36]

Advanced welding power supplies use a range of electronic power regulation techniques and either discrete component electronic circuitry or microprocessor control of the operating sequence and output level.

4.1 Introduction

Some of the more important consumables used in the fusion welding processes are:

- coated electrodes for MMAW welding;
- wires and fluxes for SAW;
- filler wires for GMAW and FCAW.

The design and formulation of consumables for the traditional welding processes such as MMAW and SAW have continued to evolve largely in response to the need to match improvements in the properties of new materials, but also to enhance the operating tolerance and stability of the processes. Filler wires for the continuous-feed consumable electrode processes such as GMAW have changed little, but significant progress has been made in the development and application of flux-cored wires.

4.2 MMAW consumables

An extensive range of MMAW consumables is now available covering the joining requirements of the more important engineering materials as well as repair, surfacing, cutting and gouging electrodes (see Appendix 2). The main developments that have taken place in these consumables have been in the following areas:

- improved toughness;
- improved hydrogen-controlled electrodes for ferritic steel;
- improved performance stainless-steel consumables.

MMAW has been used extensively in the shipbuilding, defence, offshore, and power-generation industries for the fabrication of carbon-manganese and low-alloy steels. The achievement of good toughness and resistance to hydrogen-induced cold cracking are important considerations in these applications.

4.2.1 Improved toughness

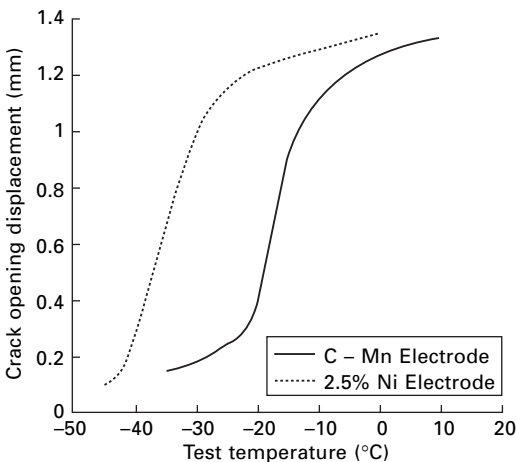
Many structures, particularly in the offshore and cryogenic industries, are expected to operate at temperatures well below 0 °C. Considerable improvements in weld metal toughness of ferritic materials at temperatures below -40 °C have been obtained by control of electrode formulation and the addition of nickel. [37] The effect of this improvement on the notch toughness of a series of ferritic MMA electrodes is shown in Fig. 4.1. [38]

4.2.2 Improved hydrogen control

Hydrogen-induced or hydrogen-assisted cold cracking (HICC or HACC) has been a significant problem with low-alloy and higher-carbon steels, particularly when thicker sections are welded. Control of the hydrogen content of the weld metal may be used to avoid this problem and this control may in turn be improved by electrode formulation, storage and packing. [39] Particular attention has been given to limiting the re-absorption of moisture (the main source of hydrogen) by the electrode coating, which is achieved by careful selection of the coating constituents and special packaging. Basic hydrogen-controlled electrodes that will give weld metal hydrogen contents of less than 50 ml kg⁻¹ with ambient conditions of 35 °C and 90% humidity for up to ten hours after opening the packaging are now available. [40]

4.2.3 MMA electrodes for stainless steel

The operating performance of common austenitic stainless steel MMA electrodes has been considerably improved by the introduction of rutile (TiO₂)



4.1 Improvements in notch toughness for MMA consumables. [38]

based flux coatings. These coatings give improved arc stability and excellent weld bead surface finish. Electrodes have also been developed for the fabrication of the new corrosion-resistant alloys and, in particular, duplex and high molybdenum stainless steels. [41]

4.3 Submerged arc welding consumables

The submerged arc process is well established and a standard range of wires and fluxes has been devised for the most common applications. Two important advances in the process have been realized by:

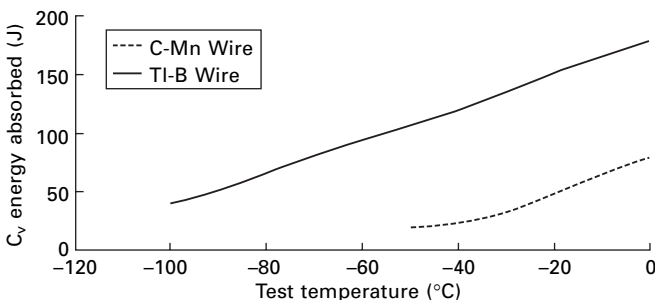
- the development of high-toughness consumables;
- the use of iron powder additions.

4.3.1 High-toughness consumables

Higher-toughness consumables have been developed in response to the requirement for reasonable impact properties down to $-40\text{ }^{\circ}\text{C}$ for offshore structures. This has been achieved by the use of wires which are micro-alloyed with titanium and boron and a semi-basic flux. [42] Typical Charpy-V notch curves showing the improvement in toughness compared with a conventional SD3 molybdenum wire are shown in Fig. 4.2. [43]

4.3.2 Addition of iron powder

The addition of iron powder to the submerged arc weld increases the deposition rate of the process by more than 60% [44–46] as well as offering improvements in weld metal quality. The technique takes advantage of the fact that excess arc energy is normally available in submerged arc welding; this usually results in increased melting of the parent plate and high levels of dilution. If a metal powder is added to the weld pool, some of the arc energy is dissipated in melting this powder and the additional metal which results improves the



4.2 High-toughness SAW consumables: lower bound Charpy-V impact transition curves for different SAW wires. [43]

joint completion rate. Unlike other methods of increasing the productivity of the process, this technique reduces the heat input to the parent plate and resultant thermal damage in the HAZ (heat-affected zone).

Iron powder may be added to the joint in three ways:

- pre-filling the joint before welding;
- using a forward-feed system;
- magnetic feeding on the wire surface.

Using the pre-filling technique, it has been found [47] that a considerable reduction in overall heat input may be obtained as well as a significant improvement in productivity. This could be particularly advantageous for fine-grained, high-strength low-alloy steels since it limits the adverse effects of high heat inputs on the thermo-mechanical treatment which is used to obtain the improved properties.

The technique has been applied to the fabrication of high-toughness steels for offshore applications and, using the forward-feed system, a basic flux and a 1.7% Mn wire Charpy-V notch, values of 173 J at -40°C have been reported [39] for a 50 mm thick single-V butt weld in a typical fine grain steel (BS 4360 50DD).

4.4 Filler wires for GMAW and FCAW

Increased utilization of the GMAW process has prompted some development of solid wire consumable/shielding gas packages, but the most significant developments in this area are related to flux cored consumables. [48]

4.4.1 Solid filler wires for GMAW

Solid filler wires usually have a composition which is nominally the same as the material being joined. Minor chemical changes, for example additions of deoxidants, have been shown to enhance transfer and bead shape but scope for change in this area is limited. Although early attempts were made to improve metal transfer by surface treatment, [49] this is not normally practicable due to the likelihood of surface coating damage.

Recent work on rare-earth (cerium) additions to the filler wire indicates that transfer of steel wires in pure argon can be improved, but this is of little practical significance unless very low levels of weld metal oxygen are being sought, (e.g. in the welding of 9% Ni steel with matching fillers). Oxidation of the metal as it transfers across the arc may reduce the level of certain alloying elements and this will, in turn, depend on the oxidation potential of the gas and the reactivity of the element involved.

It has also been found [50] that very small changes in the residual chemical composition of ferritic steel wires can have a marked effect on low-temperature

toughness. These changes are insufficient to affect the weld metal property requirements for most applications, but may be significant in critical low-temperature and cryogenic joints.

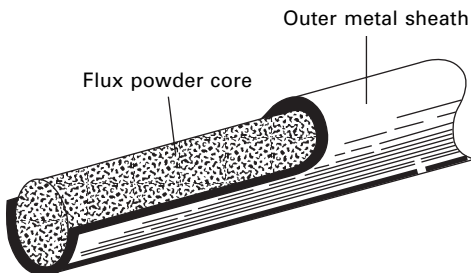
In carbon steel wires, it has been found that excessively thick copper coating can cause feedability problems, and it was feared at one time that copper fumes from the coating might represent a health hazard. As a result uncoppered wires became available. These wires give good feedability, by virtue of a surface lubricant, and it has been demonstrated [51] that they can reduce breathing zone fume levels. However, higher contact tip wear has been suggested to be a potential problem. It is now common for copper coating thickness to be controlled to a relatively thin layer and it has been demonstrated that this overcomes fume and feedability problems.

4.4.2 Flux-cored wire

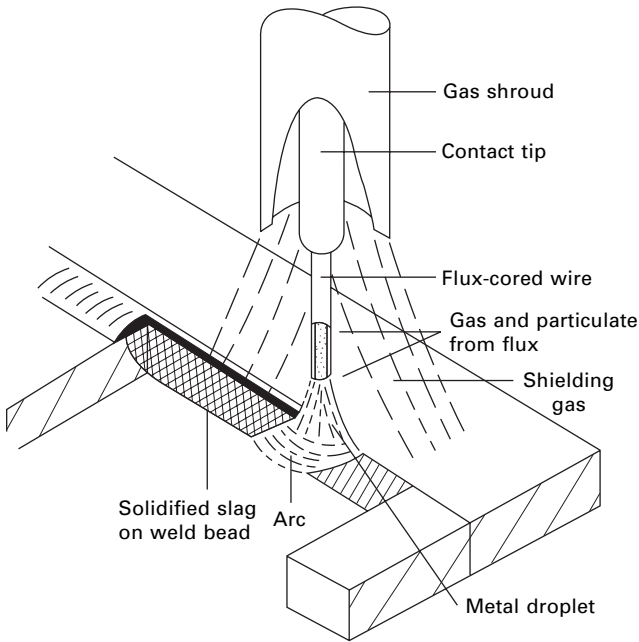
Flux-cored wires consist of a metal outer sheath filled with a combination of mineral flux and metal powders (Fig. 4.3). The FCAW process is operated in a similar manner to GMAW welding and the principle is illustrated in Fig. 4.4. The most common production technique used to produce the wire involves folding a thin metal strip into a U shape, filling it with the flux constituents, closing the U to form a circular section and reducing the diameter of the tube by drawing or rolling.

The production process is illustrated diagrammatically in Fig. 4.5. The seam is closed during the reduction process. Alternative configurations (Fig. 4.6) may be produced by lapping or folding the strip or the consumable may be made by filling a tube with flux followed by a drawing operation to reduce the diameter. Typical finished wire diameters range from 3.2 to 0.8 mm. Flux-cored wires offer the following advantages:

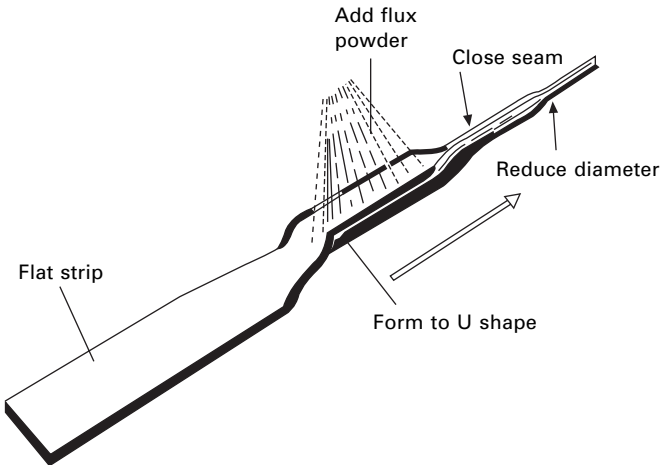
- high deposition rates;
- alloying addition from the flux core;
- slag shielding and support;
- improved arc stabilization and shielding.



4.3 Construction of a flux-cored wire.



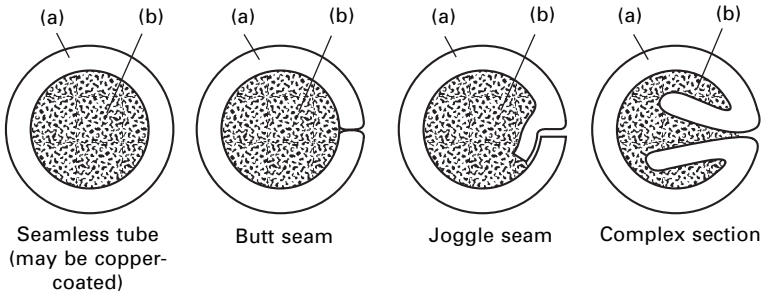
4.4 Principle of operation of FCAW.



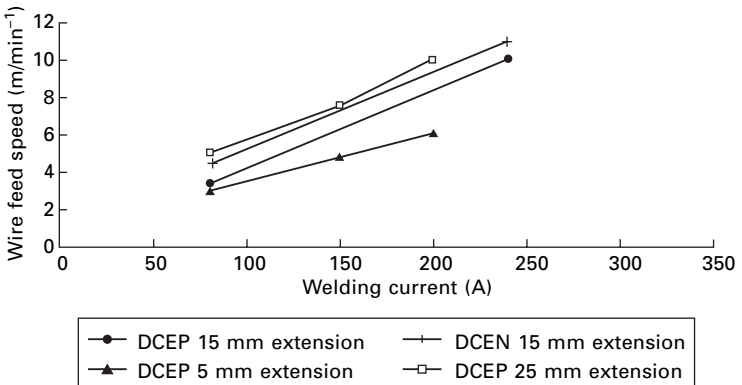
4.5 Production of a flux-cored wire.

Deposition rate

The deposition rate will be substantially higher than that normally achieved with MMAW and marginally better than that obtained with a solid wire GMAW. This increase in deposition rate is attributable to the increased current



4.6 Alternative configurations for flux-cored wires (a) outer sheath, (b) flux powder.



4.7 Effect of polarity and electrical extension on the burn-off rate of a basic flux-cored wire.

density and the fact that all of the current is carried by the sheath. The deposition rate will, however, depend on the thickness and resistivity of the sheath material, the polarity and the electrode stick-out (Fig. 4.7). The melting rate MR of a flux cored wire may be expressed as:

$$MR = k + \alpha I + \frac{\beta I l^2}{A} \tag{4.1}$$

where k , α and β are constants, I is the mean current, l is the stick-out length and A is the cross-sectional area of the conductor. The term αI represents arc melting whilst the $\beta I l^2/A$ term indicates the resistive heating in the wire extension. (For typical burn-off curves which illustrate this relationship, see Appendix 3). It is obvious from this equation that significant increases in burn-off rate may be achieved by increasing the wire extension and the operating current.

Alloying addition

The range of compositions of solid GMAW wires is limited by the technical and commercial difficulties involved in producing relatively small quantities of special compositions. Flux-cored wires can, however, be modified by minor adjustments in the flux formulation to produce a range of weld metal compositions and operating characteristics. The range of compositions currently available for plain carbon and alloy steels (the Australian, UK and US specifications for flux-cored welding consumables are summarized in Appendix 4) is similar to that for MMA electrodes; with rutile (TiO_2) based formulations for ease of operation, basic (CaO) high-toughness, hydrogen-controlled formulations and metal powder cores for high recovery and low slag formation.

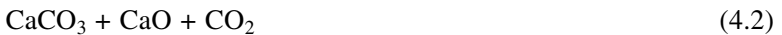
It is also possible to extend this technique to produce low-cost austenitic stainless steel or highly alloyed hardfacing deposits from wires with a plain carbon steel sheath.

Slag shielding and support

The solidification characteristics of the slag may be designed to enhance the performance of the process. For example, a fast freezing rutile slag may be used to support the weld pool in vertical or overhead welding enabling higher operating currents, improved productivity and better fusion characteristics to be obtained. Alternatively, the slag characteristics may be adjusted to provide additional shielding and control of bead shape. This is particularly important in the case of the stainless-steel consumables discussed below.

Arc stabilization and shielding

The decomposition of the flux constituents may be used to generate shielding gases as in MMA welding, for example CO_2 may be produced by the decomposition of calcium carbonate



Arc ionizers may also be added to the flux to obtain improved running characteristics and arc stability. It is possible using these techniques to produce electrodes that operate with alternating current or DC electrode negative and this may have beneficial effects on the melting rate and weld bead properties.

4.4.3 Modes of operation

Flux-cored wires may be operated successfully with or without an additional gas shield.

Self-shielded operation

In self-shielded flux-cored wires, the flux must provide sufficient shielding to protect the molten metal droplets from atmospheric contamination as they form and transfer across the arc. Since some nitrogen and oxygen pick-up is inevitable the weld metal chemistry is often modified to cope with this (by adding aluminium for example). In addition to this shielding action, the flux must also perform arc stabilization, alloy addition and slag control functions. Formulation of suitable flux compositions is consequently more difficult, but several successful consumable designs are available. These self-shielded wires do have benefits for site use where moderate side winds are experienced, but the demands on the design of flux may be reflected in poorer process tolerances; for example, for some positional structural wires, the operating voltage range must be held within ± 1 V of the recommended level to produce the required mechanical properties and prevent porosity. These constraints are reduced if an additional shielding gas is used.

Gas-shielded operation

Auxiliary shielding may be provided if a conventional GMAW torch is used. For steel it is common to use either CO₂ or argon/CO₂ mixtures for this purpose; this allows the positional performance, mechanical properties and process tolerance to be improved and, in spite of the additional cost of the shielding gas, the overall cost of the process may often be reduced.

4.4.4 Types of flux-cored consumable

The following groups of flux-cored wires have been developed:

- plain carbon and alloy steels;
- hardfacing and surfacing alloys;
- stainless steel.

Plain carbon and alloy steels

Details of some of these wires are listed in Appendix 5, but for discussion they may be subdivided into:

- rutile gas-shielded;
- basic gas-shielded;
- metal-cored-gas-shielded;
- self-shielded.

Rutile gas-shielded

Rutile gas-shielded wires have extremely good running performance, excellent positional welding capabilities, good slag removal and provide mechanical properties equivalent to or better than those obtained with a plain carbon steel solid wire. By alloying with nickel, good low-temperature toughness (e.g. 100 J at $-40\text{ }^{\circ}\text{C}$) may be achieved.

Basic gas-shielded

Basic gas-shielded wires give reasonable operating performance, excellent tolerance to operating parameters and very good mechanical properties. Alloyed formulations for welding low-alloy and high-strength low-alloy steels are available. The positional performance of these wires, particularly in the larger diameters, is not as good as that of the rutile consumables.

Metal-cored-gas-shielded

Metal-cored wires contain very little mineral flux, the major core constituent is iron powder or a mixture of iron powder and ferro-alloys. These wires give very smooth spray transfer in argon/ CO_2 gas mixtures, particularly at currents around 300 A although they may also be used in the dip and pulse modes (see Chapter 6) at low mean currents. They generate minimal slag and are suitable for mechanized applications.

Self-shielded

Self-shielded wires are available for general-purpose downhand welding and positional welding and a limited range of wires are available for applications which require higher toughness. As in the rutile wires, the higher toughness requirements are usually met by alloying with nickel. Considerable use has been made of these consumables in offshore applications, [52] where it has been demonstrated that by close control of the operating parameters consistently high toughness values may be achieved under site conditions.

Hardfacing and surfacing alloys

A wide range of hardfacing and surfacing alloys are produced in the form of flux-cored wires. (A summary of the normal range of hardfacing consumables is provided in Appendix 5). These include plain carbon steels, austenitic stainless steels, alloys containing high chromium and tungsten carbide and nickel- and cobalt-based consumables. Many of these wires are self-shielded and intended primarily for site use. The running performance is not normally

as good as that found in the constructional wires described above due to the increase in the ratio of alloying elements to arc stabilizers in the core material, but they provide a cost-effective means of depositing wear- and corrosion-resistant material.

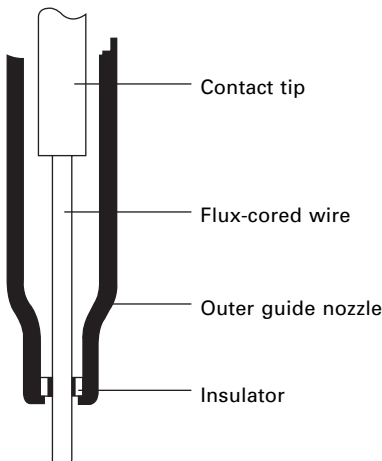
Stainless steel

Stainless steel flux-cored wires have also been introduced and matching consumables are available for most of the common corrosion-resistant materials. Both gas-shielded metal-cored and rutile-based formulations are available with the latter giving exceptionally good operating characteristics, wide process tolerance, low spatter and excellent surface finish.

4.4.5 Practical considerations

Gas-shielded flux-cored wires are often easier to use than the solid wire GMAW process, but certain differences exist in operating technique. The sensitivity of these consumables to stick-out has been indicated above. Long electrode extensions give higher burn-off rates, but the permissible extension may be limited in the case of gas-shielded wires by loss of effective secondary shielding. In the case of self-shielded wires, where exceptionally long wire extension may be required to achieve high deposition rates, an insulated guide incorporating fume extraction may be recommended (Fig. 4.8).

Very short extensions may be undesirable; for example, it has been found that with rutile wires designed for positional use, the combination of fast-freezing slag and excess surface lubricant on the wire can cause surface



4.8 Insulated extended electrode guide and fume extraction system.

porosity (referred to as ‘worm tracks’) if short electrode extensions are used, particularly in the downhand position. Increasing the extension allows the excess lubricant to be driven off and avoids the problem. Short electrode extensions are also associated with higher weld metal hydrogen levels. For manual operation, the minimum extension may be controlled by the relative position of the gas shroud and contact tip as shown in Fig. 4.9. The equipment required for flux-cored wire operation is basically the same as that required for GMAW welding, although, for the less tolerant types of self-shielded consumable, a voltage stabilized power source may be specified (the electronic designs discussed in Chapter 3 will meet this requirement). For all flux-cored wires, it is important to use specially designed feed rolls to avoid crushing the wire in the feed system.

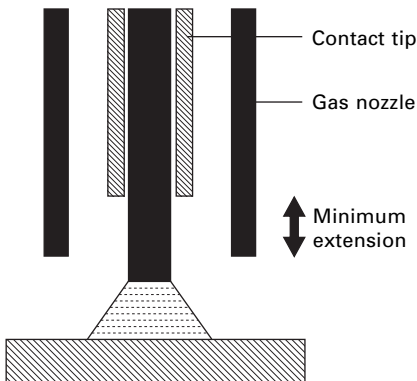
4.4.6 Applications of FCAW

The applications of flux-cored wires include the joining of thick-section high-strength steels for critical applications as in high-speed mechanized welding of lighter sections using metal-cored wire or the fabrication of high-quality stainless-steel process plant.

4.4.7 Limitations of flux-cored wires

The apparent limitations of flux-cored wire are:

- cost;
- fume;
- consistency of the consumable.



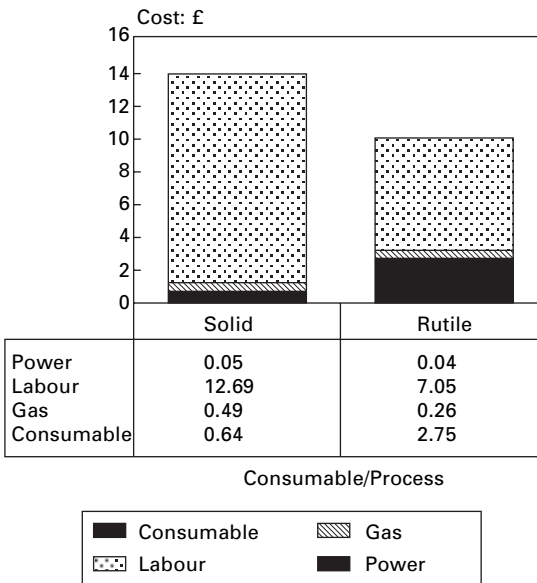
4.9 Limiting the minimum electrode extension by means of contact tip to gas nozzle adjustment.

Cost

The cost of flux-cored wires may be four times that of a solid wire, but this must be considered in the light of potential improvements in productivity and the fact that the cost of consumable represents a relatively small part of the total fabrication cost (see Chapter 2). In fact, the use of a flux-cored wire can often reduce the total cost; for example, in trials on a vertical V butt joint in 25 mm thick BS 4360 50D material [53] it was found that the use of a rutile flux-cored wire enabled a saving of 28% in the cost of the joint compared with GMAW welding with a solid wire. The saving resulted from a decrease in labour costs due to the increased welding speed (the flux-cored wire could be used at a higher mean current). The results of these tests are shown in Fig. 4.10.

Fume

Due to the high burn-off rate, the presence of mineral flux constituents and the continuous mode of operation, it is inevitable that flux-cored wires will produce more particulate fume than either MMA or GMAW welding with a solid wire. Whilst most of this particulate may be considered to be fairly



4.10 Cost savings produced when a rutile flux-cored wire is used for vertical butt joints. Costs of 300 mm test weld calculated using 'Symphony' spreadsheet.

inert dust, some of the consumables and flux constituents give rise to substances that are thought to be toxic; hexavalent chromium from chromium-bearing consumables and barium compounds found in the fume of some self-shielded wires are the main areas of concern.

The level of both the particulate fume and, in particular, potentially toxic substances must be controlled to comply with health and safety requirements and this is normally achieved by means of simple local fume extraction.

Consistency of the consumable

The manufacture of flux-cored consumables is more complex than the manufacture of solid wires, but similar to that involved in the production of MMAW electrodes. It is important that the flux core is chemically homogeneous and evenly distributed throughout the consumable. It is also important that the surface of the wire is clean and free from excess drawing lubricant. Although these requirements presented a problem in early consumables the introduction of improved manufacturing techniques and on-line quality monitoring [54] now ensures that consistent consumable properties are maintained.

4.5 Summary

There have been steady improvements in consumables for MMAW, SAW and GMAW welding. The introduction of high-toughness, moisture-resistant low-alloy steel and enhanced-performance rutile-coated stainless steel MMA electrodes, iron powder addition and Ti–Bo microalloyed wires for SAW and the use of low-residual wires for GMAW are useful examples of this evolutionary process. The introduction and exploitation of FCAW is perhaps more remarkable as indicated by the application trends that have been discussed in Chapter 2.

5.1 Introduction

Shielding gases are an essential consumable in many of the more recently developed welding processes, for example:

- as the primary shielding medium in GTAW, GMAW, plasma and gas-shielded FCAW;
- gases for laser formation, shielding and plasma control in laser welding.

5.2 Shielding gases for arc welding processes

The primary functions of the shielding gas in the arc welding processes are to provide a suitable medium for the stable operation of a sustained low-voltage arc and to provide shielding from atmospheric contamination. Secondary, but equally important, functions include the control of weld bead geometry and mechanical properties.

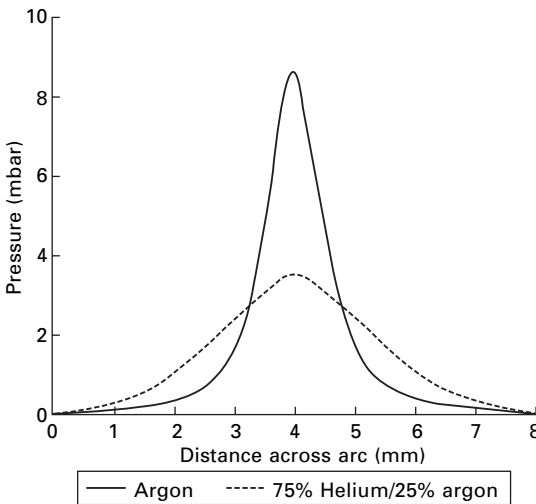
5.2.1 Arc support and stability

The arc is sustained by the flow of current in an ionized gas. The ease of ionization of the gas will therefore influence the ability to initiate and maintain the arc. The ease of ionization is indicated by the ionization potential of the gas and values for the common gases are given in Table 5.1. Argon, in particular, has a low ionization potential and is commonly used in the TIG process.

The thermal conductivity of the gas will also influence the arc stability; a high thermal conductivity may result in a reduction in the diameter of the conducting core of the arc and this can lead to an increase in voltage and a reduction in arc stability. Hydrogen, which has a lower ionization potential but a higher thermal conductivity than argon, increases the arc voltage when

Table 5.1 Basic properties of common shielding gases

Element	First ionisation potential	Density (kg m^{-3})
Argon	15.75	1.784
Helium	24.58	0.178
Hydrogen	13.59	0.083
Nitrogen	14.54	1.161
Oxygen	13.61	1.326
Carbon dioxide	(14.0)	1.977



5.1 Pressure distribution for GTAW (150 A) with 3 mm arc length. [56]

mixed with argon and may affect both arc stability and arc initiation if more than 8% is added.

Arc stiffness is usually regarded as beneficial in low-current GTAW arcs but as the current increases the force on the weld pool increases and this may result in undercut. It has been shown, [55] however, that helium-rich gas mixtures produce a significantly lower arc force which may be beneficial at high currents (Fig. 5.1 [56]). Arc stability in GMAW and FCAW arcs is largely dependent on the mode of metal transfer, which, in turn, is influenced by the effect of the gas on the surface tension, the work function of the material and the resultant arc root behaviour.

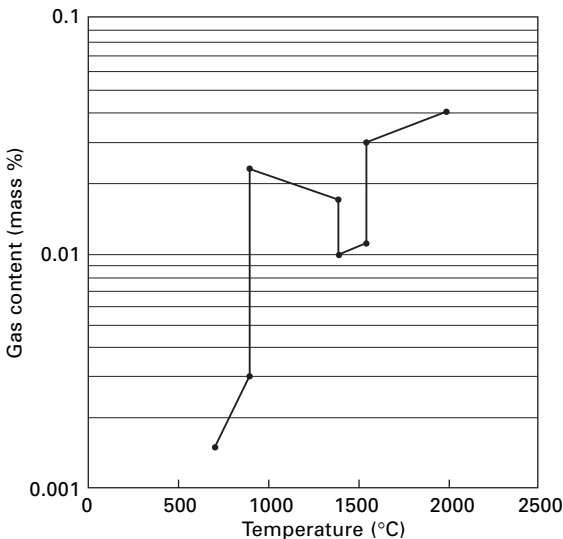
5.2.2 Shielding from atmospheric contamination

The effectiveness of the gas in providing shielding from atmospheric contamination will depend on its chemical reactivity and its physical properties.

In TIG welding, it is necessary to protect the tungsten electrode from oxidation and, for this reason, the inert gases argon or helium are normally used. In GMAW and FCAW welding, it is usually necessary to use oxidizing additions to promote good metal transfer, but the effect of these gases on the loss (by oxidation of metal droplets in the arc) of alloying elements must be considered.

It is also necessary to protect the weld metal from adverse gas-metal reactions such as the formation of porosity, inclusions, surface oxidation or embrittlement. Common active gases which may cause problems in this respect are oxygen, nitrogen and hydrogen. Most materials form oxides when heated in an oxidizing atmosphere, whereas nitrogen may form insoluble nitrides with reactive metals (Ti, Ta, V and Nb) and soluble compounds with other metals (Fe, Mn, Cr and W). Hydrogen is soluble in most metals, but can form compounds with the reactive metals.

The equilibrium solubility of both nitrogen and hydrogen is high in the liquid phase of many common metals, but much lower in the solid (Fig. 5.2 [57]). If the molten metal absorbs more of these gases than the solid solubility limit, there is a potential for porosity formation as the excess gas attempts to escape from the solidifying weld pool. Under arc welding conditions, it is found that the amount of gas absorbed is higher than that which is expected under equilibrium conditions with non-arc melting [58] and, in the case of nitrogen, absorption in steel is affected by the alloying elements present and the level of oxygen and nitrogen. This is particularly interesting in terms of shielding efficiency since oxygen tends to increase the amount of nitrogen absorbed and hence, as recent work [59] has shown, the effect of air entrainment



5.2 Equilibrium solubility of nitrogen in iron. [57]

Table 5.2 Compatibility of shielding gases with common materials

Shielding gas	Compatible	Problem area
Argon and helium	All materials	None
Oxygen-containing mixtures	Plain carbon and stainless steels up to around 8%	Embrittlement of reactive metals (e.g. Ti), oxidation, poor weld profile and loss of alloying elements in some materials
Carbon dioxide	Plain carbon and alloy steel	Carbon pick-up in extra low carbon stainless steels
Nitrogen	Copper	Porosity in ferritic steel and nickel, embrittlement of reactive metals, reduced toughness in alloy steels
Hydrogen	Austenitic stainless steel and high nickel alloys up to around 5%	Porosity in aluminium and other materials. HICC in hardenable ferritic steels

into the arc atmosphere is far more serious than the presence of nitrogen as a minor impurity in the gas.

The ability to maintain a lamellar gas flow and prevent atmospheric contamination will depend on the physical properties of the gas and in particular its density, viscosity and Reynolds number.

The compatibility of the common shielding gases with a range of materials is summarized in Table 5.2.

5.2.3 Secondary functions of the gas

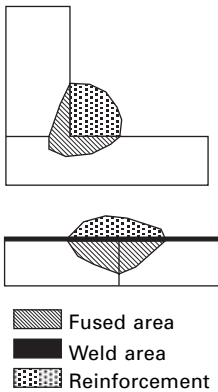
The secondary characteristics of shielding gases are no less important than the primary functions and, in some cases, may determine the most suitable gas for a given application. Some of the most important secondary functions are control of fusion characteristics and joint properties.

Fusion characteristics

The shielding gas has a significant influence on the weld bead profile and fusion characteristics (Fig. 5.3). The total fused area is increased (at an equivalent current) by using gases which increase the arc energy (e.g. He, H₂, CO₂).

In GMAW welding, the use of pure argon produces a pronounced 'finger' or 'wine-glass' penetration profile, whereas argon/CO₂ and argon/helium mixtures produce a more rounded profile.

The profile of the reinforcement can also be improved; for example, argon/CO₂ mixtures normally give flatter weld beads and consequent improvements



5.3 Fusion geometry of fillet and square butt welds. The gas can affect the ratio of fusion area to total area, the fusion profile and the reinforcement geometry.

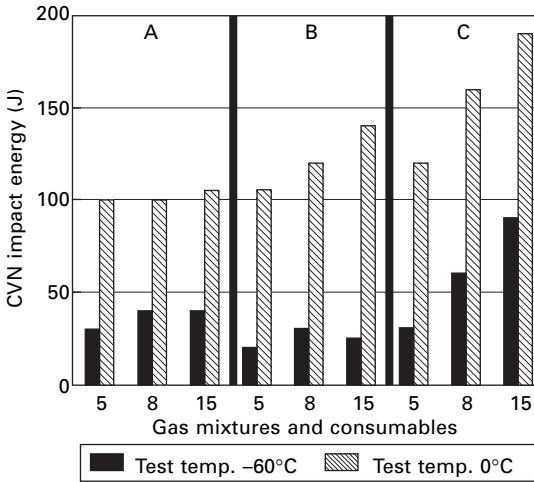
in resistance to fatigue as well as cost savings compared with pure CO_2 shielding (see also Chapter 7).

In some cases, the shielding gas mixture may improve the consistency of fusion; argon/hydrogen mixtures have been found to have a beneficial effect on cast-to-cast variation in the GTA welding of austenitic stainless steel (as discussed in Chapter 6).

Joint properties

The mechanical properties of the weld will depend on freedom from defects and the final weld metal microstructure, both of which are influenced by the shielding gas. Porosity may be controlled by selecting an appropriate shielding gas and ensuring that an efficient gas shield is maintained. Fusion defects may be minimized by selecting a gas that gives increased heat input, and oxide inclusions may be limited by controlling the oxidizing potential of the gas.

The final weld microstructure may be influenced by the gas as a result of its effect on heat input and weld metal composition. For example, it has been found [60] that with ferritic steels an improvement in toughness may be produced by increasing the oxidizing potential of the GMAW shielding gas (by adding up to 2% oxygen and 15% CO_2 to argon) as shown in Fig. 5.4. This is thought to be due to the nucleation of fine-grained acicular ferrite by controlled levels of micro-inclusions. A further increase in the oxidizing potential could, however, lead to the formation of coarse oxide inclusions which would result in a deterioration of weld metal toughness. These effects are relatively small and also rely on the composition of the welding wire and the ability to maintain stable process performance.



5.4 Toughness of high-strength, low-alloy steel welds made in various gas mixtures using pulsed GMAW. A, 70S6 wire; B, 70S6 wire; C, K5Ni wire: 5, 8, 15% CO₂ in argon. [60]

5.2.4 Shielding gas options

The range of viable shielding gas options is limited by the need to satisfy the criteria listed above. Some of the common gases are listed below.

Argon

Argon is one of the most widely used shielding gases for GTAW welding. It is totally inert and has a high density relative to air. The low ionization potential facilitates arc striking and stability.

Helium

Helium is chemically inert, has a lower density than air and requires a higher arc voltage (at the same current and arc length) than argon. The resultant increase in power produces increased heat input and fusion area although lower depth-to-width ratios are normally experienced. The cost of helium is considerably higher than that of argon, but the welding speeds that are usually obtained make it a viable option, particularly for high-conductivity materials.

Carbon dioxide

Carbon dioxide is chemically active, but has a higher density than air. It can dissociate in the arc to release oxygen and carbon monoxide and this can result in a reduction in the weld metal content of elements such as silicon,

manganese and titanium and an increase in carbon. Because of its chemical activity its use is restricted to GMAW welding of steel. The arc voltage is 1–2 V higher in CO₂ (for an equivalent current and arc length) than that found in argon-based mixtures and the heat input is slightly higher resulting in increased fusion. Transfer behaviour, operating tolerances and arc stability are generally poor, especially at high currents.

Oxygen

Oxygen is not used as a shielding medium, but is an important constituent of many gas mixtures. When added to argon it improves arc stability, reduces the surface tension of steel and improves arc root behaviour. The reduced surface tension improves metal transfer and bead shape. Like CO₂, the use of oxygen will decrease the recovery of the more reactive alloying elements.

Hydrogen

Hydrogen increases the arc voltage and heat input when mixed with argon. Its use is usually restricted to the GTAW and plasma processes, and to materials that do not suffer any adverse chemical or physical changes in its presence. Its chemically reducing properties may be used to advantage on austenitic stainless steels where it promotes wetting and produces improved weld bead finish.

5.2.5 Shielding gas mixtures for specific applications

By analysing the effects of the various individual gases it is possible to produce mixtures to satisfy the requirements of most material–process combinations. The composition and properties of the range of gas mixture available are described below.

Gas mixtures for GMAW welding of plain carbon and low-alloy steels

Carbon dioxide may be used for dip transfer GMAW, but mixtures based on argon with additions of oxygen and carbon dioxide are found to give improved arc stability, reduced spatter and an increased operating range (i.e. voltage, wire feed speed and inductance settings are less critical). In addition, weld bead profile is improved, giving a saving in weld metal and weld time. The mixtures available normally fall into one of the following groups:

- argon plus 1–8% oxygen;
- argon plus 1–8% carbon dioxide;
- argon plus 8–15% carbon dioxide;

- argon plus 15–25% carbon dioxide;
- pure carbon dioxide;
- argon/carbon dioxide/oxygen mixtures.

Pure argon is unsuitable for GMAW welding, since the arc is unstable and the resultant weld bead profile is irregular. The addition of less than 1% oxygen gives a remarkable improvement in arc stability, although the weld bead reinforcement is usually excessive and the penetration profile has a wine-glass appearance. Mixtures containing 1 to 2% oxygen may be used for pulsed spray transfer GMAW welding, but, whilst arc stability is very good, the penetration profile does not improve with the addition of oxygen. Higher oxygen levels, up to 8%, can be used for dip transfer welding of thin sheet. If more than 8% oxygen is added, unacceptable surface oxidation may occur.

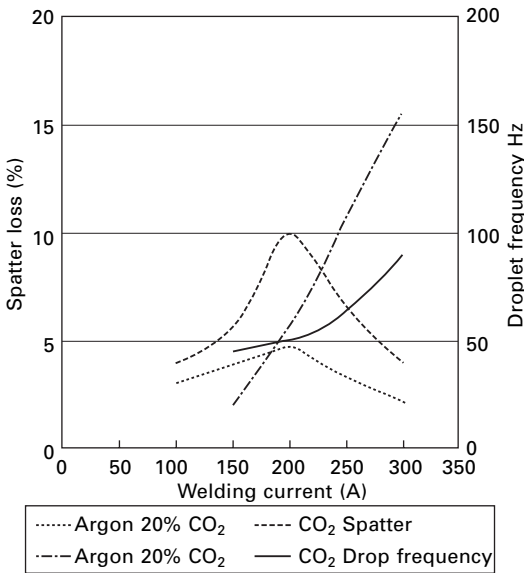
The addition of up to 8% CO₂ to argon promotes stable operation and gives a slightly improved bead shape, although the wineglass penetration shape is still apparent. Mixtures containing about 5% CO₂ give smooth spray and pulsed transfer and low spatter levels in dip transfer. These mixtures are most suitable for welding thin material, for pulsed transfer welding of positional welds in thicker material or for high-current downhand and horizontal vertical fillet welds. The application of these low oxygen and carbon dioxide mixtures for multi-pass welding of thicker materials is limited by the sporadic appearance of fine inter-run porosity. This has been ascribed to argon entrapment and nitrogen absorption [61] and is known to be reduced by increasing the operating current or raising the CO₂ level of the gas.

Intermediate levels of CO₂ (argon plus 8–15% carbon dioxide) give a decreased risk of porosity, improved fusion and still maintain good operating characteristics in the spray and pulse transfer operating modes.

Mixtures of argon with 15–25% carbon dioxide are characterized by increased fusion with bowl-shape penetration profiles, but arc stability tends to decrease as the CO₂ level approaches 25%. These mixtures are ideally suited to the welding of thicker sections and for multi-run butt welds. When the CO₂ content exceeds 25–35%, the characteristics of the gas are similar to those of pure CO₂.

Pure CO₂ gives good fusion characteristics, but higher weld bead reinforcement than the argon-rich mixtures. The heat input of the arc is increased and this may provide slightly better performance on oxidized or primed plate. Although satisfactory dip transfer can be obtained in CO₂, the setting tolerances are narrower than those for argon-based mixtures and transfer under spray and pulsed conditions tends to be globular with much higher levels of spatter. [62] An indication of the difference in spatter levels associated with the use of CO₂ compared with an argon/CO₂ mixture is shown in Fig. 5.5.

Ternary argon/carbon dioxide/oxygen mixtures have similar performance characteristics to argon/CO₂, but slightly improved arc stability has been



5.5 Comparison of spatter losses for CO₂ and argon/20% CO₂ mixtures (GMAW, 1.2 mm wire). [62]

observed. The results of arc stability measurements for dip transfer in these three-part mixtures are illustrated in Fig. 5.6, and it can be seen that mixtures containing 12–15 CO₂ and 2–3% O₂ give excellent stability. Mixtures in this range also give good spray transfer performance, even with electrode negative operation [63] and good fusion characteristics.

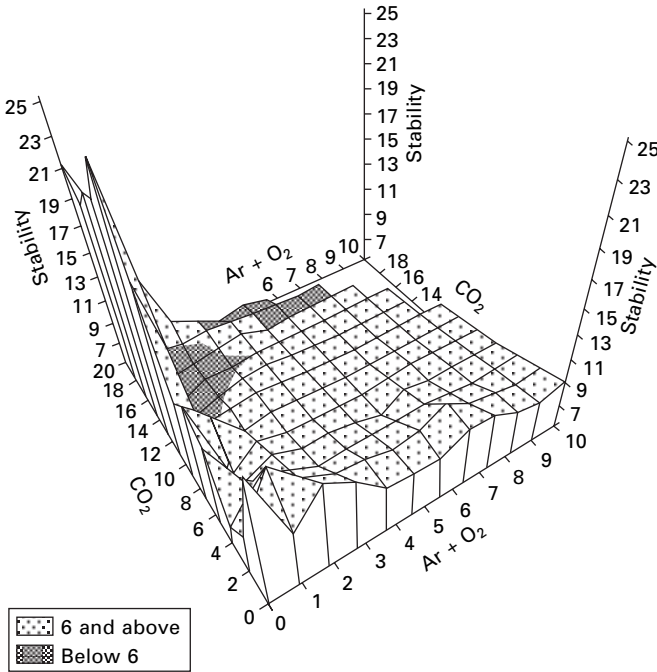
Gas mixtures for GMAW welding of austenitic stainless steel

Stainless steel may be welded in the spray mode using argon with small additions of oxygen (1–2%), but, if these mixtures are used for dip transfer operation, bead appearance and fusion characteristics tend to be poor. Argon/5% CO₂ mixtures may be used to weld austenitic stainless steel, but the carbon level of the resultant welds can increase above 0.04% making this mixture unsuitable for the low-carbon 'L' grade steels.

Helium additions to an argon/CO₂ mixture give improved fusion, reduced wetting angle and improved bead appearance, and several proprietary mixtures are based on mixtures of argon, helium and CO₂, with small additions of O₂ and hydrogen in some cases.

The common mixtures for stainless steel GMAW fall into two categories:

- high helium (60–80%);
- low helium (20–40%).



5.6 Arc stability, dip transfer GMAW in argon/CO₂/O₂ mixtures. (Stability is measured as the standard deviation of arc time, i.e. low values of the standard deviation indicate good stability.)

The high-helium mixtures are used predominantly for dip transfer, where the higher helium level increases welding speeds, improves bead appearance and increases the dip transfer frequency. The arc voltage is increased and fusion is improved especially at low currents.

Lower-helium mixtures have been developed mainly for spray and pulsed transfer welding. They promote smooth spray transfer, good fusion and excellent bead profiles. The addition of 1–2% hydrogen to these mixtures improves wetting and bead appearance by chemically reducing the surface oxide.

Although these mixtures were specifically developed for austenitic stainless steel they can be used for plain carbon steel, where increased speed and improved surface appearance are required (e.g. in automated welding of thin sheet steel components).

Gases for GTA welding of steels

Argon is the most widely used gas for GTAW although mixtures of argon with up to 5% hydrogen are often used, particularly for austenitic stainless steels where increased speed, improved profile and improved process tolerance

are required. Hydrogen additions cannot be used on ferritic steels, which are susceptible to hydrogen induced cold cracking.

Helium/argon mixtures with 30–80% helium can be used for high-speed welding of steels and, on stainless steels, both helium/argon and argon/hydrogen mixtures have been found to increase the tolerance to cast-to-cast variation problems. [64]

Gases for GMAW and GTA welding of aluminium alloys

Argon is normally recommended for both GMAW and GTA welding of aluminium and its alloys, although mixtures of argon and helium with up to 80% helium offer improvements in fusion and bead profile. [65, 66] These mixtures are particularly useful on thicker materials where the preparation angles and the number of weld runs can be reduced.

Gases for GMAW and GTA welding of copper and its alloys

For materials such as copper with high thermal conductivity, a higher heat input in the arc is desirable, particularly for GTAW. Helium or helium/argon mixtures give the necessary increase in heat input and reduce the need for preheat and/or give higher welding speeds and improved process tolerance. Nitrogen and nitrogen/argon mixtures have been used for GMAW; the nitrogen increases the heat input, but transfer is poor and spatter levels can be high.

Gases for GMAW and GTA welding of nickel and its alloys

Argon or argon/helium mixtures may be used for all nickel alloys. High-nickel alloys are susceptible to nitrogen porosity, but small additions of hydrogen (1–5%) improve weld fluidity and reduce porosity. Argon/hydrogen mixtures are often used for GTA welding of the cupro-nickels such as Monel (66% Ni, 31% Cu).

Gases for plasma welding

In plasma welding, two gas supplies are required; the plasma gas and the shielding gas. For many applications, the most suitable plasma gas is argon. It allows reliable arc initiation and protects the tungsten electrode and the anode orifice from erosion. The shielding gas may be argon, although, for austenitic stainless steel, additions of up to 8% hydrogen may be made to increase arc constriction, fusion characteristics and travel speed.

Gases for FCAW welding of steel

The gases used for the FCAW process are dependent on the type of consumable, i.e.:

- gases suitable for rutile and basic consumables, carbon and low-alloy steels;
- gases suitable for metal-cored consumables, carbon and low alloy steels;
- gases suitable for stainless steel FCAW.

Most of the rutile and basic flux-cored wires are formulated to give good operating characteristics and mechanical properties with CO₂ shielding. The use of argon/20% CO₂ and the three-part argon/12–15% CO₂/2–3% O₂ mixtures usually gives a slight improvement in arc stability and improved recovery of easily oxidized alloying elements.

Metal-cored wires were originally designed to give smooth spray transfer in argon/5% CO₂ mixtures, but the three-part argon/oxygen/carbon dioxide mixtures above give excellent transfer characteristics and slightly improved fusion. Metal-cored wires, which operate satisfactorily with CO₂ shielding have also been introduced.

Most stainless-steel flux-cored wires are designed to operate in argon/20% CO₂ mixtures, but the three-part mixtures referred to above have also been found to be satisfactory. Recent work [67] has shown that the use of argon/CO₂ gas mixtures with lower levels of CO₂ improves the recovery of alloying elements, reduces weld metal oxygen levels and increases the yield and ultimate tensile strength of the weld. As with solid carbon steel wires, optimum toughness was obtained with specific mixtures and this is attributed to a combination of weld chemistry modification and the effect of the gas on the thermal cycle.

In the case of flux-cored wires the flux formulation will be designed on the assumption that a particular range of shielding gas mixtures will be used and it is important to ensure that any deviation from the intended gas mixture will not adversely affect the operating performance or weld properties.

Gases for MIAB welding

MIAB welding can be performed without a shielding gas although it is reported that the use of CO₂ can offer some improvement in joint quality. [68]

Special mixtures

Certain special gas mixtures have been produced for specific applications. For example:

- argon/chlorine, argon/Freon mixtures;
- argon/sulphur dioxide;
- argon/nitric oxide gas mixtures;
- gases for high-deposition GMAW.

*Chlorine and Freon.*¹ Argon/chlorine mixtures have been investigated [69] as a means of reducing porosity and improving process tolerances in the GMA welding of aluminium. Although some improvements were reported the application of these mixtures is unlikely due to the extreme toxicity of chlorine.

Certain argon/Freon mixtures are non-toxic and it has been found that the Freon may be substituted for chlorine to produce similar effects; [70] in particular arc stability and weld bead geometry were found to be improved. Although non-toxic, the industrial exploitation of these mixtures is restricted by environmental concerns.

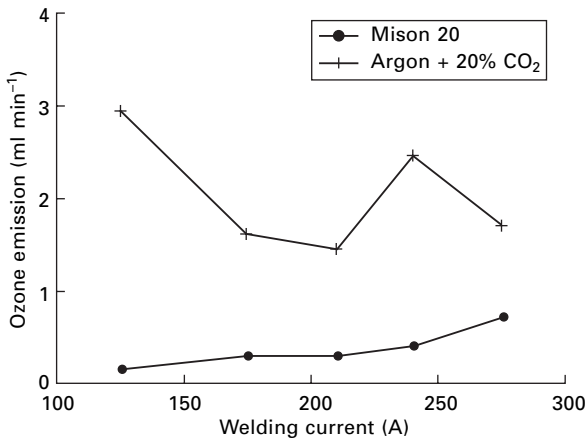
In spite of the limitations on the use of both of these groups of mixtures, it is possible that they may be useful for totally automated applications in totally enclosed controlled-environment chambers.

Sulphur dioxide. Argon/SO₂ mixtures have been used [71] to reduce the effect of cast-to-cast variation in GTA welding of austenitic stainless steel. Whilst the experiments offer a useful indication of the desirable influence of sulphur on the weldability of these materials, the toxicity of the gas precludes its use in practical applications.

Nitric oxide. A range of gas mixtures containing a small amount of nitric oxide (nitrogen monoxide, NO) has been developed as a means of controlling ozone levels in the vicinity of GMAW and GTAW arcs. [72] Ozone is formed by the irradiation of the oxygen in the air surrounding and in the immediate vicinity of the arc with ultraviolet light. Radiation with a wavelength in the 130–170 nm range is particularly effective in promoting ozone formation [73]. Ozone is toxic and the maximum recommended level in the welder's breathing zone is extremely low. Fortunately, the ozone will react with other gases and substances in the atmosphere to form oxygen and oxides and, at low currents or in the presence of a reasonable amount of particulate fume, the rate of ozone formation is low and the likelihood of its recombination before reaching the welder's breathing zone is high. In certain applications with high-current GTAW arcs and particularly in the GMA welding of aluminium, very high levels of ozone are, however, formed. If nitric oxide, which is much less toxic than ozone, is added to the shielding gas, it will combine with the free ozone to form oxygen and nitrogen dioxide.

It has been shown that the use of NO additions of 0.03% to an argon/20%

¹Freons are gaseous combinations of carbon, chlorine, fluorine and bromine, e.g. Freon 12 is CCl₂F₂.



5.7 Effect of addition of nitric oxide on ozone formation during GMAW welding of steel. (Composition of MISON 20 is: argon/20% CO₂/max. 0.03% NO.) ([74] Courtesy AGA.)

CO₂ mixture can significantly reduce ozone formation in the GMA welding of steel [74, 75] as shown in Fig. 5.7 and is effective in controlling ozone in GMAW and GTAW welding of aluminium. These gas mixtures are usually recommended in combination with local ventilation to ensure the removal of all traces of toxic gases from the welding environment.

High-deposition GMAW. High deposition rates may be achieved with electrode negative operation with the aid of argon/O₂/CO₂ gas mixtures as discussed above. Alternatively, special gas mixtures, which, when used with extended electrical stick-out, give very high deposition rates (up to 15 kg h⁻¹) have also been developed; these mixtures are based on argon/helium/CO₂ and are intended for automated applications. A special torch design is required to ensure adequate shielding with the increased electrical extension. [76]

5.3 Gases for laser welding

Gases are required in the laser welding process for operation of the laser, shielding and plasma control. In gas or CO₂ lasers, a gas mixture is used to support the electrical discharge and generate the laser beam. The exact mixture will depend on the type and manufacturer of the laser, but typical gas mixtures are: [77]

- 80% helium/15% nitrogen/5% carbon dioxide;
- 61% helium/4% carbon dioxide/31.5% nitrogen/3.5% oxygen.

The way in which these gases are supplied (i.e. separate or premixed) will also depend on the type of gas laser being used. For both gas and solid state YAG lasers, additional gases are required for shielding and plasma control.

For shielding, the gases used are similar to those employed for GTAW and plasma welding, but, in the case of laser welding, ionization of the gas or metal vapour to form a plasma is undesirable (see Chapter 8) and gases with a high ionization potential, such as helium, are favoured. The common gas mixtures used for shielding are:

- argon, helium and argon/helium mixtures, used for most materials including steel and the reactive metals titanium and zirconium;
- nitrogen can be used for less demanding applications on austenitic stainless steel.

If a plasma does form, a jet of gas may be used to displace or disrupt the plasma; [78] the normal gas used for this purpose is helium.

5.4 Summary

The range of gases used for shielding in arc and laser welding processes is limited but gas mixtures containing from two to four active components may be used to obtain the optimum welding performance. The range of gases commonly used for gas-shielded arc welding and their applications are summarized in Table 5.3.

