HANDBOOK OF STRUCTURAL WELDING

Processes, materials and methods used in the welding of major structures, pipelines and process plant

John Lancaster

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Preface

So far as the fabrication of heavy equipment is concerned, fusion welding has been a slow starter. Welding with a stick electrode was invented in the 1890s, but it was not applied to large structures to any significant extent for half a century. There were, of course, exceptions. The technique of stovepipe welding for pipelines was developed in the USA during the 1920s, and has survived more or less unchanged to the present day. However, not all of the early welding applications were so successful. A torpedo-boat was fabricated by welding in 1895; unfortunately the material chosen was the aluminium, 6% copper alloy, which is highly susceptible to stress corrosion cracking, and the boat did not survive long enough to demonstrate its military potential.

Structural welding on a large scale began with the construction of Liberty ships and T2 tankers in the Kaiser shipyards during World War II. To many welding technologists these ships epitomize catastrophic brittle fracture, and a picture of the 'Schenectady', which broke in two whilst moored in calm water, is still sometimes used to chill the hearts of aspiring young welding engineers. In fact, the Kaiser shipbuilding effort was a major success, enabling large quantities of supplies to be shipped from the United States across all the oceans of the world. Even some of those ships that suffered catastrophic failure were (unlike Humpty Dumpty) put together again and subsequently provided years of useful service. More important, perhaps, was the fact that fusion welding then became the norm for the fabrication of boilers, pressure vessels, bridges, structural steelwork and, of course, shipping.

In the post-war years such applications have stimulated a remarkable development of welding technology, and processes have multiplied at a considerable rate. Materials have likewise changed, very much for the better as far as welding is concerned. The original incentive for the invention of the basic oxygen converter was to increase steelmaking capacity, but from this and other improvements such as hot metal desulphurisation has emerged a new generation of clean steels that possess the levels of notch-ductility and through-thickness ductility essential for heavy structural fabrication.

It is the purpose of this book to describe the current state of welding technology as applied to large structures, and to say something of the problems that have been encountered in this work, together with the means that are used to assure reliability. Recent steelmaking developments have been included because, as noted earlier, they are highly relevant to the integrity of welded structures.

It seems likely that some major hazards, in particular catastrophic brittle fracture, are now avoidable but others, such as fatigue failure, will continue to present difficulties in the future. It is increasingly necessary for engineers at all levels to be aware of such problems and to take all reasonable steps to avoid them. It is hoped that this book will help to promote such awareness, and, in a small way, contribute to the increasing dependability of welded fabrication.

The author would like to acknowledge the encouragement and help of colleagues and friends in assembling this material, but most particularly wishes to thank his wife, Eileen, for her contribution to the finished manuscript. Thanks are also due to Ralph Yeo for advice on welding processes, to Peter Lane of Lloyds Register and to staff at The Welding Institute (now TWI), in particular Richard Dolby and Trevor Gooch for helpful advice. The librarians at TWI have given most valuable assistance in providing literature. And finally the author acknowledges the help of companies such as Cooperheat and Magnatech, who furnished background materials and illustrations.

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Contents

1 Processes

Introduction

The materials with which this book is concerned are used in the fabrication of process plant for power generation, or for structures such as steel buildings, bridges and offshore oil rigs. The joining method appropriate to this field of construction is predominantly fusion welding. Exceptionally a solid-phase process may be practicable, as for example in the longitudinal welding of pipe and tube using the electrical resistance welding process.

Amongst the more industrialized nations competition provides a spur to seek more economical methods of fusion welding. One route to greater productivity is through automation and by the use of robots, and to this end the process must be capable of operating consistently over as long a period of time as possible. When automatic techniques are not practicable the use of gas metal arc (GMA) welding, where wire is fed continuously, gives higher deposition rates than welding with coated electrodes as shown for the case of fixed position welding on an offshore oil rig in Table 1.1.[1]

Consequently there is a trend towards increased use of GMA welding and a corresponding decrease in that of coated electrodes. At the same time variants of the GMA process have been developed so as to widen the current range over which it can be used, make it applicable to all-position welding and generally to increase its versatility. One of the most important contributions to such improvements has been through changes in the design of welding power sources. This has been made possible by the availability of high power switching devices;

Table 1.1 Typical deposition rates for welding of carbon steel in offshore fabrication

Process	Position	Deposition rate, kg/hr (lb/hr)
Manual metal arc 7018	All	1.2–1.8 (2.6–4.0)
Self-shielded flux-cored	All	1.5–2.0 (3.3–4.4)