Table 5.3 Common shielding gases for arc welding processes

Gas	Applications	Features
Argon	GTAW all metals, GMAW spray/pulse Al, Ni, Cu	Inert. GTAW; good arc initiation, stable arc, efficient shielding, low cost. Poor bead profile in GMA welding of steel
Helium	GTAW all metals; especially Cu, Al. GMAW; high current spray with Al	Inert. High heat input, higher voltage than argon, improved fusion, low arc pressure. Require higher gas flow for effective shielding
Argon + 25 to 80% helium	GTAW and GMAW Al and Cu	Inert. Improved fusion and bead profile, good shielding efficiency, stable arc
Argon + 0.5 to 15% hydrogen	GTAW austenitic stainless steel and Cu/Ni alloys	Active. Improved fusion, edge wetting and reduced oxides
Carbon dioxide	GMAW plain carbon and low alloy steels. Dip transfer and FCAW	Active. Low cost, good fusion, effective shield. May have poor process stability and high spatter

Table 5.3 Continued

Gas	Applications	Features
Argon + 1 to 7% CO ₂ + up to 3% O ₂	GMAW plain carbon steel and low alloy steels, spray and pulse	Active. Low heat input, stable transfer, finger penetration
Argon + 8 to 15% CO ₂ + up to 4% O ₂	GMAW plain carbon steel and low alloy steels, dip spray and pulse	Active. Good arc stability, improved fusion and bead profile
Argon + 16 to 25% CO ₂	GMAW plain carbon steel and low alloy steels, dip, FCAW	Active. Increased fusion but reduced stability and increased spatter
Argon + 1 to 8% O ₂	GMAW plain carbon steel and low alloy steels, dip spray and pulse	Active. Lower O ₂ for spray and pulse. Reduced carbon pick-up in stainless steels
Helium + 10 to 20% argon + CO ₂ + O ₂	GMAW dip transfer of austenitic stainless steel.	Active. Improved fusion and bead profile
Helium + 30 to 40% argon + CO ₂ + O ₂	GMAW, dip, spray and pulse, stainless and low alloy steels	Active. Good fusion. Can be used with high deposition GMAW for improved fusion

The gas mixture selected will have a significant effect on the quality and economics of the resultant weld and the high basic cost of some of these mixtures must be evaluated against the overall cost of process as discussed in Chapter 2.

6.1 Introduction

The gas tungsten arc welding (GTAW) process is well established as a high-quality fusion welding technique. Developments in the process have extended the potential application range and offer improved process control.

6.2 Process developments

Some of the more significant process advances are described below and further developments in the field of automation, computer control and adaptive control are discussed in Chapter 11.

The basic process developments and the principles involved in the control of the process will be discussed under the following headings:

- arc initiation and electrode development;
- pulsed GTAW and high-frequency pulsed GTAW;
- square-wave AC GTAW and plasma;
- cold- and hot-wire feed additions in GTAW;
- dual-gas GTAW and plasma welding;
- multicathode GTAW;
- A-TIG welding;
- buried arc GTAW;
- high current GTAW;
- control of GTAW and related processes.

6.2.1 Arc initiation and electrode development

Arc initiation in the GTAW process is a two-stage process consisting of initial breakdown of the arc gap (stage I) and stabilization of the arc (stage II).

Stage I is influenced by the electrode, the open-circuit voltage of the

power supply and the striking technique used. Stage II is controlled mainly by the rate of response of the power supply.

Initial breakdown of the arc gap may be achieved by one of the following:

- touch striking;
- high-voltage DC;
- high-frequency–high-voltage.

Each of these techniques has limitations, as discussed below, and this has led to the development of new systems which are also described.

Touch striking

Touch striking is probably the simplest technique available. The electrode is brought into contact with the workpiece then rapidly withdrawn. The tungsten electrode is heated resistively by the short-circuit current of the power source and the initial arc is established from the heated electrode immediately the electrode is withdrawn. The striking process is assisted by the very small arc length which exists the instant the electrode contact with the workpiece is broken and metal vapour is present in this gap. The effectiveness of the technique depends to a large extent on the skill of the operator, but there is always a likelihood of tungsten contamination occurring and this will adversely affect the electrode running performance and weld quality.

High-voltage DC

It has been shown that to obtain reliable arc breakdown at normal arc lengths DC voltages of 10 kV would be required. [79] These voltages would pose serious safety hazards and are not feasible for normal applications. The use of short-duration high-voltage surges has been shown to reduce the danger of lethal electric shock [80] but there is still a risk of injury from reaction to accidental contact with such high pulse voltages. The application of this technique is therefore restricted to automatic systems in which the operator is protected from contact with the high-voltage supply.

High-frequency–high-voltage

High-frequency currents tend to be carried in the outer layers of a conductor and this 'skin' effect can be used to advantage in GTAW arc striking systems. High-frequency–high-voltage supplies (e.g. 3 kV at 5 MHz) are effective in breaking down the arc gap and are non-injurious to the operator. This type of system has been used extensively for arc starting and AC arc stabilization in GTAW and continues to be the main method of striking used in manual GTAW systems. In some cases, arc starting using high-frequency ignition

systems becomes inconsistent; this may be due to electrode characteristics or an adverse phase relationship (i.e. lack of synchronization) between the power supply and the arc-starting device. It has also been suggested that a negative space charge may be generated around the end of the electrode and the gas cup. In this case, improved consistency may be obtained by discharging the charge by connecting the gas cup to the positive terminal of the power supply. Where a ceramic gas cup is used, a conductive foil may be wrapped around the nozzle to provide an electrical connection, whereas, with metallic cups, a resistor is inserted between the cup and the positive connection.

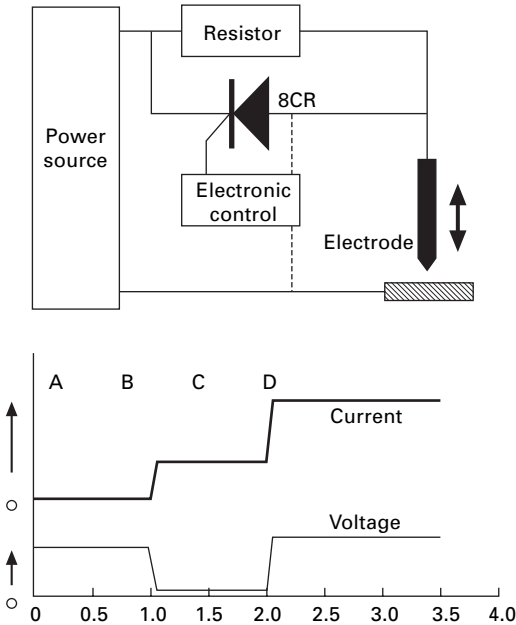
The main problem with the high-frequency starting technique, however, lies in the use of high-frequency voltage oscillations, which, depending on the design of the oscillator circuit, can cover a wide range of radio frequencies and produce both airborne and mains-borne interference. In the past, this problem has resulted in interference with communication systems and domestic television and radio reception, but it is also likely to create significant problems with electronic control and computing equipment in the welding environment.

New arc striking techniques

Programmed touch striking. The main problem with conventional touch striking is the high short-circuit current which tends to overheat the electrode and increase the risk of contamination. This limitation can be overcome by controlling the current during the short circuit. Various systems exist [81] but the operation is essentially as follows (see also Fig. 6.1). After closing the torch switch (A), a low voltage is applied between the electrode and the workpiece via a current-limiting resistor. When the electrode touches the workpiece (B), the short circuit is detected electronically and a low current (2 to 10 A) is allowed to flow; this current is sufficient to preheat the electrode without overheating (C). When the electrode is lifted the voltage rises (D) and signals the power supply to initiate the main current supply. The initial arc current may be programmed to rise rapidly to ensure arc stabilization before reverting to the working value. Trials have shown [82] that no evidence of tungsten contamination or electrode weight loss could be detected after repeated re-striking with a system of this type. The system is also ideally suited to automatic application, where the contact of the electrode with the workpiece and its retraction can be mechanized (see Chapter 11).

Pilot arc starting. The use of an auxiliary electrode in the torch enables a low-current pilot arc to be struck before initiation of the main arc. This system allows consistent striking, although it does require a slightly more complex torch.

Piezoelectric arc starting. Piezoelectric arc-starting devices have been investigated [83] and it has been shown that a torch-mounted piezoelectric device can be used successfully for GTAW arc starting. Problems were,



6.1 Programmed touch striking system for GTAW. Top: simplified circuit diagram. Bottom: current and voltage during programmed touch striking.

however, encountered with high-voltage leakage and the system has not been exploited commercially.

Arc stabilization

Stage II arc initiation or stabilization is largely dependent on the rate at which the power source can supply current to the embryo arc after initial breakdown. Conventional GTAW power sources have been shown to have a current response of around 10^4 A s^{-1} at the optimum settings and with a favourable phase relationship, [84] although much lower rates of rise could be experienced, particularly on single-phase units, when the arc initiation takes place out of phase with the mains supply. It would be expected that this rate of rise of current could lead to striking difficulties especially at low set currents and when long, inductive welding cables are used. In these circumstances effective arc initiation often depends on the use of a capacitor in parallel with the output which can discharge into the arc.

Electronically controlled power sources, such as the series regulator and inverter designs described in Chapter 3, are capable of giving much higher rates of initial current rise (typically $5 \times 10^4 \text{ A s}^{-1}$) and are less sensitive to phase relationship problems.

Electrode composition

The tungsten electrodes used in GTAW are usually alloyed with a small amount of thoria or zirconia in order to improve arc starting, by reducing the work function of the tungsten and improving its emission characteristics.¹

Thoriated electrodes give very good striking and DC running characteristics, but it has been demonstrated that the consistency of performance is closely related to the homogeneity of the electrode and, in particular, the regularity of the thoria distribution. [85] In this study, it was shown that the stable arc operating time (continuous arc operation) may be extended by up to 100% when an electrode with a fine, homogeneous distribution of thoria particles (70 h stable arc operation at 125 A) is substituted for an electrode with a less regular composition (35 h stable operation), whilst re-ignition delays can be reduced from 4% of the total number of arc starts to 1% with the better-quality electrode.

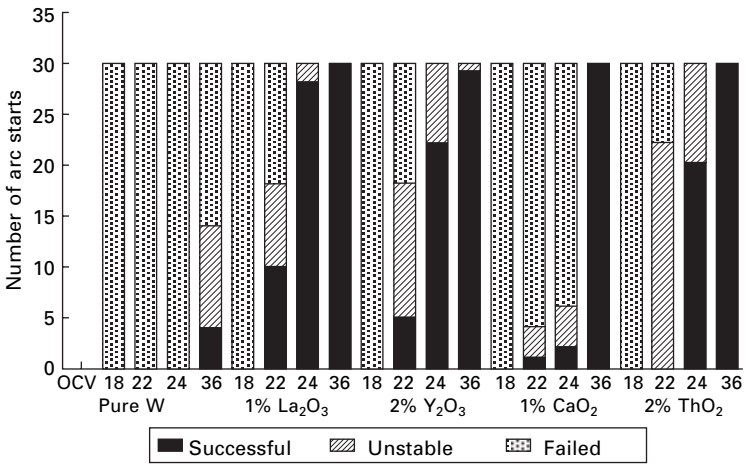
Although thoria (ThO_2) is effective in improving arc striking and tip shape retention, it is naturally radioactive. Concern about potential safety implications, in particular in electrode manufacture, has led to the investigation of alternative alloying additions. Oxides of the rare earth elements lanthanum, yttrium and cerium appear to offer similar characteristics to thoria. Laboratory investigations [86] indicate that electrodes doped with these substances may perform better than conventional thoriated types. In these tests the number of successful arc initiations using high-frequency (HF) arc starting and an open-circuit voltage (OCV) range of 18 to 36 V was assessed. The results are summarized below and in Fig. 6.2.

Follow-on current was set to 20–30 A. The electrode vertex angle was 45° , and the total number of attempts at each open circuit voltage was 30. At 30 V OCV, the performance of ThO_2 , La_2O_3 , CeO_2 , and Y_2O_3 , is very similar, whereas at 24 V OCV, the lanthanum oxide gave the best results. Measurements of electrode temperature indicated that La_2O_3 , Y_2O_3 and CeO_2 gave lower operating temperatures than those for pure tungsten and zirconiated tungsten, and in addition, the amount of electrode melting and tip shape deterioration was much less.

Rim formation and weight loss

A rim of tungsten ‘whiskers’ forms on the upper vertex of the electrode, particularly if there is more than 0.05% oxygen present in the shielding gas. This effect is thought to be associated with the volatilization of tungsten oxide and the condensation and growth of pure tungsten crystals on the

¹The work function of pure tungsten is around 4.54 eV, whereas that of a 2% thoriated electrode is around 2.63 eV.



6.2 Electrode performance (arc start rate versus OCV) for various GTAW electrodes with rare earth additions. [86]

cooler part of the electrode. This rim can lead to arc asymmetry and instability. The effect is not directly affected by the alloying addition, although weight loss of the electrode was less significant with the rare-earth-doped electrodes. The improvements in electrode life and striking performance obtained with rare-earth-doped electrodes are relatively small, but, where reliable and consistent operation is required, for example in automated welding, these marginal improvements may prove beneficial. Alternatively, high-quality thoriated electrodes may be specified in situations where consistency is important.

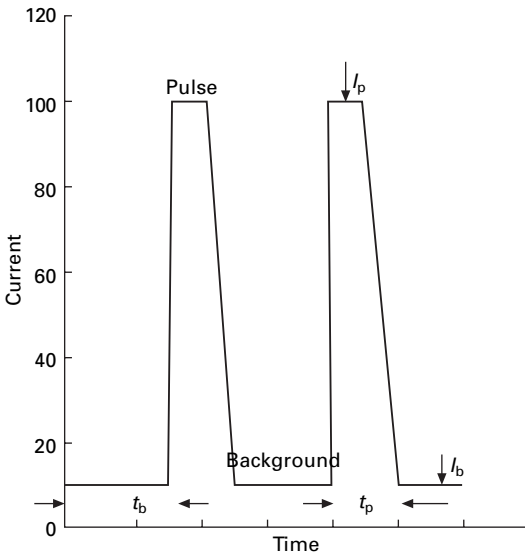
6.3 Process variants

6.3.1 Pulsed GTAW

Low-frequency (1–10 Hz) modulation of the current in the GTAW process has been used [87] to provide the following process characteristics:

- reduced distortion;
- improved tolerance to dissimilar thicknesses;
- improved tolerance to dissimilar materials;
- reduced thermal build-up;
- improved tolerance to cast-to-cast variation.

Using electronic power sources, it is possible to generate a range of alternative pulse profiles, although in practice nominally square wave pulses are usually used as illustrated diagrammatically in Fig. 6.3. The low current or background level is set at a value just sufficient to maintain an arc without



6.3 Typical GTAW pulse waveform: variation of current with time.

Table 6.1 Operating parameters for pulsed GTAW

Material	Pulse amplitude (A)
Pure nickel	250 to 300
Stainless steel	150 to 200
Cupro-nickel alloys	150 to 200
Plain carbon steel	100 to 150
Nimonic alloys	50 to 80

causing significant plate melting. The ideal pulse current level is determined by the thermal properties of the material [88] and should be set at a level which will ensure that the weld pool can propagate at a rate which is fast enough to ensure the maximum thermal efficiency.

Table 6.1 gives some guidance on the optimum values for a range of materials. The duration of the pulse is determined by the thickness of the material and, if the pulse current exceeds the values given in Table 6.1, a relationship of the form

$$I_p t_p = K \tag{6.1}$$

should hold, where I_p is pulse current, t_p is pulse time and K is a constant. The background duration is adjusted to allow solidification to occur between pulses and the time required will in turn be related to the travel speed.

The pulsed GTAW process has been applied widely for demanding applications such as the joining of austenitic stainless steel for cryogenic

expansion bellows, orbital welding of nuclear reprocessing plant pipework and the welding of aero-engine components in nickel-based super-alloys (Nimonic).

6.3.2 High-frequency pulsed GTAW

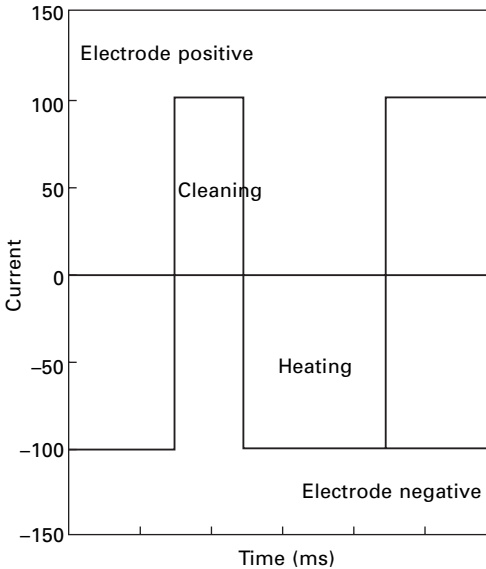
High-frequency (above 5000 Hz) pulsed GTAW has been investigated as a method of improving arc stiffness, giving high energy density and efficiency [89] and enabling higher welding speeds to be achieved. The improved arc stiffness is claimed to be most significant at low average arc currents and at frequencies in the range 5 kHz to above 20 kHz. The arc stiffness is likely to be due to the high pulse current amplitude; the high-frequency pulsing between this high peak and very low background level allowing a low mean current to be maintained. At higher mean currents, high-frequency pulsing gives an increased resistance to undercut and this enables the maximum welding speed to be increased in mechanized welding applications.

6.3.3 Square wave AC, variable polarity GTAW

The recognized operating mode for aluminium and its alloys is AC GTAW welding. However, self-rectification effects in the arc make it necessary to provide DC component suppression and some means of assisting re-ignition of the arc at every current zero. Limitations on allowable open-circuit voltages and radio interference from the high-voltage-high-frequency units make it difficult and costly to design conventional GTAW equipment to overcome these problems.

The developments in power source technology already discussed in Chapter 3 have made it possible to produce a 'rectangular' variable polarity output waveform instead of the normal sine wave. [33,90,91] This has several beneficial effects on the process. Firstly the rapid polarity reversal at current zero reduces the degree of cooling and recombination in the arc and assists the arc to re-strike more easily in the opposite direction. This re-ignition process may be further assisted by arranging for high-voltage transients to coincide with current zero. Improved control of the process is also provided by the ability to adjust the balance between alternate half cycles. It is, for example, possible to increase the arc cleaning effect by increasing the relative duration of positive (electrode) half cycles whilst plate fusion may be increased by extending the negative half cycle. These effects are shown in Fig. 6.4. In addition to the benefits described above, it is normal for this type of unit to have mains voltage stabilization plus low-voltage remote control.

A further development of this technology is the use of high frequency transistor reversing switch circuits, which, when added to the output of a conventional or inverter-based DC power source, enable a square wave AC



6.4 The effect of square wave AC operation on GTAW.

output to be obtained. It is reported [34] that a unit of this type is capable of reversing the polarity of the output within $100\ \mu\text{s}$ and gives effective cathodic cleaning on aluminium alloys with 20 ms electrode negative polarity and 4 ms positive (i.e. a pulse frequency of 41.66 Hz).

6.3.4 Cold- and hot-wire feed additions in GTAW

A useful feature of the GTAW process is the ability to control weld pool temperature and size by means of independent cold-wire addition. This is used in manual welding operations to control the weld profile and penetration, particularly in positional work. Mechanized wire addition by means of a separate hand-held wire dispenser or a torch-mounted feed system are available for manual operation, but, although these can increase the operating efficiency of the process, they tend to be restricted to simple weld geometry and joints with good access.

In automated GTAW, the wire is normally fed at a set constant rate and the element of control exerted by the welder is lost. A mechanized wire-feed addition system, called 'Dabber TIG'^{TM2}, which feeds the wire with a reciprocating motion similar to that used by manual welders, has been introduced. [92] The frequency of wire addition may be set between 2 and 10 Hz. A controlled low heat input deposit may be achieved and the technique

²Dabber TIG is a trade name of the Hobart Company Ltd.

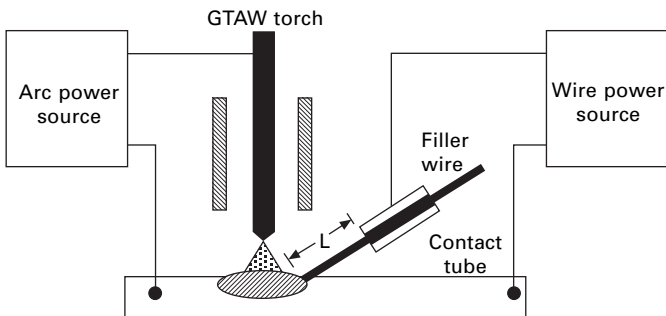
is particularly useful for building up fine edges of cutting tools or components such as turbine blades.

6.3.5 Hot-wire GTAW

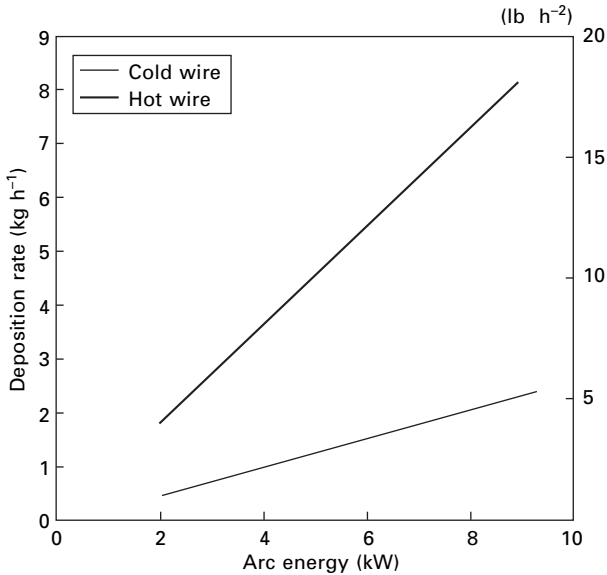
Normally GTAW is regarded as a ‘low-productivity–high-quality’ process due to the relatively slow travel speeds employed and low deposition rate achieved with cold filler additions. It has been shown, however, that significant improvements in deposition rate, to match those produced in the GMAW process, may be achieved by using a ‘hot-wire’ addition. [93,94]

The process arrangement is illustrated in Fig. 6.5. The principal features are the addition of a continuously fed filler wire, which is resistively heated by AC or DC current passing between the contact tip and the weld pool. Normally the wire is fed into the rear of the weld pool (unlike cold-wire addition) although hot-wire additions to the front of the pool have been used for positional work. The equipment required comprises a precision power source (e.g. electronic control mains-voltage stabilized), a high-quality wire-feed system and an effective gas-shielding system. The use of an AC power source for filler wire heating minimizes the possibility of magnetic disturbance of the arc. The deposition rates possible are shown in Fig. 6.6.

A novel system based on an inverter power source has been developed for evaluation in the power generation industry; this consists of a DC inverter-based GTAW power source which supplies the arc power. An additional power circuit and control system is powered from the high-frequency AC output of the inverter and provides the heating supply to the wire. This design is cost effective and electrically efficient and compact. [95] Although the equipment is more complex than GMAW it has been shown that deposition rates of 10–14 kg h⁻¹ are possible and high joint integrity may be expected. The hot-wire GTAW process has been applied in the oil industry for butt welding 30 mm wall line pipe. In this application, four heads rotate around the pipe simultaneously.



6.5 Hot-wire GTAW.

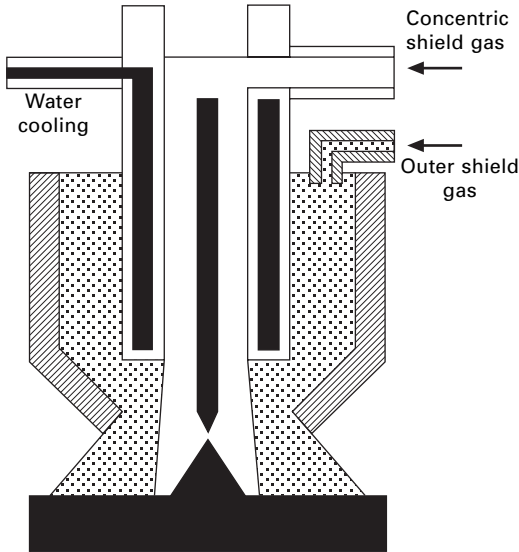


6.6 Comparison of deposition rates for hot- and cold-wire GTAW. [93]

6.3.6 Dual-gas GTAW

Constriction of the core of a GTAW arc occurs under normal operating conditions due to the effect of the compressive Lorentz force, which is produced by the interaction of the arc current and its associated magnetic field. The Lorentz force is proportional to the square of the arc current and the resultant constriction may be very low at currents below 20 A, but pronounced at currents above 100 A. The effect can be induced by applying an external axial magnetic field or by thermal constriction caused by the impingement of cold gas jets on the outer region of the arc. Reducing the temperature of the outer core of the arc decreases the area available for current flow, restricts the number of charge carriers (ionized particles) and increases the temperature and energy density of the inner core of the arc.

This effect has been utilized in the 'dual-shielding' GTAW technique [96] illustrated in Fig. 6.7. A cylindrical nozzle surrounding the electrode directs a flow of cool shielding gas along the outer surface of the arc. This gas provides shielding of the electrode and the immediate arc area, but also causes some thermal constriction and stiffening of the arc. An additional concentric gas shield provides protection of the weld pool and outer regions of the arc. The gases used for the inner and outer shields may be of different compositions, for example argon/5% hydrogen may be used for the central gas (giving a potential increase in constriction and stiffness (see Chapter 4), while argon or even argon/20% CO₂ may be used for the outer shield when welding low-carbon steel. The dual-gas system has been used for stainless



6.7 Dual-shielded GTAW.

steel, carbon steel and non-ferrous materials including aluminium. At low currents (20 to 50 A), the process gives improved arc stability and the mean current required is 30 to 40% lower than that required for conventional GTAW. On thicknesses up to 3 mm in aluminium alloys and 4 mm in steel, square butt preparations may be used and welding speed increases of up to 20% compared with conventional GTAW are possible. If the current is increased to 335 A and above keyhole (see Chapter 8), welding is possible on plate thicknesses from 4 to 6 mm.

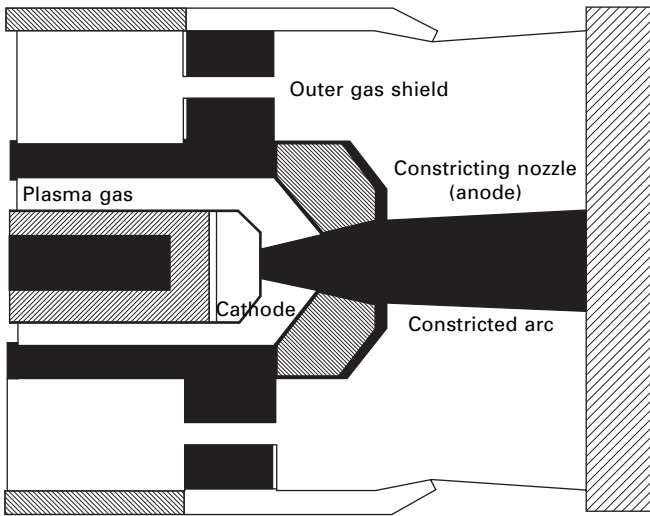
Physical constriction of the GTAW arc by a water-cooled copper nozzle, as shown in Fig. 6.8, will produce an even higher current density and arc core temperature for a given mean current. When this technique is used, the process is referred to as the plasma process [97] (see also Chapter 1).

6.3.7 Plasma welding

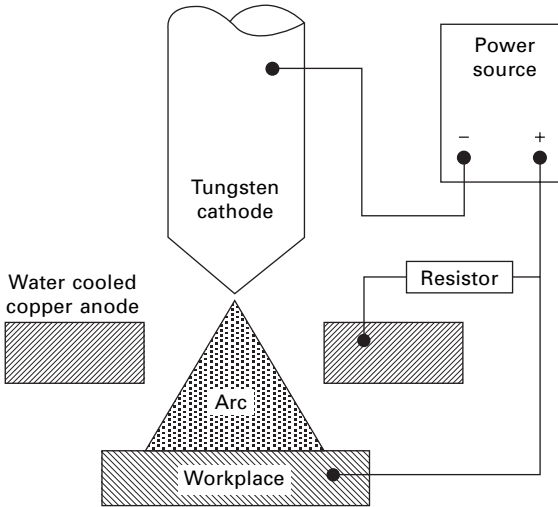
In plasma welding, the arc is formed between the tip of a non-consumable electrode and either the workpiece or the constricting nozzle. Again, it is possible to select different shielding and plasma-forming gases, although argon is commonly used as the central plasma gas whilst argon or argon/hydrogen (where appropriate) may be used for the outer shielding medium.

Two basic operating modes are possible for plasma welding. These are:

- the transferred arc mode;
- the non-transferred arc mode.



6.8 Constriction of arc in plasma torch.



6.9 Transferred arc mode.

Transferred arc mode

In the transferred arc mode, the arc is maintained between the electrode and the workpiece as shown in Fig. 6.9. The electrode is usually the cathode and the workpiece is connected to the positive side of the power supply. In this mode, a high energy density is achieved and this energy is efficiently transferred to the workpiece.

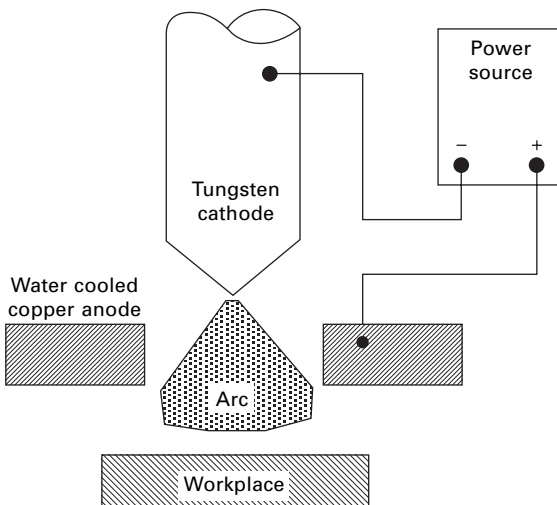
Non-transferred arc mode

In the non-transferred arc mode of operation, the power supply is applied between the electrode and the constricting orifice. The electrode is usually connected to the negative side of the power supply and, for this reason, the orifice is referred to as the anode. This process mode is illustrated schematically in Fig. 6.10. In this mode, very little energy is transferred to the workpiece and its main use is as a 'pilot' arc which enables the main transferred arc to be established rapidly. The pilot arc may be established by high-frequency arc starting or a simple touch-starting system within the torch. Once the pilot arc is established, a main or transferred arc may be started at any time by completing the circuit between the power source and the workpiece as shown in the diagrams above.

Equipment requirements

The basic equipment requirements for the plasma welding system are slightly more complex than either the conventional or dual-gas GTAW system. They consist of a welding power source, a control unit and a plasma torch.

A power source with a direct current (DC) output is normally used (although it is possible with suitable equipment to use AC for aluminium alloys and variable polarity or 'square wave' AC units referred to above have been developed as plasma power supplies). The constant-current static volt-amp output characteristic used for GTAW power sources provides a suitable main arc supply.



6.10 Non-transferred arc mode.

The control unit which usually contains the non-transferred pilot arc supply, the gas controls and the arc ignition system may take the form of an 'add on' box or may be built into the main power supply.

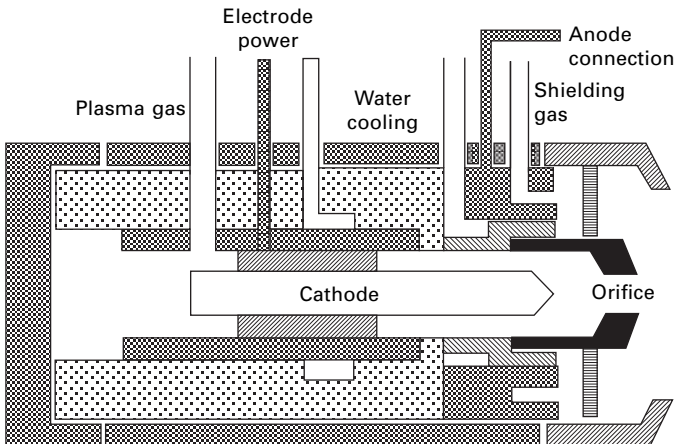
The torch is slightly more complex than a GTAW torch as shown in Fig. 6.11. It must have provision for cooling of the replaceable copper constricting orifice, supply of plasma gas, and a separate supply of shielding gas. The non-consumable electrode material is usually thoriated tungsten. As in GTAW, the process may be used without added filler (autogenous welding) but, if a filler is required, this is usually added to the leading edge of the molten pool.

Modes of operation of plasma welding

The plasma welding process is normally operated with direct current electrode negative (DCEN). Although, as with GTAW, both AC and DCEP (direct current electrode positive) operation can be used for aluminium and its alloys, this usually requires special torch designs and larger electrodes. Welding may be carried out in the 'melt in' mode in a similar manner to GTAW, the only difference being the use of a constricted arc as the heat source. Alternatively, the keyhole mode may be used; this takes advantage of the higher energy density and the increased arc force in the plasma and is described in more detail in Chapter 8.

Features and applications of plasma welding

The features and applications of plasma welding differ according to the current range used, i.e.:



6.11 Plasma welding torch.

- low current: 0.1–15 A;
- intermediate current: 15–200 A;
- high current: above 200 A.

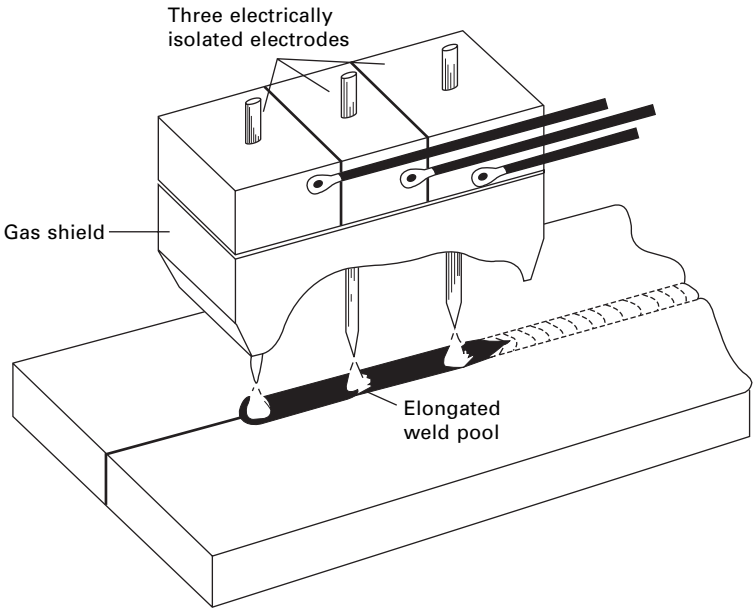
Low-current or ‘microplasma’ welding: In the low-current range the principal advantage of the process over GTAW is the excellent arc stability even at levels of 1–2 A at which it would be difficult to operate a GTAW arc. Restricted arc root area and improved directionality are added advantages. At low currents, the pilot arc ensures reliable main arc starting and can also be used to illuminate the joint before welding. These features of the process make it suitable for joining very thin materials, for the encapsulation of electronic components and sensors, the joining of fine-mesh filter elements [98] or repair of turbine blades.

Intermediate-current plasma welding. In the range 15–200 A, the process is similar in characteristics to GTAW but, for the same mean current, higher speed or improved melting efficiency may be achieved. In addition, the plasma process is more tolerant to variations in stand-off and the tungsten electrode is protected from accidental touch-down and contamination. The process has been used in this range for the joining of silicon iron transformer laminations where contamination of the electrode presents problems in the GTAW process.

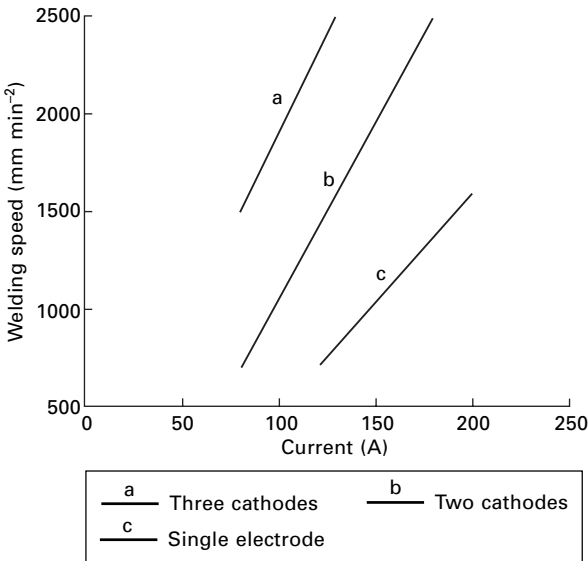
High-current plasma operation. At high currents, the keyhole mode of operation may be used. This makes it possible to perform single-pass square butt welds from one side in plate thicknesses up to about 9 mm. Accurate alignment of the torch and stable travel speed are important in this mode to avoid undercut. Typical applications of keyhole plasma welding are high-speed longitudinal welds on strip and pipe. The process has also been used for root runs in thick-wall pipe.

6.3.8 Multicathode GTAW

One of the principal factors which limits the maximum welding speed of the GTAW process is the occurrence of undercut [99] (see Section 6.4 below) and although dual-shield and plasma techniques increase the potential heating efficiency of the arc, they also have a tendency to increase the risk of undercut and this, in turn, limits their usefulness for high-speed welding. This problem may be overcome by creating an elongated heat source using two or more arcs in series (Fig. 6.12). This technique is called multicathode GTAW and was originally developed in the 1970's. [100] The welding speed obtained is determined by the number of electrodes and their separation but, as shown in Fig. 6.13, these are significantly higher than the travel speeds obtained with conventional GTAW. This process variant has been used mainly for specialized applications in the high-speed welding of the longitudinal seams in tube mills. In order to avoid the tendency for the arcs to deflect under the influence



6.12 Multicathode GTAW.



6.13 Increases in welding speed achieved using multiple electrodes for full-penetration butt welds. (Material used: 1.2 mm 304-type stainless steel.)

of the local magnetic fields (Fig. 6.12) techniques such as high-frequency pulsing, dual-shield and magnetic stabilization are used.

6.3.9 A-TIG welding

The Paton Institute in the Ukraine has developed a novel technique for extending the operating range of GTAW by the use of surface pastes. These pastes are applied to the weld joint before welding either by brush or aerosol. They have been shown to radically alter the weld profile; increasing depth-to-width ratio and eliminating the 'cast-to-cast problem'. When these activating pastes or fluxes are employed the process is referred to as A-TIG (Activated TIG) welding or PA-TIG (Paton Activated TIG) welding. [101] The composition of the fluxes varies depending on the material and application; in some cases halide salts are used whilst in others simple oxides such as TiO_2 and SiO_2 have been shown to be effective. The exact mechanism by which the process improvements are achieved is not fully resolved but it has been proposed that surface active salts may influence the surface tension of the molten material or release ionic species, which promote arc constriction, into the arc.

6.3.10 Buried arc GTAW

The buried arc GTAW process was first developed in the USA, but has been further developed in the Ukraine and Australia. The arc is initiated on the plate surface, then, using the plasma force to depress the molten pool, the electrode is lowered until it is below the level of the workpiece surface. The arc then operates in a cavity as shown in Fig. 6.14.

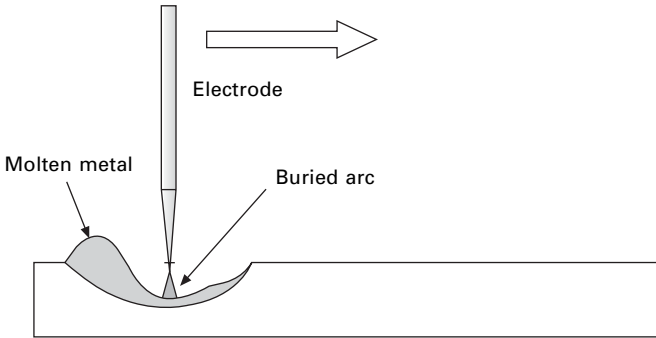
This mode of operation enhances the thermal efficiency of the arc and enables higher travel speeds to be used. It is normally only possible at very high currents with mechanised systems.

6.3.11 High current GTAW

Further increases in current allow the GTAW arc to develop sufficient arc pressure to form a keyhole and torches with capacities of up to 1000 A have been developed. In this mode, the process offers a high travel speed alternative to plasma techniques.

6.4 Control of GTAW and related processes

GTAW and related processes are capable of producing very high quality welds but, for consistent results, the influence of the welding parameters on weld geometry and quality must be identified and controlled.



6.14 Speed/current relationship for GTAW.

Table 6.2 Main control parameters in conventional DC GTAW

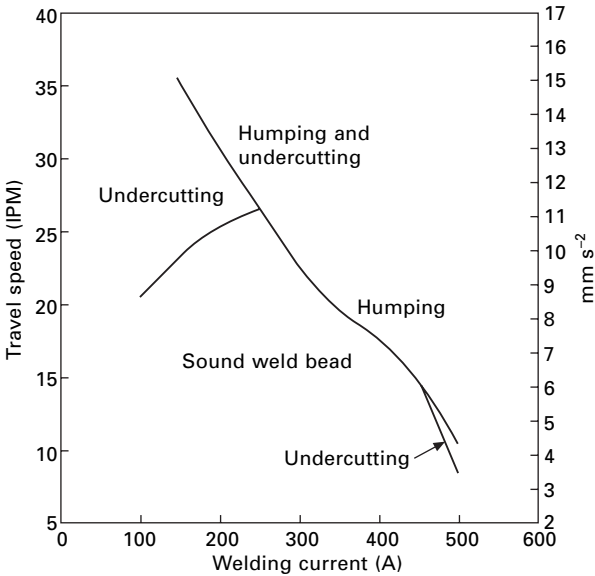
Primary	Secondary
Current	Arc length
Travel speed	Polarity
	Shielding gas
	Electrode vertex angle
	Filler addition

6.4.1 Conventional GTAW

In conventional DC GTAW, the main control parameters are as given in Table 6.2.

Current and travel speed

The mean current normally determines the heating effect of the arc and the arc pressure and stiffness. The penetration and fusion characteristics for a fixed set of secondary parameters are determined by a combination of mean current and travel speed. However, the maximum speed, penetration and fusion area are limited by the onset of unacceptable weld bead profile at high currents. The force generated in the high-current arc displaces the molten weld pool and, at high travel speeds, there is insufficient time for the displaced metal to flow into the joint before solidification. The result is a discontinuous bead, undercut or ‘humping’. The occurrence of this defect has been investigated by Savage *et al.*, [102] and the limiting current and speed have been determined for a range of conditions as shown in Fig. 6.15. The effect of this limitation may be reduced by controlling some of the secondary variables or using multicathode techniques.



6.15 Incidence of humping and undercut. [102]

Arc length

The arc length in GTAW is usually taken to be the same as the separation distance between the electrode tip and the workpiece. The effect of increasing this distance is to decrease the heating efficiency of the arc and the fusion and penetration level. This reduced efficiency, which is due to radiation losses from the arc column, occurs even though arc voltage increases and the total power (current \times voltage) may increase. For consistent results with conventional GTAW, it is therefore important to maintain a fixed electrode-to-workpiece separation. The arc voltage gives a useful indication of electrode-to-workpiece distance.

Polarity

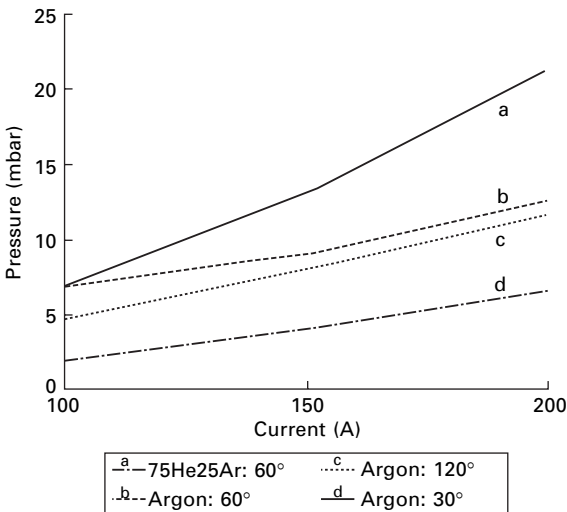
The thermal balance between the anode and cathode in GTAW is such that some 60–70% of the heat input to the electrodes is absorbed by the anode whilst only 30–40% is absorbed at the cathode. [103] For most applications electrode negative polarity is used since this provides the best heating characteristics and minimum electrode/torch heating. For aluminium and its alloys, electrode positive polarity offers one important benefit in providing cathodic cleaning of the plate surface, but, in order to optimize the efficiency of the process, alternating current is normally used for these materials; this provides plate heating during the electrode negative half cycle and plate cleaning during the electrode positive period.

Shielding gas

The shielding gas can have a significant effect on the thermal characteristics of the arc and fusion behaviour of GTAW as discussed in Chapter 5. These effects can be used to extend the operating range of the process and, for example, the maximum speed before the onset of weld bead humping at 400 A may be increased from 7.6 mm s⁻¹ to 23.3 mm s⁻¹ by replacing argon with helium as the shielding medium.

Electrode vertex angle

The angle at which the tungsten electrode is ground has a marked effect on the arc pressure [56] (Fig. 6.16). Small angles increase the arc pressure and arc voltage and large included angles reduce the pressure. For the avoidance of undercut and humping at high currents, it is therefore preferable to use a large vertex angle. The vertex angle also has an influence on weld bead geometry at much lower currents, the effect is related to *relative plate thickness*³ and is summarized in Table 6.3. For a high depth-to-width ratio on thin plate, a small vertex angle is desirable whereas for high depth-to-width welds on thick plate, or low penetration welds, a larger angle is required. These effects are, however, also related to material composition, shielding gas and joint



6.16 Effect of vertex angle on arc pressure. [56]

³Relative plate thickness is the thickness of the plate relative to the penetration achieved: ‘thick’ plate in this context means a penetration of less than 30%, ‘medium’ is 30 to 70% penetration and ‘thin’ plate represents the 70 to 100% penetration situation.

Table 6.3 Penetration profile in relation to electrode vertex angle

Electrode vertex angle (degrees)	Bead profile (depth-to-width ratio) as a function of relative plate thickness		
	Thin plate	Medium	Thick plate
30	High	Low	Low
120	Low	High	High

geometry and, whilst it is clear that there is a significant change in penetration characteristics with any change in electrode angle, the resultant weld profile will depend on the material and the other welding variables discussed above.

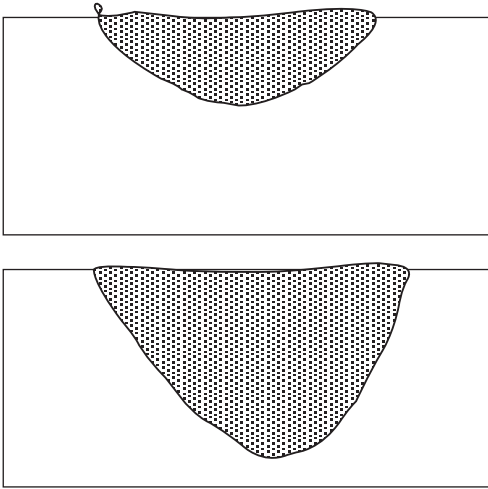
Filler addition

The addition of cold filler wire will cool the weld pool and reduce the heat available for plate fusion; however, in some circumstances, small traces of elements that alter the surface tension of the weld pool may be added via the filler to improve the fusion characteristics as discussed below.

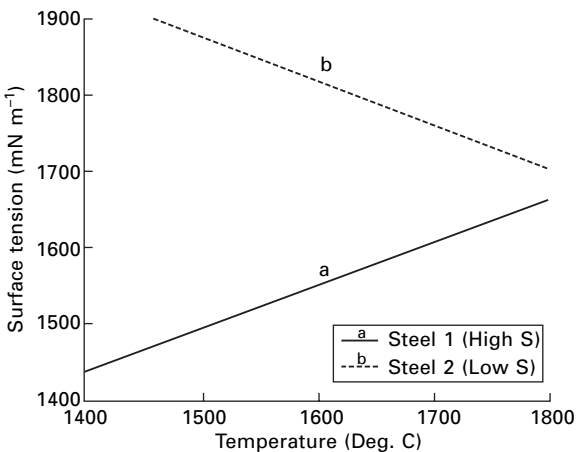
Cast-to-cast variation in GTAW

Although control of the GTAW process is straightforward if the variables listed above are considered, variable weldability has been experienced, particularly in the fabrication of stainless steel at relatively low currents. This phenomenon is referred to as ‘cast-to-cast’ variation since it commonly occurs when a new batch of material of nominally identical composition is used. The problem has received considerable attention and is believed to be associated with the level of trace elements in the material and, in the case of austenitic stainless steel, variation in levels of sulphur, calcium and oxygen has been identified as having a major influence. For example, for two welds shown in Fig. 6.17 made under identical welding conditions on low-carbon austenitic stainless steel (304L), the only difference in the analysis of the plate material was in the level of sulphur, which was 0.004% for (a) the low depth-to-width ratio weld and 0.007% for (b) the high depth-to-width weld.

The influence of such small fluctuations of elements such as sulphur has been explained in terms of their effect on the surface tension–temperature gradient of the liquid weld pool and the subsequent flow within the pool. It is known that the surface tension gradient of molten iron can be altered by the presence of trace elements as shown in Fig. 6.18. [104a+b] If the slope of the surface tension–temperature curve is negative (the surface tension is higher at low temperatures), surface-tension-driven flow of liquid metal will take place across the surface of the pool from the high temperature region at



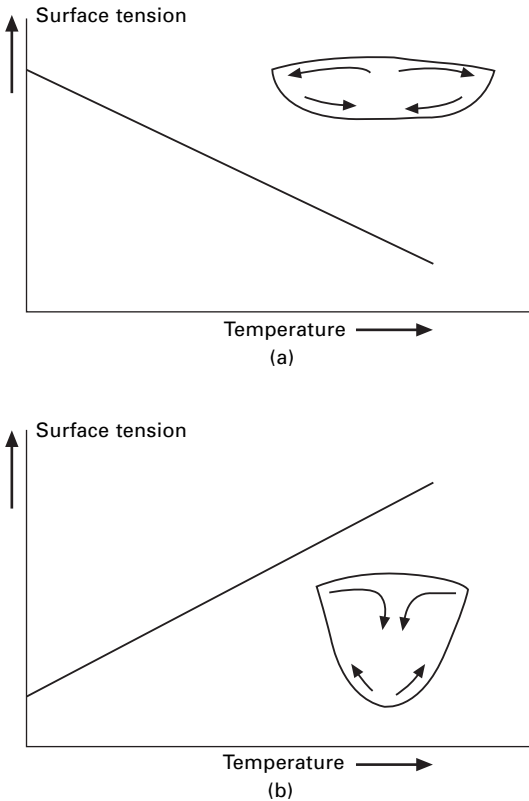
6.17 Profiles taken from two GTAW spot welds on 3-mm-thick 304L stainless-steel tube. Welds made under identical conditions.



6.18 Variation in surface tension–temperature curves for iron and the influence of trace elements. [104b]

the centre to the low-temperature area at the outer edge as shown in Fig. 6.19(a). If the surface tension gradient has a positive slope, the metal will flow inwards from the periphery of the pool, and the higher-temperature liquid will flow down the axis to promote increased central fusion as shown in Fig. 6.19(b). This effect is known as ‘Marangoni Flow’. [105] The mechanism would appear to explain the sensitivity of many materials to variations in trace elements and the resultant weld geometry.

The penetration may also be influenced by other factors: electromagnetic



6.19 The effect of surface tension gradients on weld pool flow.

or Lorentz forces, buoyancy (flow induced by density differences in the pool due to the temperature gradient) and aerodynamic drag forces (due to the flow of gas plasma jets over the pool surface) are all thought to have an effect. At higher currents, the energy transfer and flow within the pool are likely to be dominated by the effect of the arc plasma and depression of the pool surface.

The effects of cast-to-cast variability can be reduced by using higher currents, pulsed operation, by choice of shielding gas (e.g. argon/5% hydrogen for austenitic stainless steel) or by adding a filler containing elements which promote a positive surface tension–temperature gradient (e.g. sulphur in austenitic stainless steel). It has also been reported that the problem may be alleviated by coating the material with a surface-active paste, as in the A-TIG process which has previously been described. In order to control the problem, however, it is necessary to identify potentially problematic materials. Several approaches may be adopted, i.e. chemical analysis, direct weldability trials or indirect weldability trials.

Chemical analysis may be a useful indicator of potential problems, but it may be costly and unreliable in view of the low levels of surface-active elements which need to be identified and the uncertainty of the correlation between the analysis and the penetration profile.

Direct weldability trials involve making a joint of the required type using an established welding procedure, sectioning the bead and measuring its cross sectional area. This approach has been common but it is time consuming and requires expert analysis.

A variety of indirect weldability tests have been investigated [106–108] and it has been found that it is feasible to identify the cast-to-cast effect by measuring the time for a weld to penetrate a known thickness of plate under controlled conditions. Alternatively, the material characteristics may be identified from direct observation of the weld pool using video techniques or by monitoring light and voltage signals from the arc.

6.4.2 Control of pulsed TIG

In pulsed GTAW, the process is controlled by the variables described above for conventional GTAW plus the pulse parameters. The influence of the pulse parameters has been described above.

6.4.3 Control of plasma welding

The control of plasma welding is slightly more complex than GTAW. The main control variables are the same as GTAW, but plasma gas flow rate and the diameter and geometry of the plasma orifice will also have a significant effect on the operation of the process. A smaller plasma orifice will produce an increased arc force, whereas a large nozzle diameter will result in a ‘soft’ plasma which is more like a GTAW arc. If the plasma gas flow is too low, the current too high, or the nozzle cooling is restricted, an arc may form directly across the gap between the electrode and the nozzle; this ‘double arcing’ phenomenon will result in serious damage to the orifice.

As with GTAW, higher currents allow higher travel speeds to be used, but, as the current is increased, there is a more noticeable increase in arc force which may result in undercut. If both the plasma gas flow and current are increased, the keyhole mode of operation is possible as described in Chapter 8.

The main factors controlling GTAW and related processes are summarized in Table 6.4.

6.5 Summary

The capabilities of GTAW have been extended by basic modifications to the operating technique such as pulsing, multicathode and hot-wire addition, the

Table 6.4 Principal control parameters for GTAW and plasma processes

Control parameters GTAW

Current, pulse parameters, current rise/decay times, electrode polarity, welding speed, electrode geometry, shielding gas type, shielding nozzle size, shielding gas flow stabilisation (gas lens), shielding gas flow rate, electrode protrusion

Additional control parameters for PLASMA

Electrode set back, nozzle geometry, orifice diameter, plasma gas type, plasma gas flow, pilot arc current

use of alternative shielding gases, surface active coatings and sophisticated power sources, as well as fundamental variations such as the dual-gas and plasma welding systems. The application of these techniques can offer improved weld quality and increased productivity. A better understanding of the way in which the process control variables influence joint quality has been developed and this has enabled further advances to be made in the automation of the process. Some of the resultant developments will be discussed in Chapter 11.

7.1 Introduction

Due to its high operating factor and deposition rate, gas metal arc welding (GMAW) has the potential to improve productivity over that obtained with the GTAW and SMAW processes. Although the requirement to exploit the economic benefits of the process has led to a clear trend towards greater use of GMAW worldwide, it has in the past proved difficult to obtain reliable quality. The main thrust of development has therefore been to improve control and achieve more consistent quality.

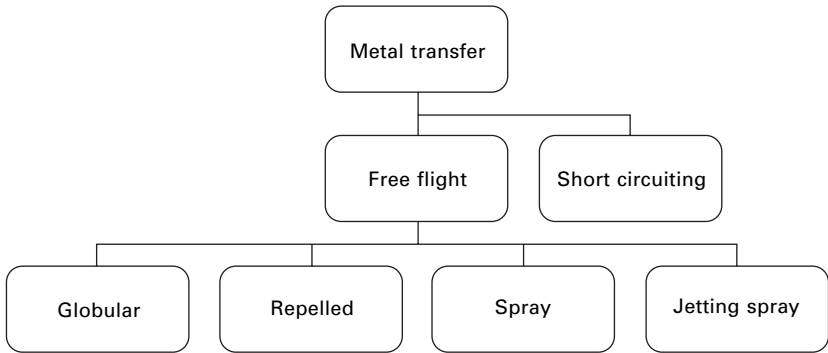
In order to discuss the advances which have been made in this direction it is necessary to reconsider the process fundamentals, in particular metal transfer in GMAW and control of conventional GMAW.

7.2 Metal transfer in GMAW

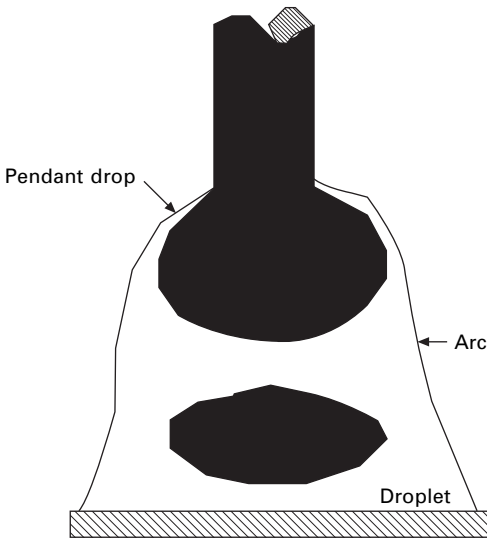
The way in which material is transferred from the tip of the consumable electrode into the weld pool has a significant influence on the overall performance of GMAW: it affects process stability, spatter generation, weld quality and the positional capabilities of the process. Phenomenological studies of the mode of metal transfer have been carried out using high-speed cine or stroboscopic cine and video techniques. [109] The various natural types of transfer have been classified into groups. A simplified basic classification is shown in Fig. 7.1.

In free-flight transfer an arc is maintained between the electrode and the workpiece and the metal is transferred across the arc in the form of droplets. The size of the droplets and frequency of transfer may vary considerably and several subdivisions of free-flight transfer are necessary to accommodate these variations. The common free-flight modes are:

- globular (drop and repelled);
- spray (drop projected streaming).



7.1 Classification of metal transfer in GMAW.



7.2 Globular transfer.

7.2.1 Globular drop transfer

Globular drop transfer is characterized by large droplets and low transfer rates (Fig. 7.2). It is normally found at low currents and fairly high arc voltages, although this will depend on the diameter of the filler wire, its composition and the shielding gas used. For example, with 1.6 mm diameter aluminium wire in an argon shield droplet transfer frequencies of less than 1 Hz may be observed at 100 A. In CO_2 -shielded GMAW of steel, globular transfer occurs with a range of wire sizes at currents above 200 A.

Both the appearance of the droplet and observation of droplet formation indicate that the transfer mechanism is dominated by gravitational forces; i.e. the droplet detaches when its size has grown to a stage where the downward

detachment force due to its mass overcomes the surface tension force which acts to prevent droplet separation. Although electromagnetic forces exist they are not sufficiently developed to influence the droplet detachment at low currents.

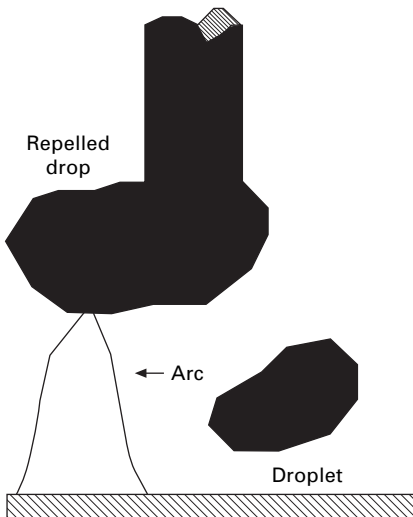
A low mean current is used but the process has very limited positional capabilities with solid wire GMAW because of the dominant nature of gravitational forces.

7.2.2 Globular repelled transfer

In some circumstances, a droplet may form at the end of the electrode and be deflected to one side or even expelled from the arc. This behaviour is commonly found when electrode negative polarity is used with a solid wire and is illustrated in Fig. 7.3. The dominant transfer force is gravitational but repulsion is caused by electromagnetically induced plasma forces or vapour jets which act on the base of the droplet, at the arc root, to lift the molten material. Once the droplet has been lifted in this way an asymmetrical magnetic field is created and the droplet may be rotated or expelled under the influence of the resultant forces as discussed below. This mode of transfer is usually undesirable due to the poor stability and high spatter levels which result.

7.2.3 Projected spray transfer

As the current is increased, the size of the droplet usually decreases and the frequency of transfer increases. In addition, it is found that the droplets are

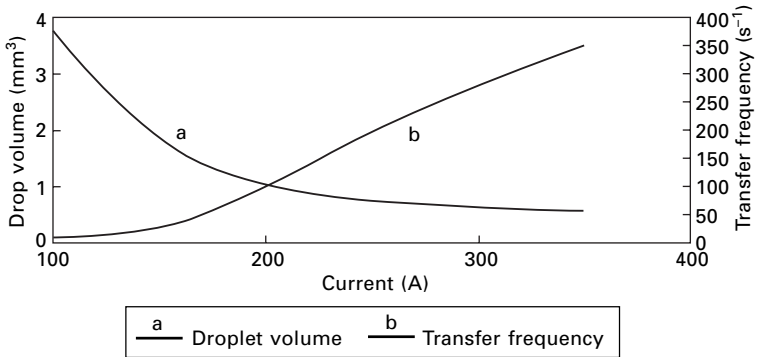


7.3 Repelled transfer.

projected axially through the arc with some force. In some cases (e.g. carbon steel in argon-rich gas mixtures and aluminium in argon) there is a clear transition between the globular and projected spray modes of transfer as the current is increased [110] (Fig. 7.4). The current at which this transition occurs is an important process characteristic and is known as the spray transition current. Its value depends on the filler material size and composition as well as the composition of the shielding gas. Typical values for steel are shown in Table 7.1. Below the transition current, the transfer is either globular or dip and, above the transition current, the transfer is in the form of a steady stream of small droplets, whose diameter is similar to that of the filler wire. Since this mode of transfer only occurs at relatively high currents, the heat input is high and the weld pool large. These features are attractive for high-deposition-rate downhand welding, but limit the positional capabilities of the process.

7.2.4 Streaming transfer

As the current increases, the droplet size decreases further and the electrode tip becomes tapered. A very fine stream of droplets is projected axially



7.4 Transfer characteristics for 1.2-mm-diameter stainless-steel wire in argon/2% oxygen. [110]

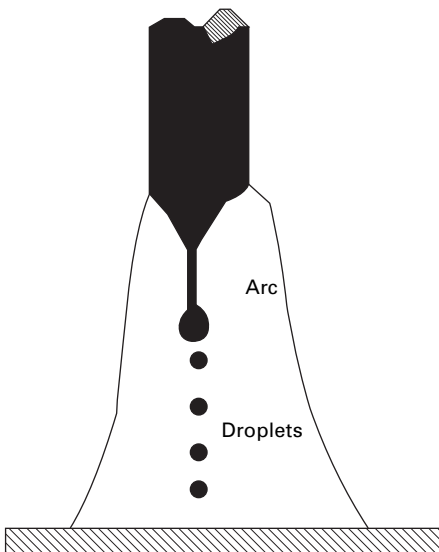
Table 7.1 Spray transition currents for plain carbon steel wires

Wire diameter (mm)	Spray transition currents (A) in various shielding gas mixtures		
	Argon/5%CO ₂	Argon/15%CO ₂	Argon/20%CO ₂
0.8	140	155	160
1.0	180	200	200
1.2	240	260	275
1.6	280	280	280

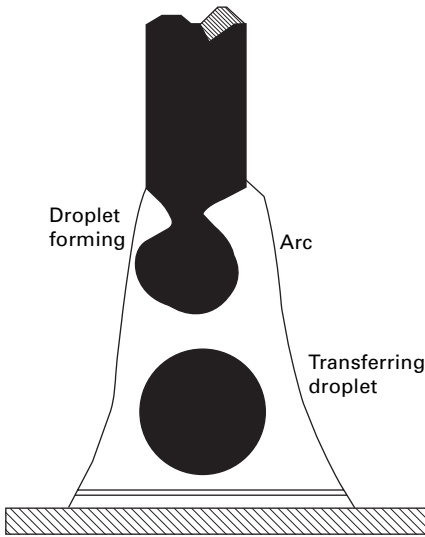
through the arc as shown in Fig. 7.5. This mode of transfer is called streaming and it is caused by a significant increase in electromagnetic forces. It occurs more readily with high-resistivity, small-diameter wires (e.g. austenitic stainless steel) operating at currents above 300 A. Weld pool turbulence and gas entrainment may limit the usefulness of this mode of transfer.

7.2.5 Drop spray transfer

The transition to projected spray transfer occurs over a relatively narrow current range but it has been found [111] that an important intermediate transfer mode can occur in this transition range. This mode of transfer is characterized by the formation of a solid conic neck on the wire tip and spherical droplets slightly larger in diameter than the diameter of the filler wire are initially suspended from the tip before being detached (Fig. 7.6). Detachment occurs very efficiently and high droplet velocities and very low spatter losses are measured. With a 1.2 mm carbon steel wire this transfer mode occurs between 250 and 270 A in argon/5% CO₂, drop velocities of 7 m min⁻¹ have been recorded and a slight increase in melting rate is observed. The drop spray mode is efficient and 'clean' with very low spatter and particulate fume levels, but, under normal steady DC operating conditions, it requires very close control of the welding parameters and this can only be achieved with the high-quality electronic power sources described in Chapter 3; in addition, the operating range is very restricted. The process range can,



7.5 Streaming transfer.



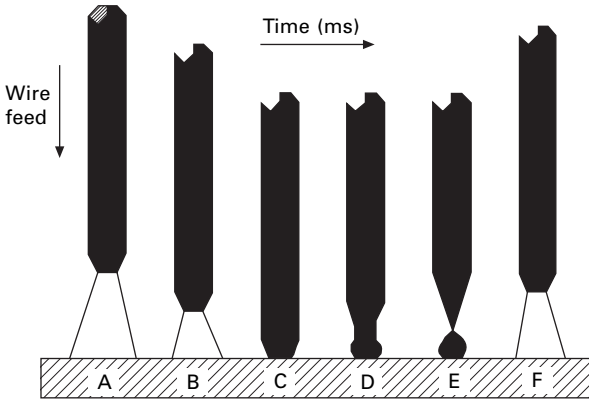
7.6 Drop spray transfer.

however, be extended by utilizing the pulsed transfer techniques described below.

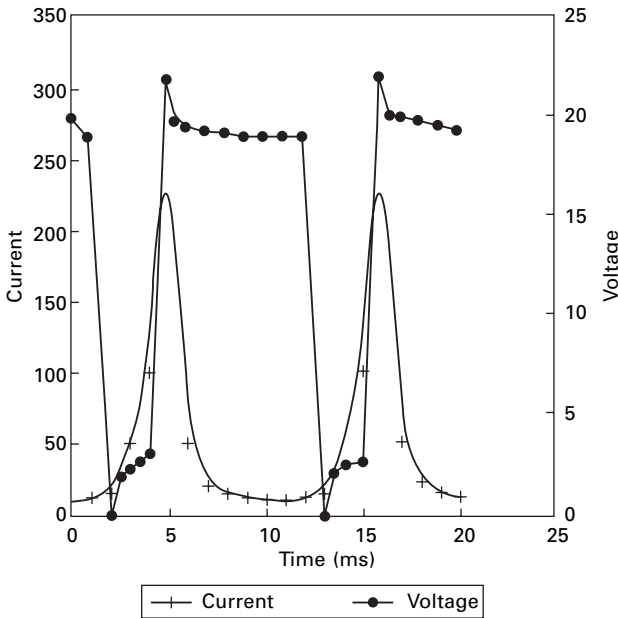
7.2.6 Dip transfer

If the electrode is fed toward the workpiece at a speed which exceeds the rate at which the arc alone can melt the wire, it will ultimately bridge the arc gap and dip into the pool. This behaviour may occur occasionally during free-flight transfer and is regarded as a fault condition, but, if the parameters are carefully chosen, it is possible to induce regular short circuiting of the arc gap at frequencies above 100 Hz. This mode of transfer is known as dip or short-arc transfer and is illustrated diagrammatically in Fig. 7.7.

The sequence of operation is as follows. The wire is fed at a constant speed, but burn-off during the arcing period is insufficient to maintain a constant arc length. The arc gap closes and the wire eventually contacts the weld pool. In response to this electrical short circuit, the current from the power supply rises rapidly causing resistive heating in the thin filament of wire which bridges the gap. The bridge ruptures, a portion of the heated electrode material is transferred to the weld pool and the arc is re-established. If the wire feed rate and power source output are carefully matched the short-circuiting process is repeated at regular intervals. The typical form of transient voltage and current waveforms is shown in Fig. 7.8. In practice, the arc must remain relatively short (2–3 mm) to maintain a regular, high dip frequency and it is not uncommon for upward movements in the weld pool to initiate the short circuit.

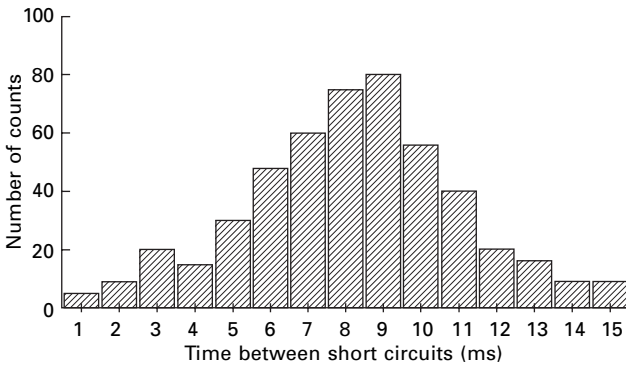


7.7 Mechanism of dip transfer.



7.8 Current and voltage waveforms in one dip transfer mode.

High currents (typically 200–400 A) are required to rupture the short circuit, but the arcing current is low and the arcing time is usually longer than the short-circuit time; as a result, the mean current is maintained at a low level. If the current during the short circuit is excessive, the short circuit will rupture explosively and metal will be ejected from the arc as spatter. During normal operation of the process, there is some uncertainty concerning the exact amount of metal detached during each short circuit. The time between short circuits, the arc time and, hence, the frequency of transfer,



7.9 Histogram of time between short circuits (arc time) for stable dip transfer.

varies but the interval between short circuits usually follows a normal distribution as shown in Fig. 7.9. The standard deviation of the distribution may be used as an indicator of process stability, optimum conditions having the lowest value of standard deviation in arc time. The low mean current, low heat input and resultant small, fast freezing weld pool make dip transfer suitable for positional work and the welding of thin sheet steel.

The random nature of the short circuiting together with process instability and risk of high spatter levels are potential limitations of dip transfer. These problems can, however, be controlled either by choice of shielding gases (see Chapter 5) or by electronic techniques as discussed below.

7.2.7 Other transfer phenomena

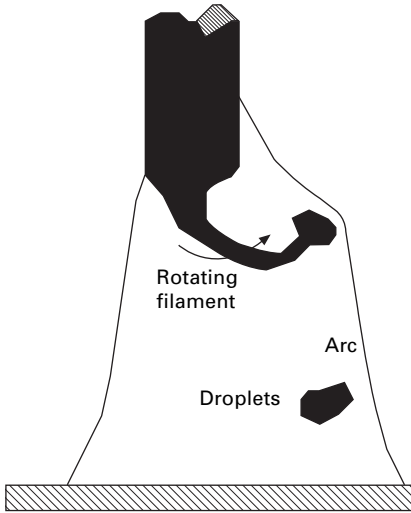
Metal transfer may usually be classified into one of the categories above, but several variations of normal transfer do occur.

Explosive droplet transfer

It has been observed that pendant drops on the electrode tip can eject material in an explosive manner. This is thought to be due to chemical (gas–metal or slag–metal) reactions inside the droplet. These explosions may assist transfer in FCAW, but usually cause instability in GMAW.

Rotating transfer

Rotation of the droplet may occur in the repelled mode as described above but the term rotating transfer is also used to describe the rotation of an extended metal filament between the solid wire tip and the droplet in streaming transfer as shown in Fig. 7.10. The occurrence of this mode of transfer at



7.10 Rotating transfer.

high currents is usually undesirable, although it has been used for surfacing applications using the ‘plasma-MIG process’ as well as the ‘T.I.M.E.’ process described below.

7.2.8 FCAW and slag-protected transfer

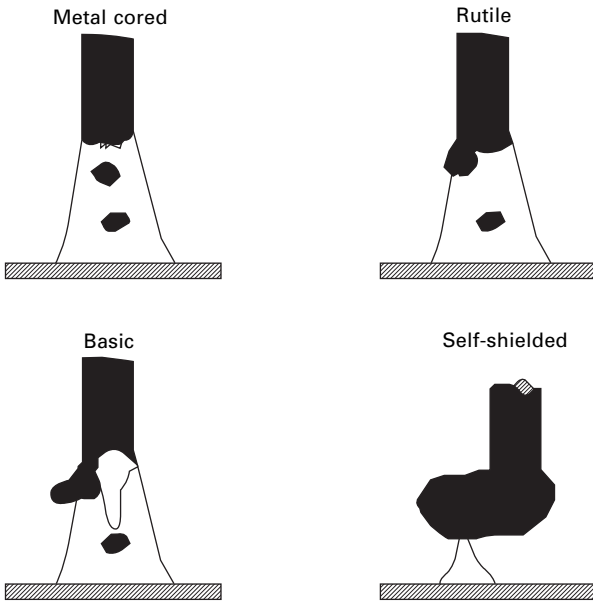
In flux-cored wires, the slag formed from the flux constituents may affect the transfer phenomena. The type of transfer depends on the flux system used, but the following transfer phenomena have been identified [112, 113] using a high-speed image converter camera. These effects are illustrated in Fig. 7.11.

Metal-cored wires

Metal-cored wire consumables contain very little non-metallic flux and tend to behave like solid wires. Good dip transfer performance is obtained at low currents and axial projected spray at higher currents. In addition, stable electrode negative operation may be achieved in argon-rich argon/CO₂ gas mixtures. The streaming spray transfer which occurs at high currents (e.g. 350 A for a 1.2 mm diameter wire) gives high burn-off rates and smooth weld bead profiles.

Rutile flux-cored wires

Rutile flux-cored wire consumables are normally operated in the spray mode where they give smooth non-axial transfer. Some of the flux melts to form a



7.11 Schematic representation of transfer types observed with flux-cored wires.

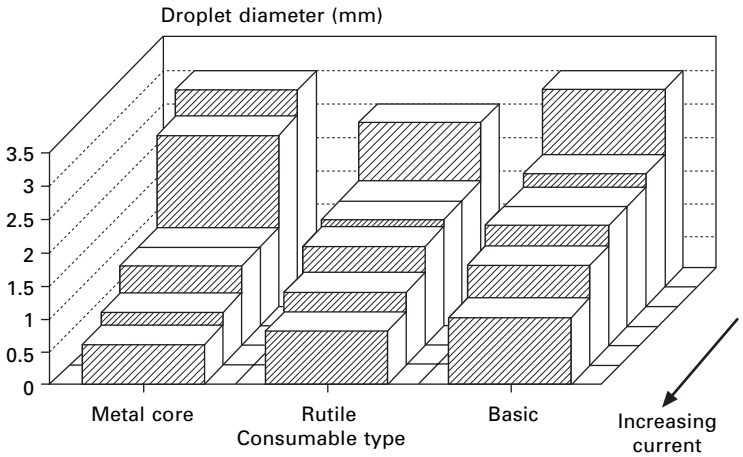
slag layer on the surface of the droplet, a small amount decomposes to form shielding gases whilst some un-melted flux is transferred to the weld pool where it melts and produces a protective slag blanket. The un-melted flux projects from the tip of the wire as shown in Fig. 7.11.

Basic flux-cored wires

The basic flux formulation gives irregular dip transfer at low currents and non-axial globular transfer at higher currents. The un-melted flux forms a pronounced finger which projects from the wire into the arc. The effect of the flux formulation on the droplet size for gas-shielded flux-cored wires is shown in Fig. 7.12.

Self-shielded flux-cored wires

Dip and globular repelled transfer are commonly found with this type of consumable and very large levitated globular 'boots' may form at the wire tip. The globular tendency may be reduced by flux formulation and there is evidence of secondary transfer occurring from the base of the globule as well as explosive droplet transfer.



7.12 Droplet diameter range using image analysis. Note transition to small droplets in the case of metal cored wire. Large droplets for basic wire.

7.3 The physics of metal transfer

In order to understand and improve transfer behaviour it is necessary to consider the mechanisms involved in more detail. The transfer behaviour described above is a result of a balance of forces acting on the metal droplet. The principal forces involved are:

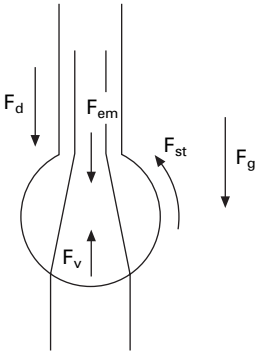
- gravitational force, F_g ;
- aerodynamic drag, F_d ;
- electromagnetic forces, F_e ;
- vapour jet forces, F_v ;
- surface tension, F_{st} .

The dominant forces and their influence on metal transfer will depend on the operating conditions (current, voltage, wire diameter, shielding gas, etc.) used but in free-flight transfer the static balance of forces at the point of droplet detachment is illustrated diagrammatically in Fig. 7.13 and described by an equation of the form

$$F_g + F_d + F_{em} = F_{st} + F_v \tag{7.1}$$

In dip transfer, the surface tension force may act to assist detachment and with the exception of F_{em} the other forces may be quite small.

An indication of the magnitude of these forces is given below, based on the commonly accepted classical physics approach, but many of the parameters involved are time and temperature dependent and a full theoretical analysis requires a consideration of the dynamic phenomena.



7.13 Balance of forces acting on a droplet.

7.3.1 Gravitational force

The gravitational force is given by:

$$F_g = mg \quad (7.2)$$

where m is the mass of the droplet and g is the vertical component of the acceleration due to gravity (i.e. $9.81 \cos \theta \text{ m s}^{-1}$ where θ is the angle between the arc axis and vertical). The force will have a maximum positive value in downhand welding (when $\cos \theta$ is +1) and a negative value in positional welding (when θ is between 90° and 180° and $\cos \theta$ has a negative value). Measured values of this force [114] for 1.6 mm wires in argon shielding gas at low currents (globular transfer) indicate values of 260 dyn for aluminium and 600 dyn for iron.

7.3.2 Aerodynamic drag

The gas flow within the arc can induce a force on a droplet, F_d , which may be calculated from

$$F_d = 0.5\pi V^2 d r^2 C \quad (7.3)$$

where V is the gas velocity, d is the gas density, r is the droplet radius and C is the drag coefficient. The magnitude of this force will be highest when the droplet diameter and gas velocity are high. It is unusual for both gas velocity and droplet diameter to be at their maximum values at the same time; large droplets are normally found at low currents whilst high gas velocities are more commonly experienced at higher currents; drag forces are consequently small in most situations.

7.3.3 Electromagnetic forces

When a current flows through a conductor, a magnetic field is produced and

electromagnetic forces will be generated. The magnitude of these forces in the area surrounding the tip of the electrode, the molten droplet and the arc is strongly influenced by the geometry of the current path. The magnitude of the force may be calculated from

$$F_{em} = \frac{\mu I^2}{4\pi} \ln \left| \frac{r_a^2}{R} \right| \tag{7.4}$$

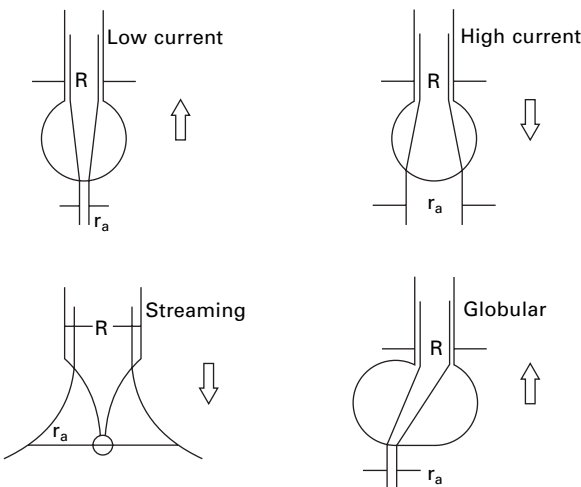
where μ is the magnetic permittivity of the material, I is the current, r_a is the ‘exit’ radius of the current and R is the ‘entry’ radius (see Fig. 7.14). Electromagnetic forces can have relatively large values (e.g. up to $0.02 \times I^2$ have been measured in GTAW arcs) and are clearly dependent on the current. These forces tend to dominate the transfer at the currents required for spray transfer.

7.3.4 Vapour jet forces

At high currents, significant vaporization of the surface of the molten droplet can occur in the arc root area. Thermal acceleration of the vapour particles into the arc plasma results in a force which opposes droplet transfer. The value of this force for a flat surface of uniform temperature and composition can be shown to be

$$F_v = \frac{m_0}{d_v} IJ \tag{7.5}$$

where m_0 is the total mass vaporized per second per amp, I is the current, J



7.14 ‘Geometry’ of current path in various transfer modes.

is the current density and d_v is the vapour density. The vaporization force usually only becomes significant at higher currents or when low-vapour-pressure elements are present.

7.3.5 Surface tension

Surface tension plays a very important role in metal transfer; in free-flight transfer it is the principal force which prevents droplet detachment and, in dip transfer, it is the major force which pulls the droplet into the weld pool. A simple static analysis of the drop-retaining force in globular transfer would suggest that the force is given by

$$F_{st} = 2\pi r_w \sigma f(r_w/c) \quad (7.6)$$

where r_w , is the wire diameter, σ is the surface tension and $f(r_w/c)$ is a function of wire diameter and the constant of capillarity c . For large droplets, the value of this equation approximates to $2\pi r_w$.

Calculation of the magnitude of the force due to surface tension is, however, complicated by the significant temperature dependence and the dramatic influence of certain surface-active elements (for example at the melting point of steel its surface tension will be reduced by around 30% by a concentration of 0.1% oxygen and the effect of small amounts of sulphur in changing the surface tension/temperature gradient has already been discussed in Chapter 6). Values of 300 dyn for aluminium and 600 dyn for steel have been calculated, however, for globular transfer with a 1.6 mm diameter wire.

7.4 Summary: metal transfer phenomena

Metal transfer phenomena may be classified as free-flight or dip and within the free-flight mode several alternative transfer types may be observed. A classification which embraces these phenomena has been devised by the International Institute of Welding [115] and this is illustrated in Table 7.2. The mode of metal transfer is influenced by a balance of forces which will depend on the operating parameters for the process. Gravitational, electromagnetic and surface tension are the most significant forces controlling metal transfer. In conventional GMAW, the level of these forces and the resultant transfer behaviour is determined by the physical properties of the system (material and the shielding gas), but is controlled to a significant extent by the welding current.

7.5 Control of conventional GMAW

Mean current determines the transfer mechanism of the process as described above and also controls the melting rate of the filler wire.

Table 7.2 Classification of transfer modes (modified version of IIW classification) [115]

Transfer group	Sub group	Example
1.0 Free flight		
1.1 Globular	1.1.1 Globular drop	Low current GMAW
	1.1.2 Globular repelled	CO ₂ shielded GMAW
1.2 Spray	1.2.1 Projected	GMAW above spray transition
	1.2.2 Streaming	Medium to high current GMAW
	1.2.3 Rotating	High current, extended stick-out GMAW, plasma MIG
	1.2.3 Explosive	MMAW
	1.2.4* Drop spray	On transition current (pulsed transfer) GMAW
2.0 Bridging transfer		
2.1 Short circuiting		Low current GMAW
2.2 Bridging without interruption		Welding with filler wire addition
3.0 Slag protected transfer		
3.1 Flux wall guided		SAW
3.2 Other modes		SMAW, FCAW

* Note: author's modification [116] to IIW classification.

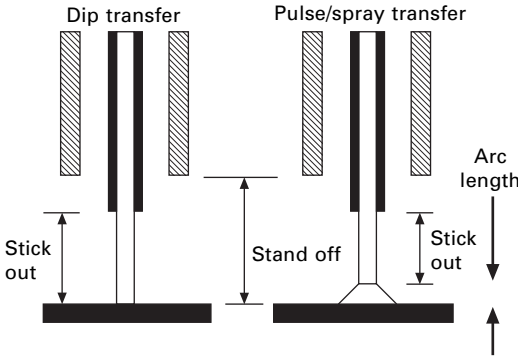
7.5.1 Melting rate phenomena: GMAW

The melting rate, MR, is usually expressed as

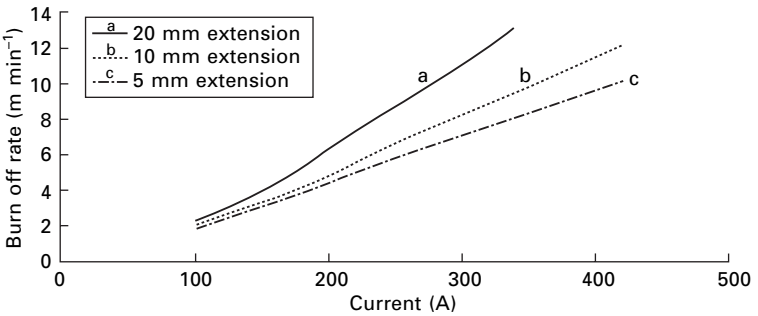
$$MR = \alpha I + \frac{\beta I l^2}{a} \quad (7.7)$$

where I is the current, l is the electrical stick-out or extension (Fig. 7.15), a is the cross sectional area of the wire and α and β are constants. Measured values of α and β for 1.2 mm plain carbon steel wire are $\alpha = 0.3 \text{ mm A}^{-1} \text{ s}^{-1}$ and $\beta = 5 \times 10^{-5} \text{ A}^{-2} \text{ s}^{-1}$; for aluminium $\alpha = 0.75 \text{ mm A}^{-1} \text{ s}^{-1}$ and β is negligible. The area term is absent in these figures since they apply to a fixed wire diameter.

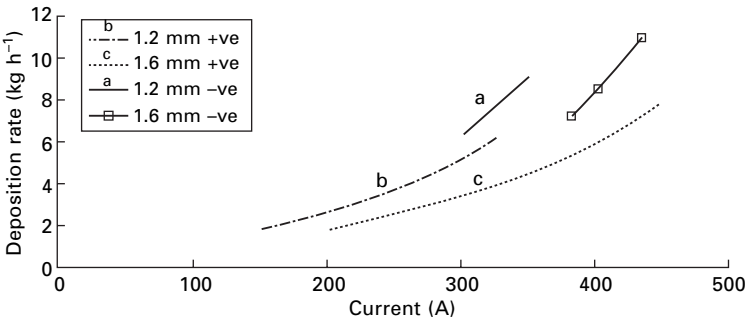
The first term in equation (7.7) represents the arc heating effect whilst the second term is due to resistive heating of the electrode. Melting rates are affected significantly by the electrical resistance of the stick-out as shown [117] in Fig. 7.16. The stick-out resistance depends on the electrode diameter/cross sectional area, electrode resistivity, and the length of the extension. DCEN (direct current electrode negative) operation increases the melting rate [118] as shown in Fig. 7.17, but it is normally difficult to maintain a stable arc and ensure adequate fusion with this mode of operation.



7.15 Terms used to describe torch position.



7.16 Influence of electrode extension (stick-out) on the burn-off rate for 1.2-mm-diameter steel argon/5% CO₂. [117]



7.17 Influence of electrode polarity on deposition rate for steel in Ar/O₂/CO₂ mixture. [118]

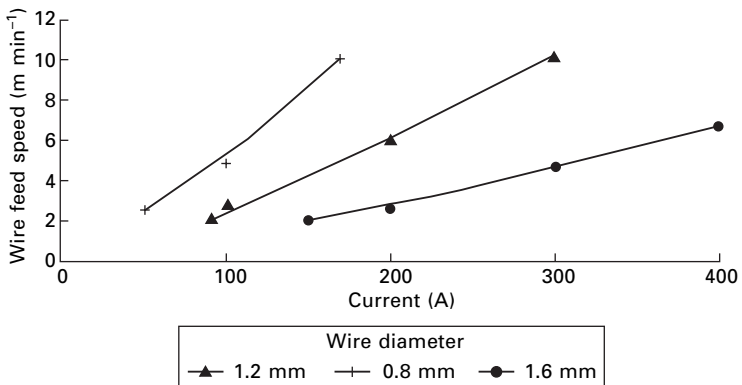
If the electrode polarity and the extension are fixed, then, for stable operation of the process in any transfer mode, the wire must be fed at a rate (the burn-off rate) which is equal to the rate at which it is consumed (i.e. the melting

rate¹). The relationship between wire feed speed and current, which is given by equation (7.7), is usually shown graphically in the form of burn-off curves of the type shown in Fig. 7.18 and this allows the appropriate wire feed speed to be selected for a given mean current.

7.5.2 Voltage–current characteristics

The voltage developed between the end of the contact tip and the workpiece in the GMAW process is the sum of the resistive drop in the wire extension plus the voltage fall across the arc. Calculation of the resistance of the electrode stick-out is complicated by the temperature dependence of resistivity and the steep temperature gradient which exists in the wire. Measurements of the total voltage drop under a range of operating conditions show that the relationship between mean current and voltage in the free-flight operating modes of the GMAW process is very similar to the characteristic of a GTAW arc. In the working range, the arc has a positive resistance and for any shielding gas–filler wire combination at a fixed arc length the voltage increases linearly with current.

In dip transfer, the mean current–voltage characteristic represents the average of the short-circuit resistance and the arc resistance and follows the same trend. In both dip and free-flight transfer, the relationship between mean current and voltage may be expressed in an equation of the form:



7.18 Burn-off characteristics for plain carbon steel filler wire.

¹The term melting rate is usually used to describe the mass of electrode material consumed per unit time. Burn-off rate is the rate at which the wire is consumed or the wire feed speed. Melting speed is sometimes used to describe the speed at which the melting isotherm or solid–liquid boundary travels along the electrode wire.

$$V = M + AI \quad (7.8)$$

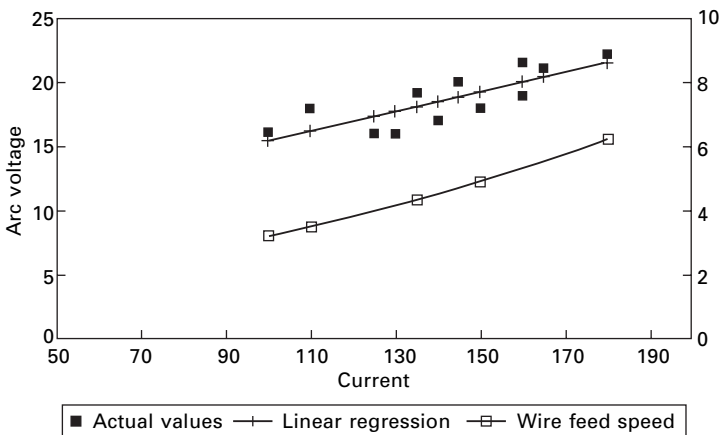
where V is the arc voltage, I is the current and M and A are constants. The resultant relationship is illustrated in Fig. 7.19.

7.5.3 Control in conventional GMAW systems

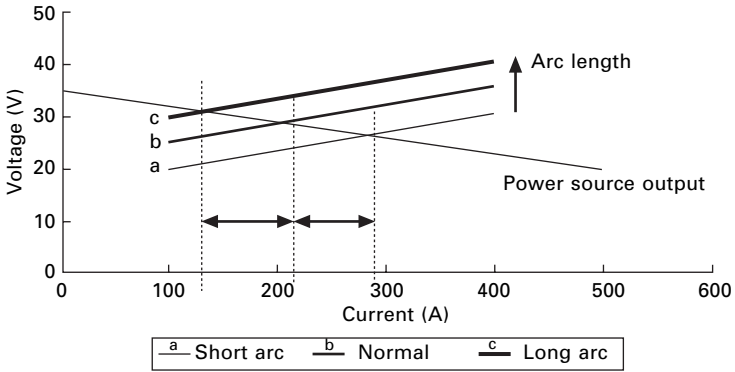
Conventional wire feed systems are designed to maintain the feed speed constant at a preset value irrespective of any variations in the arc behaviour. Conventional GMAW power sources have for some time been designed with constant-voltage (CV) characteristics in order to provide self-adjustment and stabilization of the arc length. With these systems, if the arc length tends to change, the current varies significantly and the burn-off behaviour acts in such a way as to counteract the change in arc length. An increase in arc length causes an increase in arc voltage and the power source output current must reduce in order to meet the higher voltage demand; since melting rate is current dependent, the reduced current will result in reduced melting and since less wire is consumed the arc length is shortened. Shortening the arc will produce an increase in current, increased melting and again the arc length will return to its original value (Fig. 7.20).

7.5.4 Welding parameter selection: CV power source

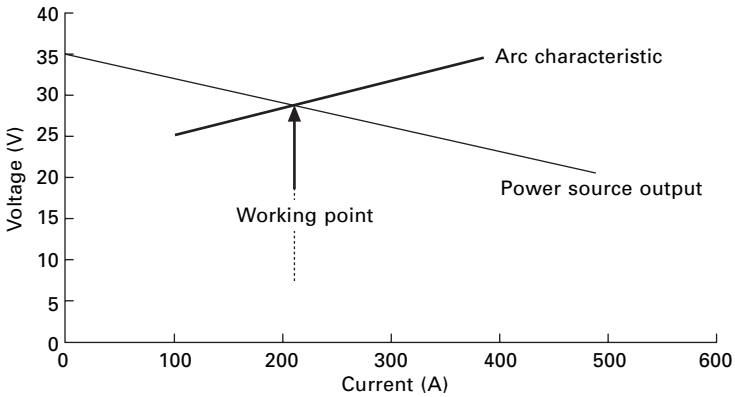
Current is normally chosen according to the plate thickness being welded and the travel speed required. The wire feed speed may be determined from the burn-off curves as described above and the voltage is set to provide the required current and satisfy the arc voltage–current characteristic. The operating point for the process will be defined by the intersection of the power source



7.19 1.0-mm wire dip transfer.



7.20 Self-adjustment with a constant-voltage power source.

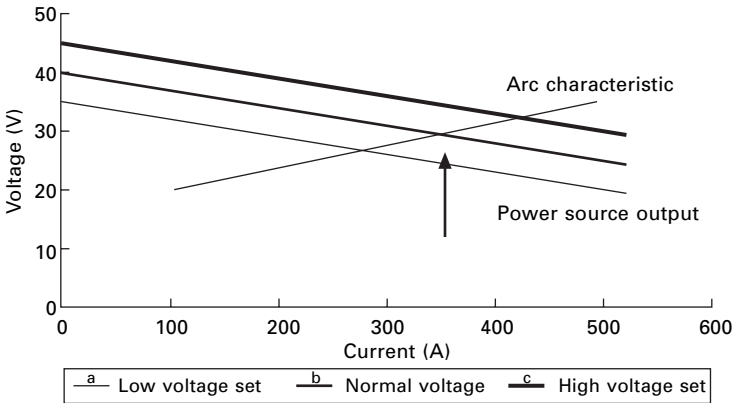


7.21 Working point with a constant-voltage power source.

and the process characteristics, as shown in Fig. 7.21. The practical effects of incorrect adjustment are reflected in arc performance. If the voltage is too low for a given wire feed setting, ‘stubbing’² occurs. If the voltage is too high, a long arc will occur with eventual burn-back of the filler wire to the contact tip.

In conventional GMAW equipment (e.g. tapped transformer–rectifier designs), voltage is often varied in steps by switches which set the open-circuit voltage and short-circuit current as shown in Fig. 7.22. The arc voltage must be estimated from a knowledge of the static slope of the power source characteristic. The maximum short-circuit current which is automatically determined by selection of the voltage is the maximum level to which the current can rise when the output of the power source is short circuited, for

²Stubbing is the undesirable contact of partly melted filler wire with the workpiece.



7.22 Switch output power supply control.

example during dip transfer. With a CV characteristic power source this level may be very high and result in explosive rupture of the short circuit with high levels of spatter. In order to limit this current, it is usual to incorporate inductance in the output of the power source, this reduces the rate of rise of current and limits the maximum value reached before the short circuit ruptures. If the inductance is too high, the current will not reach a sufficiently high level to cause detachment and irregular operation will result. In the dip transfer mode, the voltage and inductance should therefore be adjusted to optimize the short circuit current and obtain stable spatter-free detachment.

7.5.5 Alternative control techniques

If a constant-current output power source is used, the heating effect (current) of the arc does not vary with small changes in stand-off and voltage. Furthermore, an inherent self-adjustment mechanism operates with resistive wires since, if current and wire feed speed are fixed, a unique value of ' l ', the electrical stick-out, is defined by equation (7.7). If l decreases momentarily due to some process disturbance, the second term in the equation decreases and the melting rate decreases thereby restoring the original extension length. Unfortunately, this self-regulation does not occur with high conductivity materials such as aluminium.

Constant-current power sources may be used for GMAW of high conductivity materials by using a variable-speed wire feed unit which responds to arc length changes by adjusting the wire feed speed. Electronic AVC (arc voltage control) systems may be used with more modern power sources to cope with this situation. Some of the developments in this area are described in Section 7.7.

7.6 Summary: process control

A well established relationship exists between mean current and wire feed speed but current must be set indirectly in conventional CV GMAW systems. The arc voltage, operating current and maximum short-circuit current are normally determined by the open-circuit voltage setting. The rate of rise of current and its peak value during a short circuit are controlled by secondary inductance. Constant-current power sources may be used with resistive wires, but additional regulation is required to cope with process fluctuations with high-conductivity consumables.

7.7 Recent developments in the GMAW process

The object of the developments of the GMAW process has been to control metal transfer, improve process stability, simplify process control, and improve operating tolerances. The introduction of solid-state power sources has enabled the process performance to be analysed in more detail and improved control systems to be developed. The process operating ranges have also been extended and high deposition techniques have been introduced to provide improved productivity. Some of these developments are discussed below.

7.7.1 Controlled transfer techniques

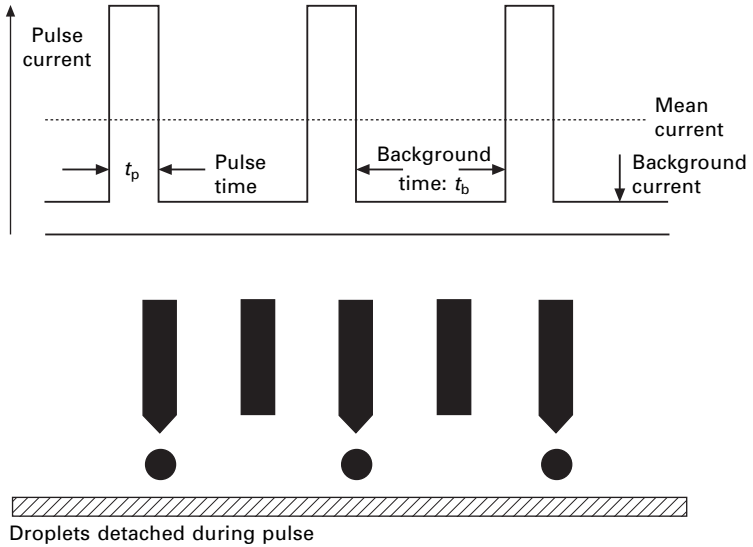
The ‘natural’ modes of transfer which have been described above have several limitations, these include:

- Spray transfer only occurs when the mean current exceeds a relatively high transition current. This limits the capability of the process for positional work or the joining of thinner sections.
- Dip transfer, whilst particularly suitable for joining thin section plain carbon steel, is less effective on non-ferrous materials.

Advances in the control of metal transfer have led to the development of pulsed GMAW and controlled dip transfer.

Pulsed GMAW

Pulsed transfer was devised to allow spray-type transfer to be obtained at mean currents below the normal transition level. A low background current (e.g. 50–80 A) is supplied to maintain the arc, and droplet detachment is ‘forced’ by the application of a high current pulse (Fig. 7.23). The pulse of current generates very high electromagnetic forces, as would be expected from the foregoing analysis of metal transfer, and the metal filament supporting the droplet is constricted, the droplet is detached and projected across the arc gap.



7.23 Pulsed transfer.

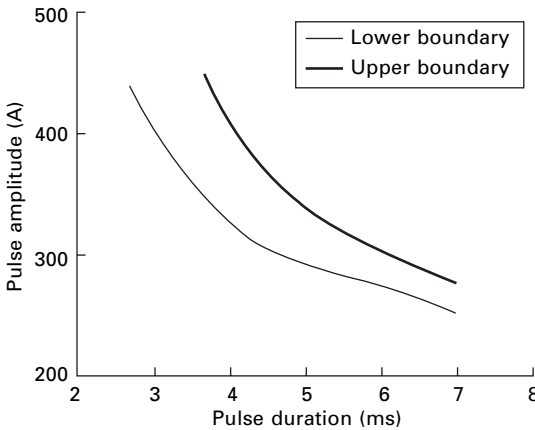
The use of high-current pulses to control detachment and transfer metal droplets has been known for some time, but the potential process benefits of low-current spray transfer, with minimum spatter and improved positional control were not widely realized due to the limitations of early pulsed GMAW equipment. The major problem with early pulsed GMAW equipment was its fixed frequency (50 to 100 Hz) operation and the additional complexity of establishing and setting the welding parameters. Using the electronic power sources described in Chapter 3, it is possible to generate variable-frequency output waveforms and to optimize metal transfer conditions.

Controlled droplet detachment

The pulse parameter required to detach a single metal droplet of a fixed size may be determined for any combination of wire size, composition and shielding gas. The pulse time t_p and pulse current I_p have been shown to follow a relationship

$$I_p^n t_p = D \quad (7.9)$$

where D is a constant (the detachment constant) and n has a value that is normally between 1.1 and 2. The value of I_p is always above the spray transition current and I_b , the background current, has little influence on detachment. The experimentally determined values are usually plotted in the form of an I_p/t_p curve as shown in Fig. 7.24. There is some latitude in these experimentally determined pulse parameters for single-droplet detachment,



7.24 Pulse current–pulse duration relationship for one drop per pulse transfer (1.2 mm diameter carbon steel wire in argon/5% CO₂).

Table 7.3 Typical pulse parameters for controlled droplet detachment

Wire diameter (mm)	Pulse amplitude I_p (A) and duration t_p (ms) for a range of common materials					
	Plain carbon steel		Austenitic stainless steel		Aluminium alloys	
	I_p	t_p	I_p	t_p	I_p	t_p
0.8	300	1.5	300	1.5		
1.0	300	2.0	350	2.0		
1.2	350	4.0	350	3.0	250	2.5
1.6	400	4.0			200	5.0

this gives rise to the band of conditions and it is possible to select a range of values which lie within the operating area.

Typical values for I_p and t_p for a range of consumables are given in Table 7.3. Ideally, the parameters are chosen to produce droplets of similar diameter to that of the filler wire and similar in size to those found in the drop spray transfer mode.

If it is assumed that a constant length of wire is burnt off at each pulse, a simple relationship between pulse frequency and wire feed speed may be defined where W is wire feed speed, F is pulse frequency and l_d is the length of wire detached per pulse:

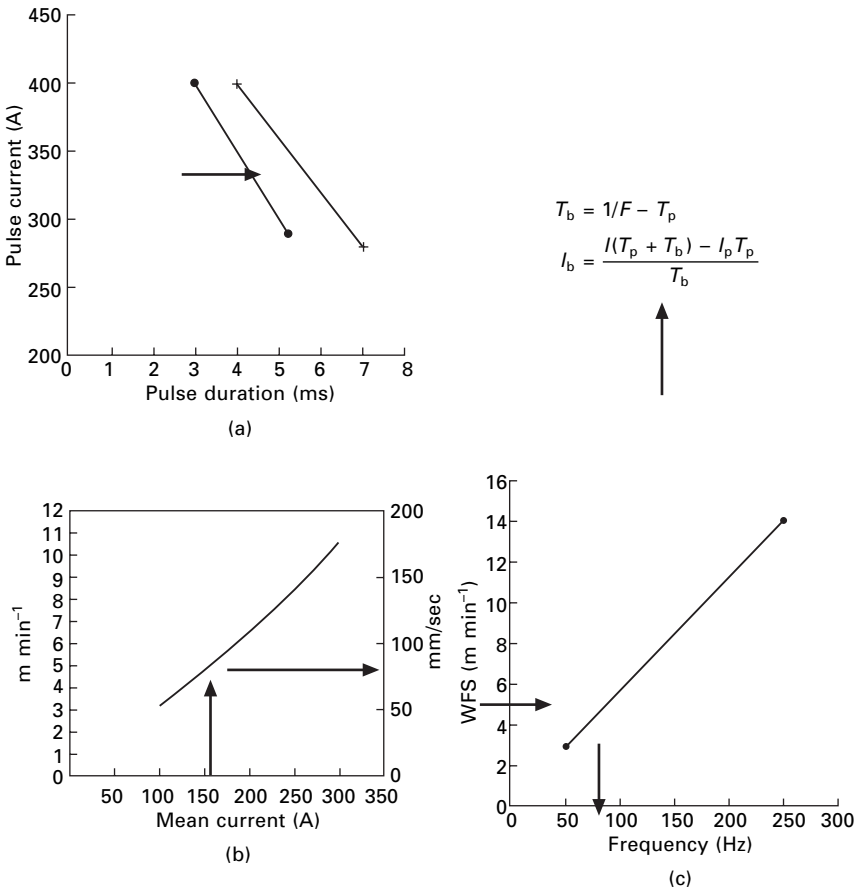
$$W = Fl_d \tag{7.10}$$

The mean current for a rectangular waveform will be given by

$$I_m = \frac{I_p t_p + I_b t_b}{t_p + t_b} \tag{7.11}$$

where I_m is the mean current and t_b is the background time. Since detachment is controlled by the pulse amplitude and duration, the mean current may be reduced to well below the transition current simply by increasing the background time or reducing the pulse frequency. In practice, controlled drop spray transfer may be achieved at currents down to 50 A with a 1.2 mm diameter steel wire (transition current ≈ 240 A).

Using the simple equations above, it is possible to predetermine the operating parameters for the process as shown in Fig. 7.25. The procedure is as follows:



7.25 Pulse parameter prediction for 1.2 mm wire in argon/5% CO₂: A pulse parameters; B burn-off rate and C frequency versus wire feed speed.

- Select the pulse current amplitude I_p and duration t_p from the relevant detachment curve or table;
- Choose a suitable mean current (I_m) for the application;
- Determine the required wire feed speed (W) from the burn off curve for the chosen wire;
- Select the required pulse frequency (F) from the wire feed speed–frequency curve;
- Determine t_b from

$$t_b = (1/F) - t_p \quad (7.12)$$

- Determine I_b from:

$$I_b = \frac{[I_m(t_p + t_b) - I_p t_p]}{t_b} \quad (7.13)$$

This procedure allows the operating parameters to be accurately predetermined but it is time consuming and tedious. Computer programs have been devised to overcome the calculation problems, but development of power sources with in-built microprocessor control, capable of storing the basic parametric data and the equations above have greatly simplified the selection and setting of suitable welding conditions. Using these techniques further improvements in the control of the process have also been made as described below.

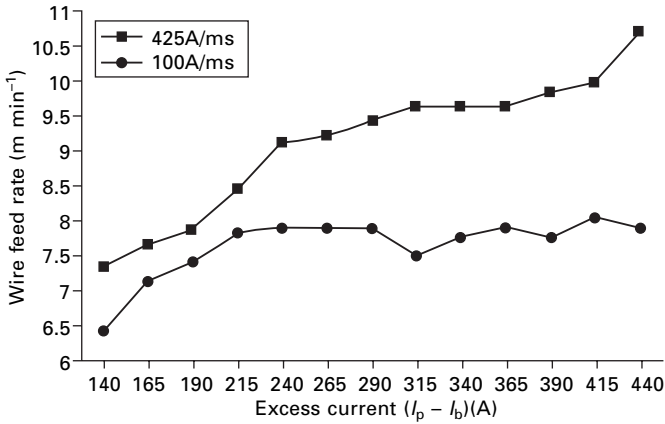
Effect of pulse parameters on burn-off behaviour

Although it may be assumed that to a first approximation the pulse amplitude and duration may be varied within the limits of equation (7.9) without any change in burn-off behaviour, it can be shown that, at high pulse currents, significant increases in melting rate may occur. This effect results from increased resistive heating during the pulse and the melting rate equation (7.7) may be modified [119] to include this effect as follows:

$$MR_p = \alpha I_m + \beta l \left(I_m^2 + \frac{(I_p - I_b)^2 t_p t_b}{t_p + t_b} \right) \quad (7.14)$$

The significance of the difference between the background and pulse current can clearly be identified in this equation. An increase in the excess current I_e where $I_e = (I_p - I_b)$ will cause a significant increase in melting rate. Calculated and experimentally determined values for a steel wire are shown in Fig. 7.26.

In practical welding situations, the increased burn-off resulting from the use of high-pulse currents may result in weld bead convexity or decreased dilution at a given mean current. It has also been demonstrated [120] that the burn-off behaviour is influenced in a similar manner by variations in the rate



7.26 Effect of pulse parameters on melting rate.

of change of current; high rates of current rise give higher burn-off rates than slower rates of current increase at the same mean current as shown in Fig. 7.26. For a 1.2 mm diameter plain carbon steel wire the burn-off rate increases by 10% when the slew rate (dI/dt) of the current changes from 100 A m s⁻¹ to 425 A m s⁻¹. The burn-off rate equation may be modified to reflect this effect and equation (7.14) becomes

$$MR_p = \alpha I_m + \beta I \left(I_m^2 + \left(\frac{I_p - I_b}{t_p + t_b} \right)^2 t_p t_b \right) - \frac{(I_p - I_b)^3}{3S(t_p + t_b)} \quad (7.15)$$

where S is the slew rate = dI/dt .

These variations may account for the differences in performance between power sources of a similar design but different dynamic characteristics.

Pulsed flux-cored wire welding

Limited success was achieved using conventional pulsed transfer techniques for flux-cored wire welding, but the use of the more flexible variable-waveform power sources described in Chapter 3 has enabled controlled transfer to be obtained with all types of gas shielded flux-cored wires. The effect of pulsing varies with the wire type, but the following phenomena have been identified: [121]

- Metal-cored wires behave in a very similar manner to solid consumables and pulsing may be used to enhance positional performance and control whilst at the same time exploiting the alloying potential of the wire. If the appropriate parameters are selected, as discussed in the previous section, the burn-off rate may also be increased at a given mean current.

- Rutile flux-cored wires require slightly different parameters to achieve controlled transfer, but these are readily obtained with most commercial advanced pulsed GMAW systems. With the exception of controlling burn-off behaviour the use of pulsed techniques is not easy to justify with this type of consumable since the performance is usually excellent under normal DC operating conditions.
- Basic flux-cored wires normally have poor positional performance and transfer usually occurs in a globular manner. It has been found, [122] however, that pulse techniques may be used to improve transfer and enhance positional performance. In the case of basic wires some form of arc voltage control, as described below, is essential.

Controlled dip transfer

As discussed above, dip transfer is a statistically variable process. The amount of wire transferred by each short circuit is not predetermined and this will influence arc time and the arc heating available. Attempts to impose a pulsed waveform at a fixed frequency on the process have been unsuccessful because of variations in the amount of metal transferred. In order to achieve an improvement in transfer it is therefore necessary to alter the power source output dynamically to match the rate of transfer.

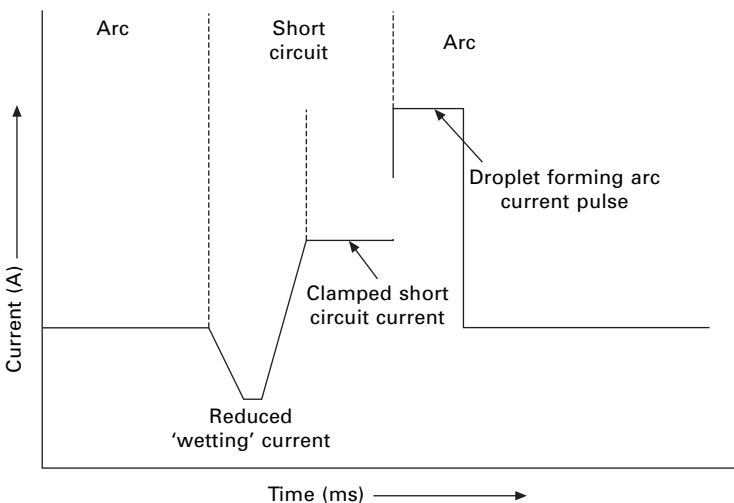
In one of the earliest attempts at controlled dip transfer, a transistor series regulator power source was used to supply controlled pulses of current during the short circuit. [123] A preset level of short-circuit current was initiated at the onset of the dip and current was reduced to the arc level immediately before rupture. The onset of a short circuit was detected by measuring the transient voltage (this falls to near zero when the wire comes into contact with the weld pool). Resistance heating of the wire extension immediately after the short circuit has occurred causes an increase in voltage during the short circuit and necking results in a sharp rise immediately before rupture. It was found that a short delay was required before the current was increased to allow reasonable contact (wetting in) to be established between the wire and the weld pool. For a 1.2 mm steel wire, the duration of this delay was 500 μs after the onset of short circuit. Similarly, at the end of the short circuit, it was found that the detection voltage should be set to a low enough value to allow the high current to be reduced more than 50 μs before rupture of the short circuit. The resultant process was much more regular than standard dip transfer and spatter levels were much lower. It should be noted that in this case the short-circuit time is not fixed but adapts to the process requirements.

The difficulty of reliably predicting the impending short-circuit rupture was the main limitation of this early approach, but, by the mid 1980s, Ogasawara *et al.* [124] had devised a reliable means of achieving this by detecting the rate of change of short-circuit voltage rather than a threshold level.

Improvements to the arcing period waveform were also devised, namely, applying a current pulse of suitable magnitude and duration to produce an adequate arc length to avoid premature short-circuiting. In 1989, Stava [125] reported another commercially available power source, which further improved the prediction of the short-circuit rupture and also incorporated circuitry designed specifically to turn off the welding current very rapidly (within 50 μ s) when such an event is predicted. An alternative approach to generating similar current waveforms for the short-circuiting CO₂ process has also been described by Ou *et al.* [126] This approach uses programmable voltage-current characteristics rather than time-oriented wave shapes. This results in a power source that is more self-adaptive to the process, and is more conducive to the implementation of a 'one knob control' facility.

A further development of controlled short circuit transfer has been reported by Cuiuri *et al.* [127] In this case an optimum droplet size is achieved during the arcing period and the peak current level is clamped at a low level during the short circuit. If a large enough droplet is grown during the arcing period and effective wetting in is achieved the droplet is drawn into the weld pool by surface tension and high short-circuit currents are unnecessary. This approach avoids the requirement for premonition of the short-circuit termination and removes the need for high current switching before the end of the short circuit. The current waveform used in this approach is shown in Fig. 7.27.

The developments described above have concentrated on manipulating the power source output current to achieve the desired process behaviour,



7.27 Idealized dip transfer waveform (for a single short circuit).

while feeding the electrode at a constant rate. Researchers have also used mechanical means of rapidly adjusting the wire feed rate to improve the process, without resorting to complex power sources. Earlier attempts involved the unidirectional stepped feeding of wire. [128–130] This approach used the stepped feeding to dictate the dipping frequency of the process. More recently, Huismann [131] has described in detail the operation of a dynamic wire-feeding system, which rapidly reverses the direction of the electrode at the start of the short circuit. In this system, the dipping frequency is not enforced. Instead, the wire-feeding control system merely responds to the incidence of a short circuiting event. The withdrawal of the electrode away from the weld pool guarantees that the rupture of the short circuit can successfully occur even at low currents for large electrodes, with minimal disturbance to the weld pool. Once the arc is re-established after the short circuit, the wire is fed forward at the desired feed rate.

These techniques offer improved process stability, especially under CO₂ shielding and also enable the fusion characteristics of the process to be more effectively controlled.

7.7.2 Single-knob and programmed control

The complexity of setting welding parameters in conventional DC and pulsed GMAW promoted the development of equipment with ‘single-knob’ controls as early as 1968 [132, 133]. These systems relied on selection of combinations of preset welding parameters (e.g. wire feed speed/mean current and voltage) by means of a single control. They were, unfortunately, hampered by the power source technology available at the time and, in particular, by the difficulty of protecting non-electronic designs from mains voltage fluctuations. There was also the problem of producing a limited number of ‘ideal’ welding parameters which would suit a wide range of applications. Many of these problems were overcome with the introduction of electronic power regulation and microprocessor control, and programmable equipment able to supply a large number of predetermined welding conditions as well as allowing users to record and retrieve their own customized parameters is now available.

A further step has been to incorporate the algorithms described above into control systems which allow continuous control of output over a wide range by the adjustment of a single control. This technique, which was originally developed for pulsed GMAW, is called synergic control.

Synergic control

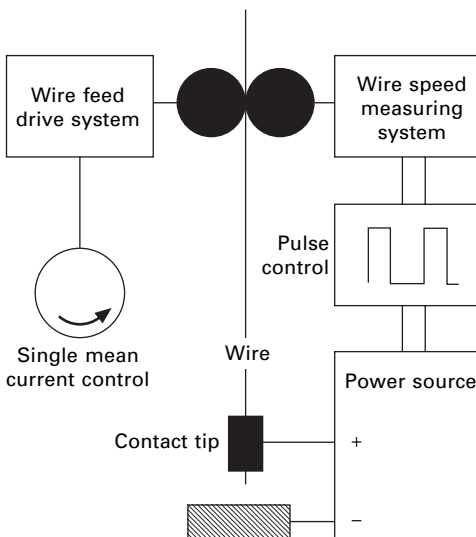
Although in the pulsed GMAW process the optimum welding parameters may be accurately predetermined using the procedures outlined above, if a change in mean current is required, the control settings must be recalculated

and a number of the welding parameters reset. This could impose significant practical problems, including the possibility of error and resultant deterioration in operating performance. Fortunately, it is possible to store both the predetermined parameters and the control equations in the equipment and automatically adjust the output in response to a single input signal. This system is known as synergic control [134] and has been defined [135] as follows:

Synergic control embraces any system (open or closed loop) by which a significant pulse parameter (or the corresponding wire feed speed) is amended such that an equilibrium condition is maintained over a range of wire feed speeds (or average current levels).

In a typical synergic control system, the pulse duration and amplitude for single-drop detachment [derived experimentally or from equation (7.9)] are preset. The system may incorporate a tachometer which measures wire feed speed and feeds the speed signal to a control circuit, which generates the appropriate pulse frequency. This ensures that a balance between wire feed and melting rate is automatically maintained, using equation (7.10). When the wire feed speed is varied, either intentionally or accidentally, the welding condition is adjusted to maintain stability. The mean current is determined by the pulse parameters given in equation (7.11) and the system is illustrated schematically in Fig. 7.28.

The major advantage of this control technique is that the mean current can be varied continuously over a wide range by means of a single control (e.g.



7.28 Synergic control.

50–300 A with a 1.2 mm diameter carbon steel wire) and stable projected drop spray type transfer is maintained throughout the control range. Many commercial systems now dispense with the direct wire feed speed feedback, relying instead on the inherent accuracy and stability of electronic power and wire feed speed regulation.

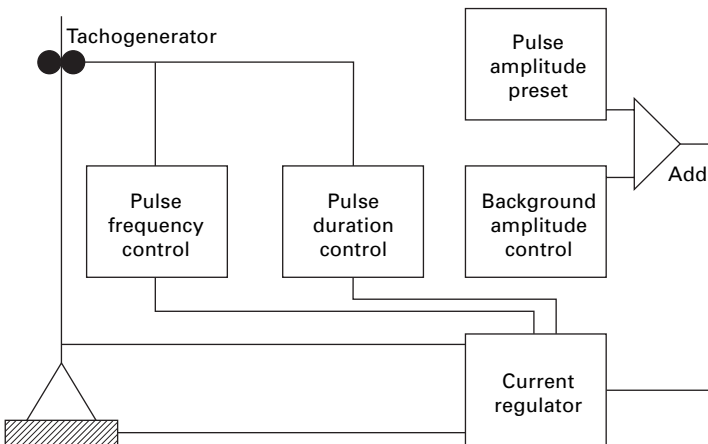
Developments of synergic control

The synergic control technique has been further enhanced by:

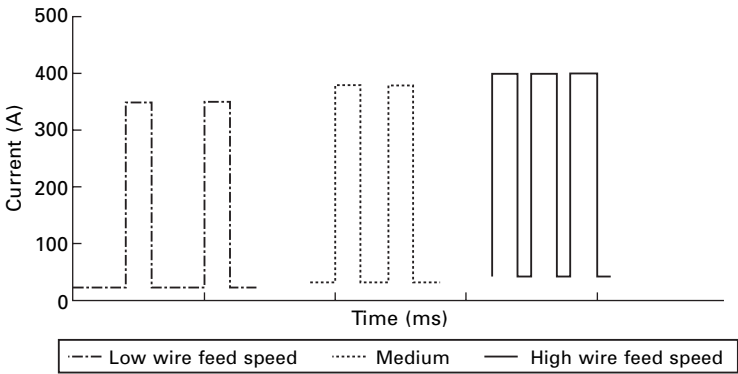
- improved control strategies;
- arc length control;
- parameter selection by the user;
- synergic control of dip and DC spray transfer.

Improved control strategies. Although these systems should only require a single adjustment, it is quite common to incorporate a trim control to accommodate minor deviations in arc behaviour. This fine control usually adjusts the relationship between the wire feed speed and the pulse parameters, changes the burn-off behaviour and lengthens or shortens the arc. It may be required to allow the operator to select arc conditions appropriate to a specific application or to correct any shortcomings in the control algorithm.

Three basic control strategies are adopted. In the original synergic control systems, electronic circuits of the type shown in Fig. 7.29 were used and the effect of increasing wire feed speed was to increase pulse frequency, increase background current and increase pulse height. The pulse duration remained fixed. This is illustrated in Fig. 7.30. The system gives satisfactory performance over a reasonably wide current range, but the pulse current will eventually



7.29 Early control arrangement for synergic control.



7.30 Effect of increased mean current and wire feed speed with early synergic systems.

exceed the value defined by equation (7.9) ($I_p^n t_p = D$) for single droplet detachment, and control is lost.

An alternative system maintains fixed pulse and background current amplitude, fixed pulse duration and varies only frequency in response to variations in wire feed speed. In this case, the 'ideal' pulse parameters are fixed, but, as frequency rises, the background duration decreases, the preheating of the wire tip during the background period is decreased, and this may reduce the droplet size, which again limits the range of effective control.

The third technique fixes pulse current and amplitude and varies frequency with wire feed speed, but to counter the effects of the variation in background period the product of background duration and current is maintained constant, i.e.

$$I_p t_p = B \quad (7.16)$$

This last control strategy gives an extended range of operation and minimizes the need to trim the conditions as the mean current/wire feed speed is adjusted.

The incorporation of microprocessor control enables more complex control strategies to be adopted, for example it is possible to use a non-linear approach in which the control algorithm is varied with current, but it is usually found that the systems described above will give adequate performance in most applications.

Arc length control. The use of constant-voltage power sources in conventional GMAW was justified on the basis of the self adjustment required. The undesirability of current fluctuation and the need to preset current in pulsed and controlled dip transfer has led to the use of constant-current power sources for these process modes. Under ideal conditions, the regular burn-off behaviour achieved with these improved methods of control should ensure constant arc length, but transient fluctuations in wire feed speed, electrical

contact in the tip, workpiece surface condition and torch movement may all cause deviations from ideal behaviour. Some inherent regulation of arc length is still obtained with resistive wires, such as steel, operated under constant-current conditions, due to the changes in resistance which accompany any change in electrode extension. For a fixed current and wire feed speed, there is a unique (equilibrium) value of stick-out length defined by equation (7.7). An increase in extension causes an increase in resistance, which in turn increases the burn-off rate and returns the extension to its original length. Unfortunately, since the contribution of the resistance term to the melting rate is negligible for low resistivity wires such as aluminium, this mechanism does not operate and transient oscillations in arc length may cause short circuiting or excessive arc lengths. In order to overcome this problem, various dynamic control approaches have been adopted. These are usually based on the measurement of the voltage drop in the system and are called arc voltage control or AVC systems. With a constant-current power supply the value of voltage will vary with arc length, even for non-resistive wires, and the melting rate may be modified to correct the change by altering one of the following: wire feed speed, pulse frequency, or pulse height or duration.

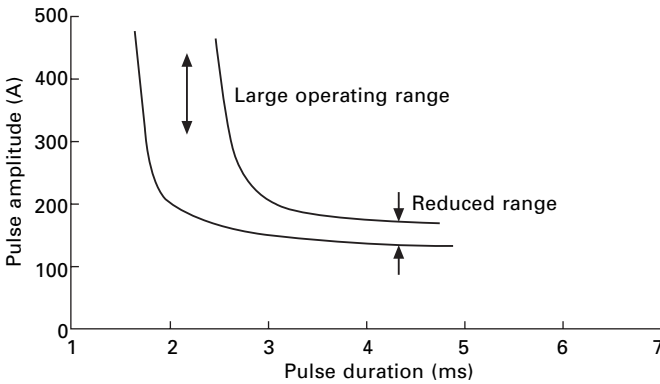
The adjustment of wire feed speed can be effective, but, due to the mechanical inertia in the feeding system, its response rate is slow and may be prone to overcompensation.

Pulse frequency can be adjusted within one pulse cycle with more precision than wire feed speed and is used in many systems. In some systems, the background current is increased in synchronization with the pulse frequency in order to achieve more effective control.

Pulse height variation in response to arc voltage may be achieved by using an electronically generated constant-voltage characteristic during the pulse and a constant current during the background period. This technique utilizes the same self-adjustment mechanism as conventional systems described above. In this mode, the best conditions are usually obtained by using the high-current short-duration parameters defined by equation (7.9) since these are less sensitive to current variation (Fig. 7.31). Some variation of mean current is inevitable using these systems, but, since the constant-voltage period only represents a small proportion of the total pulse cycle, the current will remain relatively constant at low mean currents.

Parameter selection by the user. Conventional GMAW equipment may be equipped with electrical, electronic or computer-based systems for storage of from 5 to 100 user-defined parameter sets as discussed in Chapter 3.

In early synergic GMAW equipment the pulse parameters and control algorithms were preset by the manufacturer. This limited the range of applications to those originally programmed and did not allow for new materials or special application requirements. Later units contained the program data in programmable read only memory (EPROM) and the equipment manufacturer



7.31 Operating range for a pulsed GMAW power source.

was able to customize the power source to meet the user's requirements. The latest development in this area has been to provide the user with some programming facility. For example it is possible in some units for the user to set the pulse current and duration for a specific material then use the in-built synergic control strategy to allow automatic adjustment over a wide current range. Another system enables the user to predetermine ideal pulse parameters for a 'new' material using a hand-held computer, then transfer these parameters to the equipment via a data transfer link. The special user-designed program is stored in non-volatile RAM and may be amended or recalled at any time.

Synergic control of dip and DC spray transfer

Early one-knob GMAW systems [136] can be considered to have the same features of synergic control as the more sophisticated systems which have recently been developed, but, by extending the concepts described above to DC operation with conventional dip and spray transfer, it has been found to be possible [137] to produce more flexible synergic control systems that operate with any mode of transfer.

Synergic control systems

The techniques of controlled transfer described above and synergic control techniques are incorporated in many current welding power sources. It is necessary to use electronic power regulation and common to use microprocessor control to achieve the required power source specification. The operator is required to select an initial setting corresponding to the process mode required, the filler wire type, the filler wire diameter and the shielding gas. The equipment loads the electrical control parameters and control algorithms on the basis of this input information and the only additional adjustment

required by the operator is the selection of the mean current required to suit the application.

7.7.3 Extended operation and high deposition welding

Most of the techniques described above extend the capabilities and improve the control of the GMAW process, but attempts to enhance the deposition rate have also been reported. The high deposition variants of GMAW rely on DCEN operation, high operating current, extended electrical stick out or a combination of these effects. Operating GMAW with electrode negative has been known since 1955 [138] to increase the burn off rate of the wire by up to 50% in the spray transfer mode [139]. The problem is that steel wires behave somewhat erratically when DCEN is used. To overcome this Lesnewich used surface activants, whilst Norrish used an argon-based gas mixture. Although the technique has not been used commercially with solid wires it has been adopted for high deposition welding with metal cored wires.

The relationship between melting rate and current has been quoted above (equation 7.7). If this is further examined and the cross-sectional area of the filler wire (a) is taken into account, it can be seen that increasing I or l or decreasing a will cause the burn off rate to increase. In the 1970s researchers at Union Carbide in the USA demonstrated a 30% increase in deposition rate with a 1.2 mm wire, and a 35 mm extension at around 350 A in an argon-based mixture. Halmoy [140] also indicates that with the same wire diameter at 350 A, the deposition rate would be expected to increase from around 120 to 180 g min⁻¹ when the electrical extension is increased from 25 to 35 mm. If the current is increased further the burn off rate increases (in proportion to the square of the current), the electrode extension becomes molten and rotating spray occurs. This technique has also been commercialized under the trade name T.I.M.E. and Rapidmelt [141]. Although the process operates satisfactorily under an argon-based gas shield, helium is often added to the gas mixture to promote fusion of the parent material.

The most recent development in high productivity GMAW has been the use of multi-wire systems. These commonly involve two wires sharing a common gas shield or two adjacent torches. The two wires may be operated from a single power source or independent power supplies. Blackman [142] has attempted to classify the operating modes and demonstrate the advantages of the process. Deposition rates of up to 24 kg h⁻¹ are claimed and the process is resistant to undercut.

7.8 Summary

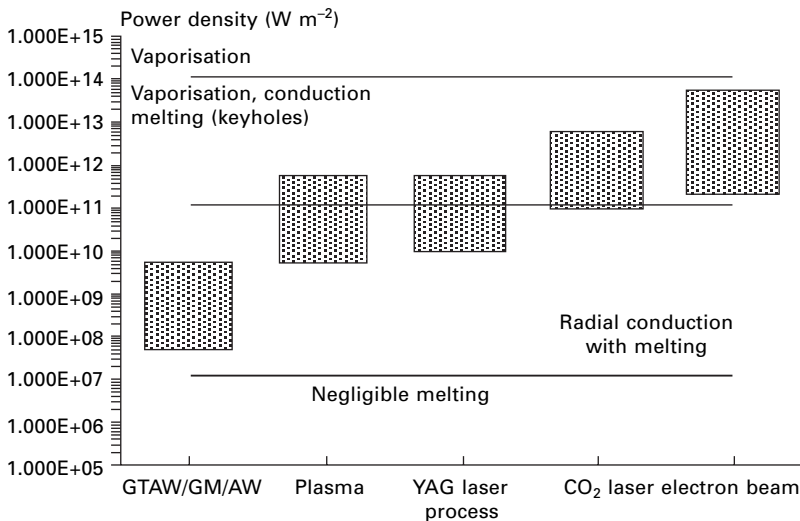
The implications of the GMAW process developments discussed above are that it is possible to improve process reliability and simplify what would

otherwise be rather complex control requirements. It is important to recognize that it is still necessary to choose an appropriate metal transfer technique for a given application; whilst the synergic control techniques improve the ease of use of the equipment, they do not alter the basic features of the transfer mode.

Additional improvements in deposition rate may be achieved by DCEN operation, utilizing the resistive heating of the electrode extension or employing multi-wire techniques.

8.1 Introduction

Advances in the high-energy processes, high-current plasma, electron beam and laser welding, have been concerned with the application of the technology to the fabrication of engineering materials. The power density of these processes is significantly higher than that of the common arc welding processes [143] and normally above 10^9 W m^{-2} ; typical values are compared in Fig. 8.1. As a consequence of the high energy concentration, the mechanism of weld pool formation is somewhat different from that normally found in other fusion welding processes. The material in the joint area is heated to very high temperatures and may vaporize, a deep crater or hole is formed immediately under the heat source and a reservoir of molten metal is produced behind this



8.1 Comparative power density of various welding processes. [143, 144]

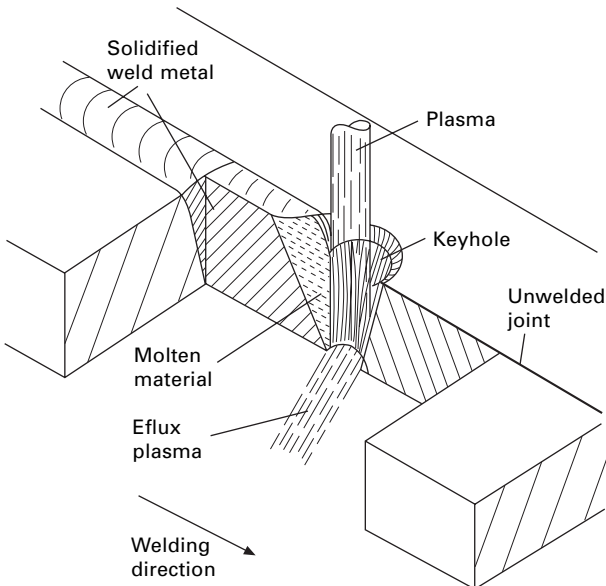
'keyhole'. As the heat source moves forward the hole is filled with molten metal from the reservoir and this solidifies to form the weld bead. The technique has been called *keyhole* welding.

The high energy density processes which operate in the keyhole mode have several features in common:

- they are normally only applied to butt welding situations;
- they require a closed square butt preparation with good fit-up;
- the weld bead cross sections have high depth to width ratios;
- they allow full penetration of a joint to be achieved from one side;
- they can be used to limit distortion and thermal damage.

The mechanism of keyhole welding is illustrated in Fig. 8.2. Very stable operating conditions and, in particular, travel speed, are required to maintain a balance between the keyhole-generating forces (gas velocity, vapour pressure and recoil pressure) and the forces tending to close the keyhole (surface tension and gravitational). The need for consistent travel speed as well as safety considerations dictate the requirement to operate these processes automatically.

Although the processes share a common operating mode their individual features and application areas vary and these will be discussed below.



8.2 Mechanism of keyhole welding.

8.2 Plasma keyhole welding

The principles of plasma welding have been described in Chapter 6. The same transferred arc operating system is used for plasma keyhole welding, but the plasma gas flow and current are usually increased and the orifice size may be reduced. The exact current where the keyhole mode is initiated will depend on the torch geometry and the joint material and thickness, but currents of over 200 A and plasma gas flows of 3 to 4 l min⁻¹ are typical with a 2 to 3 mm diameter constricting orifice. Under these conditions high arc pressures are generated by electromagnetic constriction.

The thermal efficiency of the process is high and it has been estimated that the heat transferred to the workpiece from a 10 kW plasma arc can be as high as 66% of the total process power [145].

8.2.1 Control of plasma keyhole welding

The parametric relationships for plasma keyhole welding are complicated by variations due to torch geometry and it is likely that parameters developed using a specific torch will not be transferable to a torch of a different design. The control variables may be divided, as shown in Table 8.1, into those normally used to match the conditions to the application, the *primary* controls, and those normally chosen and fixed before adjustment of the process, the *secondary* factors.

The influence of the main control parameters on process performance may be summarized as follows.

Mean welding current

The arc force produced by magnetic constriction is proportional to the square of the mean current. With high currents, very high arc forces are generated and undercut or humping may occur (see Chapter 6). The current must, however, be controlled in conjunction with welding speed to produce the required bead profile.

Table 8.1 Plasma keyhole control factors

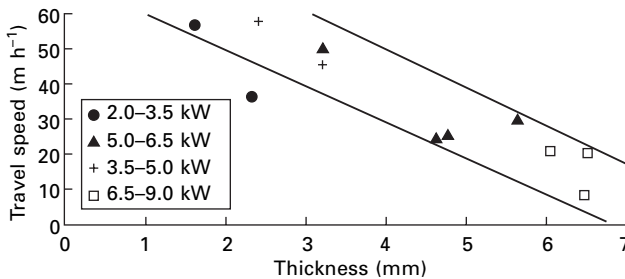
Primary	Secondary
Current	Orifice shape/type
Travel speed	Orifice diameter
Plasma gas flow	Electrode vertex angle
	Electrode set back
	Shielding and plasma gas type
	Torch stand off

Plasma gas flow rate

The presence in the orifice of an insulating layer of non-ionized gas surrounding the plasma is essential. This insulating layer may break down at excessive currents, at low plasma gas flows or when insufficient cooling is available. The resultant instability will often cause double arcing¹ and serious damage to the torch. The plasma gas flow rate also influences the arc force and, if it is too low, the keyhole effect may be lost. At high currents, it is therefore necessary to maintain the plasma gas flow rate at a reasonably high level, but the upper limit will be determined by the occurrence of undercut and decreased thermal efficiency.

Welding speed

If the speed is too high undercutting and incomplete penetration will result, whereas at low speeds the keyhole size may become excessive and the weld pool will collapse. The operating range of the process is therefore determined by a combination of mean current, welding speed and plasma gas flow. The relationship between thickness penetrated and welding speed at various plasma power² levels is indicated in Figure 8.3. Taking into consideration that this information was obtained from several unconnected sources [146–148] it shows a remarkably consistent trend. Tabulated welding data for plasma keyhole welding of some common engineering materials are provided in Appendix 6.



8.3 Thickness versus travel speed for plasma keyhole welding of stainless steel at various power levels. (Data taken from a range of studies.)

¹Double arcing is the term used to describe the formation of an arc between the electrode and the orifice and a second arc between the orifice and the workpiece.

²Plasma power taken as the product of mean current and arc voltage. Voltage is a useful parameter since it takes account of the influence of all the secondary variables on the efficiency of the process. Total arc power therefore gives a good indication of the welding capabilities of the plasma keyhole process.

Secondary controls

Orifice diameter. Decreasing the orifice size increases the arc force and voltage. For keyhole welding small, 2–3 mm diameter, orifices are normally used.

Electrode geometry. The electrode geometry and its position within the torch are critical due to their effect on gas flow within the torch. It is suggested [149] that tolerances of 0.1 to 0.2 mm on electrode position are required. Concentricity of the electrode is also important, since any misalignment may result in asymmetrical arc behaviour and poor weld bead appearance; the electrode should either be adjustable or fixed by a ceramic insert inside the torch.

Multiport nozzles. The multiport nozzle may be used to enhance constriction and produce an elliptical arc profile which is elongated along the axis of the weld. Recent work [150] has shown that a second concentric nozzle may also be used to provide an increase in arc pressure, although excessive focusing gas flow rates may reduce the thermal efficiency of the process.

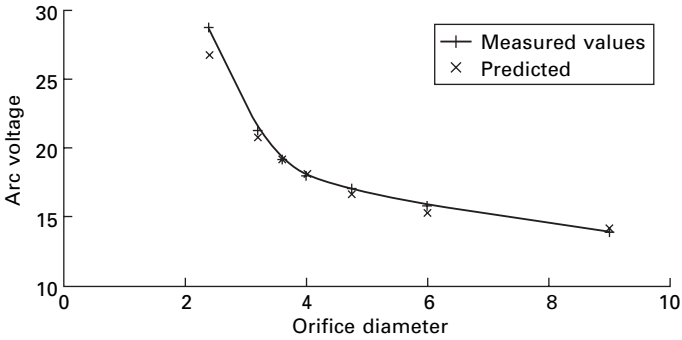
Shielding gases. The most common shielding and plasma gas is argon. From 1 to 5% hydrogen may be added to the argon shielding gas for welding low-carbon and austenitic stainless steels.³ The effect of these small additions of hydrogen is quite significant, giving improved weld bead cleanliness, higher travel speeds and improved constriction of the arc. Helium may be used as a shielding medium for high-conductivity materials such as copper and aluminium. It will tend to increase the total heat input although it may reduce the effect of the constriction and produce a more diffuse heat source. With 30% helium/70% argon shielding gas mixtures, keyhole welding speeds 66% higher than those achieved with argon shielding have been reported for aluminium. [151] The shielding gas flow is not normally critical although sufficient gas should be provided to produce effective shielding of the weld area.

Arc characteristics

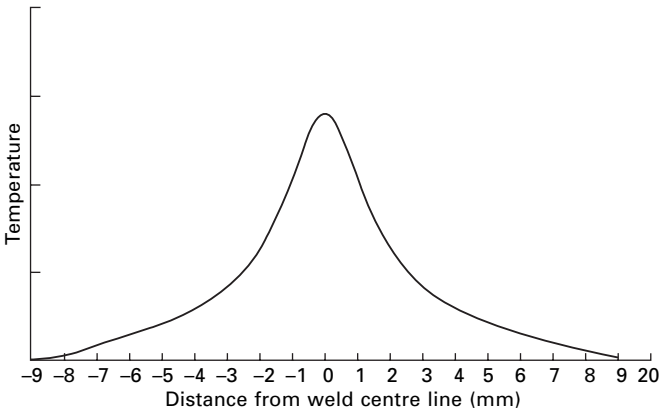
Constriction of any arc causes an increase in arc voltage. In the plasma process, increasing the plasma gas flow, decreasing the diameter of the constriction, increasing current and adding hydrogen or helium to the gas⁴

³Hydrogen additions must be avoided if there is any likelihood of cracking, embrittlement or porosity. Hydrogen should not be used on high alloy steels, titanium or aluminium alloys.

⁴Even if hydrogen or helium are only added to the shielding gas there is evidence to show that they will diffuse into the plasma stream and have a marked influence on the process characteristics.



8.4 Plasma welding: the effect of orifice diameter on voltage. The theoretical equation is $V = 19.55/r^2 + 13.18$ (r is orifice radius).



8.5 Temperature distribution of the plasma arc at the workpiece.

will all increase the arc voltage. The effect of constriction is shown in Fig. 8.4. The thermal profile of plasma arcs usually follows a Gaussian distribution as shown in Fig. 8.5.

Reverse polarity plasma

The plasma process is normally operated with the electrode negative (DCEN) and the workpiece positive. This polarity may be reversed to allow cathodic cleaning to occur when welding aluminium alloys. [151] It is usually necessary to increase the electrode size and limit the maximum current due to the additional heating effect within the torch, but helium shielding gas may be used to extend the thickness range weldable in the keyhole mode up to 8 mm.

Variable polarity plasma

The combined benefits of DCEN and DCEP operation may be achieved by employing a variable polarity power supply of the type described in Chapter 3. Excellent results have been obtained in welding aluminium alloys with this configuration.

Pulsed keyhole plasma

The normal keyhole mode of operation is restricted to welding in the downhand position and requires very critical control of speed as discussed above. The tolerance of the process may be improved by modulating the current and positional welds may be made in a wide range of materials and plate thicknesses. [152, 153] The current is modulated at relatively low frequencies, the pulse time and amplitude being based on the requirement to establish a keyhole and the background conditions being set to maintain an arc but allow solidification. The resultant weld is therefore formed from a succession of overlapping spots, the travel speed being adjusted to provide at least 60% overlap. Pulsed operation improves the resistance to undercut and generally produces a wider, flatter bead. Examples of typical applications and the features of the DC and pulsed modes of operation are described below.

Applications

The keyhole mode of operation makes it possible to perform single-pass square butt welds from one side in plate thicknesses up to about 10 mm.

Carbon–manganese ferritic steel. The plasma keyhole welding of carbon–manganese steels has recently been evaluated for circumferential root runs in pipes for power generation and offshore applications. The use of the process enables thick root sections (6–8 mm) to be welded in a single pass from one side and significantly improves productivity. Pulsed plasma keyhole has been used for these studies [154] to improve operating tolerance and positional performance.

Austenitic stainless steel. Austenitic stainless steel may be readily welded using the keyhole technique and the process has been applied to the longitudinal welding of pipe as well as the fabrication of components for cryogenic service. [155] Welding speeds of around 1.0 m min^{-1} are achievable with keyhole welds in material up to 2.7 mm thick, whilst welds in 6.0 mm thick material may be made at 0.35 m min^{-1} . The use of hydrogen additions to the shielding gas or proprietary mixtures containing from 1 to 5% hydrogen provide improved bead appearance and increased travel speed. Undercut may be limited by careful control of welding parameters, but, if this is not possible, pulsed operation or the use of cosmetic passes is recommended.

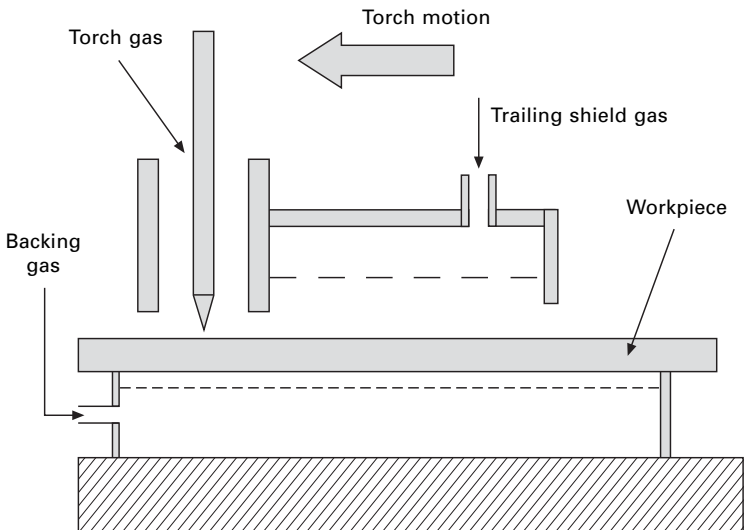
Nickel alloys. Plasma keyhole welding has been used successfully on a wide range of nickel alloys (including alloy 200, 400, 600, Hastelloy C, Inconel 718) and is particularly useful in the thickness range from 2.5 to 7.5 mm. Argon/5% hydrogen has been used for both plasma and shielding gases for the alloy series 200–600. Typical travel speeds vary from 0.5 m min^{-1} at 160 A with 3 mm thick material to 0.22 m min^{-1} at 310 A with 8.25 mm thick plate.

Titanium. Steady and pulsed keyhole plasma welding techniques have been applied to titanium and its alloys [156, 157] and, providing adequate provision is made for gas shielding, high-integrity welds may be made. The shielding requirement may be met by carrying out the welding operation in a glove-box, which is vacuum purged and backfilled with argon, or using a trailing shield of the type shown in Fig. 8.6. The major problem experienced with this material is undercut; this may be alleviated by:

- careful selection of welding parameters on thicknesses up to 3 mm;
- pulsed operation with controlled current decay on each pulse;
- cosmetic runs with plasma or GTAW and filler;
- magnetic arc oscillation along the axis of the weld.

Welding parameters for plasma keyhole welding of titanium are given in Appendix 7.

Aluminium. Plasma keyhole welding of aluminium is possible if electrode positive polarity is used as discussed above. It is also possible to use advanced



8.6 A trailing shield.

power sources with the capability of variable-polarity operation and significant improvements in quality and cost have been reported using these techniques. [158] It has been found that acceptable results are achieved with 15–20 ms of DC electrode negative operation and electrode positive pulses of 2–5 ms duration.

8.2.2 Summary: plasma keyhole welding

The plasma keyhole welding process may be used for making square butt welds in a wide range of materials in the thickness range from 2 to 10 mm. It gives high welding speeds and guaranteed penetration from one side of the joint. Although the number of parameters which influence the process performance is large and their interaction is complex, the arc power gives a useful indication of the overall performance capabilities. The major limitation of the process is undercut but this may be controlled by careful selection of the operating parameters or pulsed operation. The plasma phenomenon is present in all arcs and whilst it may be enhanced by thermal constriction as discussed in Chapter 6 it may also be used to generate keyhole welding characteristics if very high currents are used in GTAW.

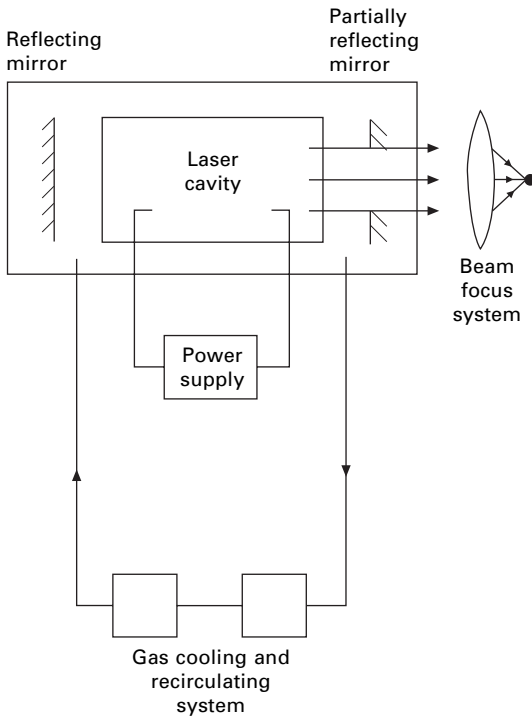
8.3 Laser welding

The laser may be used as a welding heat source and consists of a high-energy coherent beam of light of an essentially constant wavelength. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation and the medium in which it is generated may be either solid, liquid or gaseous.

Helium/neon and CO₂ are commonly used as a basis of gaseous systems whilst ruby and neodymium doped yttrium aluminium garnet (Nd:YAG) are used in solid state lasers. In welding applications, the two most commonly used lasers are the CO₂ gas laser and the Nd:YAG solid state laser. Recent developments include the availability of high-power diode lasers (HPDL) and fibre lasers suitable for welding applications.

8.3.1 CO₂ lasers

The principles of operation of the CO₂ laser are illustrated in Fig. 8.7. An electrical discharge within the gas is used to stimulate the emission of radiation. The initial low-level radiation is ‘trapped’ within the laser cavity by mirrors placed at either end. The internal reflection of the beam causes an increase in the energy level (amplification). A fraction of the laser beam generated in this way is allowed to escape from the resonant cavity via a partially reflective mirror. In the case of the CO₂ laser, the emergent light beam has a wavelength of 10.6 μm (i.e. in the infrared part of the spectrum) and is delivered to the



8.7 Principles of the CO₂ laser.

workpiece by a series of mirrors and lenses. Since glass lenses are unsuitable at the operating wavelength, lenses for CO₂ systems are usually made from ZnSe whilst mirrors are normally made from copper coated with a gold reflecting surface. A beam with low divergence is essential if long-delivery systems and flexibility of layout are required. Even with these constraints beam delivery systems have been incorporated into robot welding and cutting installations where flexible positioning of the welding head is required.

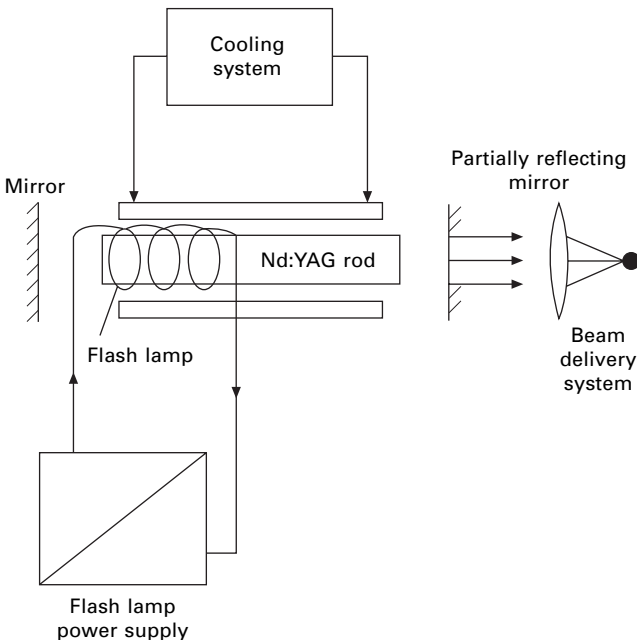
Whilst CO₂ is the gas which is responsible for the emission of radiation, industrial lasers use gas mixtures which may contain up to 80% helium and 15% nitrogen. In the process of stimulating emission, heat is generated in the cavity and, to avoid overheating and instability, the gas is continuously circulated through a cooling system.

The beam power delivered by CO₂ laser systems is commonly between 0.1 and 45 kW and the output may be pulsed or continuous. The overall efficiency is normally less than 10% and large chillers are required to remove excess heat from the system.

8.3.2 Nd:YAG lasers

The operating principle of the Nd:YAG laser is shown in Fig. 8.8. In this case, the active laser material is made up of a solid yttrium aluminium garnet crystal, which is doped with neodymium. Stimulation of the neodymium atoms is achieved by excitation with high-power flash lamps for pulsed operation or arc lamps for continuous wave output. Typically, the YAG rod has a fully reflective mirror at one end and a partially reflective mirror at the beam discharge end. The energy is amplified within the cavity and a beam of radiation in the near infrared range, 1064 nm in wavelength, is emitted through the partially reflecting mirror. Beam delivery can be made much simpler since normal optical glass can be used at Nd:YAG laser wavelengths. The cost of the optical components can be reduced and fibre optic cables may be used to provide efficient, flexible distribution systems.

Fibre delivery offers considerable advantages compared with mirror systems; for example they reduce the need for accurate mirror alignment, allow safe delivery of the laser without bulky enclosures and enable variations in laser-to-workpiece distance to be more easily accommodated. For this reason, Nd:YAG lasers are more suitable for robotic applications. In addition, the Nd:YAG radiation is absorbed more easily by most metal surfaces and allows improved process efficiency.



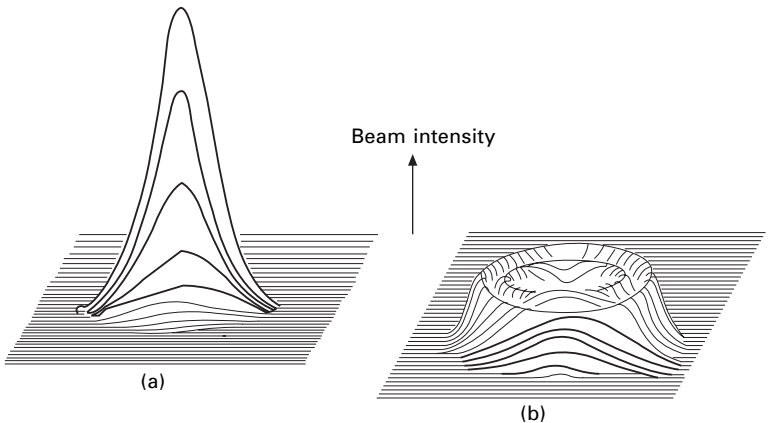
8.8 Principle of the Nd:YAG laser.

Heating of the YAG rod will occur whilst the laser is running and some form of water cooling is necessary to maintain reliable operation at the high process powers required for welding. The overall process efficiency of the Nd:YAG laser is less than 4% and large water chillers are again required.

The range of beam powers available with Nd:YAG systems is usually lower than those achieved with CO₂ lasers and for welding 0.1–1 kW average power devices are normally used. The YAG laser can, however, be pulsed to very high peak power levels (i.e. up to 100 kW).

8.3.3 Laser beam characteristics

The CO₂ laser systems give good beam quality, which approximates to a Gaussian distribution and a spot size of 0.1 mm. Higher power CO₂ systems (above 1.5 kW) have multimode outputs which do not focus to such a small spot size. Fibre-delivered Nd:YAG lasers have an integrated mode structure due to total internal reflection in the fibre; this produces a uniform power density across the beam diameter, which may be focused down to 0.2 to 1.0 mm. The literature on lasers often describes beam mode in terms of a TEM (transverse electromagnetic mode) number. A Gaussian distribution has a value of TEM₀₀ (Fig. 8.9). The difficulty of defining the outer edge of the Gaussian distribution has led to the convention of measuring the beam diameter in terms of the distance across the centre of the beam in which the irradiance equals $1/e^2$ (0.135) of the maximum irradiance; the area of a circle of this diameter will contain 86.5% of the total beam energy. More complex doughnut-shaped energy distributions may occur or a combination of beam profiles may be produced in *multimode* operation where increased output power is required at the expense of beam coherence. In practice, if the mode



8.9 Laser beam intensity distribution: (a) TEM₀₀ mode; (b) low-order mode.

remains axially symmetrical multimode beams are suitable for most welding applications.

8.3.4 Welding with lasers

Welding modes

Lasers may be used for both melt-in (conduction-limited) welding in a similar manner to GTAW, or in the keyhole mode described above. The beam energy delivered to the workpiece will be dissipated by reflection and absorption. In the case of laser welding, the reflected energy losses may be large, many materials being capable of reflecting up to 90%⁵ of the incident beam energy. The reflectivity is reduced as the temperature of the surface is increased and greater amounts of energy will be absorbed. The absorbed energy will be conducted away from the metal surface and if sufficient energy is available to establish a weld pool, convection within the pool may assist energy transfer. The conduction-limited mode is often used for micro-welding applications using low-power, pulsed lasers to ensure low heat input.

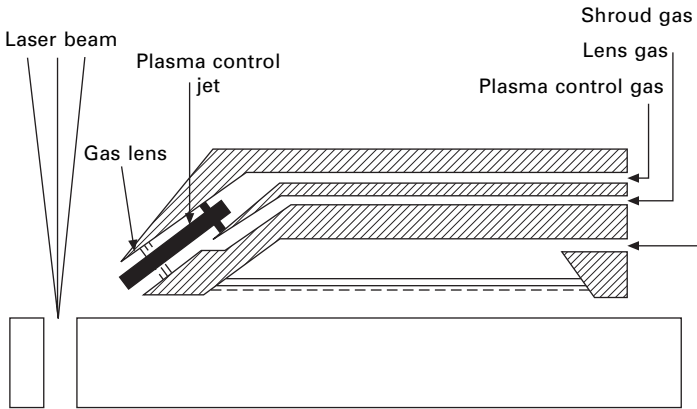
If a sufficient vaporisation pressure is developed in the weld pool the reflection losses can be substantially reduced, the beam energy is absorbed more efficiently, and a keyhole is formed. The process may be used with single high-energy pulses to produce spot welds or with continuous or repeated pulsing to produce butt welded seams as discussed above.

Conduction limited welding typically produces weld bead depth-to-width ratios of around unity, whereas the keyhole mode can produce depth-to-width ratios of 10:1.

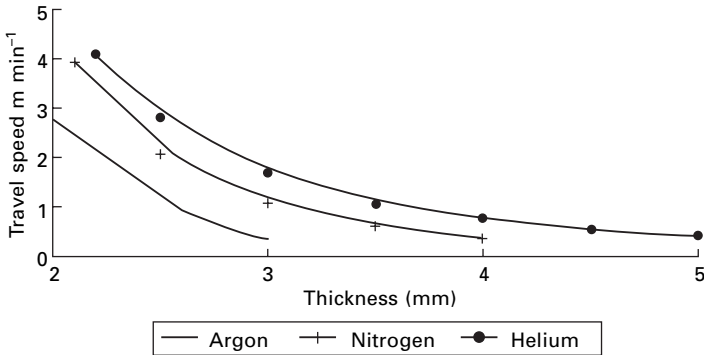
Shielding gases

It is common to supply a shielding gas to the weld area to protect the molten and solidifying metal from oxidation. Due to the high travel speeds involved this often takes the form of an elongated shroud which trails behind the beam as shown in Fig. 8.10. [159] It is also necessary to provide backing gas to the rear of the joint in order to obtain clean penetration beads with satisfactory profiles. The most common gases used for shielding are helium and argon which are inert. Because of its high ionization potential, helium is more resistant to plasma formation whilst argon, because of its density should offer improved shielding efficiency, but some additional plasma control measures may be necessary, particularly with CO₂ lasers, as a result of its

⁵The reflectivity of austenitic stainless steel to infrared radiation (1060 nm) is 92% whilst that of copper is 98%.



8.10 Laser welding trailing shield with plasma control jet. [159] (Courtesy AEA Culham.)



8.11 Thickness versus travel speed for 2 kW CO₂ laser keyhole welding in various gases.

lower ionization potential. The effect of shielding gases on welding speed and depth of penetration is shown in Fig. 8.11.

Plasma formation

Interaction between the laser beam, metal vapour and the shielding atmosphere can lead to generation of a visible plasma above the plate surface. The plasma is initiated when free electrons at the surface of the material are accelerated due to the *inverse bremsstrahlung* effect. The accelerated electrons eventually develop sufficient kinetic energy to ionize metal vapour and gases in the area immediately above the plate surface and a plasma is formed.

It has been shown [160] that there is a threshold intensity below which plasma formation is unlikely; this threshold depends on parameters such as

beam power, pulse width and the wavelength of the radiation. Typical threshold intensity values for a CO₂ laser are between 1×10^6 and 3×10^6 W cm⁻² whilst for Nd:YAG lasers intensities of 10^8 W cm⁻² are required. In the initial phases of keyhole crater formation the plasma may assist energy transfer by absorbing energy from the beam and emitting lower-wavelength radiation which is more readily absorbed. In addition, the recoil pressure generated by the plasma may assist crater formation. A pronounced improvement in coupling may be observed as the intensity is increased through the level at which plasma formation commences. Once the keyhole has formed, however, the presence of a vapour or plasma plume above the plate surface may limit energy transfer into the plate.

This problem of plasma plume formation after initiation of the keyhole is particularly noticeable with continuous-wave CO₂ lasers operating in the far-infrared region. Although it has also been reported with Nd:YAG lasers [161] the plasma formed with titanium and aluminium workpieces under pulsed Nd:YAG beams was found to have very low levels of ionization and only resulted in limited loss of power by scattering from metal and oxide particulate. For these reasons, plasma control is not normally applied in Nd:YAG laser welding.

Plasma control. In CO₂ lasers, significant attenuation of beam power are caused by absorption and scattering from the plasma plume and this has led to the development of the following plasma control techniques:

- *Plasma control jets.* The plasma may be deflected or even blown into the keyhole cavity by an auxiliary gas jet [162]. Ideally, the jet should be directed toward the plasma to impinge on the workpiece 1 mm ahead of the beam and at an angle of about 20° to the plate surface. A coaxial shield may also be necessary to prevent atmospheric entrainment by the high velocity jet. The arrangement of a typical shield incorporating a plasma control jet is shown in Fig. 8.10. Helium is again the preferred jet gas due to its high ionization potential, but argon and nitrogen have also been used.
- *High frequency pulsing.* Pulsing of the laser power at frequencies higher than 1 kHz has been shown to be effective in reducing plasma formation in CO₂ laser welding. [163] Both mechanical and electrical oscillation has been used, with increased welding speeds and higher depth-to-width ratios having been obtained.
- *Beam oscillation.* Linear oscillation of the beam along the seam [164] combined with a plasma control jet increases penetration for the same beam power. The gas jet deflects the plasma, whilst the linear motion of the beam improves beam interaction.

Pulsing of laser output

The output of both CO₂ and Nd:YAG lasers may be pulsed to a high level to achieve increased peak power output. A typical 5 kW rated CW CO₂ laser has a pulse frequency modulation of between 0 and 25 kHz, and can deliver a peak pulse power of five times the continuous output.⁶ Nd:YAG systems of 400 W average power are capable of delivering peak power levels of 5–20 kW over very short durations. The use of higher peak powers (at low average power) enable pulsed lasers to weld a larger variety of materials than those possible using the CW mode of operation. Overlapping pulses are used to achieve a continuous weld seam.

Process control

The parameters which control laser welding may be classified as primary and secondary variables as shown in Table 8.2.

Primary controls. The relationship between beam power, welding speed and material thickness is common to most materials and laser types and is illustrated in Fig. 8.12. [165] The secondary control variables have a more complex effect on welding performance, but some attempts have been made to develop operating envelopes, which describe the relationship between welding speed and focus position as shown in Fig. 8.13. Shielding gas flow can have a pronounced effect on process efficiency and with argon in particular there is a possibility of shielding gas plasma formation at critical flow rates in CO₂ laser systems.⁷

8.3.5 Applications

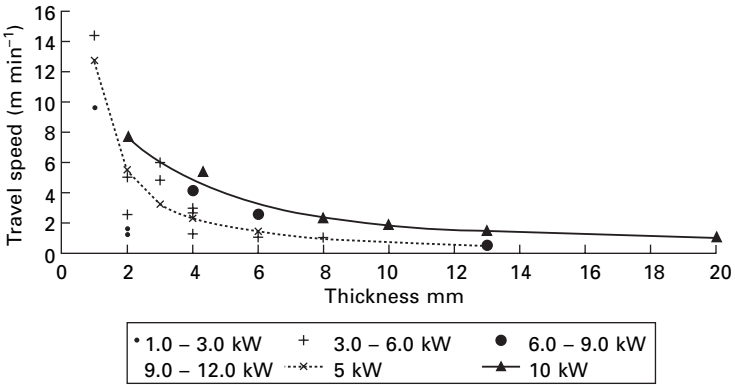
The range of materials that can be successfully welded by laser techniques is, in the first instance, determined by their physical properties, including

Table 8.2 Control parameters – laser welding

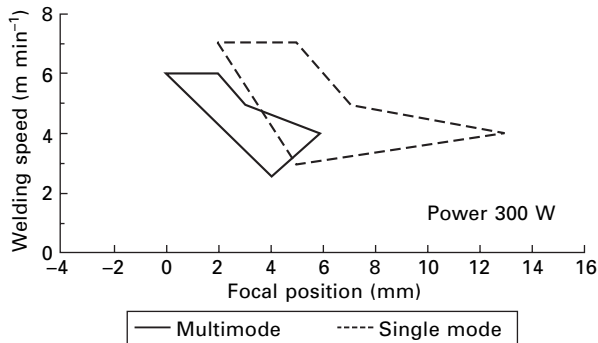
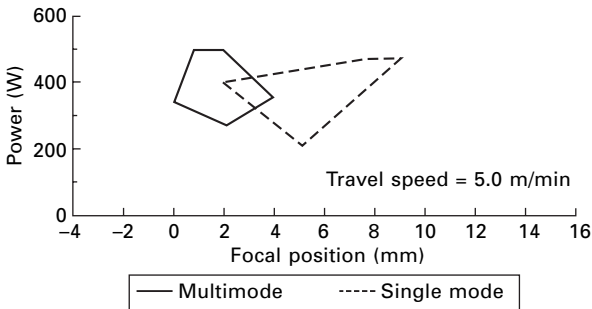
Primary variables	Secondary variables
Beam power	Pulse parameters
Travel speed	Plasma control
Spot size (and position)	Shielding gases
Operating mode (CW or pulsed)	Beam mode (normally fixed)
	Wire addition

⁶Rofin-Sinar RS 5000.

⁷Shielding gas plasma plumes are particularly problematic since they persist in the laser path even after absorption has decreased workpiece coupling. Metal vapour plasma will tend to be suppressed when absorption attenuates the beam.



8.12 Thickness versus travel speed for laser keyhole welding at various power levels and for a range of materials.



8.13 Effect of secondary variables on weld quality (for a butt weld by CO₂ laser in 0.15-mm steel). [165]

reflectivity and thermal diffusivity, and, secondly, by metallurgical considerations. In the keyhole mode, once coupling and cavity formation has occurred, even metals with high reflectivity (e.g. nickel) may be successfully welded, but copper with both high reflectivity and high thermal diffusivity can at present only be welded with difficulty.

Most of the metallurgical problems experienced with laser welding are common to other fusion welding processes; for example, cold cracking in high-carbon and alloy steels, porosity and solidification cracking in aluminium alloys, but, with suitable precautions, these problems may be restricted. Some common application areas are described below.

Austenitic stainless steel

Austenitic stainless steels have been laser welded in a range of thicknesses. Typical conditions for 13.3 mm keyhole welds are given in the figures above, but speeds of up to 1 m min^{-1} can be achieved with a CO_2 laser at 11 kW. As with other welding techniques, care is needed to avoid solidification cracking and sensitization although the thermal cycle may restrict thermal damage in the HAZ.

Low-carbon steel

Low-carbon steel is readily joined with a range of common welding processes, including GMAW and GTAW. The primary reasons for using high-capital-cost processes such as lasers is to increase productivity and to improve quality. There are no specific problems with the laser welding of uncoated plain carbon steels and both CO_2 and Nd:YAG systems have been used successfully as the following applications confirm.

In thin-section sheet material, laser welding has been used for fabrication of high-precision pressings [166] to fabricate beams for the carriages for a CNC punch press. A 5 kW CO_2 laser was used and the main objective was to limit distortion and weld finishing operations.

Lasers are being adopted for many carbon steel welding applications in the automotive industry, [167] including the welding of floor panels and engine support frames. In most cases, robotic automation is involved and integrated beam delivery systems have been developed. The use of 1 kW Nd:YAG lasers with optical fibre delivery systems have also been applied to robotic welding.

Coated steels, particularly zinc-coated or galvanized materials, are difficult to weld and, even if satisfactory parameters are developed, they are prone to batch variation. Some success has, however, been reported using a Nd:YAG laser with a multiple laser (Multilase) system. [144, 168]

Laser welding has also been evaluated for fabrication of thicker section, higher-strength steels such as ASTM A36 (0.29% C, 0.8–1.2% Mn, 0.15–0.40% Si) [169] and it was found that welding speeds of up to 1 m min^{-1} could be achieved in 19 mm thick plate using a 15 kW CO_2 laser. A cost analysis indicated a three-year payback period for the laser system in this application.

Titanium alloys

Titanium alloys can be laser welded if due care is taken to prevent atmospheric contamination and the resultant embrittlement that occurs in these materials. Welding speeds up to 6 m min^{-1} have been reported for 3.0 mm thick material using a CO_2 laser at 4.6 kW output power. [170]

Nickel alloys

A range of nickel alloys has been successfully laser welded, and welding speeds of 0.5 m min^{-1} have been reported for Inconel 600⁸ when using a continuous-wave CO_2 laser at 11 kW. C263 and Jethete M152 are also readily welded.

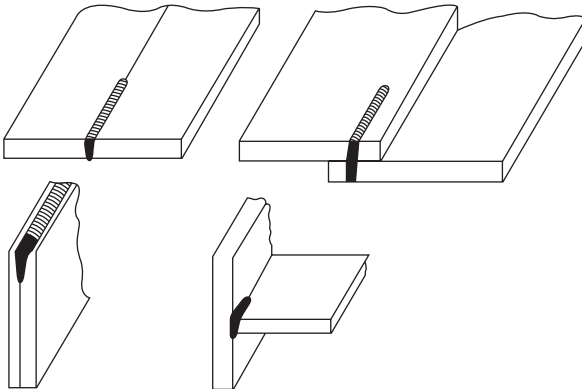
8.3.6 Practical considerations

Joint configurations and accuracy

Square butt, stake/lap, spot, edge, and T butt joints as shown in Fig. 8.14 are the normal joint configurations used for laser welding. Due to the small focal spot size, alignment of butt joints is critical and joint preparation must be accurate. In addition, any automatic positioning, work and beam-handling equipment must be made to high levels of precision.

Safety

Direct or reflected laser light from the workpiece and surrounding fixtures can be extremely dangerous, particularly with high-power systems, and



8.14 Typical laser weld joint configurations.

⁸Inconel 600: nominal composition 75%Ni, 15%Cr, 8%Fe.

adequate protective screening must be provided. It is also necessary for appropriate eye protection to be worn when performing alignment and monitoring of the process. Other hazards that must be considered are common to other welding processes and these include fume and electrocution.

8.3.7 Developments

Laser-enhanced GTAW and GTAW augmented laser welding

The use of a TIG arc to heat and pre-melt the plate combined with a laser to increase penetration and/or welding speed has been investigated by several workers. [171, 172] It has been shown that using a 300 A GTAW arc to augment the 1 kW laser may produce equivalent welding performance to a 2 kW laser device and, clearly, there is potential for extending the range of low-power lasers by this technique. The laser also assists in preventing humping of GTAW welds made at high current and high speeds. Comparisons with multicathode GTAW (see Chapter 6) have not been made, but it is likely that similar results could be achieved with this lower-cost process option.

Laser hybrid welding

More recently, combinations of laser and GMAW welding have been developed and applied in such diverse applications as automotive fabrication and shipbuilding. The process, which has become known as 'Hybrid Laser GMAW' offers increased speed and penetration compared with GMAW and improved tolerance to fit-up when compared with laser welding. The use of the laser tends to stabilise the arc root of the arc process and reduces arc ignition problems. Although systems comprising individual laser and GMAW heads have been used, commercial laser hybrid heads are now available.

Multiple laser operation

In the case of Nd:YAG lasers a novel system has been devised [168] in which three 400 W lasers are brought to a common output housing by means of fibre optic beam delivery systems. The three lasers may be pulsed in phase to produce the maximum peak output or phaseshifted to give improved control and higher welding speeds.

Laser development

Several alternative laser systems are available and improvements in efficiency both in laser generation and application are being developed. Some of the most interesting development areas are:

- excimer lasers;
- RF- and microwave-excited CO₂ lasers;
- diode-pumped lasers;
- carbon monoxide (CO) lasers;
- high-power diode lasers;
- fibre lasers.

Excimer lasers. The active component of the laser medium used for excimer lasers is a rare gas such as xenon, krypton or argon containing a halogen such as fluorine, bromine or chlorine. The pulsed output is in the ultraviolet wavelength range usually from 193 to 350 nm. The average output power of commercial excimer lasers is currently quite limited, but peak powers as high as 100 kW are possible. The photo-ablation process which allows molecular bonds to be broken without introducing excess thermal damage is used for accurate drilling, cutting, marking and cleaning applications in the electronics, semiconductor and medical component industries.

RF- and microwave-excited CO₂ lasers. The DC-excited CO₂ lasers are capable of producing high beam quality at reasonably high power levels. The use of high-frequency excitation has been shown to offer improved beam quality and RF excitation systems for welding are now available. It is expected, however, that microwave systems will offer improved quality, high efficiency and lower overall cost.

Diode-pumped lasers. In general, the pumping of solid state lasers by flashlamps is inefficient [173] because of the fairly broad spectrum of wavelengths produced by the lamps and the fairly narrow band of useful pump bands. Greater efficiency can be achieved by pumping with semiconductor lasers such as gallium–aluminium–arsenide (GaAlAs) lasers which emit wavelengths in the range 750–900 nm. Development of high-power semi-conductor pumped lasers has been limited. Commercial devices with powers of around 1 W are available, but the low power limits the applications to areas such as microsoldering.

Carbon monoxide (CO) lasers. Work on the development of CO gas lasers has taken place in Japan. [174] The wavelength of 5 µm falls between that of CO₂ and Nd:YAG and may offer potential benefits in the ability to use fibre optic beam delivery. The use of these devices for cutting has been demonstrated, but welding applications have yet to be developed.

High-power diode lasers. High-power direct diode lasers have recently been developed and are being investigated for welding and surfacing applications. Current systems offer power levels up to 4 kW and operate in the 800 to 940 nm wavelength range. The rectangular beam profile is suitable for hardening and surface treatment applications, but can be coupled to an optical fibre to facilitate welding operations. The main advantage of these devices is the increased electrical efficiency (typically 25%) and compact size when compared with CO₂ and Nd:YAG systems. Fibre delivered diode

lasers may easily be coupled with arc processes as GMAW to provide the advantages of a hybrid process. [175]

Fibre lasers. Fibre lasers utilise a doped silica glass fibre as the lasing media and are pumped by diode lasers. The dopant consists of erbium (Er) or ytterbium (Yb) or a combination of these elements. The fact that the lasing action takes place within the fibre eliminates the coupling problems which may be found with fibre coupled diode lasers. Single fibre lasers of this type have been developed with output powers up to 1 kW but for higher powers it is now possible to combine several lower power lasing fibres for delivery to the work site by a single optical fibre 10–200 m in length. Power outputs of up to 20 kW are commercially available using this approach. The major advantages of these systems are improved power efficiency, compactness, stability and beam quality. Electrical efficiency of up to 25% has been reported and this makes it possible to consider the systems for mobile applications such as pipeline girth welding. [176] Like high-power diode lasers, the fibre laser may be used in combination with arc welding heat sources as a hybrid welding system.

8.3.8 Summary: laser welding

Laser welding has been shown to be suitable for high-speed welding of thinner materials and deep penetration welding of materials up to about 12 mm in thickness (up to 25 mm is feasible using high-power systems). A wide range of materials is weldable using both CO₂ and Nd:YAG systems.

Low-power applications are found in the instrumentation and electronics industries, whilst higher-power applications continue to be developed principally in the automotive, shipbuilding and aerospace industries.

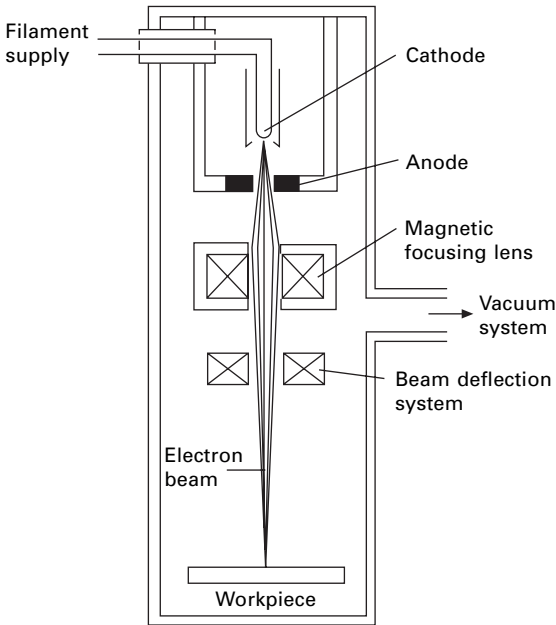
The capital cost of laser systems is high but the economic returns have justified this level of investment in many applications.

8.4 Electron beam welding

Electron beams have been used as welding heat sources since the early 1960s and electron beam welding (EBW) has become established as a high-quality precision welding process.

8.4.1 Fundamentals

In the EBW system, electrons are generated by passing a low current (e.g. 50–200 mA) through a tungsten filament. The filament is attached to the negative side of a high-voltage power supply (30–150 kV) and electrons are accelerated away from the cathode towards an anode as shown in Fig. 8.15. The divergent electron beam is focused by magnetic and electrostatic lenses



8.15 Principle of electron beam welding.

and may be deflected or oscillated magnetically. The complete electron generator assembly or electron gun is usually mounted either inside or external to a vacuum chamber which contains the workpiece.

8.4.2 Beam characteristics

Power densities of from 10^{10} to 10^{13} W m^{-2} are developed at the point of focus and keyhole welding is the normal operating mode. The forces which create the keyhole in EBW are:

- electron momentum;
- vapour pressure;
- recoil pressure.

Surface tension and gravitational forces counteract keyhole formation but, under normal circumstances, the keyhole-forming forces are much higher. For example, the electron momentum pressure P_a is given by [177]

$$P_a = 2Jm_eVle^2 \tag{8.1}$$

where J is the current density, V the accelerating voltage and m_e is the electronic mass. For a focused spot 0.3 mm in radius, 100 mA filament current and 100 kV, this force will be around 300 N m^{-2} . The vapour pressure, which is temperature dependent, can reach values of $5 \times 10^4 \text{ N m}^{-2}$ and the recoil

pressure at $3.5 \times 10^{10} \text{ W m}^{-2}$ has been calculated as 10^7 N m^{-2} . Although it is not possible to equate these forces directly, the surface tension force for a 0.5 mm diameter keyhole would be only just over $7 \times 10^3 \text{ N m}^{-2}$.

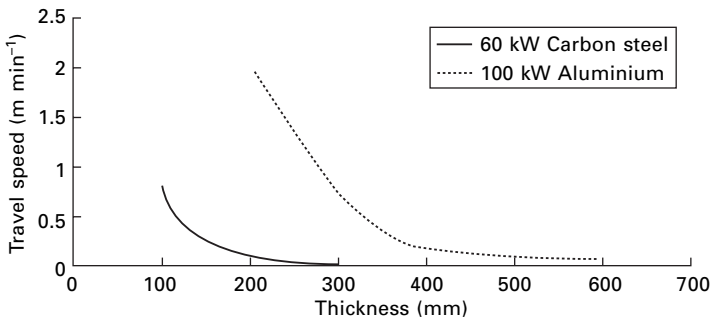
Under these circumstances, very deep penetration keyhole welds can be made with EBW, although the general form of the speed/penetration curve (Fig. 8.16) is similar to that found with both laser and keyhole plasma welds.

8.4.3 Control of EBW

Primary and secondary control variables may be identified for electron beam welding as shown in Table 8.3. However, although the inter-relationship between beam power–travel speed and thickness is clearly established, the welding performance may be changed significantly by means of the secondary controls. In particular, beam focus and deflection may be used to control the depth-to-width ratio of the welds and intentional defocusing may be used to enable cosmetic finishing runs to be made after completion of the penetration weld.

8.4.4 Applications

The EBW process has been used for joining a wide range of materials including alloy steels, nickel alloys, titanium, copper and dissimilar metals in thicknesses



8.16 Thickness versus travel speed for electron beam welding of various materials.

Table 8.3 Control parameters for EBW

Primary variables	Secondary variables
Filament current	Beam focus
Voltage	Beam deflection
Travel speed	Power supply
	Vacuum

ranging from 0.025 to 300 mm. Some typical application areas are discussed below.

Aerospace

The aircraft engine industry has used EBW extensively for the fabrication of engine parts. A single engine, the Rolls-Royce RB211, utilizes nearly 100 m of electron beam welds. [178] The principal applications include the joining of thick-section stator assemblies in titanium alloys, compressor discs and compressor rotor shafts. The use of EBW has been promoted by the requirement for high integrity welds with low distortion and minimal thermal damage to the materials.

Instrumentation, electronic and medical

The process has been used for the encapsulation of sensors and electronic parts for electronic and medical applications. The materials used include austenitic stainless steels for encapsulation and cobalt–chromium alloys for fabricated hip joints.

Automotive

The narrow, deep penetration properties of the electron beam have been used for the circumferential welding of gears to form complex clusters. The process is also used for fabrication of transmission components such as gear cages. Access and high weld quality are primary considerations in these applications as well as the ability to weld finished components without distortion or the need for post-weld machining operations.

Dissimilar metal joints

The most common production application of EBW to dissimilar metal joints is the butt welding of high-speed steel blade forms to carbon steel backing strip to form hack-saw blades. Although both laser and plasma processes have been used in this application, EBW offers very high speeds of up to 10 m min^{-1} .

Copper alloys

Unlike laser processes, EBW may be used on a wide range of copper alloys, and thicknesses up to 12 mm thick may be welded at 0.7 m min^{-1} with beam powers of 10 kW. [179]

8.4.5 Practical considerations

Use of a vacuum

The EBW process is normally performed in a vacuum to avoid dissipation of the beam by collision with gaseous atoms and to protect both the electron gun and the weld area. The advantage of this technique is that it provides a clean, inert environment, which is conducive to the attainment of consistently high joint quality. The major disadvantage is the time wasted in loading and pumping down the enclosure. The harder the vacuum the more difficult it is to achieve and, to alleviate the need for very high vacuum in the complete chamber, many systems allow a differential pressure between the gun and the welding area. In these systems, the gun vacuum may be maintained at 5×10^{-4} mbar whilst the chamber is held at 5×10^{-2} mbar.

The need to operate in a vacuum also implies the need for cleanliness and the avoidance of low-vapour pressure compounds in the weld fixturing and positioning equipment.

Safety

The collision between the electron beam and a metal surface will generate x-rays; suitable screening is incorporated in the equipment to ensure that the operator is not exposed to this secondary radiation.

Joint configuration

The joint configurations are usually variants of square butt, lap and stake welds as previously shown in Fig. 8.14. Again accurate positioning and joint preparation is usually necessary due to the small spot size.

8.4.6 Developments

Although the basic process has remained unchanged for many years, some significant advances have been made in the maximum power available, the operating techniques and the equipment.

EBW beam power

Whilst for many applications beam powers of up to 25 kW are quite adequate, there has been an attempt to extend the weldable thickness range, particularly for out of vacuum applications and systems with output powers up to 200 kW have been built.

Chamber loading systems

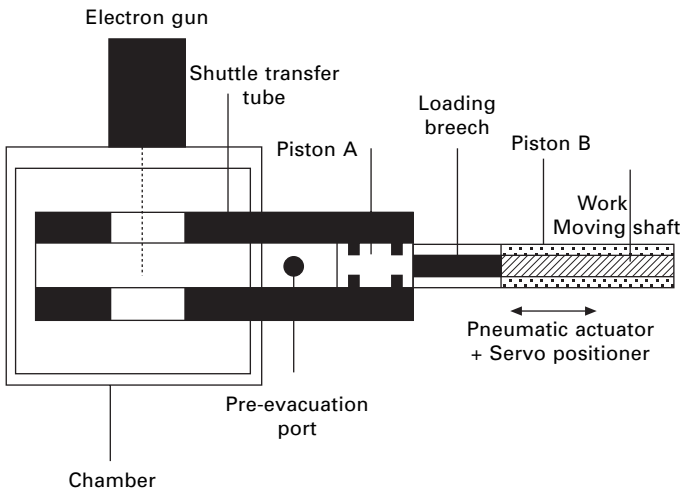
The chamber loading time may be considerably reduced, particularly for large volumes of small components, by using an integrated loading system incorporating vacuum seals and progressive pressure reduction. The ‘shuttle transfer system’ developed and patented by Wentgate Dynaweld is illustrated in Fig. 8.17 and involves the use of custom-designed workpiece carriers, into which the component to be welded is loaded. The carrier or shuttle which is fed into the welding chamber via a feed tube is equipped with ‘O’ rings which seal the enclosure and allow pre-evacuation.

Vapour shields and beam traps

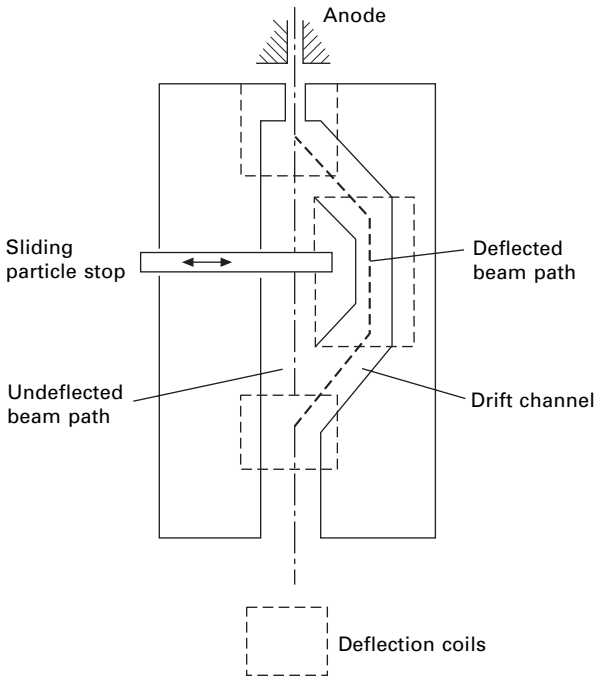
The collection of metal vapour inside the electron gun can cause unstable operation, and mechanical shields are often incorporated in the system in an attempt to exclude vapour from the gun area. A further improvement in this area is the development of the magnetic trap, developed by The Welding Institute (TWI) in the UK and shown in Fig. 8.18. This system has proved very effective for prevention of gun discharges when welding aluminium alloys. [180]

Computer control

The incorporation of CNC and computer control is common in current EBW systems. The computer can control workpiece positioning, operating cycle



8.17 Shuttle system for rapid loading of small components. (Courtesy of Wentgate Dynaweld.)



8.18 The Welding Institute (TWI) three-bend magnetic trap.

and operating parameters. These systems simplify parameter selection and may often be linked into integrated manufacturing cells. By using telecommunication data links, it is also possible to perform remote setting and diagnostics.

Non-vacuum EBW

Non-vacuum EBW (NVEB) has become more feasible as beam powers have increased. Production systems are in operation welding up to 6 mm thick aluminium and the development of systems for use in robotic installations is in progress.

8.4.7 Power sources for EBW

The solid-state power source technology described in Chapter 3 may be applied to EBW power supplies to provide improved control and consistency. Inverter designs that offer high electrical efficiency are particularly suitable for these applications.

8.4.8 Summary: EBW

Electron beam welding has been used successfully for many years to produce high-quality deep-penetration welds with limited distortion. The advances which have been made in equipment design should enable the productivity of the process to be improved.

Compared with arc welding systems, the capital cost of EBW equipment is high, but this must be evaluated against the potential improvements in quality and productivity.

8.5 Summary

Three high-energy welding processes have been discussed in this chapter. Of these plasma keyhole welding is well established but probably under-utilized, electron beam techniques are highly developed and exploited in well-defined application areas, and laser welding is being applied in an increasing number of applications. The hybrid laser arc processes offer a combination of the benefits of laser and arc processes, which include increased travel speed and improved tolerance to joint fit-up. The features of the processes are summarized in Table 8.4.

Table 8.4 Comparison of high-energy welding processes

Feature	Plasma keyhole	Laser	Electron beam
Energy density (W m^{-2})	3×10^{10}	3×10^{11}	10^{13}
Thickness range (mm)	Up to 12	Up to 20	Up to 200
Travel speed	Higher than GTAW	High	Very high
Materials weldable	All, but aluminium needs DCEP or AC	Most, but difficult on reflective surface (e.g. Cu, Ag)	Most, but not low vapour pressure, e.g. Cd, Zn and coated metal
System requirements	Simple; as for automated GTAW	Highly automated plus screening safety interlocks	Usually vacuum system, x-ray screens and high level of automation
Capital cost	Slightly more than GTAW	10 to 50 times GTAW	10 to 50 times GTAW
Running cost	Low	High	Very high
Cost of weld	Depends on application		

9.1 Introduction

Welding process economics may be improved by better control of the process to give reductions in post-weld inspection and repair, or by decreasing the joint completion time. The aim of many process developments has been to decrease the time taken to complete the joint (so reducing labour costs) by increasing metal deposition rates and using automation.

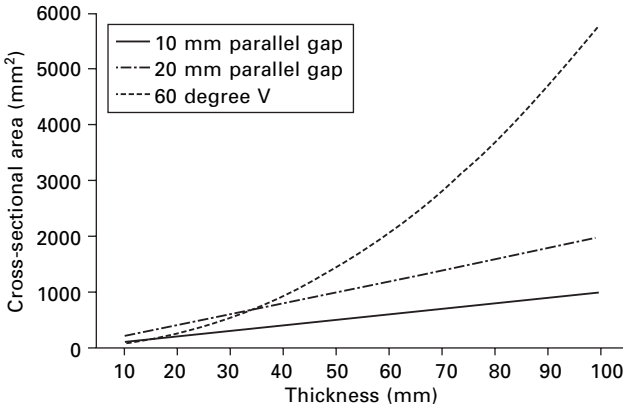
An alternative approach is to reduce the weld size or joint volume. In fillet welds the possibility of a reduction in weld size will depend on design constraints and the achievement of smaller weld volume is easily controlled by the operating parameters of the process. In butt welds significant changes in weld metal volume may require modification of the joint configuration, a change of process, or both.

The term 'narrow-gap' welding is used to describe a group of process developments which have been specifically designed to reduce weld metal volume in butt welds. Most of the development and the application of the processes described below relates to plain carbon and low-alloy steels.

9.2 Principles and features of narrow-gap welding

In conventional 'V' preparations, the joint volume and, hence, weld completion time, increases dramatically in proportion to the square of thickness (Fig. 9.1). As the angle of the preparation is reduced the weld metal volume and joint completion rate decrease and, if a narrow parallel-sided gap is used, the difference becomes significant, particularly on thicker sections. These narrow parallel sided gaps or square closed-butt preparations are inherent in certain processes, such as flash butt, friction, MIAB, plasma keyhole, laser and electron beam welding. Special techniques must be used, however, to allow the use of narrower gaps with the conventional arc welding processes.

In addition to the potential improvement in welding economics which narrow-gap techniques provide, they can also give reduced distortion and



9.1 The principle of narrow-gap welding – the effect of joint preparation on weld cross-sectional area.

more uniform joint properties. It has been reported by several investigators [181] that the mechanical properties of narrow-gap joints are better than those achieved with conventional V butt configurations. This is probably due to the progressive refinement of the weld bead by subsequent runs and the relatively low heat input. One practical problem that may arise on thicker sections is the difficulty of post-weld inspection and repair. This leads to the requirement for consistent welding performance and adequate in-process control and monitoring.

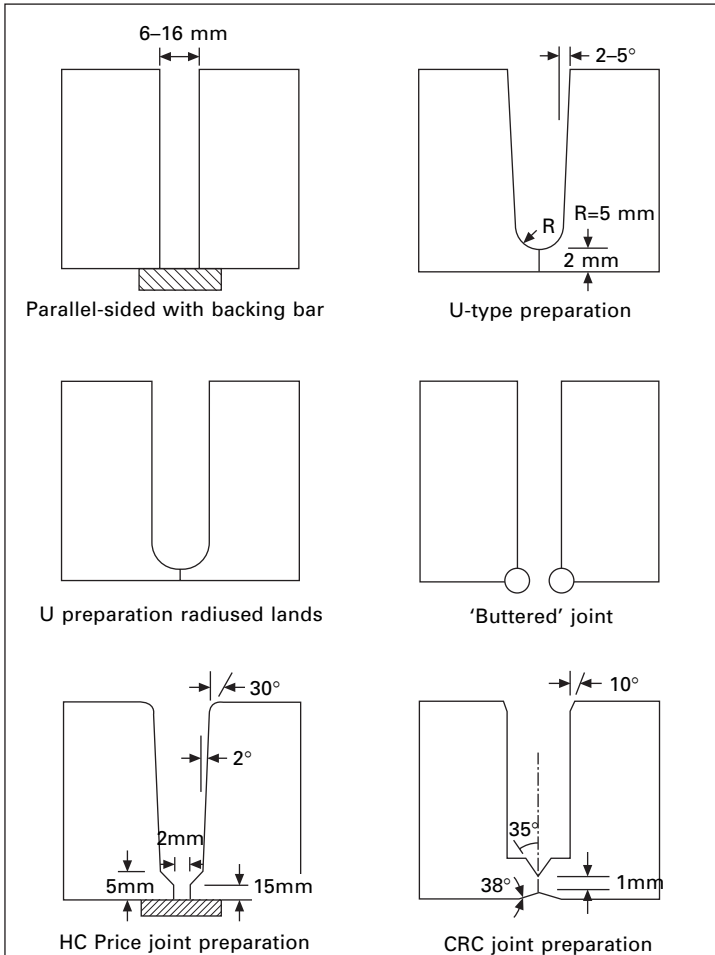
9.3 Narrow-gap welding processes

The narrow-gap welding processes have certain common features:

- they use a special joint configuration;
- they often require a special welding head/equipment;
- they usually require arc length control/seam tracking;
- they may require modified consumables.

The simplest joint configuration is the straight, parallel-sided gap with a backing strip, but there are a number of variants of preparation based on the process and the nature of the application. Some typical preparations [182] are shown in Fig. 9.2. The gap width also varies depending on the process and the equipment; from around 8 mm for GTAW up to 20 mm with SAW. It is possible to use standard automatic welding equipment with some processes, but with thicker sections (over 100 mm)¹ it is necessary to use purpose-

¹The limiting thickness for changing from conventional to special-purpose narrow-gap equipment is not fixed but depends on the application and the process economics.



9.2 Typical narrow-gap joint preparations. [182]

designed torches to provide access and ensure adequate gas or flux cover. Standard power sources and wire feed systems may also be used, but it is important that these give a stable and reproducible output. The torch height and its position relative to the sidewalls of the gap must be maintained at predetermined values, and this usually entails some form of seam tracking and height-sensing system. The consumables may require modification to give a satisfactory bead profile and, in the case of slag-shielded processes such as FCAW and SAW, to allow the solidified slag to be easily detached.

9.3.1 GTAW

Cold wire GTAW

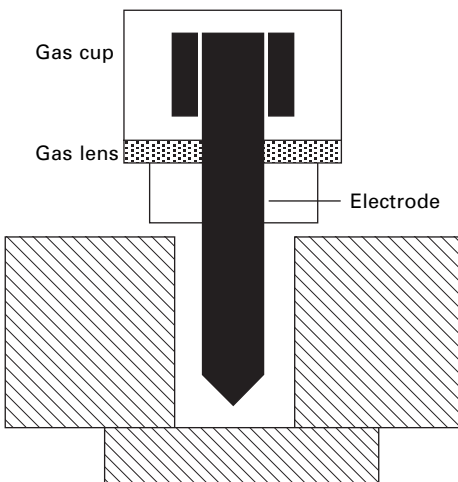
The GTAW process is easily adapted for narrow-gap operation since compact welding torches are available and, in thinner sections, it is only necessary to extend the distance by which the electrode projects from a conventional gas shroud (Fig. 9.3). Some provision must also be made for feeding a filler wire into the weld pool, but, again, conventional equipment is often suitable for thicknesses up to 12 mm. For thicker sections a special torch design is required to ensure adequate gas cover and reliable wire positioning. Torches specifically designed for narrow-gap GTAW are usually elongated as shown in Fig. 9.4, the shielding gas is delivered to rectangular slots either side of the electrode and, in addition, gas may be supplied through holes in the side of the blade.

Whilst the design is, in principle, fairly straightforward, it has been found that the achievement of adequate gas cover without entrainment of air from the surroundings is quite difficult. [183] Telescopic gas shrouds and flexible surface baffles are often added to supplement the gas shroud as shown in Fig. 9.5.

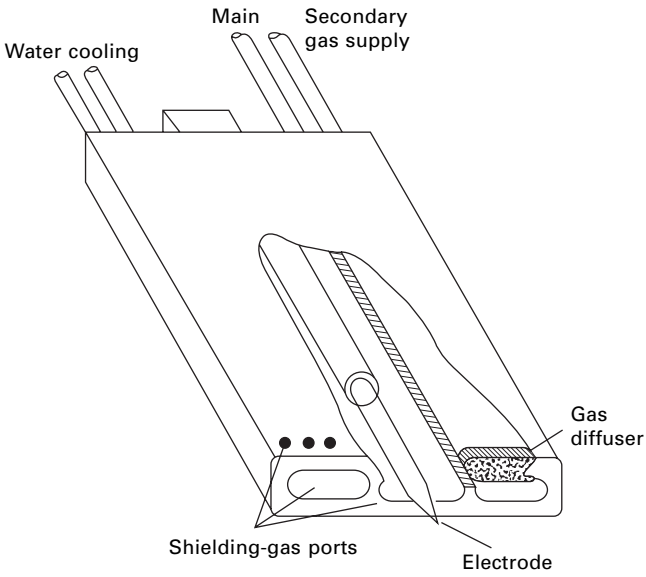
The process has been used for welding thicknesses of up to 200 mm, particularly for circumferential welds and pipe-work.

Hot wire GTAW

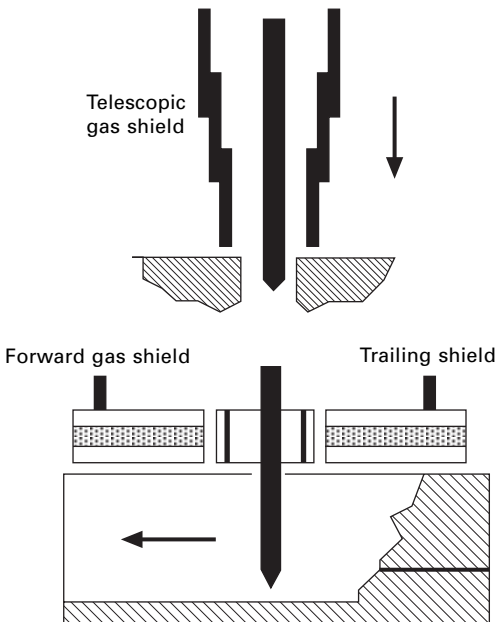
The hot wire GTAW process described in Chapter 6 is particularly suitable for narrow-gap welding, since it allows the deposition rate of the process to



9.3 Narrow-gap welding with a conventional GTAW torch. (Note that some auxiliary shielding may be needed.)



9.4 Narrow-gap GTAW torch.



9.5 Additional gas-shielding facilities.

be increased to levels similar to those of GMAW. Many commercial applications of narrow-gap GTAW employ hot wire addition and an interesting example is the Roboweld™ system which was designed for welding transmission pipelines both on land and on pipe lay barges. Seam tracking and accurate positioning of the electrode may be achieved by one of the methods described in Chapter 10, but some systems also include facilities for video monitoring of the arc and torch position with the ability for the operator to override the automatic control to correct the torch position. To improve the sidewall fusion the electrode may be oscillated or alternatively the arc may be deflected magnetically.

9.3.2 GMAW

The potential for using narrower weld preparations and smaller included angles for GMAW has often been claimed as an advantage of the process when compared with SMAW. However, although some concessions are allowed in the construction standards, this advantage has not been fully exploited in manual welding probably due to the difficulty of maintaining consistent fusion with reduced access. Reduced preparation widths are, however, used in automatic welding where improved control is possible. The developments in narrow-gap GMAW fall into two categories:

- the use of conventional automatic systems and narrower gaps;
- the use of special narrow-gap GMAW systems and narrow gaps.

Reduced gap/angle GMAW

A major application in the first category are the systems developed for transmission pipeline welding. The CRC Evans system, [184] for example, uses a compound bevel of the type shown in Fig. 9.2. In comparison with a standard American Petroleum Institute (API) bevel, this preparation reduces the weld metal volume by more than 20%. The pipe position is fixed with its longitudinal axis in the horizontal plane and welding must therefore be carried out in the 5G position (i.e. with the welding system rotating around the pipe). This is achieved by using a tractor equipped with an oscillator and typical operating conditions are shown in Table 9.1.

Systems such as this have been used successfully for welding pipe diameters of 600–1500 mm with wall thicknesses of 8–22 mm.

Narrow-gap GMAW developments

The use of narrow-gap GMAW for the welding of submarine hulls was reported as early as 1966 [185] and, by the mid 1970s, a range of developments of the process were being used on production applications in Japan.

Table 9.1 Welding conditions for CRC pipe welding procedure

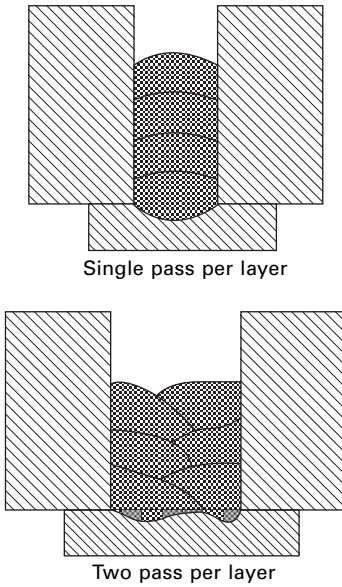
Welding variable	Conditions for each pass				
	Root run	Hot pass	Fill 1-3	Fill 4	Cap
Travel speed (mm min ⁻¹)	760	1000	330	330 ± 10%	330 ± 10%
Wire feed speed (m min ⁻¹)	8.6	12.7	14.6	14.6	9.4
Shielding gas	75% argon, 25% CO ₂	100% CO ₂	100% CO ₂	100% CO ₂	100% CO ₂
Gas flow rate (m ³ h ⁻¹)	1.4	1.4	2.8	2.8	1.4
CTWD* (mm)	6.3	8.9	14–12.7	12.7	7.9
Voltage (V)	19	23.5	23.5	23.0	20.5
Approx. current (A)	190	250	270	270	200

*CTWD = Contact tip to workpiece distance. Parameters derived from reference [184].

Very thick sections may be joined by GMAW using a parallel-sided gap if special torches are employed; these torches, like narrow-gap GTAW torches, are blade-shaped with elongated gas delivery nozzles. Several different approaches have been adopted in an attempt to minimize the risk of lack of fusion in the narrow gap GMAW process; these are discussed below.

Bead placement. The fusion may be controlled by careful placement of the weld beads and the use of a two pass per layer technique as shown in Fig. 9.6. The torch is re-positioned after each run or alternatively two separate torches may be used.

Consumable modifications. The fusion characteristics of the process may be improved by using a high level of CO₂ in the shielding gas, but this often leads to low process stability and excessive spatter build-up; whilst this may be acceptable when conventional torch designs are used it is likely to cause operational problems with specialized narrow-gap torches. The alternative is to use high helium gas mixtures (helium + argon + CO₂ + oxygen). It has been found that these give superior penetration to argon-rich mixtures and provided the oxygen and CO₂ levels are carefully controlled the arc stability

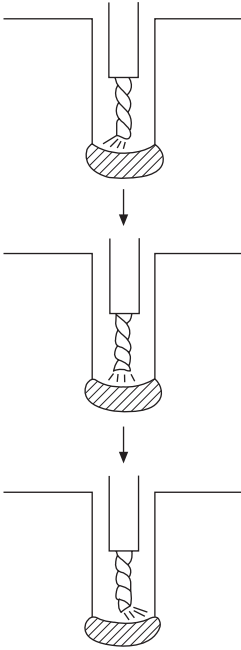


9.6 Single and two pass per layer techniques.

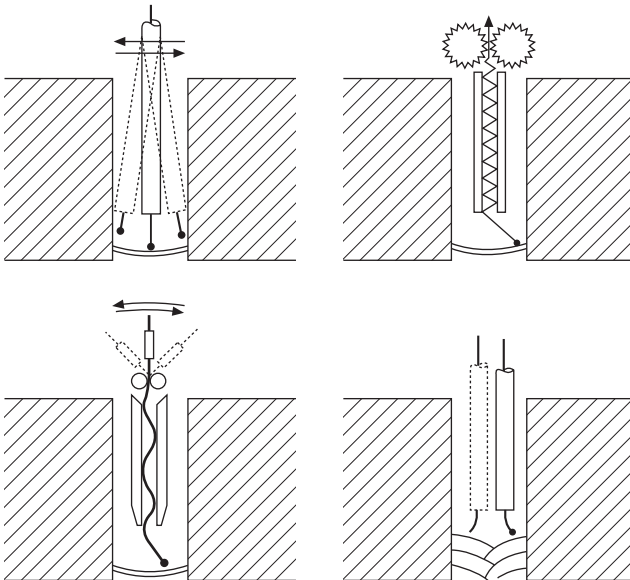
is good [186] and the mechanical properties of the joints are superior to those produced with either CO_2 or argon/ CO_2 mixtures.

The position of the filler wire within the joint determines the arcroot location and will influence the incidence of fusion defects. Normal GMAW filler wires have a natural curvature (referred to as cast) and spiral (referred to as helix), and this gives rise to random oscillation of the wire tip. Specially straightened wire is available for automatic welding and automatic equipment often incorporates some means of wire straightening. These techniques ensure a stable arc location, but a novel modification of the filler wire, which exploits the presence of a helix to produce more controlled arc oscillation, has been used as a means of improving fusion. This technique, known as twist arc, involves fabricating a special filler wire by twisting two smaller-diameter wires together. [187] The principle of the technique is shown in Fig. 9.7. The welding head tracks along the longitudinal axis of the weld and with a gap width of 14 mm adequate fusion is obtained at both sidewalls. The arc oscillation pattern may be varied by changing the relative diameter of the wires, the pitch of the spiral and the operating parameters.

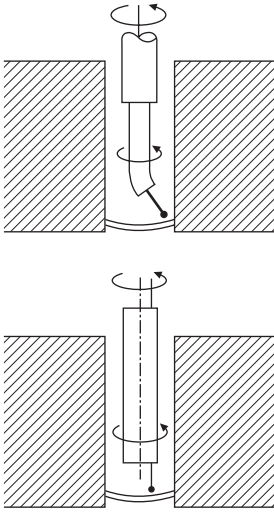
Torch or wire oscillation. Lateral oscillation of the torch may be used as shown in Fig. 9.8 or, alternatively, an eccentric contact tube may be rotated to produce circular oscillation of the wire tip as shown in Fig. 9.9. These systems are relatively complex and the minimum gap width is often limited by the need to move the whole welding head. Alternative systems that rely on controlled deformation of the filler wire as it passes through the feeding



9.7 'Twist arc' narrow-gap GMAW technique.



9.8 Oscillation techniques for narrow-gap GMAW.



9.9 Rotating tip techniques.

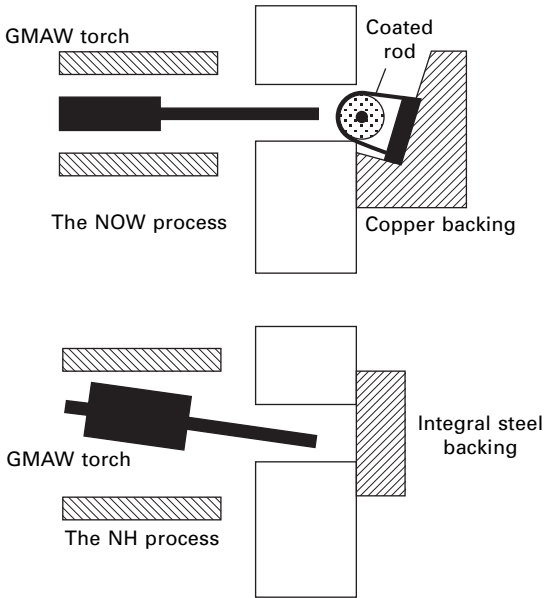
system have therefore been developed. These devices use bending rollers to introduce a wave-like or spiral deformation into the wire in order to cause controlled oscillation of the arc. Although the mechanism required to produce the deformation may be complex, the part of the torch that enters the joint is compact and satisfactory joints can be made in gap widths down to around 9 mm.

Modification of process operating mode. Many of the systems now available use the pulsed transfer GMAW techniques described in Chapter 7 to improve process control and limit spatter formation.

Applications of narrow-gap GMAW

The narrow-gap GMAW process has been used for downhand welding of circumferential joints in pipe and shafts with the workpiece rotated under the welding head. The GMAW process may also be applied to positional (5G) welding of pipe as described in Section 3.2.1 and has also been used [188] for welding horizontal joints in tubular structures and building columns as shown in Fig. 9.10, particularly in Japan.

In the offshore industry, interest has been shown in the application of the process to horizontal welds (2G) in vertical pipe for 'J' laying of transmission pipelines at sea. Although this has been found to be feasible, it requires very careful control of the process parameters and gap width to ensure that consistent bead profile and fusion characteristics are maintained.



9.10 Horizontal narrow-gap techniques. [188]

9.3.3 Narrow-gap SAW

The narrow-gap submerged arc process is capable of producing high-quality joints in thick sections in the downhand position with considerable improvements in running costs. Conventional submerged arc welding equipment may be used for relatively thick material (e.g. 70 mm) but special-purpose equipment is available for welding thicknesses up to 600 mm.

Single-pass technique

The use of a single-pass technique, which is potentially more productive, is limited by the possibility of sidewall fusion defects, slag entrapment and a higher average heat input when compared with multipass modes. Research work [189, 190] using mathematical modelling techniques has shown, however, that it is possible to optimize the welding parameters so that defects such as lack of fusion, undercut and slag removal problems may be overcome in thicknesses up to 70 mm with conventional equipment and a single pass per layer. It was found that using the parameters predicted by the model the bead geometry could be controlled to produce concave surfaces (for ease of slag detachment), optimum depth-to-width ratios (to prevent solidification cracking) and maximum lateral penetration (to prevent sidewall fusion defects).

Table 9.2 Narrow-gap submerged arc parameters [191]

Groove width (mm)	Current (A)	Voltage (V)	Travel speed (mm min ⁻¹)	Flux height (mm)
12	425	27	180	45
14	500	28	250	50
16	550	29	250	50
18	600	31	250	50
20	625	32	230	50
22	625	34	230	50

Multipass per layer technique

The multipass technique requires a larger gap width for a similar wire diameter (e.g. 18 instead of 10 mm with a 4 mm filler wire and two passes) and the joint completion rate is consequently lower. The technique does, however, allow greater control of sidewall fusion, weld metal refinement and improved access for flux removal and inter-run cleaning. For these reasons, most commercial applications of the process use the two pass per layer mode with a single electrode. Typical values of gap width and welding parameters [191] are given in Table 9.2. For thicknesses above 100 mm a special narrow-gap torch is required; this is usually rectangular with provision for flux feed and recovery, seam tracking and height control. A typical torch assembly uses tactile sensors to control torch height and optoelectronic sensing of the torch position within the gap. The process is commonly applied to longitudinal and circumferential joints in large cylindrical components; in both cases, a heavy column and boom will be required to carry the torch head and, in the case of circumferential joints, the workpiece must be rotated under the welding head. For these circumferential applications, it is essential to prevent fluctuation in the lateral position of the seam as it rotates, and feedback control devices are often incorporated in the roller bed to sense and correct the position of the component.

The single filler wires used most commonly have diameters in the range 3.2–4.8 mm; smaller wires are prone to cause random arc wander, particularly with the relatively long electrical stick-outs that are used, and larger diameter wires are more difficult to feed. Although it is possible to use standard fluxes, special flux formulations with improved slag release characteristics have been devised for narrow-gap SAW. The power used is DC electrode positive or AC; AC gives greater resistance to magnetic arc blow and square wave AC power supplies have also been used to improve control of the process.

Developments

Increased productivity and improved process control may be achieved by

Table 9.3 Applications of narrow-gap submerged arc welding

Weld type	Application
Circumferential rotated pipe	Offshore oil platform tubular fabrication
Circumferential rotated shafts	Power generation turbine components. Propeller shafts
Rotated thick wall vessels	Nuclear reactor containment vessels

applying the techniques normally applied to conventional submerged arc welding to the narrow-gap process, i.e.:

- extended stick-out;
- twin wire;
- hot wire;
- metal powder addition;
- flux-cored consumables.

These techniques are not widely used at present although some development work has been reported. [192, 193]

Applications

The standard NGSAW process has been in use in many commercial applications since the early 1980s. [194] Some of these are summarized in Table 9.3; they range from nuclear reactor containment vessels in 600 mm thick Ni/Cr/Mo alloy steels to the welding of 60 mm material for offshore tubulars.

9.4 Summary and implications

The use of narrower joint gaps and reduced preparation angles can result in significant improvements in productivity. The use of processes which involve the inherent use of a narrow gap (EBW, laser, plasma, friction, MIAB) automatically exploit these advantages, whilst systems have been developed to allow narrow gaps to be used with GTAW, GMAW and SAW processes. The potential reduction in running costs must be evaluated against the capital cost of the equipment, although it is reported [195] that high cost, sophisticated narrow gap submerged arc systems have been justified for welding 350-mm-thick high-pressure feed-water heater shells. The minimum economic thickness for narrow-gap technology varies with the process and operating mode. Narrow-gap GTAW welding may be justified on thicknesses down to 15 mm. Narrow-gap type configurations have been used for GMAW in thicknesses from 15–22 mm upwards. Narrow-gap SAW is normally considered to be viable at thicknesses above 60–70 mm, but, if conventional equipment is used, this lower economic limit may be reduced until it overlaps conventional square

butt SAW procedures in thicknesses down to 12 mm. Optimization of welding parameters and in-process control are essential to avoid defects in narrow-gap applications; the restricted access of the gap will make progressive repair difficult, but good procedure control should obviate these problems and the use of narrow-gap welding may be seen as a way of imposing a reasonable level of discipline into the control of welding operations.

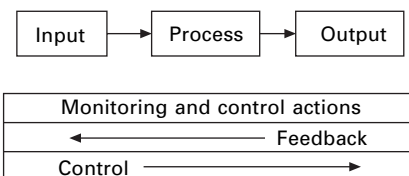
10.1 Introduction

In any manufacturing process it is necessary to ensure that the outcome of the operations carried out matches some defined objective. This involves controlling the operation of the process in some way, as shown in Fig. 10.1.

In order to achieve the desired output it is necessary to:

- Establish control relationships which enable the effect of the control variables on the process performance to be predicted.
- Monitor the process to ensure that it is operating within limits defined by the control relationships.

Compared with other manufacturing processes, welding has established a reputation for being more difficult to control and less likely to achieve consistent quality. This is probably a result of the multiplicity of interrelated control parameters, the complexity of the control relationships and the difficulty of monitoring process performance. It is also difficult to assess weld integrity without careful non-destructive examination and mechanical properties cannot be checked without destructive testing of the fabrication. These difficulties are recognized in international quality standards and welding is classified as a special process in ISO 9000 and the control measures required for welded fabrication are detailed in ISO 3834. An indication of the number of control parameters which need to be considered for two contrasting arc welding processes is given in Table 10.1.



10.1 Principles of process control.

Table 10.1 Comparison of control variables for automatic plasma and MMA welding

Control parameters SMAW	Control parameters PLASMA
Electrode type	Current, pulse parameters, current rise/decay times, electrode polarity, welding speed, electrode geometry, shielding gas type, shielding nozzle size, shielding gas flow stabilisation (gas lens), shielding gas flow rate, electrode protrusion. Electrode set back, nozzle geometry, orifice diameter, plasma gas type, plasma gas flow, pilot arc current.
Electrode diameter	
Arc current	
Direct or alternating current	
Electrode polarity	
Electrode manipulation	

The traditional manual control techniques will be outlined in this chapter and the influence of developments in processes and equipment will be discussed. Substantial progress has also been made in both the determination of control parameters, monitoring techniques and automatic process control, and these advances will be described in detail.

10.2 Manual control techniques

Traditionally, welding processes have been controlled by establishing satisfactory operating envelopes for a particular application, often by trial and error, recording the most satisfactory parameters and using these in production. In some cases, it has been left to the welder to interpret inadequate drawings and establish conditions which satisfy the design requirements; for example to produce a fillet weld of a given size.

When improved control is required a welding procedure is established. This is a formal record of the parameters that have been found to produce the required result and it is used to specify the steps necessary to achieve repeatable weld quality. *Procedure control* has become the accepted approach when high-quality joints are being produced.

10.2.1 Formal welding procedure control

Formal welding procedure control entails:

- establishing satisfactory operating parameters (procedure development);
- gaining acceptance of the proposed procedure (procedure qualification);
- following the accepted procedure in practice (procedure management).

Procedure development

Welding procedure development involves: selection of the most suitable welding process; the determination of a suitable combination of welding

parameters; assessment of the performance of sample joints; and amendment of parameters if test results fail to meet requirements. These factors are discussed below.

Selection of welding process. Choice of the process will depend on the material to be joined, its thickness and the welding position. In most cases several processes will meet the basic requirements of the application and the final choice will depend on practical considerations (e.g. availability of equipment and operators), limitations imposed by codes (see below) and economics. The choice of process will determine the number of control parameters which need to be considered and the nature of the control relationships. Computer software designed to simplify welding procedure selection is also available. [196]

Determination of welding parameters. The welding parameters include all the variables which need to be specified in order to ensure repeatable performance.¹ This may involve the joint design, cleaning and edge preparation, preheating and post-weld treatment as well as the process control parameters such as speed, voltage and current.

The application may call for a specific joint configuration, but it is usually necessary to define the details of the plate preparation. Predetermined joint profiles are available from published literature [197] and welding codes. These codes provide 'safe' preparation details which have been tested for the application covered by the standard. They provide a simple method of joint design, but, in some cases, they may restrict the choice of process and joint profile. Even when these recommended joint designs are used, it is usually still necessary to qualify the procedure especially if a new process/technique is to be used.

The process control parameters can also be determined by reference to published data, pre-qualified procedures, or codes and standards. Alternatively, welding trials may be necessary to determine suitable parameters, operating tolerances and the optimum welding conditions. At this stage, the combination of process and parameters chosen must be capable of producing a joint of the specified repeatable quality cost-effectively. The avoidance of potential defects must be taken into account when choosing the process and may significantly influence the selection of welding consumables, operating parameters, pretreatment, post-weld heat treatment and inspection.

The problems which need to be considered are determined by the weldability of the material as indicated in Table 10.2. In the case of structural steel the possibility of hydrogen-assisted or hydrogen-induced cold cracking (HACC/HICC) must be considered. Fortunately, the rules governing the formulation

¹These parameters are often referred to as 'essential variables' and if these are changed outside acceptable tolerances requalification of the procedure may be required.

Table 10.2 Typical examples of the influence of material weldability on procedure

Material	Problem	Influenced by	Control
Carbon manganese and low alloy steel	Hydrogen-assisted or hydrogen-induced cold cracking (HACC, HICC)	Microstructure, stress, restraint	Carbon equivalent of material. Electrode type (hydrogen controlled). Heat input. Cooling rate. Preheat and postheat
Carbon manganese steels	Lamellar tearing	Plate cleanliness, presence of through thickness stress	Check material. Correct joint design. Avoid through thickness loading
Ferritic steels	Porosity	Presence of nitrogen (from air). Generation of carbon monoxide	Use adequate filler deoxidation and efficient gas shield
Austenitic stainless steels	Carbide precipitation	Material composition. Thermal cycle	Choose stabilized or low carbon grade. Control thermal cycle
Austenitic stainless steels	Hot cracking in weld metal	Weld metal composition, heat input	Control ferrite content (electrode)

of safe procedures to avoid heat affected zone (HAZ) HACC² are well established and are covered in most national and international codes. These rules indicate the need for hydrogen-controlled filler materials, and enable the preheat and heat input requirements to be determined from a knowledge of the chemical composition of the steel or its carbon equivalent and the combined thickness of the material. The result of the development process will be a formal welding procedure specification (WPS) or proposal which may consist of a simple list or more usually it will be produced as a printed form (Fig. 10.2). At this stage, the procedure is a ‘proposal’ and, although it may have been derived from similar applications, it is untested or *unqualified*.

Assessment of joint performance. In order to test whether the procedure will produce the required joint characteristics, it will be necessary to carry out mechanical and non-destructive examination of sample welds which are made with the specified welding parameters.

²Whilst HAZ HACC is well understood, the incidence of weld metal HACC has increased as higher yield steels are used. The rules for the control of weld metal HACC are more complex and still under investigation.

Procedure qualification

Formal qualification of the procedure involves completion of sample joints to the agreed WPS, often under the supervision of the client or an independent approval body. The welded joints are subjected to a specified selection of non-destructive and mechanical tests, the results of which are reported in a procedure qualification record (PQR) as shown in Fig. 10.3.

The skill of the welder is often a major factor in determining the final weld quality. The welder's skill may be assessed and 'calibrated' by means of a general approval process. [198] It may also be required to qualify a named welder to carry out a specific procedure.

Procedure management

Management of welding procedures using this technique involves: maintenance of procedure specification and qualification records; calibration of welding and ancillary equipment; and monitoring compliance with the specified procedure.

Maintaining procedure records. Having established a satisfactory procedure and obtained procedure qualification, it is necessary to maintain a record of the parameters and techniques used and to control the issue of this information to the shop floor to enable consistent joint quality to be achieved. In many cases, this information will be required on an irregular basis particularly when small batches of fabrications are required. The welding procedure specification records will also be required when tendering for new projects, when preparing procedures for new work or when analysing production problems. A fabricator will quickly generate a large library of procedures and it is necessary to devise a suitable system for storage and retrieval. Many companies are now using computer database systems for procedure management in order to reduce duplication and improve access to procedure data. [199]

Validity of parameters and calibration of equipment. The validity of the procedure will depend on the possibility of establishing the same operating conditions: when the process is used with the stated parameters, by a different operator in a different workplace using equipment and consumables of the specified type. If the parameters specified are ambiguous or ill-defined, the resultant weld may well be inferior to those prepared at the procedure development stage.

For example in GMA welding when voltage is used as a control parameter, the voltage reported should be the arc voltage measured as near to the arc as possible. Open circuit (or no-load) values may be easier to measure, but are meaningless unless the static characteristics of the power source are also stated. In addition, since there may be a significant voltage drop in the

WELDING PROCEDURE QUALIFICATION										
PROJECT			W.P.O. No.:			Rev.:		Page:		
WELDING CODE:						APPROVALS				
TESTING CODES						CONTRACTOR:				
TENSILE:.....			N.D.E.			CLIENT:				
HARDNESS:						CERT. AUTH:				
TOUGHNESS:										
BEND:										
NON DESTRUCTIVE EXAMINATION					MACRO EXAMINATION					
TEST		RESULTS		REPORT	TEST		RESULTS		REPORT	
VISUAL MAG. PARTICLE DYE PENETRANT ULTRASONIC RADIOGRAPHY					CONTOUR					
					FILLET SIZE					
TENSILE TEST										
TYPE	TEST No.	AREA	ELONG. %	R of A	YIELD	U.T.S.	COMMENTS	REPORT		
HARDNESS SURVEY						BEND TEST				
TRAVERSE	PM	HAZ	WM	COMMENTS	REPORT	TYPE	FORMER	RESULTS	REPORT	
TOUGHNESS TEST										
TYPE	No.	TEMP	RESULT	REPORT						
TEST PLATE IDENTIFICATION						NOTE:				
MARKED:										
WELDER:										
No.:										
DATE:										

10.3 Typical welding procedure qualification record sheet.

welding cable at higher currents the terminal voltage of the power source, as indicated by the power source meters, is likely to be higher than the arc voltage and subject to variation with cable length and diameter. In the case

of welding consumables, these should be specified according to a recognized national or international code which defines their composition limits and performance rather than by trade names. (In some cases, the user may need to add specific limitations on performance and composition.)

The method of measurement of electrical parameters should be specified [e.g. root mean squared (RMS) or mean] and, in some cases, it may be necessary to specify the type of instrument and the measuring technique [200] (see also Section 10.3 below).

The tolerances on procedure variables should be specified with due regard to the equipment capabilities and limitations. For example, new equipment will be calibrated in accordance with a manufacturing standard, but the tolerances allowed are often quite wide; for most equipment, values of $\pm 10\%$ of those indicated are permissible and repeatability of settings between equipment cannot be guaranteed. Calibration of existing equipment may also be difficult, for example in the case of simple MMA equipment which often has poorly defined markings on controls which are subject to wear. [201] In GMAW, equipment meters, where fitted, often become damaged and deteriorate in the normal welding environment and cannot be relied on for calibration purposes.

A further source of calibration error is the variation in output of conventional welding equipment with mains input swings which may be up to $\pm 10\%$; however, it is common for more modern electronic welding power sources to incorporate output stabilization which offers greater protection against uncontrollable input voltage fluctuations. In addition it is usually possible to obtain improved accuracy and repeatability from these electronic power sources as discussed in Chapter 3.

In view of the problems listed above, it is necessary to check equipment which is intended for use on critical welding procedures with some external calibration device which itself has a known accuracy. The appropriate level of calibration will be determined by the application and a two-tier system has been proposed [202] and this is the subject of proposed codes of practice. This system consists of the following grades:

Grade 1. This is the standard grade of calibration accuracy as required by the power source design standards.

Grade 2. This higher or 'precision' grade is intended for applications requiring greater precision, such as nuclear industry joints, mechanized, orbital and robotic welding systems.

Target requirements for each of these grades are shown in Table 10.3.

It is not only the welding equipment which requires calibration; in the case of MMA welding, where electrode temperature control may be very important, it is necessary to calibrate the electrode storage ovens and, when preheat and post-heat treatment are involved, the heating equipment and the

Table 10.3 Calibration requirements

Parameter	Grade 1	Grade 2
Current	±10%	±2.5%
Voltage	±10%	±5%
Slope up/down time		±5%
Pulse time		±5%
Measuring instruments	±2.5%	±1%
Wire feed speed		±2.5%
Calibration frequency	1 yr max.	0.5 yr max.

devices used for checking temperature need to be considered. In mechanized welding processes, the travel speed and positional accuracy of the system will need to be checked regularly.

Monitoring of procedures. Once accepted, it is essential that production welding operations are monitored to ensure that the procedure is being followed and that the required results are being achieved. Traditionally, testing of the completed fabrication using non-destructive test techniques (e.g. x-ray, ultrasonic, MPI and dye penetrant) have been used to check the weld quality and, if necessary, defects have been removed and the joint repaired. Progressive monitoring at an early stage of production can, however, prevent costly rework after final inspection. Routine monitoring should at least include checking the critical procedure variables (e.g. current, voltage, wire feed speed, temperature, consumable treatment, travel speed). Improved control may be achieved by use of the monitoring instrumentation described in more detail below.

The use of portable monitoring devices which comply with traceable standards of calibration is an effective way of ensuring that the optimum parameters are being used; it is particularly beneficial to use these same devices at the procedure qualification stage. In practice, accurate high-quality analogue meters could be used for this purpose, but these tend to be less robust than digital meters; however, digital meters must be used with care especially if the parameter being measured is not either a constant DC or pure sinusoidal AC waveform. Many recent monitoring and calibration devices incorporate a computer data logger which provides permanent records of the welding parameters and also allows the data to be transferred to a computer for permanent storage. (These systems will be described more fully in Section 10.3.1.)

10.2.2 Summary: welding procedure control

Control of the welding may be an informal process, where the welding engineer or the welder is left to assess the requirements and select appropriate

welding parameters, or a more formal approach may be adopted, in which the suitability of the welding procedure is tested and documented.

The traditional method of control by means of formal welding procedures depends on:

- establishing and proving satisfactory welding parameters by procedure trials and testing;
- maintaining the same parameters in production;
- monitoring by means of final inspection and non-destructive examination (NDE);
- correction of errors by repair and rework.

It is assumed that, if all the process inputs remain fixed, a satisfactory repeatable output, in terms of weld quality, will be obtained.

Any input errors or disturbance in the process that cause deterioration of quality may not be noticed until final inspection. This may be considered to be an *open-loop* system since the quality of the output is not used directly to control the process; the control loop is closed by manual intervention to correct any errors, but this is often carried out after the weld has been completed and the only means of correction is repair.

Full qualification and approval of procedures in this way is a costly and time-consuming process and is usually only justified when specific joint quality requirements must be achieved. However, in many cases it is essential to use these techniques to achieve an adequate measure of control and satisfy quality assurance requirements.³

10.3 Monitoring

Measurement of welding parameters and calibration of equipment is essential when any method of control is to be applied. The requirements for formal welding procedure control have been discussed above, but the availability of suitable monitoring methods is also a prerequisite of any automatic control system. Considerable improvements in the methods of monitoring welding processes have been made and some of the techniques available will be discussed below.

10.3.1 Welding parameters and measuring techniques

The techniques will be discussed under the following headings:

³These techniques may need to be implemented to satisfy quality systems standards such as the ISO3834, ISO 9000 EN 29000 series or specific fabrication standards e.g. for pipelines, pressure vessels and bridges.

- conventional meters;
- computer-based instrumentation;
- measurement of welding parameters;
- stability measurement;
- dynamic resistance measurement;
- deviation monitors;
- vision systems.

Conventional meters

Analogue and digital measurement. Both analogue and digital techniques are applied in the measuring of welding parameters.

In analogue systems, the signal to be measured is converted into an indication which changes continuously in response to variations of the input signal. In analogue meters, the incoming voltage may be converted into the deflection of an indicating needle electromagnetically. Alternatively, for rapidly changing signals, the indicator may be a beam of electrons which is scanned across a cathode ray tube screen by the deflecting coils of an oscilloscope.⁴ Analogue measuring techniques give a good visual indication of the rate of change of parameters and are useful when assessing process stability. Analogue meters also give a good indication of mean output levels when the signal is subject to random variations (e.g. when measuring the current in MMA welding). Quantitative measurements may be made by reading a calibrated scale. The indication provided by this type of meter is continuous and the resolution depends on the scale and the care with which the readings are taken. In order to be accurate, the meter scale needs to be large, but, with conventional systems, this implies a fairly heavy mechanical movement which may reduce the rate of response of the instrument. To obtain a permanent record of the indicated values it is necessary to record the movement of the indicator on paper or film; this may be achieved using a strip of continuously moving recording medium, which is marked by a pen attached to a moving potentiometric carriage or a light beam which is deflected onto photosensitive paper by a galvanometer.

In digital measuring systems, the analogue signal is converted to a number on a predefined scale before it is displayed. The resolution of the instrument will depend on the analogue-to-digital conversion (ADC) device used, an eight-bit device will provide a resolution of 256 increments, whilst a 12-bit device will give 4096 and a 16-bit device will allow 65 536 increments to be resolved.

⁴Oscilloscopes give a clear indication of the amplitude and frequency of regular, periodically varying signals but for transient or irregular signals single-shot instruments such as the computer-based systems described below must be used.

If the full-scale reading of the instrument is 256 V, an eight-bit ADC would give a resolution of 1 V whilst a 16-bit device would provide 0.004 V resolution. For many welding applications, eight-bit accuracy is adequate, particularly if the signal is conditioned to limit the full-scale value. The advantage of digital measuring systems is that they provide a direct numeric output and this may be stored or recorded electronically as described below. Digital systems are generally more robust than analogue meters, but they are sometimes susceptible to electrical interference. The disadvantage of the digital approach is that it is difficult to interpret the digital display if the parameter being measured is fluctuating rapidly and the 'mean' values may be arrived at in several different ways (e.g. by electronic processing of the incoming signal or by calculation). This may lead to slight discrepancies between the values measured with different digital meters and may be responsible for large variations when compared with traditional analogue meters.

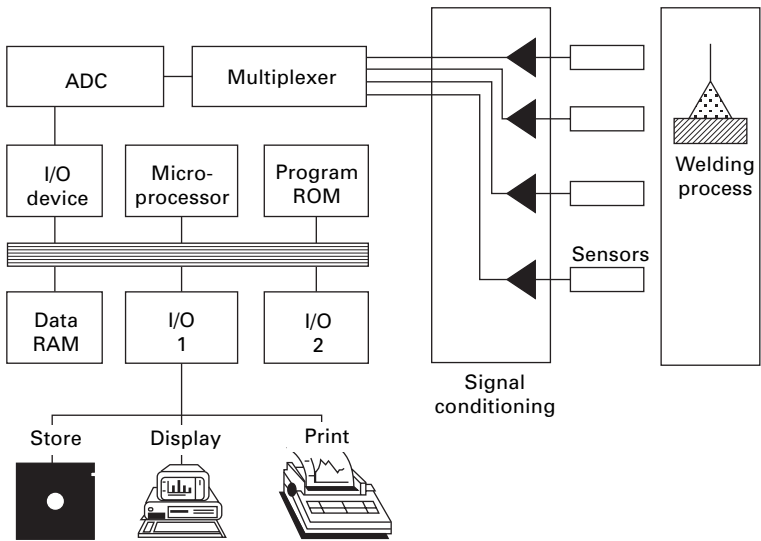
Computer-based data loggers

Computer-based data loggers as used in general process control and biomedical applications were originally only used in welding research applications, but purpose-built monitors for calibration and control of welding processes are now available. [203]

The principle of computer-based instrumentation is illustrated in Fig. 10.4. The analogue signal to be measured is amplified or attenuated by a signal-conditioning circuit, which consists of standard electronic components. The output of this stage may be electrically isolated from the remainder of the instrument by isolation amplifiers, and hardware filters may be incorporated to reduce electrical noise. Isolation is particularly important when high voltage welding signals are being measured, where common-mode problems occur⁵ and to avoid spurious signals when low currents or voltages are being monitored (e.g. from thermocouples).

The analogue signal is digitized by an ADC similar to that used in digital voltmeters. The use of eight-bit ADC converters is again adequate for many welding applications providing the input is scaled to an appropriate level. In order to provide facilities for monitoring several welding parameters, the conditioned analogue signal from a number of inputs may be scanned by a multiplexer before being passed to the ADC.

⁵Common mode problems: when measuring welding current and voltage simultaneously, it is possible to connect the instrumentation in such a way as to short circuit the output of the power supply. A high-current path may accidentally occur either in the interconnecting leads or, more seriously and less obviously, through the ground or earth connection of the instrument. Such faults can result in serious damage to welding instrumentation.



10.4 Principle of computer-based instrumentation.

The digital output from the ADC is sampled at a rate determined by the clock rate of the microprocessor and the control program. A range of programs and operating parameters may be stored in the program memory (usually an EPROM) and the appropriate sampling conditions may be chosen for a specific application. The microprocessor also determines where the digitized values are stored, how they are processed and whether they are displayed on some in-built indicator or transferred to an external device for storage or display. Systems of this type are capable of reading the instantaneous value of the input level every $100\ \mu\text{s}$ or even faster. It is possible to store these instantaneous values in the RAM and they may be displayed so as to reproduce the waveform of the incoming signal in much the same way as an oscilloscope, the difference being that the values are stored and may be examined repeatedly. The data may also be transferred to non-volatile memory (e.g. floppy disc, battery-backed RAM, tape) and hard copy of the waveform may be obtained with the aid of a printer or plotter. In more sophisticated systems, the data may be exported via an Ethernet link, the internet, or factory bus to remote locations.

In order to avoid inaccurate representation of the waveform, known as '*aliasing*', the sampling frequency should be at least ten times that of the waveform being measured; with inter-sample times of $100\ \mu\text{s}$, the sampling frequency is 10 kHz and signal frequencies lower than 1 kHz are accurately represented; this response is perfectly adequate for general assessment of the common welding waveforms found in pulsed GTAW and GMAW although higher sampling speeds are sometimes required when investigating high-speed transient events.

The welding waveform in memory may be displayed on a monitor and analysed. Some instruments also allow calculations to be performed on the waveform and discrete values of pulse parameters may be displayed. The number of data which may be captured is, however, restricted by the memory available and, at high sample rates, the random access memory will be filled very quickly. If detailed information concerning the waveform is not required the incoming signal may be processed in real time and a more compact data file maintained. Two common techniques which have been used in welding applications are event monitoring and derived data storage.

In event-monitoring techniques, only the data relating to those transient features of the waveform which satisfy certain criteria are recorded. A common application is the recording of pulse or short circuit current peaks in GMAW. A threshold current is preset and only excursions of the current which exceed this threshold are recorded. Each time the current rises above the threshold, the time, amplitude and duration of the event are stored. Since only events of interest are captured and the data concerning these phenomena are compressed, a large amount of relevant information may be obtained over an extended sampling period. The application of this type of system for stability analysis is described in Section 3.1.2.

The information may also be compressed by performing calculations on the raw data during the measuring process and storing only the results. Derived data such as mean current and voltage may be obtained for example for every thousand readings, the raw data may then be discarded and the averages stored in RAM. Alternatively, secondary process parameters such as heat input, or dynamic resistance may be calculated on-line in this way.

A purpose-designed welding data logger monitor has been designed to master arc voltage, current and wire feed speed and has facilities for waveform capture and analysis and the capability of monitoring mean values for each weld run. In the case of waveform capture, variable sample rates and pre-triggering facilities are available. The output may be directed to:

- an external oscilloscope for general analysis and measurement of the waveform;
- an internal display which gives a digital read-out of the values of current or voltage identified by a movable cursor on the oscilloscope screen;
- an internal printer which prints the calculated values of peak and background current and voltage, peak and background time and mean current and voltage;
- a removable battery-backed RAM cartridge or 'thumbdrive', which may be used to store data and transfer it to a personal computer for more detailed display and analysis. Using this facility, the measured data may be presented as a welding procedure, a weld costing or a comparison of the measured values with a preset procedure.

Portable instruments of this type provide a useful means of calibration, monitoring and problem solving in welding applications. These systems provide information after the weld being monitored is complete, but the techniques employed may also be applied to permanent data recording and control in real time as described below.

The recent development of low-cost remote computer-based data loggers has made it possible to record welding parameters in the welding environment, store the data in battery-backed memory and interrogate the results by downloading the data through high-speed serial links (USB), Ethernet, internet or factory bus systems such as 'Field' or 'Can' bus. Systems such as this have been used for measurement of heat-affected-zone temperature cycles, thermal testing of welding torches and monitoring of current and voltage. [204] The improved availability of high-speed analogue-to-digital cards for personal computers has also made it possible to develop flexible cost-effective purpose-designed welding data loggers suitable for research, production and quality-monitoring applications. [205] Using embedded processors it has also been possible to develop very low cost computer-based factory instrumentation.

Normal welding parameter monitoring

Temperature. The high temperatures experienced in welding may be measured using temperature-indicating paints or crayons, fusible indicators, bi-metal thermometers, thermocouples, infrared thermometers or by thermal imaging.

Temperature-indicating paints and crayons change colour in response to the surface temperature of the material. They are convenient for site use, but their accuracy depends to a certain extent on the care with which they are applied and the interpretation of the colours.

Fusible indicators melt and in some cases change shape when they reach a prescribed temperature. They give a clear indication that a certain temperature has been reached, but little guidance on the actual temperature of the material during the heating and cooling cycle.

Bi-metal thermometers are contact devices which rely on the response of a bi-metal strip to temperature, deflection of the strip being converted mechanically into movement of a needle. The indication of temperature is continuous and easily read, but the accuracy is often less than 10% of full scale.

A more accurate means of temperature measurement involves use of a thermocouple as a sensor. The thermocouple junction produces a small voltage which is proportional to its temperature; this voltage may be measured directly by an analogue meter or it may be digitized and displayed directly or stored as a permanent record⁶. The signal from the thermocouple is usually small

⁶Thermistors and resistance thermometers may be used to produce similar electrical output signals, but thermocouples are usually more suitable for the range of temperatures normally encountered in welding and ancillary operations.

and may need to be amplified; in addition, corrections need to be applied for the cold junction temperature and the current must be converted into a temperature reading. These functions are most easily performed electronically and, since most temperature signals change relatively slowly, digital meters often provide a convenient output display.

Non-contact measurements may be made by detecting the infrared radiation from the material and thermal imaging cameras which give an indication of the temperature profile over the area of interest are available. These devices are, however, relatively costly and their use is at present restricted to research and automatic sensing systems.

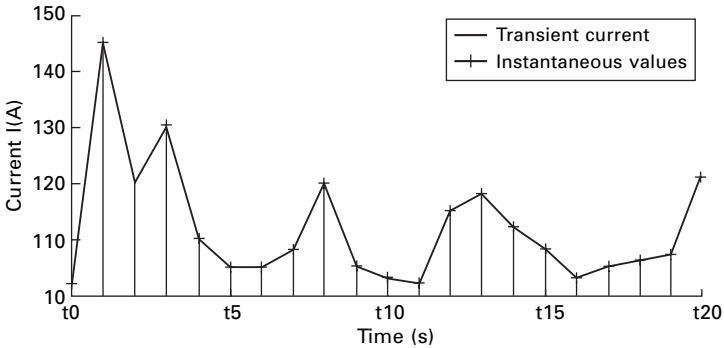
Current. Instantaneous current values may be displayed on an oscilloscope and the overall shape of both AC and DC waveforms may be examined. However, the input of the oscilloscope amplifier will usually be calibrated in $V\text{ cm}^{-1}$ and the maximum level of input will often be around 5 V cm^{-1} . In order to convert the normal high currents used in welding into a low-voltage signal, one of the following devices is normally used: current shunt; current transformer or Hall-effect probe.

The current shunt is a high-power, low-value resistance, which is placed in series with the circuit through which the current to be measured is flowing. It produces a low-voltage signal (e.g. 50–200 mV) proportional to the current passing through it. Whilst this is suitable for measuring relatively slowly changing waveforms, most shunts do have some inherent inductance, which limits the rate of change of the signal and distorts the observed waveform. Resistive heating of the shunt can also lead to inaccuracies. For improved response and accuracy, water-cooled non-inductive shunts have been devised, but these are usually costly and less convenient to use.

For AC waveforms, current transformers may be used to reduce the output to a suitable level. These usually take the form of a toroid or coil placed around the conductor carrying the current to be measured, although low-cost devices that employ a clamp-type construction are available. Again, these devices may produce some distortion of rapidly varying waveforms.

Hall-effect probes are based on semiconductor elements which respond to the magnetic field produced when current passes through a conductor. They are capable of detecting and indicating DC and AC current and have excellent frequency response which enables them to be used to detect transient phenomena in rapidly changing waveforms.

The use of oscilloscopes is, however, generally restricted to research and the servicing of welding equipment. For production purposes, a quantitative, single-value measure of current is normally required. Steady DC current may be measured with analogue, moving-coil and digital meters. For DC currents, the value indicated is the steady DC value or, in the case of fluctuating current waveforms, the mean value. Analogue moving-iron meters indicate



10.5 Mean of fluctuating current waveform.

the RMS value of a fluctuating signal. For the waveform shown in Fig. 10.5 the mean value is given by

$$I_m = (I_1 + I_2 + \dots + I_n)/n \tag{10.1}$$

where I_1 to I_n are the currents at regular intervals and n is the number of values measured. Alternatively, the average is given by the area under the curve divided by the equivalent length of time measured along the x axis. For a rectangular waveform this is given by

$$I_M = (I_p t_p + I_b t_b)/(t_p + t_b) \tag{10.2}$$

where I_p is the peak current, I_b is the background current, t_p is the peak time and t_b is the background time.

The mean value of a balanced AC waveform would, however, be zero, but its effect may be measured by considering the steady DC value of current which would give an equivalent amount of resistive heating. This value is known as the RMS current and is given by

$$I_{RMS} = \frac{\sqrt{I_1^2 + I_2^2 + \dots + I_n^2}}{n} \tag{10.3}$$

Alternatively, the alternating current may be rectified and the mean value of the resultant DC waveform may be taken; this value is referred to as the mean absolute value (MA). For steady DC and symmetrical square waveforms, the mean absolute value of current is equivalent to the RMS value, but, for any other waveform, these values will differ. For example with a pure sinusoidal waveform, the RMS value is $1.111 \times MA$.⁷ In the case of rectangular

⁷The RMS value divided by the mean value of the current is known as the form factor of the waveform, i.e. 1.111 is the form factor of a pure sine wave. The peak current divided by the RMS value gives a factor known as the peak or crest factor, the higher the crest factor the greater will be the difference between mean absolute and RMS values.

Table 10.4 Difference between mean and RMS current values for rectangular waveforms

Pulse current (A)	Background current	On-off time ratio	MA value (A)	True RMS value (A)	Scaled RMS value* (A)
600	0	1/1	300	424	333
550	50	1/1	300	390	333
500	100	1/1	300	360	333
450	150	1/1	300	335	333
300	300	1/1	300	300	333
600	0	1/3	150	300	167

*The scaled RMS value is typical of the reading obtained with a low-cost meter which derives the RMS from the measured mean absolute current.

waveforms, there may be a substantial difference between MA and RMS values, [206] as shown in Table 10.4. It is most important to specify the methods being used to measure current and to adopt the same techniques when comparing equipment or processes.

Voltage. The voltages used in welding usually need to be attenuated before measurement either by oscilloscope or by analogue or digital meters. Most metering systems do however, incorporate suitable attenuation for the normal levels of voltage to be measured. The system of measurement and type of instrumentation must again be specified since variations will occur between different waveforms or instrumentation as described above. The simplest method of checking the output of power sources is by the use of an ammeter and voltmeter or a combined instrument. This may comprise a Hall-effect current-sensing device and a digital voltmeter.

Speed and time. Linear travel speed and wire feed speeds are often measured manually by timing over a measured travel distance or amount of wire fed. Measurement using electrical and mechanical tachometers may also be used, but it is necessary to translate the linear motion to rotational movement. Suitable sensors are available; these usually use either slotted disc optical tachometers or small DC generator devices. The voltage generated may be displayed on analogue or digital instruments or in the case of the slotted disc encoder the frequency pulses may be easily converted into rotational speed.

Stability monitors

The measurement of process stability is of interest when monitoring the performance of the consumable electrode arc welding processes. It may be used to assess the process performance during production as well as assisting the development of consumables and equipment.

The operating performance of conventional SMAW and GMAW processes may be evaluated by welding trials conducted by an experienced welder.

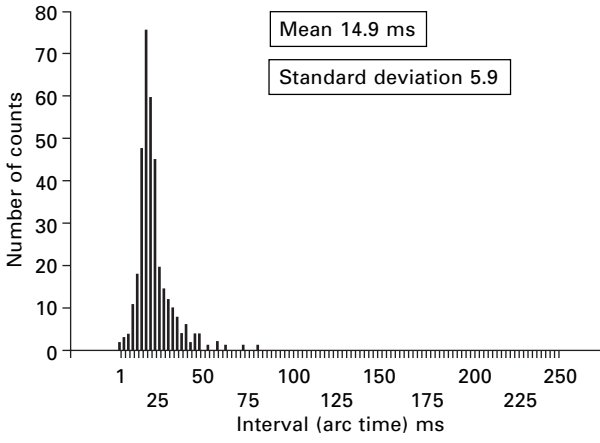
Table 10.5 Stability criteria

Criteria	Application	Reference
$C_{crit} = S^2 / X_m^2$	CO ₂ -shielded GMAW	[204]
As above but deviation of current peaks used	ac MMAW	[205]
$R = w/W$ and i/l	dc power source evaluation	[206]
$K = \frac{T_m}{\sigma_T}$	Element recovery in GMAW	[207]
Standard deviation of current peak values	General purpose monitoring	[208]
K factor (as above)	Shielding-gas evaluation GMAW stainless steel	[209]
Standard deviation of arc time	Shielding-gas evaluation short circuit GMAW carbon steel	[210]
Probability distribution of short circuit and arc time	CO ₂ -shielded GMAW	[211]
Statistical analysis of arc and short circuit times	GMAW spatter level investigation	[212]
$\frac{\sigma_{tarc}}{t_{arc-mean}}$	GMAW dip transfer	[213]
$W_s = W_a + W_r + W_p$	GMAW	[214]
Statistical analysis of short circuit time	MMAW and GMAW	[215]

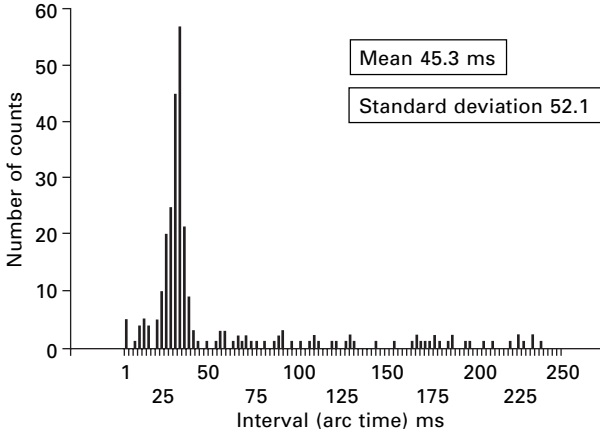
Key : S is the standard deviation of time between short circuits measured on a voltage trace. X_m is the mean value of the time between short circuits. w is the minimum value of power in the arc, just after droplet transfer. W is the average power under steady conditions. i is the minimum value of current and l is the average value of current under steady conditions. W_a is a stability criterion based on factored values of the standard deviation of arc time, short circuit time, arc current and peak current. W_r is a stability criterion based on the ratio of the observed resistance during arcing and the average resistance. W_p is a criterion based on the ratio of observed power during arcing over the average power. T_m is the mean cycle duration, σ_T is the standard deviation of the cycle duration, σ_{tarc} is the standard deviation of arc time, and $t_{arc-mean}$ is the mean arc time.

These subjective assessments require considerable skill, are time consuming and the results are often inconsistent. Objective measurements of stability may be achieved by examining the statistical variation of various operating parameters. A wide range of stability criteria have been developed [207–218] and some of these are listed in Table 10.5.

In dip transfer GMAW, the standard deviation of the arc time, the standard deviation of the peak current and the ratio of arc time to short-circuit time give a good indication of stability and are easily measured using computer-based instrumentation. Figure 10.6 shows histograms of arc times for two nominally similar GMAW consumables. It is apparent that the consumable



(a)



(b)

10.6 Histogram of arc time for dip transfer GMAW with (a) a good wire and (b) a poor wire.

with the better stability, as indicated by the lowest standard deviation of arc time, gives the best operating performance, lowest spatter levels and better bead shape.

Although this type of monitoring has been used successfully in the research environment, few commercial stability meters have been produced. It must also be remembered that arc stability, though important, may not be the main criterion for weld quality assessment; in GMAW welding in particular, optimum stability may be sacrificed if an improvement in fusion characteristics can be achieved. The possibility of using this type of measurement to detect unacceptable deviations in operating performance is, however, an interesting prospect and may be exploited in on-line quality monitoring systems as discussed below.

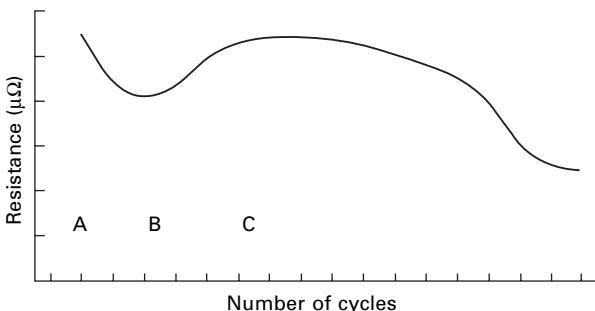
Deviation monitors

Dynamic resistance. The quality of resistance spot welds may vary due to the surface conditions of the plate being welded, electrode wear, electrode force fluctuations, current shunting and transient changes in the welding parameters. Various methods of monitoring spot weld quality in order to detect the effect of these variations have been proposed but the dynamic resistance technique is probably the most suitable for industrial application. [219, 220] In this system, the instantaneous welding current and voltage are measured and the resistance of the metal between the electrodes is calculated. If computer-based techniques are used to collect the data, the resultant dynamic resistance curve may be plotted on the monitor screen immediately after the weld has been completed. The normal dynamic resistance curve for a satisfactory weld in plain carbon steel is shown in Fig. 10.7. The curve may be divided into three zones:

- Zone A: the area corresponding to the reduction of contact resistance;
- Zone B: the area corresponding to resistive heating and increasing resistivity of the material;
- Zone C: the area corresponding to a reduction in thickness and weld nugget growth with consequent steady reduction in resistance.

Changes in shape of the curve indicate deviations from the normal weld nugget formation and, at the limit, a defective weld. A computer-based dynamic resistance instrument [221] may be used to monitor the performance of the process in the following manner.

The welding parameters are set and a test specimen is welded with the monitor set in its 'test' mode. The welded specimen is checked visually and by destructive testing and, if a satisfactory weld has been achieved, the dynamic resistance curve which has been obtained is stored as a master for the application (if the weld is unsatisfactory the parameters are adjusted and a new test is conducted). With the equipment switched to its 'monitoring' mode, the dynamic resistance curves of subsequent welds are compared with



10.7 Typical dynamic resistance curve for a normal spot weld.

the master curve and deviations which exceed preset limits are reported, used to initiate an alarm, or even used to initiate the printing of a 'reject' label. Welding current, voltage and time are also checked against preset values to ensure that satisfactory tolerances are maintained.

The recorded welding parameters may be stored in the monitor's memory and measured data may be stored on a non-volatile memory device (e.g. a floppy disc). This type of equipment may also be configured as a series of local monitors mounted on individual welding machines which feed the collected data back to a central computer for permanent storage or analysis. Distributed computer-based dynamic resistance monitors of this type are suitable for on-line surveillance of automation systems and robotic welding stations. [222]

Arc welding deviation monitors. Arc welding processes may be monitored using similar techniques to those described in Section 10.3; however, in this case it is usually necessary to monitor a continuous weld rather than a discrete spot. One computer-based device suitable for quality assurance of automated GMAW welds measures arc current and arc voltage signals and analogue circuitry is used to derive short-circuit resistance and a radio-frequency (RF) component of the voltage waveform. [223] The data are analysed by comparing the sample data with preset limits for voltage, current, RF component and dip resistance. To allow continuous updating of the data collected the four input channels are sampled at approximately 15 kHz and the data are analysed on-line. In normal dip transfer GMAW welding operations, an assessment equivalent to each 2 mm increment of weld length is stored, passed to an external computer or used to initiate weld quality signals. Using real-time analysis and a knowledge of the inter-relationships between the monitored variables and potential weld failure modes, [224] the unit is able to predict a large number of weld quality deviations from the limited input data. For example, the dip resistance may be used to indicate variations in torch-to-workpiece distance, whilst excessive voltage in conjunction with a satisfactory dip resistance may indicate wire feeding problems. The RF component of the voltage waveform is used to indicate process stability and, in particular, the disturbance of gas shielding. Some of the common quality deviations which can be monitored with a device of this type are indicated in Table 10.6.

When applied to an automated welding system a pass/fail assessment may be made for each increment of weld and as a percentage of the individual weld length; in addition the results of the assessment may be used to initiate a controlled shutdown of the welding cell or operations such as torch cleaning.

The monitor is provided with a serial output port (e.g. RS232 or 422) to enable data to be downloaded to a central computer from a number of welding cells where they may be compared and production statistics and overall performance may be assessed.

Monitoring systems which provide on-line indication of deviation from

Table 10.6 Quality problems identified by 'Arc Guard'

Problems
Current high or low
Voltage high or low
Shielding-gas failure
Poor arc stability
Wire feed slip
Wire run-out
Stick-out long/stick-out short
Mid-weld power loss
Welding supply failure

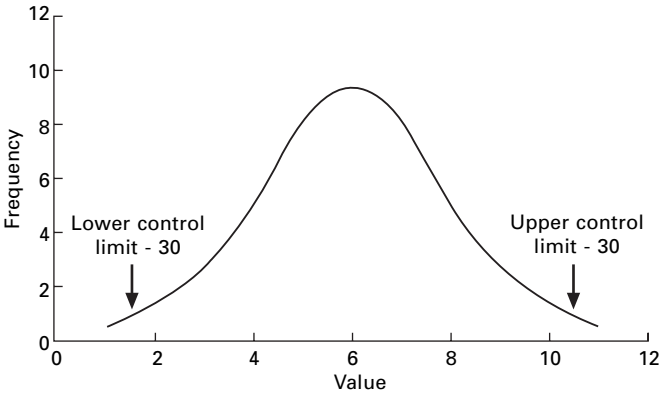
some preset parameter are sometimes called programmable error monitors [225] and these may vary in sophistication from microprocessor-controlled devices to simple low-cost electronic alarms. [226]

Statistical process control. The ability to transfer or download large volumes of data to a personal computer allows statistical process control techniques to be used. [227, 228]. Statistical process control is defined [229] as:

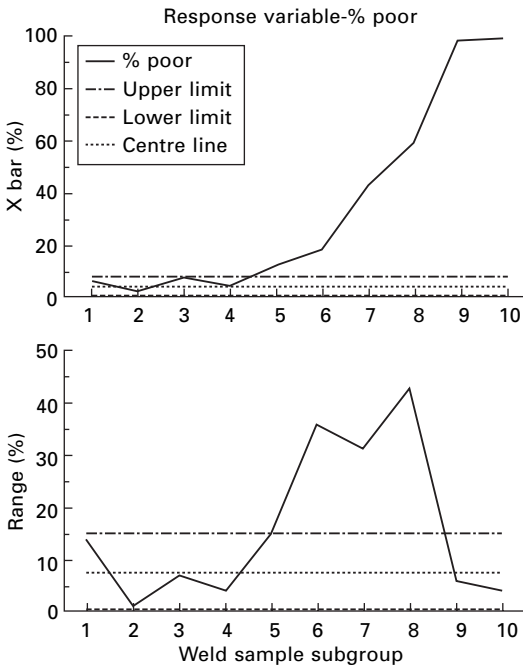
The monitoring and analysis of process conditions using statistical techniques to accurately determine process performance and preventative or corrective actions required

It has been shown [230] that the laws of probability may be used to define predictable limits of variation in quality characteristics, and excursions of the observed data outside these limits should be taken as an indication of potential quality problems. In any welding process, there will be a natural scatter in the observed parameters resulting from inherent process characteristics and environmental conditions. This natural random scatter is known as 'common cause' variation. Under many circumstances if the process is operating normally and sufficient data are collected, the values will fall within a standard probability distribution similar to that shown in Fig. 10.8. If the observed parameters fall outside the established distribution then abnormal or 'special cause' process disturbances are responsible. By monitoring the process during normal operation, calculating the sample mean (X_m), the range of each sample (R) and the standard deviation (a), it is possible to set upper and lower control limits (UCL and LCL, usually = 3σ). If any of the parameters subsequently measured fall outside these control limits, it may be regarded as an indication of abnormal performance. These techniques may be applied to any welding process and have been implemented for both the resistance and the arc monitoring systems described above.

With the arc monitor, control limits may be established in a similar way by collecting data from normal welding operations and a control chart may be produced. The effect of abnormal conditions may then be identified by



10.8 Normal probability distribution.



10.9 Control chart output from Arc Guard showing indication of poor gas shielding.

plotting subsequent data on the chart. The charts shown in Fig. 10.9 show the effect of deliberate process disturbances. In the case of gradual reduction of shielding gas flow, the % POOR values⁸ indicate an adverse trend which

⁸% POOR is derived by expressing the number of weld segments which have failed to remain within the preset limits over the total number of segments in a weld as a percentage.

exceeds the control limit at subgroup 5. At this stage, the gas flow had been reduced from its original value of 12 l min^{-1} to around $7\text{--}8 \text{ l min}^{-1}$ and, although the effect was just discernible by visual inspection of the finished welds, the welds were still acceptable for the intended application. By the time the gas flow had been reduced to 2 l min^{-1} (subgroup 9) the welds were 100% POOR and visually unacceptable. The charts do provide early warning of unacceptable performance and alert the user to adverse trends before the weld quality reaches an unacceptable level.

Visible spectrum monitoring. The use of a spectrographic technique for real-time monitoring and control of weld quality has been reported. [231] The system can detect changes in the chemical composition of the arc and, in particular, the loss of shielding gas, the increase in hydrogen in the arc atmosphere and changes in the flux composition during the FCAW process. Although the equipment used in the feasibility study was costly and complex, it is envisaged that, once the specific monitoring requirements are identified simple band-pass filters could be used to produce a compact welding monitor.

10.3.2 Summary: process monitoring

Monitoring techniques are available for calibration and troubleshooting in welding processes; these vary from simple meters to on-line computer-based systems which collect and report the status, trends and production statistics on a large number of welding cells.

Regardless of the type of monitoring system used, it is important to ensure that the correct measuring techniques are applied and the procedure and type of instrumentation are recorded.

Computer-based monitors provide facilities for on-line quality assurance which can make a significant contribution to the cost and reliability of the welding operation and reduce the need for post-weld testing. [232, 233] It is reported, for example, that one manufacturer has used on-line data logging to reduce post-weld destructive testing by 50% and saved over \$90 000 per year. [234] The data obtained may also be used for optimizing the welding process and preventative maintenance programmes. Significantly, many quality systems standards recognize the use of continuous monitoring as an important control technique; BS 5750, [235] for example, stated that 'Continuous monitoring and/or compliance with the documented procedures' are required to ensure that the specified requirements are met. It is important to note that, although these systems may be relatively sophisticated and provide clear indications of process deviations, they require manual intervention to correct the process performance.

10.4 Automated control techniques

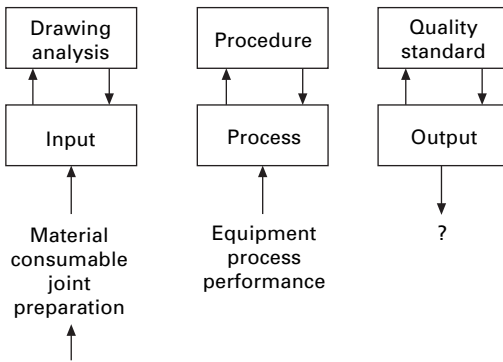
Using suitable monitoring systems and mechanized welding, it is possible to correct process deviations automatically without the need for manual

intervention. All of the methods involved rely on the application of a control systems approach and it is important to understand the basic principles of control as applied to industrial processes before discussing the common applications.

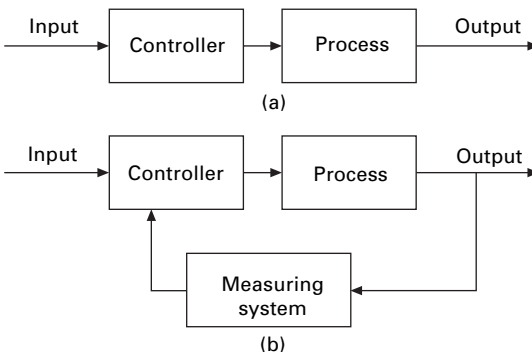
10.4.1 Control systems

The fabrication system may be illustrated as shown in Fig. 10.10. The inputs to the system are materials and consumables, which are converted by the process into finished welds. Control systems of this type are divided into two types: [236]

- open-loop, in which the output has no direct effect on system control as shown in Fig. 10.11(a);
- closed-loop, in which some signal derived from the output is used to directly control the system as shown in Fig. 10.11(b).



10.10 Normal control techniques used in welded fabrication.



10.11 (a) Open-loop control system. (b) Closed-loop control system.

The welding of joints to a predetermined procedure is effectively an open-loop system. Although every effort may be taken to ensure that the predetermined parameters are maintained (e.g. by equipment calibration and monitoring), any corrective action taken as a result of post-weld inspection is indirect and occurs some time after the process is complete.

Closed-loop systems are also referred to as feedback systems, since a signal derived from the output is fed back for comparison with a reference parameter. The result of this comparison is an error signal which is fed to the controller in such a way as to reduce the error. The error correction system or controller may be a manual operator. In dip transfer GMAW operations, for example, the welder often tunes the process performance by adjusting the wire feed speed, voltage or inductance in response to the sound of the arc; in this case, the sound is an indication of the short-circuit frequency. In more advanced control systems, the human operator is replaced by an automated control, which monitors the output and corrects the system continuously using an error signal derived by comparing a suitable output parameter with the preset reference. In automated closed-loop control systems, the rate at which the error is corrected is critical, as slow response rates or over-correction may both lead to instability and the design of suitable control strategies will have a significant effect on system performance.

Several variations of closed loop control are used in welding applications. These may be referred to as: direct control; indirect control; adaptive control; and learning control.

Direct control implies the measurement and feedback of the parameter which it is sought to regulate. For example in the case of a power source, the current may be regulated by monitoring its output level as described in Chapter 3. Unfortunately, in many welding situations, it is not possible to use direct control and indirect systems based on the measurement of secondary variables must be used. Several indirect control systems will be described below, but typical examples are: weld bead temperature for penetration control and dynamic resistance for resistance spot weld geometry.

The term 'adaptive control' is often used to describe recent advances in welding process control, but strictly this only applies to systems which are able to cope with dynamic changes in system performance. [237] Adaptive systems should have the ability to self-adjust in accordance with unpredictable changes in operating conditions. It has been pointed out [238] that, in welding applications, the term adaptive control may not imply the conventional control theory definition, but may be used in the more descriptive sense to explain the need for the process to adapt to the changing welding conditions.

Learning control systems are systems which progressively improve their performance by experience – the most common example is the human operator – but computer-based learning systems have also been developed for welding applications.

10.4.2 Basic requirements for closed-loop control

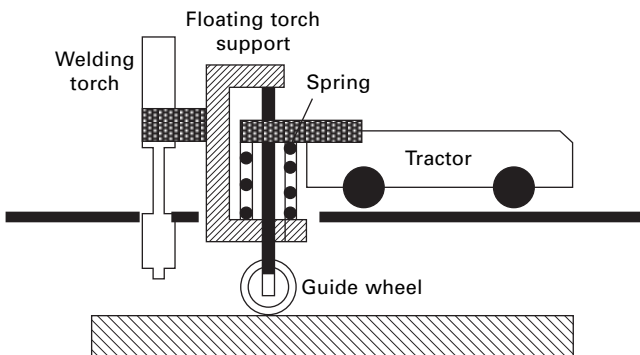
For successful closed-loop control in welding, appropriate feedback signals must be obtained; these must be related in some way to the parameter to be regulated. A suitable error signal must be generated and the system must be able to respond to the required correction. The feedback signals may be obtained by monitoring the normal welding parameters or by employing sensors or transducers which supply indirect data. The relationship between the output and the control parameters may be defined by a mathematical model, algorithm or equation. The way in which the control parameters are corrected is defined by the control strategy and its effectiveness will largely depend on the response rate of the system. The introduction of electronically regulated power sources has enabled major improvements to be made in this area.

The main applications of automatic process control in welding are line following/seam tracking, arc length control, penetration control and on-line quality control. These are discussed below.

Line following

Many line-following and seam-tracking systems have been developed for welding and these may be classified according to the sensor systems used.

Tactile sensors. The simplest tactile sensor is the spring-loaded guide wheel which maintains a fixed relationship between the welding head and the joint being followed as shown in Fig. 10.12. This low-cost system may be used very effectively on simple mechanized tractors and gives reduced set-up times and improved consistency. A more sophisticated tactile sensor utilizes a probe which converts displacement to an electrical signal which is fed back to the motorized welding head causing the torch to be repositioned to follow the seam.

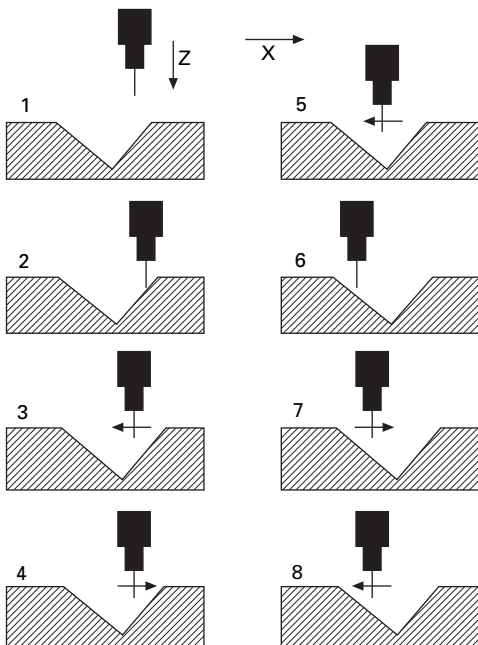


10.12 Tactile torch height control.

Whilst these systems are inherently simple, tracking errors may result if the surface condition of the plate is poor or in multi-run situations, where the probe must track a convex weld deposit. These problems may be minimized by using special probe tips (e.g. to cope with tack welds).

Pre-weld sensing/joint location. In fully automated and robotic welding cells, the seam may be located before welding using tactile or non-contact sensors. A common technique is to utilize the end of the GMAW electrode as a contact probe. [239] In robot applications the torch moves to a taught point in the vicinity of the joint (Fig. 10.13), the head is then moved from the taught point along the z axis until it comes into contact with the workpiece, (contact is detected by a high-voltage, low-current DC signal). The contact point is confirmed by a short slow sweep along the x axis away from the contact point and back. The torch then travels along the x axis until it contacts the other plate and again a short, slow-speed traverse away from and back to the second contact point is performed. From the measured data the joint intersection point is calculated and the torch is moved to an appropriate start point.

Similar systems have been used for applications involving portable robots in shipbuilding. In this case the robot uses a tactile search routine to check its position within the welding cell and adjusts the program datum point to correct any errors. [240]

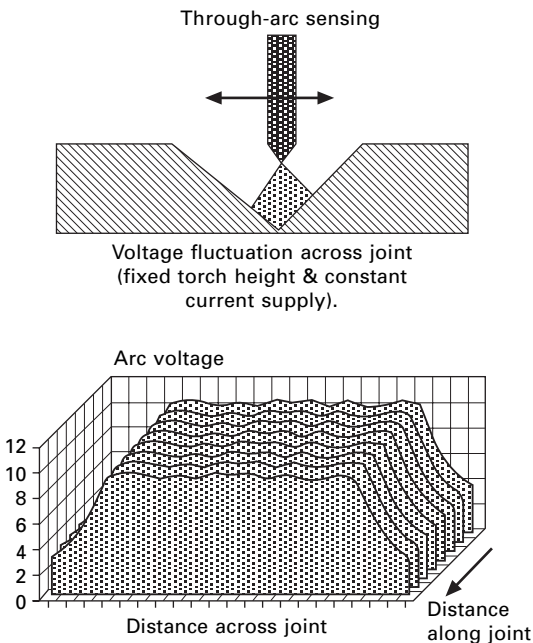


10.13 Tactile sensing – seam location.

Pre-weld sensing with optical sensors has been applied to large aluminium structures fabricated by GMAW, [241] where, due to the complexity of the component, a significant tolerance build up may occur. In this case, a laser vision system (see ‘Structured light/vision sensors’ below) was used to track and correct the weld path before welding.

Through-arc sensors. Through-arc sensing techniques utilize the change in one or more of the electrical parameters of the arc during oscillation of the torch tip to locate the joint position. These techniques are usually employed in fillet, heavy-section V butt and narrow-gap welding situations. If the welding head or the arc is oscillated laterally across the seam, the arc length or electrode-to-workpiece distance will decrease as the joint edges are reached (Fig. 10.14). In GTAW with a constant-current power source, the voltage will decrease at the outer edges of the weld, whereas when a constant-voltage power source is used for GMAW or SAW the current will increase. The limit of torch travel may be controlled by the change in parameters such that the centre of oscillation is always maintained on the joint axis. In GTAW and plasma welding, the arc may be oscillated magnetically to provide the joint scanning required for through-arc seam tracking. [242]

These through-arc tracking systems are now commonly available on welding robots and have also been applied to the orbital GTAW of pipelines. [243]



10.14 Through-arc sensing.

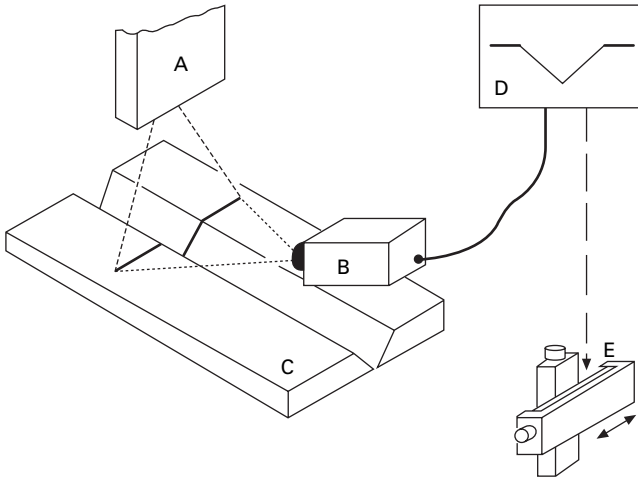
Inductive sensors. Inductive proximity sensors may be used to track fillet welds, whilst eddy current sensors may be used to follow square butt joints. Inductive sensors are relatively compact, robust and unaffected by the visible radiation from the arc but spurious signals may be generated by magnetic fields in the workpiece or the holding fixture. They have been used successfully for GMAW seam tracking of butt, lap and fillet welds in robotic applications.

Photoelectronic sensors. The simplest photoelectronic seam-tracking sensors use a photoemitter and collector which are directed at a clearly defined joint line. In some cases, it is necessary to employ a tape laid parallel to the seam to ensure that a clear signal is obtained. These systems are relatively low cost, but require a clearly defined joint line and may be affected by arc glare. A system that involves scanning the joint ahead of the welding torch with an infrared transmitter/receiver assembly has been described [244] and this gives improved joint line resolution without the need for a pre-placed tape. An alternative system illuminates the joint area 30 mm in front of the torch with conventional lamps, infrared diodes or laser diodes; the reflected light is measured by a photodiode array or line transducer consisting of 256 diodes. [245]

Structured light/vision sensors. In most structured light/vision systems a small CCD⁹ video camera is used to capture the image of a line of structured light which is projected onto the weld seam in a transverse direction. The principle is illustrated in Fig. 10.15. The structured light may be obtained from a conventional lamp and projection lenses, but more commonly a low-power helium:neon or diode laser is used. The laser stripe may be generated by optical techniques (cylindrical lens) or the use of a mirror to oscillate the laser across the seam. The joint profile will be reproduced in the video image and this information may be digitized and the difference between the real and a reference image may be used to generate an error signal which is used by the control system to correct the lateral position of the torch. To avoid interference from the arc, a band-pass filter corresponding to the wavelength of the light source is used; in most cases, this will be at the red or infrared part of the spectrum where arc radiation levels are lower. This type of system has been used successfully in robotic and automatic applications for tracking lap, corner, fillet, V butt and multipass welds. Applications include:

- Pressed steel components for automotive suspensions with complex three-dimensional seams. Welded with dip transfer GMAW. Weld placement being maintained to an accuracy of 0.5 mm.
- Welding of 0.4 mm thick Inconel tubing by GTAW for aerospace applications (tracking accuracy of 0.1 mm).

⁹CCD or CMOS cameras are preferred for these applications due to their compact size and robustness.



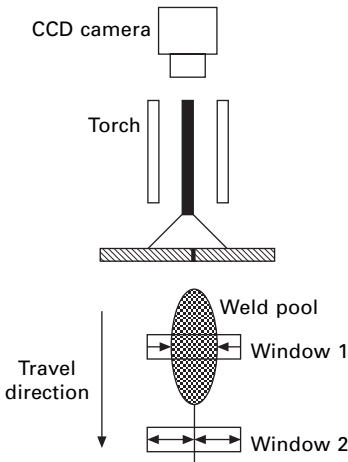
10.15 Principle of laser structured light seam tracking system:
 A – laser light source; B – CCD video camera; C – joint; D – image analysis; E – torch positioning system.

- Welding of multipass joints in thick-section steel using FCAW.

The original laser/vision systems were relatively bulky and costly but recent developments have allowed these tracking systems to be made more compact as well as improving the response rate. The technique may also be used for pre-weld inspection and adaptive control of the welding variables [246] as discussed in ‘Bead geometry prediction’ below.

Direct vision sensors. The weld area may be viewed by means of a video camera without the use of structured light. With a single camera, it is difficult to obtain three-dimensional information concerning the joint profile, but, by using optical viewing systems concentric with the torch, the relative position of the joint may be determined as shown in Fig. 10.16. [247] By analysing the position of the joint line in a window of the video image, the lateral error of the torch position may be determined. Although the torch assembly is rather complex, this approach has the advantage that the arc radiation is effectively blocked by the electrode, and by measuring the weld width from the video image an additional feedback signal may be obtained for control of welding speed. The system was originally developed for GTAW; it has been reported [248] that the technique can in principle be used with GMAW.

Ultrasonic sensors. Ultrasonic sensors may be used to detect the un-fused joint line in the parent plate. The principal problem involved in using these techniques has been the need for intimate contact between the ultrasound transducers and the plate, but a recent development [249] using pseudo-immersion probes allows the joint line to be detected to an accuracy of 0.2 mm, with normal plate surface conditions.



10.16 Concentric video monitoring system for GTAW.

Chemical composition sensor. A novel approach to seam tracking is the use of a component of the arc spectrum to detect the presence of particular chemical species. [250] The arc emission is collected by a fibre optic and passed to an on-line analysis device, which monitors the level of the signal produced by specific element. In a dissimilar metal joint, this signal indicates the lateral position of the arc and may be compared with a reference level to generate an error signal for correction of the torch position. In joints of uniform composition, tracer elements may be introduced in the form of fusible inserts.

Arc length control

Control of arc length is important to ensure consistent heat input, constant melting rate, stable process performance and adequate shielding. Arc length may be maintained by good joint preparation, careful torch positioning or tactile sensors of the type described in this section. Several closed-loop systems have also been used for arc length control.

Voltage measurement. In the GTAW process constant-current power sources are normally used and the arc voltage gives a clear indication of arc length at a given current. These systems directly measure arc voltage, compare the actual value with a reference and control the torch height to correct the error.¹⁰ The arc voltage depends on current, shielding gas, workpiece composition, polarity and electrode vertex angle and the system reference

¹⁰Arc length control by means of voltage is often referred to as AVC or arc voltage control.

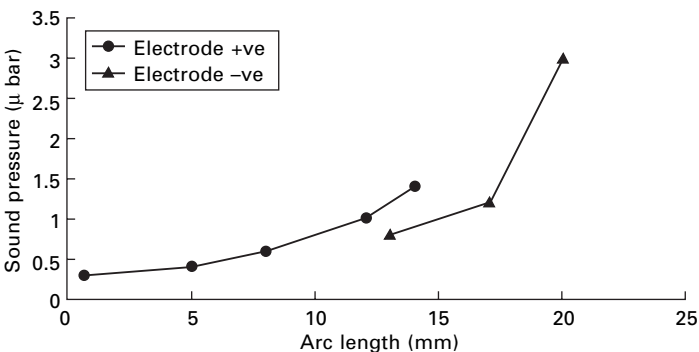
must be set for the particular conditions being used. When the system is applied to pulsed GTAW or plasma welding, the measurement of voltage must be synchronized with the pulsed waveform in order to avoid instability. Arc voltage sensing is probably the most common system of arc length control, no external sensors are required and the technique may be implemented using conventional analogue electronics or digital microprocessor control.

Sound measurement. Control of arc length in GTAW arcs may be achieved by applying an oscillation frequency to the arc and measuring the sound level. The sound pressure has been found to increase with arc length as shown in Fig. 10.17 [251] and this may be used to monitor changes in arc length and produce signals for arc length correction. One problem in the practical application of this technique is the interference from ambient noise, which may be minimized by operating at frequencies outside the normal audible range. Problems may also arise with high-frequency switching techniques used in modern power supplies, but filtering may be used to overcome this.

Photoelectric sensors. Simple optoelectronic sensors comprising an infrared emitter and collector are used as proximity sensors for many non-welding applications. These devices may be used for torch height sensing. They are of low cost, relatively robust and unaffected by transient arc voltage instability.

Laser range finders. Laser range finders may be used as torch height sensors for robotic and automatic applications. These devices employ a low-power solid state laser and can measure distances very accurately using triangulation techniques. Due to their high cost, they are rarely employed simply for height sensing and usually incorporate seam location and tracking facilities.

Light and spectral radiation sensors. The total arc light intensity does increase fairly linearly with arc length in GTAW at a fixed current and may be used as a feedback signal. It has been found, however, [252] that at shorter arc lengths the intensity may also rise due to an increased concentration of



10.17 Effect of arc length on sound pressure for GTAW. [251]

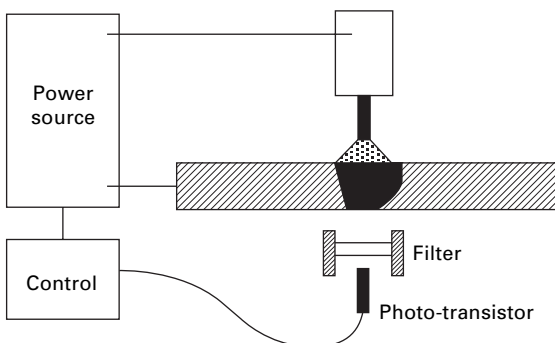
metallic ions in the arc. Improved signals are obtained by selectively monitoring the arc emission spectrum and, in particular, the intense argon lines at wavelengths of 7504, 7514, 8006 and 8015 Å. This technique avoids problems with arc voltage fluctuations unrelated to arc length and may utilize a relatively simple sensor that is placed at a safe distance from the arc.

Penetration control

Penetration control techniques have been developed mainly for situations where a full-penetration butt weld is required and welding is to be carried out from one side of the joint. These techniques may also be applied to critical root beads, for example in circumferential welding of pipe.

Back face sensing. It has been shown that the energy of certain wavelengths of radiation emitted from the back of the weld pool is a function of the weld bead area or width. [253] The radiation from the weld pool may be distinguished from that emitted by the parent metal by restricting the bandwidth of the sensor system to 450–550 nm, i.e. in the green part of the visible spectrum. In practice, the radiation sensor may be a photodiode or phototransistor that is sensitive to visible radiation; this is mounted beneath the joint with a suitable filter and protective shield (Fig. 10.18), and the signal from the sensor is passed to the control unit, where it is compared with a preset reference value. The error signal may be used to control a range of process parameters, the most common of which is pulse duration in pulsed GTAW. In this case, the pulse is maintained at the high level until penetration is achieved, and the feedback signal reaches the reference level. When this occurs, the current is reduced to its background level for a fixed time and the torch is indexed along the seam. The pulse duration varies to suit the joint conditions, decreasing if there is a tendency for heat build-up and increasing if the thickness of the plate increases.

For industrial applications the radiation may be conducted to the



10.18 Principle of back face penetration control system.

optoelectronic sensor via a fibre optic cable. The technique is simple and reliable; it requires access to the backface of the weld, but this is often easily achieved if optical fibres are used. Applications have included the butt welding of small-diameter tube to make transducers as well as the circumferential joining of stainless steel tanker shells.

The technique has also been investigated for GMAW using pulsed metal transfer and is capable of maintaining control of bead width with variations of root gap up to 2.5 mm and progressive variations in speed and thickness for butt welds in steel up to 3 mm thick. [254, 255] It is possible to replace the optoelectronic sensor with a CCD camera and successful control systems based on this approach have been developed. [256] In plasma keyhole welding the process may also be controlled by monitoring the efflux plasma emerging from the rear of the keyhole with an optoelectronic sensor or video camera.

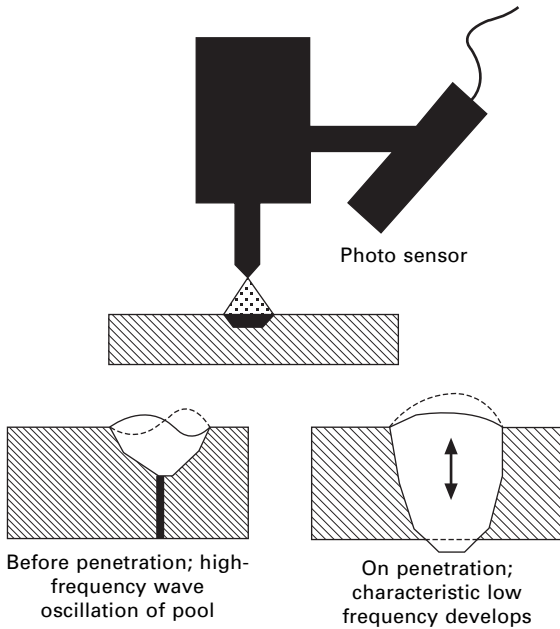
Front face light sensing. Penetration monitoring from the top face of the weld pool has recently become more practicable [257] with the development of a system that detects weld pool oscillations in the GTAW process. The technique involves the application of a short-duration high-current pulse (e.g. 100 A for 1–2 ms), which excites the pool and creates an oscillation. The oscillation frequency is observed using an optical sensor which picks up the reflected light fluctuations from the weld pool surface. It is found that an un-penetrated weld produces a higher frequency of oscillation than a penetrated weld and the difference is significant. By analysing the frequency the reduction due to penetration may be detected and fed back to the controller. The arrangement and the proposed mechanism are shown in Fig. 10.19.

Voltage oscillation. The detection of forced weld pool oscillations by measurement of arc voltage has also been successfully demonstrated, [258] but this technique is complicated by the electrical noise and its application may be restricted.

Ultrasonic penetration control. Ultrasonic techniques for penetration control are less well developed than the corresponding seam tracking systems, but control systems based on similar principles have been demonstrated. The combination of seam tracking and penetration control using a single sensor is attractive, but the cost and complexity of the systems is likely to be high.

Pool depression. When the fully penetrated bead develops in GTAW, the weld bead tends to drop and a depression is formed in the surface. If the torch height is fixed, the corresponding increase in voltage may be taken as an indication of penetration. [259] Alternatively, if an AVC system is being used, the displacement of the torch may be used as a feedback signal. The feasibility of the technique as a continuous closed-loop control system has been demonstrated for welds in the downhand position but its application to other welding positions is likely to be restricted.

Front face vision. Direct observation of the weld pool shape may be used in conjunction with suitable models of the relationship between pool profile



10.19 Principle of front face penetration control system.

and penetration to predict the onset of full penetration. Although the system appears to be feasible, complex image analysis facilities are required and mathematical models capable of accurately predicting the pool profile/penetration relationships are required.

Radiographic control. Radiographic monitoring has been used for analysis of process performance in the slag-shielded processes such as SAW and ESW. The availability of high-quality real-time radiography and image-processing techniques has led to the development of an on-line penetration and quality-control system. [260] The x-ray source is placed above the plate being welded and the image intensifier and camera are positioned below the workpiece. A computer control system is used to analyse the image and this provides appropriate corrections to the control system to ensure consistent penetration is maintained.

This approach is obviously complex and costly and is only likely to be used in special applications where no alternative technique is available and the overall cost is justified by quality constraints.

Quality control

The seam tracking, arc length and penetration control systems described above are intended to compensate for relatively small variations in joint

preparation, fit-up and material properties. Their application restores the welding performance to a predetermined level and reduces the likelihood of poor joint quality. Taking a pessimistic view, even if the weld is in the right place, it may still contain metallurgical defects such as porosity and cracking. Ideally the control system should monitor the quality of the joint in real time and take corrective measures to ensure that the required standard is achieved.

Some steps towards the automatic control of quality have been taken, but this area is still the subject of considerable research.

Bead geometry prediction. The finished bead geometry may itself be a quality criterion or there may be a clear relationship between geometry and secondary quality considerations. (For example, convex weld bead reinforcement may lead to stress intensification and subsequent cracking or high depth-to-width ratios may be responsible for solidification cracking.) If a sufficiently accurate model for the relationship between the weld variables and the geometry is obtained the process parameters may be adjusted on-line to produce the required geometry. Progress in the development of suitable mathematical models has recently been made but their application in process control is still at the research stage.

Thermographic sensing. Remote thermographic imaging of the weld pool has been found to be a practical [261, 262] method of assessing the temperature profile of the joint in real time and enables the control of penetration, seam tracking and metallurgical characteristics of the weld. Using an expert system, the observed temperature measurements may be related to the likelihood of defects and the probable mechanical properties of the joint. Sensing may be performed by a fibre optic and remote thermal imaging system or a thermal line scanner. The system is no more expensive than a laser stripe sensor but offers the possibility of much more comprehensive control.

Hybrid control systems. It is often possible to combine the information from several simple sensors to obtain a better indication of process performance and ensure more effective control. A torch displacement sensor when combined with through-arc measurements of voltage and current may, for example, be used to distinguish between wire feed slip and torch height variation. Increasing use of these hybrid systems combined with computer control should improve the ability to achieve true on-line quality control.

10.5 Summary and implications

The range of control options for welding varies from the traditional open-loop manual systems based on welding procedures to complex closed-loop automated techniques. Improved monitoring techniques and a wide range of sensors make it possible to measure process performance in both manual and automated applications and should enable more consistent weld quality to be achieved.

The application of the appropriate control approach should result in improved productivity and lower total cost. The application of all monitoring techniques and in particular computer-based systems is increasingly justified by economic and quality requirements.

The sophisticated adaptive control systems should not, however, be used to compensate for avoidable deficiencies in joint preparation and component quality; this will often prove costly and ineffective.

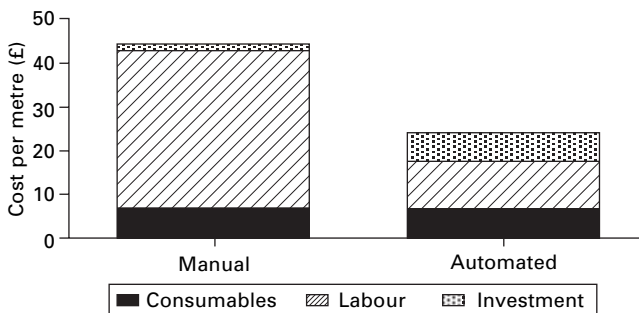
Of the automated closed-loop systems described, some of the simplest are the most effective.

11.1 Introduction

Many traditional welding processes are labour intensive and an analysis of welding costs shows that some 70 to 80% of the total cost may be accounted for by the labour element as shown in Fig. 11.1. Welding automation is a means of reducing the overall cost of the welding operation by replacing some or all of the manual effort with a mechanized system. The introduction of automation may, however, have much more significance than its primary effect on labour costs; in particular its influence on the following factors must be considered: safety and health; product quality and supply flexibility.

11.1.1 Safety and health

Most welding processes are potentially hazardous; they generate particulate fume, toxic gases, noise and a range of electromagnetic radiation, which varies from ultraviolet radiation with arc processes to x-rays in electron beam welding. These hazards are well known and procedures for dealing with them have been established. The measures which must be taken to



11.1 Comparative costs of butt weld in 20-mm-thick steel (IG V butt, IG position, 60° V GMAW).

protect the welder and associated workers are, however, costly and may complicate the welding operation or involve the use of cumbersome protective clothing. There is also the risk of human error which may expose welders and those around them to unnecessary risk.

In addition to these process-related hazards, there are risks associated with the application; such as welding in confined spaces, underwater or in radioactive environments. Automation offers a means of removing the operator from the process- and application-related hazards and, in addition, it offers the prospect of improving the control of the welding environment.

11.1.2 Product quality

Reproducible product quality may often be difficult to achieve with manual welding techniques, particularly when advanced materials and complex joint configurations are involved. Increasing the level of automation can significantly improve consistency, increase throughput and reduce the cost of inspection and rejection.

11.1.3 Supply flexibility

It is often easier to match output to demand with automated systems than it is with labour-intensive operations. This is particularly true in welding situations where protracted training and qualification of welders may be required before an increase in output can be obtained.

11.2 Automation options

Welding automation may vary from simple positioners to fully integrated systems. For clarity, the various options will be discussed under the following headings:

- simple mechanization;
- dedicated and special-purpose automation;
- robotic welding;
- modular automation;
- programmable control;
- remote-control slave and automated systems.

11.3 Simple mechanization

The most common simple mechanization systems may be grouped under the following headings:

- tractor systems;
- positioners and manipulators.

11.3.1 Tractor systems

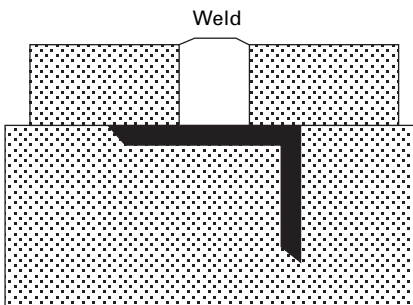
These are based on a simple electrically propelled tractor, which may be driven along the plate surface or may be mounted on a track and driven by a rack and pinion. The welding head is mounted on the tractor usually in some form of adjustable clamp. Direct-mounted friction drive systems are usually considered satisfactory for submerged arc welding, but, for GMAW and flux cored wire welding, track-mounted gear-driven systems are preferred since they are less prone to slip.

The track is normally supplied in straight lengths for linear seams but it is possible to obtain circular track rings for pipe welding and integral annular tracks for circle cutting and welding.

The user may also adapt these devices to suit a particular application using a wide range of standard accessories; these include torch oscillation devices to allow positional GMAW welds to be performed, trailers to carry ancillary equipment (e.g. wire feed units), motorized cross slides and tactile seam-following devices.

11.3.2 Applications of tractor-driven devices

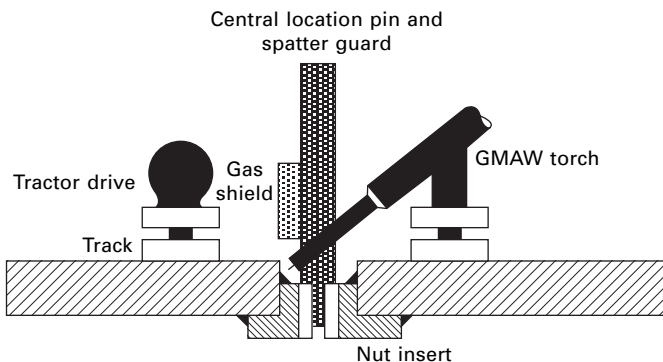
The portability of the equipment makes this type of unit particularly suitable for welding applications on large fabrications such as marine structures, buildings, and storage tanks. A good example of this type of application is the use of a tractor and oscillator for the completion of some 5000 m of vertical and horizontal butt welds in the fabrication of austenitic stainless-steel cell liners at the British Nuclear Fuels Ltd. (BNFL) reprocessing plant at Sellafield. [263] The joint configuration was a square butt weld in 304L stainless steel, welded onto a plain carbon-steel or stainless-steel angle which was precast into the concrete of the cell walls (see Fig. 11.2). In this application, pulsed transfer GMAW was used with a solid filler wire and electronic power sources equipped with synergic control. In this case, the fabricator



11.2 Weld joint configuration used in stainless-steel cladding operation. [263]

was able to produce consistent high-quality joints in a time scale which would have been impossible to meet using manual welding. A similar system was used [264] in the fabrication of 96 m of butt welds in a 24.4 m diameter crane tub in 35 mm thick BS 4360 50D material. It was estimated in this application that the cost saving was some £30 000 compared with vertical welding using the manual metal arc process.

These tractor-based systems are very adaptable and with a little ingenuity may be configured to suit a wide range of applications. An example of the use of a standard tractor system for a novel application is shown in Fig. 11.3. The application required the stainless-steel nut insert to be welded at intervals into large carbon-steel plates. A leak-proof fillet weld was required and skilled GTAW welders were not available. GMAW welding with a small-diameter stainless-steel filler wire and a helium/argon/CO₂ shielding gas was found to give acceptable bead profile, but access and the high welding speed made it difficult to achieve consistent quality using manual techniques. The tractor and track system were therefore adapted as shown; a GMAW torch was substituted for the normal oxy-fuel cutting system, and an insulated peg was used to locate the assembly in the insert (and protect the thread from spatter damage). The total cost of the mechanization system was under \$2000 and a large number of high-quality joints were produced with an average welding time of 20 s. This example illustrates that, although these systems are usually most suitable for long weld seams with simple geometry they may also be applied to much smaller joints. They are also more easily applied with the consumable electrode processes (GMAW, FCAW, SAW) but special systems for GTAW and plasma welding are also available. This type of automation still requires constant supervision by a welder, but the welder is removed from the immediate vicinity of the heat source and the exposure to fumes is reduced; the fatigue factor is also reduced.

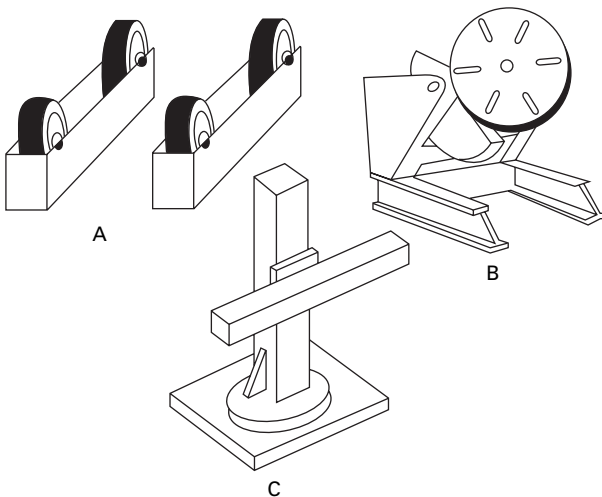


11.3 Fender nut welding system.

11.3.3 Fixed welding stations

Simple rotary positioners and welding lathes may be used to move relatively small components under a fixed welding head or even a manually held torch. Using simple jiggging, this type of automation may easily be justified for relatively small batch sizes. It is particularly suitable for circular weld paths, but fixed linear slides are also available for straight seams. Even the low-cost units can include facilities for synchronization of power source switching and weld crater fill facilities. For larger workpieces, column and boom positioners, motorized beams, roller beds and turntables are available. [265] Like the tractor systems these units are most suitable for simple geometric shapes and the consumable electrode processes, and they are adaptable to a range of applications limited only by the size and weight of the components being joined. The major advantage of this type of system is the ability to carry out welding in the downhand position which enables higher deposition rates and higher quality to be achieved. These advantages are most significant on heavier sections and can result in large cost savings in spite of the high initial cost of the positioning equipment. Typical configurations of these systems are illustrated in Fig. 11.4.

The most common application area for column and booms, roller beds and heavy turntables is for longitudinal and circumferential seams in the fabrication of pressure vessels and power generation plant. Very large units have also been used for making circumferential joints in submarine hull sections and power generation system drums.



11.4 Heavy positioning equipment (not to scale): A, roller bed; B, tilting turntable; C, column and boom.

11.4 Dedicated and special-purpose automation

11.4.1 Dedicated automation

Dedicated automation involves the design of a special welding system for a particular application and the resultant equipment may not be adaptable to changes in joint or component design. This type of automation is usually only justified for large production volumes of components with an extended design life.

Dedicated automation has traditionally been used for automotive components such as road wheels and exhaust systems with a wide range of welding processes including resistance spot, GTAW and GMAW.

The welding head is often only a single station in a multi-station automation system, which prepares the component for welding and also carries out finishing operations; in such cases a 'carousel' design with a single load-unload station is often used. Dedicated welding systems have also been employed, where lower production volumes and shorter product life cycles are envisaged, but the welding environment is particularly hostile or the quality of the end product is of primary importance. Examples of this type of application are to be found in the nuclear industry, both in processing of radioactive materials and the construction of critical fabrications. An example of the type of equipment used for this latter application [266] was used for GTA welding of advanced gas-cooled reactor (AGR) standpipe joints on the Heysham II and Torness (UK) power station projects. The use of costly dedicated automation with a sophisticated power source¹ and control system was justified on the grounds of the unacceptability of defects and the repeatability of performance.

The need to purpose design the dedicated systems around a specific component usually makes the cost of such equipment high and many dedicated automation applications are now being tackled using the modular or the robotic approach.

11.4.2 Special-purpose automation systems

Special-purpose automation has been developed for particular applications where similar joints are to be made on a range of component sizes. Some examples are simple seam welders, orbital welding systems and the GMAW stitch welder.

¹The power source used was a transistor series regulator with facilities for pulsed GTAW, programmed touch starting and arc length control. The welding head was also equipped with a vision system for remote monitoring of the weld area.

Seam welders

The seam welding of sheet metal by the GTAW, plasma and GMAW processes to form simple cylinders or continuous strip has been a commonly recurring requirement. In order to cater for this type of application, standard automated equipment which clamps the adjoining edges and moves a welding head along the seam has been developed. The equipment is adaptable to a range of material thicknesses and workpiece dimensions but dedicated to longitudinal seam welding.

Orbital welding systems

The need to perform circumferential welds in pipe and tube fabrication applications is met by a range of orbital welding systems, which include tube-to-tube heads, tube-to-tube plate and internal bore welders. These are usually portable systems which locate on or in the tube to be joined and rotate a GTAW head around the joint. Larger devices may be tractor-mounted on a circumferential track similar to the simple tractor systems described above, whilst the smaller systems utilize a horseshoe clamp arrangement. Wire feeding and arc length control may be incorporated in the welding head and more sophisticated systems may allow the welding parameters to be changed progressively as the torch moves around the seam.

These systems are commonly used in power station construction for boiler tube joints and tube-to-tube plate welds. A good example of the productivity savings that can be achieved with these techniques when compared with manual welding is the application of orbital welding techniques to the fabrication of more than 60 000 butt welds in stainless-steel pipework at the BNFL reprocessing plant. [267, 268] The application of orbital welding systems, together with improved pipe preparation and purging techniques, gave an improved first-time pass rate (from 50–60% to 87–90%) for each weld and more than halved the person hours per weld. The use of a pre-placed consumable socket [269] enabled simple square-edge pipe preparations to be used, provided joint alignment, avoided the use of a wire feed system, and allowed a single-pass welding procedure to be adopted. As in many applications of this type, additional benefits were obtained by adapting the automation technique to suit the application.

GMAW stitch welder

The GMAW stitch welder is a novel development in which a GMAW welding torch is mounted on a small motor-driven slide. The assembly is mounted in a head which automatically locates in the weld seam and mechanically fixes the torch height and angle. The weld length and welding speed are preset by

the operator (up to a maximum of 150 mm with this unit) and the welding process is initiated by a simple press button. The unit is ideal for producing consistent-size fillet welds and has been designed for ease of use with the operator holding the unit in a vertical or horizontal orientation.

11.5 Robotic welding

Industrial robots are not humanoid welders², but are defined by the British Robot Association as:

An industrial robot is a reprogrammable device designed to both manipulate and transport parts, tools or specialized manufacturing implements through variable programmed motions for the performance of specific manufacturing tasks.

In the case of welding robots, the ‘tools or specialized manufacturing implements’³ consist of welding heads, wire feed systems and tracking devices. The processes for which robot welding systems are now available include GMAW, FCAW, SAW, GTAW, plasma, resistance spot, laser and NVEB welding.

The normal industrial robot welding system consists of:

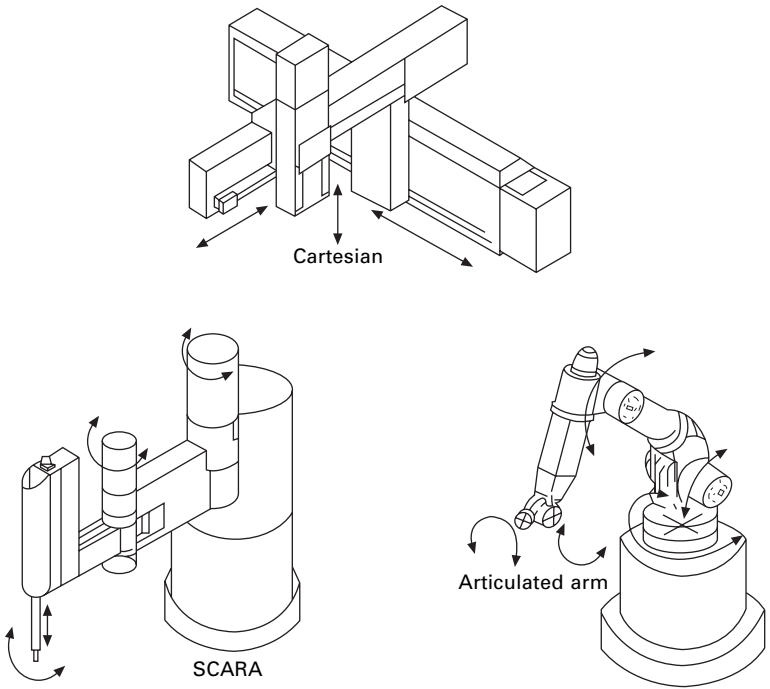
- a mechanical arm or manipulation system;
- a welding package;
- a control system.

11.5.1 Mechanical manipulation systems

A range of common configurations of manipulating system has evolved and these are illustrated in Fig. 11.5. The most common configuration for general-purpose welding robots is the articulated arm usually with six or more axes of movement. The advantage of the articulated arm is its flexibility and the

²The word robot was first used by Karel Capek in his play *Rossum's Universal Robots* which was first published in 1920. The image of computer controlled humanoids has persisted in science fiction and if anything the robot has been humanized further first by Asimov and more recently by Adams, [270] ‘Marvin the Paranoid Android’. Although industrial robots may be attributed human characteristics, particularly when they fail to operate in the intended manner, they are in fact simply programmable and, usually, computer-controlled actuators. Unfortunately, the fictional image has tended to colour our perception of industrial robots and may have raised our expectations or influenced our judgement concerning their application.

³Often referred to as ‘end effectors’.



11.5 Typical welding robot configurations.

ability to reach difficult access areas (it may be no coincidence that it has a similar configuration to the human arm).

The SCARA (Selective Compliance Assembly Robot Arm) configuration has traditionally been employed for assembly operations and has limited positional capabilities; it has, however, been used by some manufacturers as the basis of a simple, easily taught four to five axis machine for small batch production. A SCARA robot system has also been employed for refurbishment of worn crusher hammers. This is not a traditional application of robots due to the unpredictable wear profile. In this case, the variations in wear were accommodated by using the tolerance of the FCAW process combined with the manual selection of one of three preprogrammed ‘jobs’ based on visual assessment of the wear. Other applications of robotic wear replacement have relied on pre-machining the worn part to a known profile before robotic build-up.

Cartesian or gantry robots have been developed for very small high-precision applications and when very large operating envelopes are required. These standard configurations may be adapted to particular applications; for example, it is common to suspend articulated arm robots from overhead gantries for improved access and it is possible to construct special robot configurations by rearrangement of the axes. Whilst the latter system may not appear to be

related to the conventional welding robot, it still has the essential facility for re-programmability to suit different applications. One variation of the common configuration is the use of a linear slide to enable the whole robot to traverse the length of a component or a weld seam. Miniature portable and rail-mounted robots of this type have been developed for welding large structures.

Drive systems

The arm may be driven by pneumatic, hydraulic or electrical actuators. Hydraulic power systems are suitable for applications requiring high load-carrying capacity (above 35 kg) [271] and limited speed control and may be used for resistance spot welding. Most fusion welding robots, however, are now equipped with DC servo motor drives. Stepper motor drives have been used for small precision systems; these have the advantage of inherent feedback of output shaft position, but suffer from lack of power.

11.5.2 The welding package

The welding package for robotic welding will obviously depend on the process being used, but some important characteristics of these packages may be identified.

Welding packages for resistance welding

For resistance welding, the robot end effector needs to carry a portable resistance welding gun. It is important that the gun is robust to ensure repeatable operation but it must also be compact and manoeuvrable. Inevitably, this leads to some compromise in design and, in order to carry the weight of the normal resistance welding head and the associated cables, it is usually necessary to use a heavy-duty robot. The welding transformer may be separated from the welding head, but this involves the use of heavy secondary cables and potential power losses. Some gun designs allow the electrode assembly to be changed during normal operation in order to access different parts of the fabrication.

Resistance welding is a 'pick and place' type application: the robot places the welding head at the joint location; the electrodes close on the joint and the weld is made; the robot then moves the welding head to the next point and repeats the welding operation. The travel between points is carried at a high speed and neither the speed nor the absolute position in space need be accurately controlled during this motion. Since the resistance spot welding robot is not usually required to follow a seam, it is not normally necessary to use joint location and following devices.

Welding packages for arc welding

For arc welding applications a power source with facilities for remote control and output stabilization is required. The use of the electronic regulation systems and computer control discussed in Chapter 3 simplifies the control interface between the robot controller and the welding system as well as ensuring that repeatable performance can be achieved. In the GTAW system, the robot simply needs to carry a fairly lightweight torch and cables, whereas in GMAW and FCAW applications, the filler wire must be fed to the welding head. Trouble-free wire feeding is essential to avoid system failure and it is desirable to mount the wire feeder at the rear of the robot arm with a fairly short conduit to conduct the wire from this feeder to the torch. Some systems employ an auxiliary feeder immediately adjacent to the torch to ensure positive wire feeding and it is common to use large-capacity pay-off packs of low-curvature wire to improve feedability. Wire cutting and torch cleaning facilities must also be provided and in some cases interchangeable torch heads are also used; these are stored in a carousel and may be automatically replaced during the robot cycle.

Welding packages for laser welding

In laser welding applications the laser beam may be conducted along the robot arm to the workstation by a series of mirrors in the case of a CO₂ laser or by means of flexible fibre optic cables in the case of Nd:YAG diode and fibre lasers.

11.5.3 Robot control systems

The robot control system is required to:

- control the position of the welding head;
- control the welding package;
- interface with auxiliary systems;
- interface with the operator;
- provide program storage.

Control of position

By driving three or more actuators simultaneously the end of the robot arm may be made to trace any path within its three-dimensional operating envelope. However, to enable the position and velocity of the end effector to be controlled, information concerning the position and rate of change of position of each actuator or axis must be obtained and processed. The position of the individual actuators is usually obtained from a shaft encoder which is attached to the

output shaft of the drive motor. The information from these encoders is fed into the control system, where it is recorded to enable the position of the arm to be duplicated. Very early systems recorded the encoder positions directly on magnetic tape and the information was played back through the servo motor controllers to duplicate the prerecorded path. The present generation of robots use microprocessor control systems and the positional information is usually compressed and stored in some form of non-volatile memory.

Control of welding functions

The control system must coordinate the motion of the arm with the required welding functions. It must be able to initiate and terminate the welding operation in a controlled manner and should have facilities for setting the operating parameters for the process.

Interface with auxiliary functions

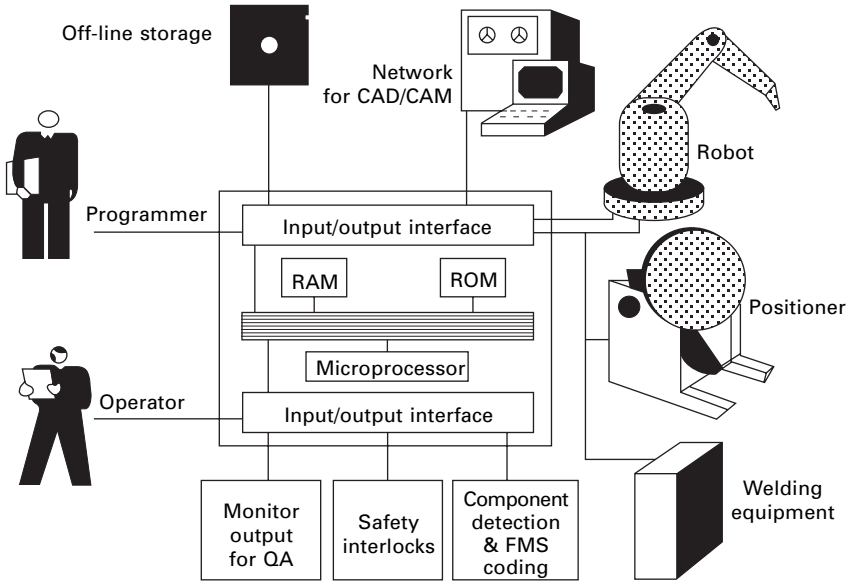
The control system must be capable of receiving information from a number of auxiliary systems; for example, it must be able to respond to an instruction to start the welding operation and should be capable of checking various conditions, such as the presence of the workpiece in the welding jig and the closure of safety doors. It should also be capable of sending output signals to auxiliary systems; to initiate the motion of a work-handling fixture for example. Most robot controllers are equipped with a large number of programmable input/output facilities of this type. Ethernet and other factory bus systems (such as CAN bus) are becoming popular as auxiliary and welding system interfaces. Such systems allow access via remote networks.

Interface with the operator

There are several levels of operator interface with most robot systems. The simplest of these are the teaching/programming interface and the production/operator interface. The programming interface allows the welding operation to be taught and checked, whilst the production/operator interface may allow the selection of a particular preprogrammed job, but often only allows the welding cycle to be initiated or terminated. The general structure of the robot controller and its interfaces is illustrated in Fig. 11.6.

11.5.4 Programming/teaching

The flexibility of robot systems relies on the ability to teach the system to perform a set of welding operations. The action of teaching or programming the robot is often discounted as being a relatively straightforward and rapid



11.6 Robot controller functions.

operation, but, in practice, the creation of a satisfactory welding program may take a considerable time. The details of the teaching procedure depend on the robot, but usually involve teaching the robot motion and operating instructions followed by editing the program and adding welding parameters. Two techniques are normally employed:

- teach-by-doing, or playback, mode;
- point-to-point with interpolation.

Teach-by-doing

The teach-by-doing, or playback, mode of programming was one of the earliest techniques to be used and involves the operator leading the robot through the weld path and continuously or periodically recording the position of the welding head. A commercial SCARA system utilizes this approach; the robot is set in the 'TEACH' mode, the program is allocated a number by means of keys on the controller and the operator then moves the head manually to the first point to be taught, pressing a button at the rear of the arm to record the point. Successive points on the weld path are taught in a similar manner and weld start positions are identified by means of an alternative button. The program is terminated and stored in memory by means of another key on the controller. Welding parameters and input/output (i/o) sequences may then be edited into the program using the key pad and VDU screen on the controller. The whole procedure may then be run under computer control

in the 'TRACE' mode (without welding) for final checking, and the 'PLAY' mode, which performs the whole sequence in production, may be initiated by a simple switch or push button connected to one of the i/o ports.

The procedure is very easy to learn and the programming operation is extremely rapid, but, for curved or complex shapes, a large number of points need to be recorded. An alternative system uses a continuous path recording technique and a device mounted on the end of the torch to maintain the correct torch to workpiece distance. One problem which is inherent in these systems is mechanical backlash. The encoders which are recording the position of the axes in the 'TEACH' mode do not take into account any distortion in the arm caused by the method of leading the torch to the work. This may lead to some inaccuracy in playback, although the rigidity of the small SCARA systems tends to minimize this problem.

Point-to-point with interpolation

This system is the approach most commonly used on fusion welding robots. A program identification number and the 'TEACH' mode are selected at the controller. The robot is then driven through a path in space using the normal actuators which are controlled from a manually operated pendant equipped with push buttons or a joystick. At selected points, the position is recorded by pressing a key on the pendant. The mode of travel between points, the velocity and the choice of welding or non-welding operation are also possible using appropriate keys on the pendant. The travel mode choice is usually 'LINEAR, CIRCULAR or WEAVE' and the computer will interpolate an appropriate path based on the points that have been programmed. The taught program is stored at the end of the sequence and again it is possible to edit in further instructions, welding parameters or control sequences. This approach gives improved accuracy and facilities such as software-generated weave patterns, but the programming process takes significantly longer than the teach-by-doing method and it requires more care to avoid accidental collisions.

11.5.5 Program storage

The taught programs are stored in non-volatile memory (e.g. battery-backed RAM) in the controller. It is also possible to assemble a sequence of programs together into a batch file to perform a particular job and to store regularly used sets of welding parameters in a library file which may be called up during the main welding program.⁴ For additional security, or to release

⁴A library file may, for example, contain instructions to start welding, set the current, set the voltage and the travel speed or to decrease current, decrease voltage and turn off the welding system.

storage space in the control memory, the program, job, and library files may be transferred to disc or magnetic tape.

11.5.6 Practical considerations

For successful implementation of robotic welding, certain practical considerations must be taken into account; these are safety, torch cleaning, jiggling and positioning, work flow, component tolerances and joint design.

Safety

Although robotic systems remove the operator from the immediate vicinity of the welding process and reduce the risk from fume, arc glare, noise and radiation, they are in themselves a safety hazard. The robot arm can travel at high velocity with considerable force and the operator and associated staff must be prevented from entering the operating envelope at any time when the unit is active. This necessitates the use of mechanical guards and safety interlocks. In addition, any automated system can operate at much higher duty cycles than a manual operator and the total fume generated during a shift will probably be much higher than that produced by non-automated installations. It is therefore necessary to provide adequate fume extraction.

Torch cleaning

In automated GMAW operations, the gas shield may become ineffective if high levels of spatter accumulate on the end of the nozzle. This problem may be minimized by the correct choice of welding equipment and consumables, but it will usually be necessary to include a periodic torch-cleaning operation in the robot program. Torch-cleaning stations are available for this purpose.

Jiggling and positioning

The jiggling system must locate the parts to be joined accurately, be simple to load and unload and not present any undue obstructions to the movement of the robot arm. The capabilities of the robot will often be extended by mounting the workpiece on a programmable positioner, which may be synchronized with the movement of the robot arm to perform complex joint profiles. It is also advantageous in many cases to suspend the robot from an overhead gantry.

Work flow

A smooth flow of components to and from the robot system is essential if the full capabilities of the unit are to be realized; this will at the least mean careful scheduling of parts and may involve some investment in automatic delivery and discharge systems.

Component tolerances

The positional repeatability of most fusion welding robots is of the order of 0.1 mm. The standard welding robot will expect the weld seam to be in exactly the same place and in the same condition with respect to gaps and misalignment as the original part which was used for programming. Deviation from these conditions may result in a defective weld and damage to the jigging. It is, therefore, important to establish the tolerance on fit-up and maintain the component dimensions within specified limits. In some cases, this will involve improving control of component variability and may entail investment in pressing, cutting or machining equipment.

Joint design

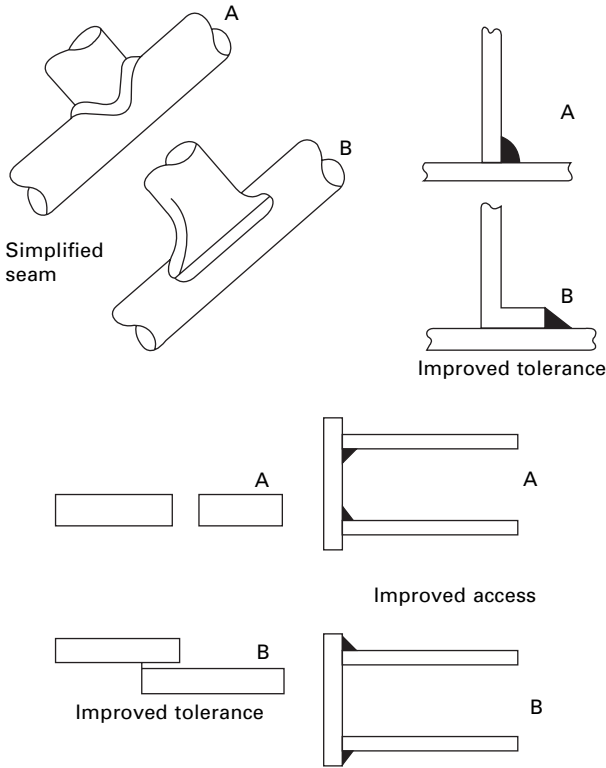
Careful joint design can be used to reduce the sensitivity to component tolerances, for example unsupported square butt joints and fillet welds in thin sheet may be replaced with lap joints to eliminate problems with gaps and give more tolerance to lateral movement. The fact that a robot can follow relatively complex three-dimensional paths should not be used as an incentive for using complex joint profiles; these not only make it more difficult to achieve the required quality, they often increase the cycle time. Simple joint profiles are usually the best. Accessibility must also be considered when designing for robot welding; it may be impossible to weld a component completely without removing it from the jig and repositioning it. This can often be avoided by repositioning the welds to suit the robot. Some of these considerations are illustrated in Fig. 11.7.

11.5.7 Applications

Resistance spot welding

Resistance spot welding robots form the largest single group of welding applications. Most of these are in the automotive industry, where a group of robots can work simultaneously on a single body shell. Articulated arm robots are most commonly used, but there are examples of gantry systems being used for larger components, such as railway wagon side panels. [272]

The robotic automation approach is appropriate in those applications where



11.7 Modification of joint design to suit automation. In each case A is the original design and B the modified version.

large production volumes are involved and model changes can be accommodated by reprogramming. The robot can also replace a physically difficult manual operation in an unpleasant environment. Although reasonable power and rigidity is required to carry the welding head and resist oscillation due to the rapid acceleration and shock loading, high levels of positional accuracy and precise control of linear velocity are not normally necessary.

Seam welding arc processes

Continuous seam welding using GMAW, FCAW, GTAW and plasma processes has been applied in a wide range of applications from car exhausts to space shuttle components as shown in Table 11.1. [273–277] The predominant applications have been concerned with the fabrication of thin-sheet-steel pressings using the GMAW process.

Seam welding applications require accurate positioning of the welding torch and precise control of the travel speed during the welding operation. Programming time is usually significant and component tolerances and jiggling

Table 11.1 Robot applications

Applications	Material	Process	Robot	Reason	Ref.
Ornamental gates	Hot-rolled mild steel	GMAW	5 axis artic. arm	Cost and productivity	270
Hydraulic hoist parts	BS 4360 43A steel 10–12 mm	GMAW	6 axis artic. arm	Reduced cost	270
Hospital beds	Square-section steel tube	GMAW	5-axis artic. arm	Reduced cost, improved quality	270
Dashboards	Aluminium	Spot	Modular Cartesian	Increased output	270
Nuclear boiler panels	Steel	GMAW	Gantry-suspended artic. arms	Quality	270
Domestic boilers	Steel	GMAW	Twin arm	Skill shortage	270
Military storage system	3-mm-thick Tenform XK-350	Spot	Cartesian	Economic	270
Vehicle chassis	Pressed steel	GMAW	16 artic. arm	Improved output and quality	271
Vehicle exhaust systems	Steel	GMAW	Artic. arm manip. plus FMS	Increased output and improved quality	272
Turbine diaphragm	Stainless steel	Pulsed GTAW with filler	6-axis artic. arm	Quality and integration into CIM	273
Space shuttle engines	Nickel-based, cobalt-based, Ti alloy and stainless steel	Pulsed GTAW	Various	Quality	274
Car bodies	Low-carbon steel	Spot	6 axis artic. arm	Output and quality	275
Engine support	Low-carbon steel	Laser	6-axis artic. arm	Output and quality	275

are important. For these reasons, reasonable batch sizes are expected to justify the investment in robotic automation.

Robotic power beam welding

The use of robots for laser and electron beam welding applications is at an early stage of development. Trials of robotic systems for out-of-vacuum

NVEB are taking place, whilst industrial applications of laser welding are in progress; for example in the welding of engine support frames for the Fiat Tipo. [278] Specially designed robots have been produced for laser welding with either mirror or fibre optic beam delivery systems incorporated in the arm.

11.6 **Modular automation**

As the cost and limitations of fully dedicated automation have become clearer, attempts have been made to design lower-cost flexible systems which may be configured to suit a range of applications. This has led to the development of modular automation systems.

Modular systems comprise a kit of common mechanical components, which can be assembled into any configuration to suit the application. The modules consist of support beams, slides, carriages, pivots, linear and rotational drives, torch holders and control systems. The advantages of this approach are rapid system design, simplicity and low cost.

A welding automation system may be developed very quickly using this approach and costly design studies are eliminated. The standard parts are easily interchangeable in the event of damage or breakdown and the total cost of the installation is kept to a minimum. The system may be used for most of the common arc welding processes and is particularly suitable for GMAW, GTAW and plasma welding. Control of position and operating sequences and interface with the welding equipment is provided by a simple electronic logic system. The capabilities of the system may be extended by using a standard industrial programmable controller.

11.7 **Programmable control**

The control systems approach used for robotic welding may be applied to special-purpose, dedicated and modular automation systems to improve their flexibility. This approach has been adopted, for example, on orbital GTAW equipment to allow complex welding procedures to be developed and stored for specific joints. In this case, a computer control system is usually incorporated in the power source or as an interface between the welding power source and the welding head.

For more general applications with dedicated and modular automation, flexible computer control systems have been developed. [279] These systems have the following facilities:

- positional control;
- weld process control;
- cell management.

The positional control system controls the position and velocity of a number of axes, either rotational or linear, to enable three-dimensional trajectories to be followed. Both the welding head and component position may be controlled. The weld process control system may control the welding parameters directly or more commonly via an interface with an intelligent welding power source (see Chapter 3). Cell management activities concern the communications between the welding system and the external production environment. The control should be able to actuate component delivery and discharge systems, provide job status and quality information. The combination of computer control and modular mechanical design offers an alternative to the normal robotic approach.

11.8 Remote-control slave and automated systems

Remote-control welding devices are used in particularly hazardous environments. They may take the form of a master-slave manipulator or a fully automated system with remote monitoring.

11.8.1 Master-slave manipulators (MSM)

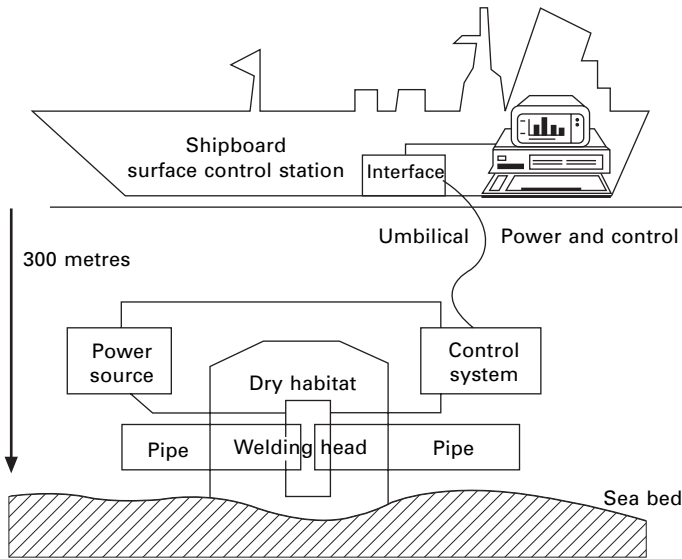
Master-slave manipulators involve the use of a multi-axis positioner, which is positioned and controlled by a remote manual operator. These devices have been used in the nuclear industry for the manipulation of radioactive components and in hyperbaric applications for positioning components or welding inside a high pressure chamber.

These systems are usually specially built to meet the specific application requirements; although some general-purpose arms are available,⁵ these are not normally designed for welding applications, and the repeatability, positional accuracy and load-carrying performance must be evaluated carefully. Welding systems of this type have been specially developed for nuclear applications.

11.8.2 Fully automated remote welding systems

The use of fully automated systems for remote welding applications reduces the possibility of manual error and should improve repeatability. Systems have been developed for deep-water hyperbaric applications, [280, 281] in which welding is carried out at depths of up to 360 m in a dry hyperbaric chamber filled with helium-rich gas. The welding head is an orbital GTAW system and an inverter-based electronic power source under computer control is situated within a service container adjacent to the welding enclosure (i.e.

⁵Special-purpose remotely controlled arms are normally designed for underwater applications or bomb detection and disposal.



11.8 Automatic hyperbaric GTAW system for orbital pipe welding.

on the sea bed). The process is controlled from a ship-board computer interface, which allows the welding parameters to be ‘downloaded’ to the welding system. The welding sequence is performed automatically with visual (CCTV) and process parameter monitoring being carried out by the remote operator on the surface. A diagrammatic overview of the system is shown in Fig. 11.8. This system has been proved technically and economically in production on more than 30 pipe welds in pipe diameters from 250 to 900 mm at depths of 110 to 220 m.

Dedicated automatic systems have also been developed for nuclear applications, [282, 283] for example to weld circumferential seams in beryllium containers; a computer-controlled system incorporating a transistor series regulator GMAW power source was used in this case.

11.9 Advances in welding automation

Advances have been made in the development of systems and applications for welding automation, in particular:

- adaptive control;
- flexible manufacturing systems;
- simulation and off-line programming;
- integrated automation systems;
- rapid prototyping;
- wear replacement.

Adaptive control (see Chapter 10) techniques may be used to improve the tolerance of automation systems to normal variations in component dimensions, joint position and material characteristics. These techniques should not, however, be regarded as the first or only solution to problems of this type; redesign of the joint or improved component preparation are often more cost effective. Major developments have, however, been made in adaptive control and a large number of alternative options are available, as already discussed in Chapter 10.

Flexible manufacturing systems (FMS) are used in many non-welding applications;⁶ they enable reductions to be made in work in progress by automatically scheduling the production operations to suit component availability and demand. A simple but effective example of this system is the Autotech flexible welding system. [284] In this system, a conveyor is used to transport standard 750 mm × 1200 mm pallets, containing the components to be welded, from the loading station to the robot. Each pallet has jiggling suitable for a specific component mounted on it and is identified by a unique arrangement of five plugs on its side. When the pallet enters the robot station, the position of the plugs is read by proximity switches and fed to the robot controller which selects the appropriate welding program. The pallets may be loaded onto the system in any sequence and the throughput may be varied to suit the availability of parts.

This approach has been extended by the use of AGVs (automatic guided vehicles) to transport the workpiece and alternative methods of component identification. [285] The use of typical FMS systems in the fabrication of heavy construction equipment is reported to have resulted in cost savings of 28%. [286] The FMS approach is not restricted to robotic welding and may be applied to dedicated and modular systems, which are equipped with suitable programmable controllers.

11.9.1 Simulation and off-line programming

Programming of robotic systems may take a significant amount of time and this results in lost production. Off-line programming allows the robot program to be developed on a remote workstation and transferred to the robot controller almost instantaneously. Various systems are available for off-line programming (e.g. GRASP, IGRIP and ROBCAD), but these share the following characteristics:

- A graphic and kinematic model of the robot is stored as a library file in a

⁶Flexible manufacturing systems are systems which are able to accept a variety of components or tasks, often in a random order, and are able to identify the component and automatically adapt the manufacturing operations to produce the required end result.

computer (either a mainframe or a personal computer depending on the system).

- The workpiece and joint description may be loaded into the program and the welding operation may be simulated using the selected robot.
- The completed simulation may be translated into the real robot's control language and transmitted to the system via a data link.

Typical simulation and off-line programming packages offer fast and realistic solid model simulations of the application enabling the proposed installation to be fully evaluated and optimized without incurring production downtime. CAD files of workpieces and fixtures may be read into the package which is equipped with a large library of robot definitions. The performance of the robot cell may be tested and potential problems (e.g. collisions and access limitations) are readily identified and displayed on the monitor. The system also offers the facility to generate CAD drawings of the final work cell and transfer the simulated program to the control system using the native language of the appropriate robot.

An interesting example of the off-line programming approach is its application to shipbuilding. A typical system consists of a portal frame, from which an articulated arm robot is suspended; the frame is lowered into the work area and an initial joint-locating program checks the orientation of the system and corrects the datum settings. Off-line programming is used to prepare the program and this is downloaded to the controller so that, once the unit has established its exact position, it may carry out the prescribed welds.

A similar system has been used in the Odense shipyard in Denmark with a Hirobo NC programmable robot. The programs created on a personal computer are, in this case, transferred to the robot controller via a plug in bubble memory and the robot is only out of production for 30 s. [287] The system has also been linked to a simulation package and the shipyard's CAD facility to enable more efficient off-line programming to be accomplished in the future.

11.9.2 Integrated automation systems

Many of the automated welding systems of the type described above have been developed into integrated systems, in which the welding cell is self-contained, but linked to other manufacturing processes by a data communication network. Several manufacturers now offer robotic welding 'cells' configured for a particular range of applications and supplied complete with all the necessary services including safety screens and fume extraction.

Alternatively, dedicated or modular systems with computer control may be used to construct the basic cell. The integrated welding system approach may also be used with computer-controlled modular automation or dedicated

systems. Designs of this type have been evaluated for the production of high-accuracy GTAW welds on a range of components of similar design which span a range of sizes. To accommodate the size range, the component pallets are equipped with radio-frequency identification tags (Eureka tags) which communicate with the controller and reset the system for the component to be welded. To ensure accurate torch positioning in this type of installation, the electrode position may be measured before each run by moving it between a pair of crossed light beams (this has been shown to be capable of ensuring positional repeatability to within ± 0.025 mm). The overall management of the system can be handled by a proprietary CNC controller, which may also act as an interface for data communication to an associated cluster of preparation and finishing stations.

Systems of this type may be regarded as the equivalent of a machining centre and are easily integrated into a totally integrated production facility. It is clear that this approach can ensure greatly improved quality, high productivity and flexibility of supply.

11.9.3 Rapid prototyping

Automated welding may be used to create metal shapes from deposited weld metal. Electroslag welding and submerged arc welding have been used in the past with simple rotators to deposit large pressure vessel shells. More recently robotic GMAW and GTAW processes have been employed to create more complex shapes. The robotic approach employs offline programming techniques to translate computer aided designs (CAD) from a package such as Autocad to the native programming language of the robot [288]. The robot follows the prescribed path to generate the required shape; building successive weld beads on top of each other. The process is a very rapid means of preparing a solid metal object directly from a CAD drawing and, providing the process parameters are optimized, the resultant metal has been shown to be sound and to possess mechanical properties that are at least equivalent to those of a casting.

11.9.4 Wear replacement

An extension of the wear replacement technique has been adapted for robotic weld build-up on worn components. Two approaches are possible:

- pre-machine the worn component to a uniform shape and size;
- measure the wear profile and program the robot path to deposit sufficient metal to restore the original profile.

The first of these approaches has been applied to wear parts of heavy earth-moving equipment. It has the advantage that a simple robot program may be

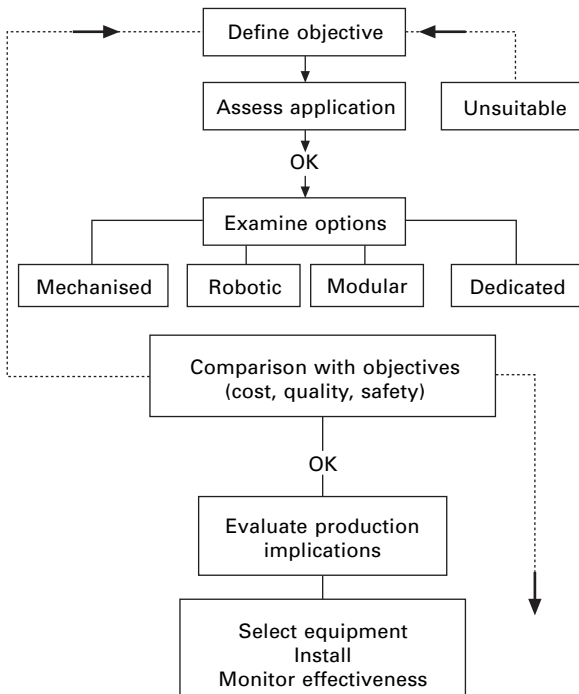
used without any need for adaptive control or profile sensing. It does, however, require a pre-machining operation.

The second approach has been investigated for hydro-turbine runner repairs. [289] In this case, the robotic cell is integrated with computer control and a preliminary scan of the surface provides initial profile data, which is converted to a robot program specifically intended to restore the worn profile. Scanning may be performed using tactile sensors (for simplicity) or vision systems. A combined tactile/vision system approach has proved effective in reducing programming times to around ten seconds.

11.10 Evaluation of and justification for automated welding

Systematic appraisal of the possibilities for automation has been studied by many authors, [290–297] but the main steps involved are shown in Fig. 11.9 and may be listed as follows:

- define objectives;
- assess the application;
- examine the options;



11.9 Automation decision network.

- evaluate alternatives;
- evaluate implications.

11.10.1 Objectives

The importance of clear objectives cannot be over-emphasized: failure to define the true reasons for seeking to use automation may result in considerable waste of effort. In general, the objectives are likely to be based on the economic, quality, safety or supply flexibility requirements outlined in the introduction, but, in some cases, the true objective may be more indirect; comments such as 'to demonstrate the company's involvement in high technology', or 'to worry the competition' or even 'because the managing director believes we need a robot' are not uncommon. These management aims are equally acceptable objectives, but their implications must be considered when the success of the installation is being measured.

11.10.2 The application

The suitability of the application can be assessed in terms of the product life-cycle, the accuracy of joint preparation, the possibility of redesign [293] and the possibility of using a process that may be automated.

11.10.3 The options

The options available have been detailed above, and, in any application, some may be readily eliminated as inappropriate at an early stage, but those with any possibility of success should be evaluated more carefully. This evaluation may involve process feasibility trials and examination of similar production systems, but it will also involve a financial justification.

11.10.4 Financial justification

The type of economic analysis used will often be a matter of company policy and may involve an evaluation of return on investment or discounted cash flow, but, in practice, most assessments are based on the simple payback period.⁷ In the case of structural steel fabrication, the labour cost often accounts for the major part of the total cost of welding. The primary cost savings are therefore associated with improvements in the operating factor

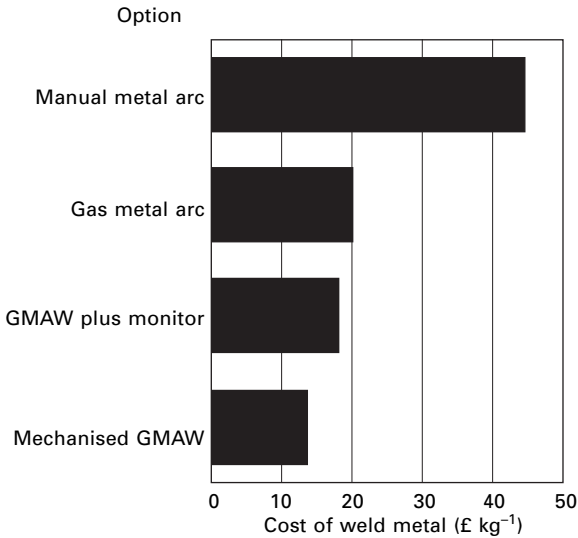
⁷In Japan, a recent survey showed that 66.8% of companies used payback periods of three to five years as justification criteria, whilst 10% used net present value techniques and only 6.5% used internal rate of return methods.

Table 11.2 Example of costing spreadsheet output showing the influence of £20000 investment in welding automation on the cost of making a butt weld in steel with GMAW, 1.0-mm-diameter filler wire. The left-hand column shows the original cost for manual GMAW, and the right-hand column shows the estimated effect of automation on the capital cost, operating factor (arc on time) and weld quality (rejection rate). The totals show the reduced cost per weld and increased productivity to be expected.

Operational parameters		Manual	Automated
Deposition rate	kg h ⁻¹	3.55	3.55
Cost for flux or gas per m ³ or kg	£	3.10	3.10
Cost per 1000 electrodes or kg wire	£	0.77	0.77
Labour cost (without equipment) per hour	£	14.08	14.08
Number of hours per annum	h	1500.00	1500.00
Process arc – on time	%	28.00	50.00
Amount of work under survey	%	100.00	100.00
Rejection rate	%	5.00	1.00
Total investments	k£	2.535	22.535
Interest	%	8.00	8.00
Depreciation period	yr	5.00	5.00
Total cost per annum	k£	28.788	36.500
Deposited weldmetal per annum	kg	1416.45	2635.88
Weight per metre	kg	0.33	0.33
Total cost per kg weldmetal	£	20.32	13.85
Cutting cost per metre	£	0.00	0.00
Cost for this process per metre	£	6.68	4.55
Cumulative cost for this weld	£	6.68	4.55

for the process (the ratio of effective to non-effective time) and the consequent reduction in labour cost. For example, a manual GMAW operator may achieve an operating factor of 15–20%, whereas, with a tractor-mounted system, an operating factor of 30–40% may be possible and fully automated systems are likely to achieve 80–90%. Secondary cost savings can also be expected from improved control of weld size; which, in turn, saves time, reduces consumable costs and improves control of operating technique; which produces more consistent quality, reduces defect levels and decreases repair costs. A preliminary evaluation of the economic factors associated with the automation of a given application is straightforward, particularly if one of the many commercial weld-costing software packages⁸ is used. Examples of simple cost comparisons made with the NIL COSTCOMP software are shown in Table 11.2 and Fig. 11.10: a comparison of manual and mechanized welding approaches to one of the most common weld configurations is shown in Table 11.2. The cost of the simple tractor involved would be recovered after

⁸For example, the UK Welding Institutes ‘WELDCOST’ programme, The Netherlands Welding Institute’s ‘NIL COSTCOMP’ or any suitably configured spreadsheet software.



11.10 Cost analysis for 6-mm fillet weld in steel with various cost-reduction options (data from COSTCOMP weld-costing program).

only 315 m of weld had been performed. In the same way, the high cost of a dedicated CNC unit may be offset by improvements in operating factor and improvements in quality (reduction in reject and repair rate).

11.10.5 The expectations

Assessments of the implications of introducing welding automation are often inaccurate and surveys [294–297] carried out before and after the introduction of automation illustrate this point. It is worth considering some of the expectations and the resultant assessments before investment in automation.

Social implications

Social implications and, in particular, shop-floor opposition, are often expected to be barriers to the introduction of automation; in practice, whilst 31% of users in one survey believed this to be the case before the purchase of automated systems, only 2% actually experienced any problems. Recent reports suggest that most workers prefer working with computer-controlled equipment and achieve additional status amongst their peers for doing so. It is also clear from these reports that insufficient attention is given to involving workers in the decision to automate and a review of successful applications shows that successful implementation of automation does depend on the commitment and ingenuity of the welding engineer and the operator.

Production implications

It is also found that most robot users underestimate the degree of after-sales support needed, the maintenance requirements and the development costs involved in bringing the application to full production. One of the most serious problems encountered is often the unsuitability of component tolerances and this may have major cost implications if preparation equipment needs to be replaced or operating procedures need to be changed.

11.11 Summary

The wide range of automation systems described in this chapter are capable of answering the need for:

- reduced production costs;
- improved safety and health;
- consistent product quality;
- improved supply flexibility.

An evaluation of the potential benefits to be gained from welding automation is always worthwhile. In the unlikely event that none of the options listed above prove viable it is often possible to use the information gained in the analysis of automation requirements to improve the manual welding operation.

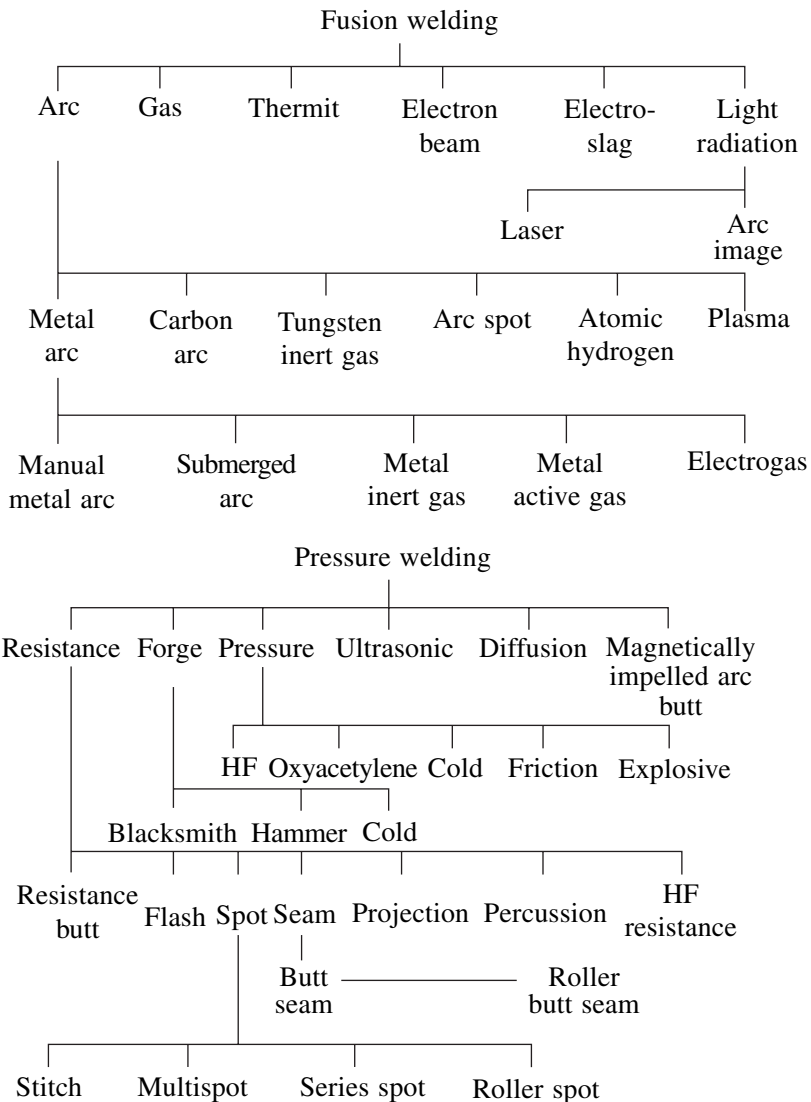
Appendices

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Appendix 1

Welding processes classification

(British Standards Institution) [1]



Appendix 2

Shielded metal arc welding (SMAW) electrode classification

(reproduced by kind permission of
Welding and Metal Fabrication)

BS 639

The standard identifies electrodes by a series of letters and digits that indicate the mechanical properties, formulation type and applications. The full electrode classification consists of a compulsory and optional parts as shown below.

Compulsory

E	Electrode for MMA
xx	Tensile strength range, minimum yield strength
x	First digit for elongation and impact strength
x	Second digit indicating temperature for minimum average impact strength of 47 J
NN	Letters indicating coating type

Optional

xxx	Three-digit indication of metal recovery
x	Welding position
x	Current and voltage requirements
H	Hydrogen-controlled electrode

This classification is quite complex and it is recommended that the standard should be consulted for full details. The following notes give an indication of the typical electrode specifications.

Tensile strength

Designation	Strength (N mm ⁻²)	Minimum yield strength (N mm ⁻²)
43	430–550	330
51	510–650	360

First digit: elongation and impact

Digit	Minimum elongation (%)		Impact test temperature (°C) for impact value of 28 J
	E43	E51	
	20	18	Not specified
1	20	18	+20
2	22	18	0
3	24	20	-20
4	24	20	-30
5	24	20	-40

Second digit: toughness

Digit	Temperature (°C)
0	Not specified
1	+20
2	0
3	-20
4	-30
5	-40
6	-50
7	-60
8	-70

Coating type

B	Basic	CaCO ₃ , CaF ₂
BB	Basic iron powder	CaCO ₃ , CaF ₂ + iron powder
C	Cellulosic	Organic
O	Oxidizing	FeO
R	Medium-coated rutile	TiO ₂
RR	Heavy-coated rutile	TiO ₂ , CaCO ₃
S	Others	

Welding position

- 1 All positions
- 2 All except vertically down

- 3 Flat and horizontal
- 4 Flat
- 5 Flat, vertically down, HV fillets
- 9 Any combination not classified in 1–5

Current and polarity

Digit	DC	AC
0	As recommended by manufacturer	Not suitable
1	+ or -	50 minimum OCV
2	-	50 minimum OCV
3	+	50 minimum OCV
4	+ or -	70 minimum OCV
5	-	70 minimum OCV
6	+	70 minimum OCV
7	+ or -	80 minimum OCV
8	-	80 minimum OCV
9		80 minimum OCV

Typical example

The classification for an all positional basic (with iron powder) hydrogen-controlled electrode with a minimum UTS of 510 N mm^{-2} and yield strength over 450 N mm^{-2} and impact properties better than 28 J at $-40 \text{ }^\circ\text{C}$ and 47 J between -40 and $-50 \text{ }^\circ\text{C}$ would be:

E 51 5 5 BB 160 2 8 H

American Welding Society (AWS) Standard A5.1

The AWS Standard is less complicated, consisting of a prefix E followed by only two sets of digits:

E	Electrode
xxx	Two or three digits indicating the tensile strength in 10000 psi units.
xx	Two digits indicating the coating type and application as follows:
Exx10	Cellulosic, DC +ve. Deep penetration, all position
Exx11	As Exx 10, but usable on AC
Exx12	Rutile, AC/DC, flat and HV positions
Exx13	Rutile, AC/DC, all positions
Exx14	Iron powder rutile, high speed
Exx15	Basic low-hydrogen, DC +ve, all positions

Exx16	Basic low-hydrogen, AC/DC, all positions
Exx18	As Exx16, with iron powder for improved recovery
Exx20	Mineral oxide/silicate, for flat and HV positions
Exx24	Similar to Exx 12, but with iron powder, flat and HV
Exx27	As Exx20, but with iron powder
Exx28	Low-hydrogen basic with 50% iron powder, flat and HV

A suffix (e.g. A1, B2) may be added to indicate the chemical composition of low-alloy-steel weld metal.

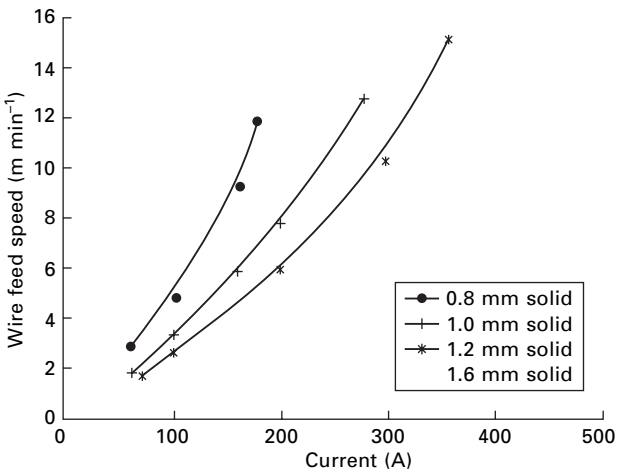
The electrode classified above as E 51 5 5 BB 160 2 8 H would be classified as E7018 according to AWS A5.1.

Appendix 3

Burn-off characteristics

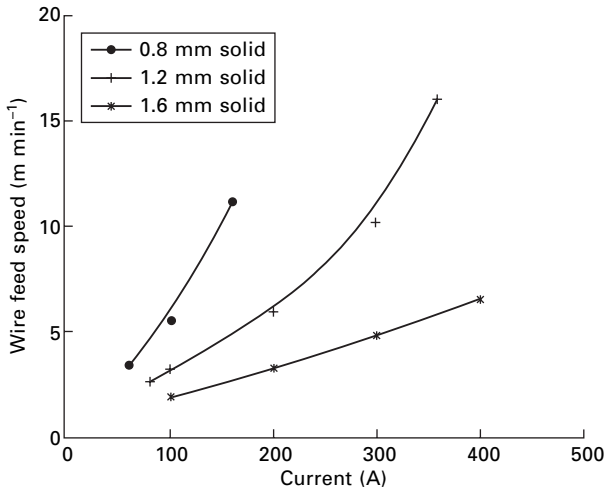
a

GMAW plain carbon steel

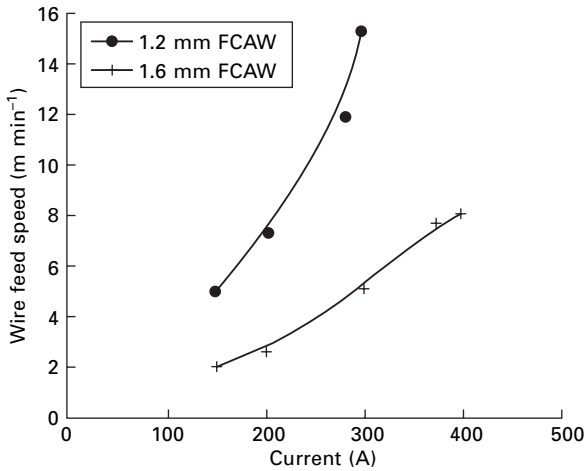


b

GMAW stainless steel

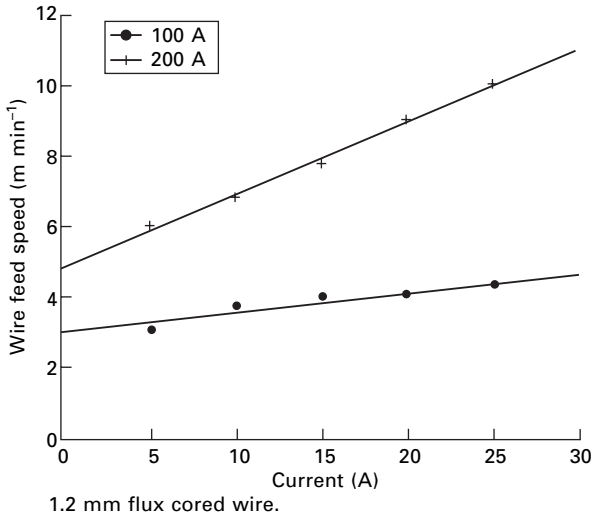
**c**

FCAW plain carbon steel



d

Influence of electrode extension
FCAW plain carbon steel



Appendix 4

American, Australian and European FCAW classification systems

American Welding Society (AWS) Classification of Plain Carbon Ferritic FCAW Electrodes

The American classification system (AWS Designation A 5.20) was the earliest and is still the most common system used to describe FCAW consumables. Its popularity undoubtedly lies in its simplicity. The classification consists of:

- a prefix letter 'E' specifying an electrode, followed by
- a number which indicates the tensile strength in ksi (that is, 7 = 70ksi), followed by
- a number which indicates the positional capabilities of the wire (0 for downhand and 1 for all positional)
- a 'T' for tubular wire'
- then a digit which defines the flux type and operating characteristics of the wire The flux core types referred to by the last digit are tabulated in the standard as:

Designation characteristics

- T1 Rutile gas shielded (carbon dioxide or mixed gas), for multipass welds
- T2 Rutile carbon dioxide shielded, for single pass welds
- T3 Self shielded, DCEP for high speed, thin material
- T4 Self shielded, DCEP for high deposition welding
- T5 Basic gas shielded (carbon dioxide or mixed gas)
- T6 Self shielded, DCEP good toughness in multipass welds
- T7 Self shielded, DCEN all positional
- T8 Self shielded, DCEN all positional, good toughness
- T10 Self shielded, DCEN high speed thin material
- T11 Self shielded, DCEN spray transfer
- T-G Any other type as specified

A full copy of the AWS A5.20 standard can be obtained through the Welding Technology Institute of Australia (WTIA) in Australia or direct from AWS in the USA.

Australian classification of consumables

The classification of ferritic steel consumables according to the Australian code AS/NZS 2203.1 is based on the designation of three groups of elements separated by hyphens as follows:

Group 1

A prefix '**E**' which denotes electrode, '**T**' which indicates the electrode is tubular, followed by a letter code which indicates the positional capabilities of the wire:

P = All positions

D = Flat or downhand and horizontal vertical fillets

S = Single run only.

Group 2

G (for gas shielding) followed by a character which indicates the shielding gas used:

C = Carbon dioxide

M = Mixed gas (e.g. Argon/carbon dioxide)

N = No external shielding.

This is followed by a letter which indicates the type of current to be used:

p = DCEP

n = DCEN

a = AC.

Group 3

A W (for weld metal properties) followed by two-digit number which indicate approximately 0.1 of the specified minimum tensile strength in megapascals followed by a digit which indicates the impact energy grade. These are followed by A (as welded) or P (postweld heat treated) to indicate heat treatment conditions. The following group indicates the weld metal chemistry using an alphanumeric code which refers to a table of compositions.

Finally the suffix H with a numeric subscript denotes the hydrogen content of the deposited metal in ml/100g.

Diagrammatically the AS 2203 designation may be represented as:

The chemistry of the weld metal are specified in Table 2.2 of the standard.

Carbon Manganese steels have a CM prefix, Carbon-Molybdenum steels an A prefix, Chromium-Molybdenum steels a B prefix, Nickel steels an Ni prefix and Manganese Molybdenum steels a D prefix and other alloys a K, G or W prefix

European classification of ferritic GMAW consumables

The European Standard EN 758 supersedes the British Standard BS 7084 and is based on the following:

Prefix 'EN 758' referring to the standard and 'T' for tubular wire followed by the following alphanumeric designation:

- X – The yield strength of the weld metal divided by 10 in N/mm²
- X – The toughness of the weld metal; a single digit representing the temperature at which 47J is achieved
- X – An alphanumeric code representing the alloy type (for example, 1 Ni = 1 %Nickel)
- X – A letter representing the flux type (R – Rutile, P – Positional Rutile, B – basic, M – Metal, U to Y self shielded)
- X – Gas type (M for mixed, C for carbon dioxide, N for no gas)
- Hx – Hydrogen control (diffusible hydrogen level indicated by suffix).

Appendix 5

Flux-cored wire for surfacing and wear resistance

Consumable type	Features	Applications
Plain carbon steel	Low alloy content, hardness up to 200 VPN. Ductile, tough deposit	Build-up of ferritic carbon steels before surfacing
Pearlitic steel	Higher carbon/manganese content, hardness 250 VPN. Ductile, tough deposit	Build-up and repair of friction (metal to metal) wear (e.g. idler rolls on tracked vehicles)
Martensitic-pearlitic steel	Low-alloy ferritic steel with hardness up to 400 VPN. Poor ductility and toughness	Friction and mildly abrasion resistant applications, e.g. crusher rolls
Martensitic steel	High-alloy (C, Mn, Cr, Mo, B). Hardness up to 800 VPN. Not machinable, low ductility	Low-impact abrasion situations. Cutting edges and digger teeth
Austenitic manganese-nickel	Carbon steel alloyed with manganese and nickel. Low hardness (200 VPN), good ductility as deposited, work hardens to 500 VPN	Repair of austenitic manganese steel. Crusher hammers. Good impact resistance and fair surface abrasion properties
Austenitic stainless steel	Normally 308- or 309-type stainless steel. Very good ductility and toughness, good impact and corrosion resistance, low abrasion resistance	Good buffer layer for high-impact loading, good wet-corrosion properties. Use as build up on gyratory crushers and heavy hammers. High cost
Chromium carbide white irons	High chromium-carbon white iron. Hard carbide particles in austenitic, pearlitic or martensitic matrix. Very good abrasion resistance, poor impact, fair corrosion resistance. Hardness depends on matrix; from 350 to 800 VPN	Abrasion-resistant surfacing of earth-moving parts. Abrasion resistance best with martensitic matrix, impact and corrosion best with austenitic matrix. Very flexible range

Consumable type	Features	Applications
Tungsten carbide white irons	Tungsten carbide in martensitic white-iron matrix. Very hard (up to 850 VPN) abrasion-resistant deposit, poor impact properties	Fine abrasion-resistant applications; sand chutes and dredger buckets
Nickel- and cobalt-based alloys	May contain carbides (e.g. tungsten carbide) in tough, ductile, corrosion-resistant matrix. Higher cost than iron-based	Good high-temperature abrasion and erosion resistance. Valves and valve seats

Note: VPN = Vickers pyramid number.

Appendix 6

Plasma keyhole welding parameters

Material	Thickness (mm)	Current (A)	Orifice diameter (mm)	Plasma gas flow ($l \text{ min}^{-1}$)	Shield gas flow ($l \text{ min}^{-1}$)	Travel speed ($m \text{ min}^{-1}$)
Plain carbon steel	1.2	130	2.8	4.2	20	0.35
	3.2	270	3.2	2.8	10	0.23
	6.4	300	3.2	2.8	10	0.23
Austenitic stainless steel	1.2	95	2.8	3.8	20	0.96
	3.2	190	2.8	4.2	20	0.84
	6.4	240	3.5	8.5	24	0.35
	12.7	320	3.2	4.7	10	0.18
Nickel	3.2	200	2.8	4.7	20	0.69
	6.4	250	3.5	7.1	20	0.35
Copper	3.2	60	3.2	1.9	10	0.23
Incoloy	3.2	180	2.8	5.7	20	0.69
	6.4	240	3.5	7.1	20	0.35
Nimonic	1.6	135	2.8	3.5	20	0.92
	3.2	200	2.8	3.8	20	0.76

Appendix 7

Plasma keyhole welding of titanium

Thickness (mm)	Current (A)	Orifice diameter (mm)	Plasma gas flow (l min ⁻¹)	Shield gas flow (l min ⁻¹)	Trailing shield (l min ⁻¹)	Travel speed (m min ⁻¹)
1.6	132	2.8	3.8	20	50	0.92
3.2	185	2.8	3.8	20	50	0.50
4.8	190	2.8	5.6	20	60	0.35
6.4	245	2.4	5.6	20	70	0.23

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-
- Activated TIG (A-TIG) 91, 97
 - adaptive control 205, 239
 - advanced materials 24–5
 - aerodynamic drag 111
 - aerospace industry 160
 - after-sales support 246
 - AGVs (automated guided vehicles) 239
 - aliasing 191
 - alloying additions to flux-cored wires 51
 - aluminium welds 68, 144
 - analogue measuring systems 189–90
 - analogue moving-iron meters 194–5
 - arc characteristics 140–1
 - arc initiation 74–9
 - electrode composition 78
 - electrode weight loss 78–9
 - high-frequency high-voltage 75–6
 - high-voltage DC 75
 - piezoelectric arc starting 76–7
 - pilot arc starting 76
 - programmed touch striking 76
 - rim formation 78–9
 - stabilization 51, 77
 - touch striking 75, 76
 - arc ionizers 51
 - arc length control 117, 131–2, 211–13
 - in GTAW 93
 - laser range finders 212
 - light sensors 212–13
 - photoelectric sensors 212
 - sound measurement 212
 - spectral radiation sensors 212–13
 - voltage measurement 211–12
 - arc stabilization 51, 77
 - arc stiffness 59
 - arc support and stability 58–9
 - arc welding
 - deviation monitoring 200–1
 - robotic welding 228
 - see also* fusion welding
 - argon 58, 63, 64–5, 67–8, 72–3
 - argon/chlorine mixtures 70
 - argon/Freon mixtures 70
 - argon/sulphur dioxide mixtures 70
 - asymmetrical SCRs 36
 - atmospheric contamination 59–60
 - austenitic stainless steel welds 66–7, 142, 153
 - automated control 203–17
 - adaptive control 205, 239
 - closed-loop systems 204–5, 206–16
 - direct control 205
 - learning control 205
 - open-loop systems 188, 204–5
 - automated guided vehicles (AGVs) 239
 - automation 23–4, 218–46
 - after-sales support 246
 - cell management 237
 - control systems 236–8
 - costs 243–5
 - dedicated automation 223
 - evaluation of systems 242–6
 - fixed welding stations 222
 - fully remote welding 237–8
 - integrated systems 240–1
 - master-slave manipulators (MSM) 237
 - mechanized wire-feed 82–3
 - modular automation 236
 - objectives 243

- orbital welding 224
- positioners and manipulators 222
- product quality 219
- production implications 246
- rapid prototyping 241
- remote-control 237–8
- safety 218–19
- seam welders 224
- simple mechanization 219–22
- simulation 239–40
- social implications 245
- special-purpose automation 223–5
- stitch welding 224–5
- supply flexibility 219
- tractor systems 220–1
- wear replacement 241–2
 - see also* robotic welding
- automotive industry 160
- AWS classification of consumables
 - 257–8

- back face sensing 213–14
- basic gas-shielded wires 53
- bead geometry prediction 216
- bead placement 171
- beam oscillation 150
- bi-metal thermometers 193
- British Nuclear Fuels Ltd. 220
- BS classification of consumables 259–60
- buried arc GTAW 91
- burn-off 116, 124–5, 254–6
- butt welds 165

- calibration of equipment 184–7
- carbon dioxide lasers 144–5
 - microwave-excited 156
- carbon dioxide shielding gas 63–4, 64–6
- carbon monoxide lasers 156
- carbon steel welds 64–6, 142, 153
- carbon steel wires 48, 52–3
- cartesian robots 226–7
- cast-to-cast variation 95–8
- CDD cameras 209
- cell management 237
- cerium 47, 78
- chamber loading systems 162
- chemical composition sensors 211
- chlorine 70
- classification of welding processes 1–2,
 - 249
- closed-loop control systems 204–5,
 - 206–16
 - arc length control 211–13
 - feedback signals 206
 - line following systems 206–11
 - penetration control 213–15
 - quality control 215–16
- CMOS cameras 209
- cold pressure welding 4–5
- cold wire GTAW 82–3, 168
- completion times 18–19
- component tolerances 233
- computer-based data loggers 190–3
- computer-numerical-controlled (CNC)
 - systems 23–4
- consumable trends 22–3
- control systems *see* automated control;
 - manual control; process control
- controlled droplet detachment 121–2
- controlled transfer techniques 120–8
- copper welds 68, 160
- cost effectiveness 16–20
 - of automation and robotics 243–5
 - and deposition rate 16–17
 - of flux-cored wires 56
 - joint completion times 18–19
 - joint design 18–19
 - joint quality control 17–18
 - operating efficiency 19
 - post-weld operations 20
- current measurement 194–6
- current shunt 194
- current and travel speed 92

- Dabber TIG 82
- data loggers 190–3
- dedicated automation 223
- defect rectification 20
- definitions of welding 1–2
- deposition rates 16–17, 49–50, 71
- design
 - of joints 18–19, 233
 - of power sources 27
- determination of parameters 181–2
- deviation monitoring 199–203
 - in arc welding 200–1
 - dynamic resistance curve 199–200
 - statistical process control 201–3
 - visible spectrum monitoring 203
- diffusion bonding 7

- digital measuring systems 189–90
- digital signal processor (DSP) 40–1
- diode-pumped lasers 156
- dip transfer 105–7, 116–17, 126–8, 133, 197–8
- direct control 205
- direct vision sensors 210
- discrete component electronic control 40
- double arcing 138
- drive systems 227
- drop spray transfer 104–5, 133
- dual-gas GTAW 84–5
- duty cycle 19
- dynamic characteristics of power supply 30–1
- dynamic resistance curve 199–200
- electrodes
 - arc initiation 74–9
 - long extensions 54
 - plasma keyhole welding 140
 - short extensions 54–5
 - SMAW classification 250–3
 - stainless steel MMA 45–6
 - sticking 43
 - thoriated electrodes 78
 - vertex angle 94–5
 - weight loss 78–9
- electromagnetic forces 111–12
- electron beam welding 14–15, 157–64
 - applications 159–60
 - beam characteristics 158–9
 - beam power 161
 - beam traps 162
 - chamber loading systems 162
 - computer control 162–3
 - control systems 159, 162–3
 - copper welds 160
 - electron momentum 158–9
 - joint configuration 161
 - non-vacuum EBW 163
 - power sources 163
 - recoil pressure 158–9
 - safety 161
 - vacuum operation 161
 - vapour pressure 158–9
 - vapour shields 162
- electronic power regulation systems 31–9, 42–3
 - design features 37–9
 - feedback control 39
 - hybrid designs 36–7
 - primary-rectifier inverters 35–6
 - SCR (silicon-controlled rectifiers) 31–3, 36
 - secondary switched transistors 34–5
 - transistor series regulator 33
- environmental hazards 21
- EPROM chips 40
- event-monitoring 192
- excimer lasers 156
- explosive droplet transfer 107
- explosive welding 7
- extended operation of GMAW systems 134
- extensions on electrodes 54–5
- external computer control 42
- FCAW *see* flux cored arc welding (FCAW)
- feedback control 39
- feedback signals 206
- ferritic steel wires 47–8
- fibre lasers 157
- filler addition GTAW 95
- filler materials
 - flux cored arc welding (FCAW) 48–57
 - gas metal arc welding (GMAW) 47–8
 - manual metal arc welding (MMAW) 44–6
 - submerged arc welding (SAW) 46–7
- fillet welds 165
- fixed welding stations 222
- flexibility 219
- flexible manufacturing systems (FMS) 239
- flux cored arc welding (FCAW) 22
 - applications 55
 - filler materials 48–57
 - metal transfer 108–9
 - shielding gases 69
- flux-cored wires 48–57, 261–2
 - alloying addition 51
 - arc stabilization 51
 - AWS classification 257–8
 - carbon and alloy steel 52–3
 - consistency 57
 - cost 56
 - deposition rate 49–50

- fumes 56–7
- gas-shielded 52, 54–5
- hardfacing and surfacing alloys 53–4
- limitations 55–7
- metal-cored 53, 108, 125
- modes of operation 51–2
- pulsed flux-cored 125–6
- rutile flux-cored 53, 108–9, 125
- self-shielded 52, 53, 54, 109
- slag shielding 51
- stainless steel flux-cored 54, 69
- free-flight transfer 100
- Freon 70
- friction welding 5–7, 24
- front face light sensing 214
- front face vision 214–15
- fully automated remote welding 237–8
- fumes 56–7
- fusion characteristics 61–2
- fusion welding 2, 8–15
- gantry robots 226–7
- gas metal arc welding (GMAW) 12–13, 22–3, 47–8
 - arc length 117, 131–2
 - burn-off 116, 124–5, 254–6
 - control systems 113–20, 128–34
 - controlled droplet detachment 121–2
 - deposition rates 71
 - extended operation 134
 - filler materials 47–8
 - high deposition welding 134
 - Hybrid Laser GMAW 155
 - melting rate phenomena 114–16
 - metal transfer 100–13
 - narrow-gap GMAW 170–4
 - parameter selection 117–19, 132–3
 - power source 117–19
 - programmed control 128–34
 - pulsed GMAW 120–1, 124–5
 - shielding gases 64–7, 68
 - single-knob control 128–34
 - stability monitoring 197–8
 - stitch welders 224–5
 - synergic control 128–34
 - tractor systems 221
 - user parameter selection 132–3
 - voltage-current characteristics 116–17
 - wire feed systems 117
- gas tungsten arc welding (GTAW) 8–9, 74–99
 - A-TIG welding 91
 - arc initiation 74–9
 - arc length 93
 - buried arc GTAW 91
 - cast-to-cast variation 95–8
 - cold-wire GTAW 82–3, 168
 - control systems 91–8
 - current and travel speed 92
 - dual-gas GTAW 84–5
 - electrode development 74–9
 - electrode vertex angle 94–5
 - filler addition 95
 - high current GTAW 91
 - high-frequency pulsed GTAW 79–81
 - hot-wire GTAW 83, 168–70
 - laser-enhanced 155
 - multicathode GTAW 89–91
 - narrow-gap welding 168–70
 - polarity 93
 - process developments 74–9
 - pulsed GTAW 79–81, 98
 - shielding gases 67–8, 94
 - tractor systems 221
 - variable polarity GTAW 81–2
- gas-shielded flux-cored wires 52, 54–5
- gases
 - gas-metal reactions 60
 - for laser welding 71–2
 - shielding gases 58–73
- globular drop transfer 101–2
- globular repelled transfer 102
- GMAW *see* gas metal arc welding (GMAW)
- gravitational force 111
- GTAW *see* gas tungsten arc welding (GTAW)
- Hall-effect probes 194
- hardfacing and surfacing alloys 53–4
- heat affected zone (HAZ) 182
- helium 59, 63, 66–7, 72
- high current GTAW 91
- high deposition welding 134
- high frequency pulsing 150
- high-current plasma welding 89
- high-energy density processes 136–64
 - electron beam welding 14–15, 157–64
 - keyhole welding 137–44
 - laser welding 15, 24, 144–57

- high-frequency high-voltage arc initiation 75–6
- high-frequency pulsed GTAW 79–81
- high-power diode lasers 156–7
- high-voltage DC arc initiation 75
- hot wire GTAW 83, 168–70
- hybrid control systems 216
- Hybrid Laser GMAW 155
- hybrid power regulation systems 36–7
- hydrogen control 45
- hydrogen shielding gas 58–9, 60, 64, 72
- hydrogen-assisted cold cracking (HACC) 181–2

- inductive sensors 209
- inductor control 29
- integrated automation systems 240–1
- intermediate-current plasma welding 89
- inverse bremsstrahlung effect 149
- ionization 58
- iron powder additions 46–7
- ISO 4063 numbering system 2–3

- jigging systems 232
- joining processes 1
- joints
 - completion times 18–19
 - configuration 154, 161, 166
 - design 18–19, 233
 - location sensors 207–8
 - performance assessment 182
 - preparation 166–7
 - profiles 181
 - properties 62
 - quality control 17–18

- keyhole mode laser welding 148, 152
 - see also* plasma keyhole welding

- laser range finders 212
- laser welding 15, 24, 144–57
 - applications 151–4
 - austenitic stainless steel welds 153
 - beam oscillation 150
 - carbon dioxide lasers 144–5
 - microwave-excited 156
 - carbon monoxide lasers 156
 - characteristics of laser beams 147–8
 - control systems 151
 - diode-pumped lasers 156
 - excimer lasers 156
 - fibre lasers 157
 - gases 71–2
 - high frequency pulsing 150
 - high-power diode lasers 156–7
 - Hybrid Laser GMAW 155
 - inverse bremsstrahlung effect 149
 - joint configuration 154
 - keyhole mode 148, 152
 - laser-enhanced GTAW 155
 - low-carbon steel welds 153
 - melt-in (conduction-limited) mode 148
 - metallurgical problems 153
 - multiple laser operation 155
 - Nd:YAG lasers 146–7
 - nickel welds 154
 - plasma control 150
 - plasma formation 149–50
 - pulsing of laser output 151
 - RF excitation systems 156
 - robotic systems 228
 - safety 154–5
 - shielding gases 71–2, 148–9
 - titanium welds 154
 - laser-enhanced GTAW 155
 - learning control 205
 - light sensors 212–13
 - line following systems 206–11
 - location sensors 207–8
 - long extensions on electrodes 54
 - Lorentz force 84
 - low-current plasma welding 89

- MAG welding 12–13
- magnetic amplifiers 29–30
- magnetic impulse welding 24
- magnetically impelled arc butt (MIAB) welding 7–8, 69
- manipulators and positioners 222
- manual control techniques 180–8
 - calibration of equipment 184–7
 - determination of parameters 181–2
 - joint performance assessment 182
 - open-loop system 188
 - procedure amendment 183
 - procedure control 180–7
 - procedure development 180–1
 - procedure management 184–7
 - procedure monitoring 187

- procedure qualification 184
- record keeping 184
- selection of welding processes 181
- validity of parameters 184–7
- manual metal arc welding (MMAW)
 - 9–10, 22
 - consumables 44–6
 - filler materials 44–6
 - hydrogen control 45
 - stainless steel MMA electrodes 45–6
 - toughness of weld metal 45
- Marangoni Flow 96
- master-slave manipulators (MSM) 237
- measuring systems 189–90
 - sound measurement 212
 - see also* parameters
- mechanical manipulation systems 225–7
- mechanized wire-feed systems 82–3
- melt-in (conduction-limited) laser
 - welding 148
- melting rate phenomena 114–16
- metal active gas (MAG) welding 12–13
- metal inert gas (MIG) welding 12–13
- metal transfer 100–13
 - aerodynamic drag 111
 - controlled transfer techniques 120–8
 - dip transfer 105–7, 116–17, 126–8, 133, 197–8
 - drop spray transfer 104–5, 133
 - electromagnetic forces 111–12
 - explosive droplet transfer 107
 - flux cored arc welding (FCAW) 108–9
 - free-flight transfer 100
 - globular drop transfer 101–2
 - globular repelled transfer 102
 - gravitational force 111
 - physics 110–13
 - projected spray transfer 102–3
 - rotating transfer 107–8
 - slag protected transfer 108–9
 - streaming transfer 103–4
 - surface tension 113
 - vapour jet forces 112–13
- metal-cored wires 53, 108, 125
- MIAB welding 7–8, 69
- microplasma welding 89
- microprocessor control 40–1
- microwave-excited lasers 156
- MIG welding 12–13
- MMAW *see* manual metal arc welding (MMAW)
- modular automation 236
- monitoring techniques 188–203
 - computer-based data loggers 190–3
 - deviation monitors 199–203
 - event-monitoring 192
 - measuring systems 189–90
 - parameter monitors 193–6
 - stability monitors 196–8
- MOSFETS 36
- moving-iron control 28–9
- moving-iron meters 194–5
- multicathode GTAW 89–91
- multiple laser operation 155
- multiport nozzles 140
- narrow-gap welding 165–78
 - bead placement 171
 - filler wire positioning 172
 - GMAW 170–4
 - GTAW 168–70
 - joint configuration 166
 - joint preparation 166–7
 - oscillation techniques 172–4
 - SAW 175–7
 - shielding gas 171–2
 - torch oscillation 172–4
 - twist arc technique 172
 - wire oscillation 172–4
- Nd:YAG lasers 146–7
- nickel welds 68, 143, 154
- nitric oxide mixtures 70–1
- nitrogen 60, 68
- non-vacuum EBW 163
- nuclear industry 220, 223
- objectives of automation and robotics 243
- off-line programming 239–40
- one-knob control 41–2, 128–34
- open-loop control systems 188, 204–5
- operating efficiency 19
- orbital welding systems 224
- orifice diameter 140
- oscillation techniques 172–4
- oscilloscopes 194
- oxygen 64
- ozone formation 70
- parameters

- current measurement 194–6
- determination 181–2
- monitoring 193–6
- programming 41–2
- pulse parameters 124–5
- selection 117–19
- user selected 132–3
- speed measurement 196
- temperature measurement 193–4
- time measurement 196
- validity 184–7
- voltage measurement 196, 211–12
- Paton Activated TIG (PA-TIG) 91
- penetration control 213–15
- photoelectric sensors 209, 212
- piezoelectric arc starting 76–7
- pilot arc starting 76
- plasma control 150
- plasma formation 149–50
- plasma keyhole welding 137–44, 263–4
 - aluminium welds 144
 - arc characteristics 140–1
 - austenitic stainless steel welds 142
 - carbon-manganese ferritic steel welds 142
 - control systems 138–44
 - double arcing 138
 - electrode geometry 140
 - mean welding current 138
 - multiport nozzles 140
 - nickel alloy welds 143
 - orifice diameter 140
 - plasma gas flow rate 139
 - plasma power 139
 - pulsed keyhole plasma 142
 - reverse polarity plasma 141
 - shielding gases 140
 - titanium welds 143–4, 264
 - variable polarity plasma 142
 - welding speed 139
- plasma welding 13–14, 85–9
 - control systems 98
 - equipment requirements 87–8
 - features and applications 88–9
 - high-current 89
 - intermediate-current 89
 - low-current 89
 - microplasma 89
 - modes of operation 88
 - non-transferred arc mode 87
 - shielding gases 68
 - transferred arc mode 86
- point-to-point with interpolation systems 231
- pool depression 214
- positioners and manipulators 222
- post-weld operations 20
- power beam welding 235–6
- power source technology 26–43
 - basic power requirements 26–7
 - design features of power sources 27
 - dynamic characteristics of power supply 30–1
 - for electron beam welding 163
 - electronic power regulation systems 31–9, 42–3
 - function control 39–42
 - for GMAW 117–19
 - magnetic amplifiers 29–30
 - moving-iron control 28–9
 - output levels 39–42
 - Scott connection system 26
 - sequence control 39–42
 - static characteristics of power supply 30–1
 - tapped transformers 27–8
 - variable inductor control 29
- pre-weld sensors 207–8
- pressure welding 2, 3–8
- primary-rectifier inverters 35–6
- procedures
 - amendment 183
 - control 180–7
 - development 180–1
 - management 184–7
 - monitoring 187
 - qualification 184
- process application trends 22–5
 - advanced materials 24–5
 - automation 23–4
 - consumable trends 22–3
 - new processes 24
- process control
 - automation and robotics 236–7
 - electron beam welding 159
 - computer control 162–3
 - GMAW 113–20, 128–34
 - GTAW 91–8
 - laser welding 151
 - plasma keyhole welding 138–44

- plasma welding 98
- remote-control 237–8
- robotic welding 228–9
- TIG systems 98
- process monitoring *see* monitoring
- programmed touch striking 76
- programming parameters 41–2
- programming robotic systems 229–31, 239–40
 - off-line programming 239–40
 - program storage 231–2
- projected spray transfer 102–3
- pulsed flux-cored wire welding 125–6
- pulsed GMAW 120–1, 124–5
- pulsed GTAW 79–81, 98
- pulsed keyhole plasma 142
- pulsed laser output 151
- quality
 - and automation and robotics 219
 - control systems 17–18, 215–16
 - and improved repeatability 42
 - of joints 17–18
- radiographic control 215
- rapid prototyping 241
- rare-earth elements 47, 78
- recoil pressure 158–9
- record keeping 184
- rectifiers 26–7
- reduced gap GMAW 170
- remote-control systems 237–8
- resistance welding 3–4, 227, 233–4
- reverse polarity plasma 141
- RF excitation systems 156
- rim formation 78–9
- robotic welding 23–4, 225–36
 - applications 233–6
 - arc welding 228
 - cartesian robots 226–7
 - component tolerances 233
 - control systems 228–9
 - drive systems 227
 - gantry robots 226–7
 - jigging system 232
 - joint design 233
 - laser welding 228
 - mechanical manipulation systems 225–7
 - operator interface 229
 - PLAY mode 230–1
 - point-to-point with interpolation 231
 - position of the arm 228–9, 232
 - power beam welding 235–6
 - programming 229–31, 239–40
 - program storage 231–2
 - resistance welding 227, 233–4
 - safety 232
 - SCARA configuration 226, 230, 231
 - seam welding 234–5
 - TEACH mode 230, 231
 - teach-by-doing 230–1
 - torch cleaning 232
 - TRACE mode 230–1
 - welding package 227–8
 - work flow 233
 - see also* automation
- roll bonding 5
- rotating transfer 107–8
- rutile flux-cored wires 53, 108–9, 125
- safety 21
 - and automation and robotics 218–19, 232
 - and electron beam welding 161
 - and laser welding 154–5
- SAW *see* submerged arc welding (SAW)
- SCARA configuration 226, 230, 231
- Scott connection system 26
- SCR (silicon-controlled rectifiers) phase control 31–3, 36
- seam welding 224, 234–5
- secondary switched transistor power supplies 34–5
- selection of welding processes 181
- self-shielded flux-cored wires 52, 53, 54, 109
- Sellafield 220
- sensors 206–11
- shielded metal arc welding (SMAW) 9–10
 - electrode classification 250–3
- shielding gases 58–73
 - arc stiffness 59
 - arc support and stability 58–9
 - argon 58, 63, 64–5, 67–8, 72–3
 - argon/chlorine mixtures 70
 - argon/Freon mixtures 70
 - argon/sulphur dioxide mixtures 70
 - atmospheric contamination 59–60

- carbon dioxide 63–4, 64–6
- chlorine 70
- ease of ionization 58
- for FCAW 69
- Freon 70
- fusion characteristics 61–2
- gas-metal reactions 60
- for GMAW 64–7, 68
- for GTAW 67–8, 94
- helium 59, 63, 66–7, 72
- hydrogen 58–9, 60, 64, 72
- and joint properties 62
- for laser welding 71–2, 148–9
- for MIAB 69
- for narrow-gap welding 171–2
- nitric oxide mixtures 70–1
- nitrogen 60, 68
- oxygen 64
- for plasma keyhole welding 140
- for plasma welding 68
- sulphur dioxide 70
- thermal conductivity 58–9
- short extensions on electrodes 54–5
- simple mechanization systems 219–22
- simulation 239–40
- single-knob control 41–2, 128–34
- skill requirements 21
- slag protected transfer 108–9
- slag shielding flux-cored wires 51
- SMAW *see* shielded metal arc welding (SMAW)
- social implications of automation and robotics 245
- solid filler wires 47–5
- sound measurement 212
- special-purpose automation 223–5
- spectral radiation sensors 212–13
- speed measurement 196
- stability monitoring 197–8
- statistical process control 201–3
- steel
 - carbon steel welds 64–6, 142, 153
 - carbon steel wires 48, 52–3
 - ferritic steel wires 47–8
 - stainless steel flux-cored wires 54, 69
 - stainless steel MMA 45–6
 - stainless steel welds 66–7, 142, 153
- sticking electrodes 43
- stitch welding 224–5
- streaming transfer 103–4
- structured light/vision sensors 209–10
- stud welding 6
- submerged arc welding (SAW) 11–12, 46, 46–7
 - filler materials 46–7
 - iron powder additions 46–7
 - multipass per layer technique 176
 - narrow-gap SAW 175–7
 - single-pass technique 175
- sulphur dioxide 70
- supply flexibility 219
- surface tension 113
- synergic control 128–34
- tactile sensors 206–7
- tapped transformers 27–8
- teach-by-doing 230–1
- temperature measurement 193–4
- thermal conductivity of shielding gases 58–9
- thermocouple sensors 193–4
- thermographic sensing 216
- thoriated electrodes 78
- through-arc sensors 208
- TIG *see* tungsten inert gas (TIG) welding
- time measurement 196
- titanium welds
 - laser welding 154
 - plasma keyhole welding 143–4, 264
- torch cleaning 232
- torch oscillation 172–4
- touch striking 75, 76
- toughness
 - and submerged arc welding (SAW) 46
 - of weld metal 45
- tractor systems 220–1
- training 21
- transfer behaviour *see* metal transfer
- transformers *see* power source
 - technology
- transistor series regulator 33
- tungsten inert gas (TIG) welding 8–9, 60
 - Activated TIG (A-TIG) 91, 97
 - control systems 98
 - Paton Activated TIG (PA-TIG) 91
- twist arc technique 172
- ultrasonic penetration control 214
- ultrasonic sensors 210–11
- user parameter selection 132–3

- vacuum EBW 161
- validity of parameters 184–7
- vapour jet forces 112–13
- vapour pressure 158–9
- vapour shields 162
- variable inductor control 29
- variable polarity GTAW 81–2
- variable polarity plasma 142
- vertex angle 94–5
- visible spectrum monitoring 203
- voltage measurement 196, 211–12
- voltage oscillation 214
- voltage-current characteristics 116–17
- waveform representation 191–2
- wear replacement 241–2
- weight loss of electrodes 78–9
- welding procedure specification (WPS)
182
- wire feed systems 82–3, 117
- wire oscillation 172–4
- wolfram inert gas (WIG) welding 8–9
- work flow 233
- worm tracks 55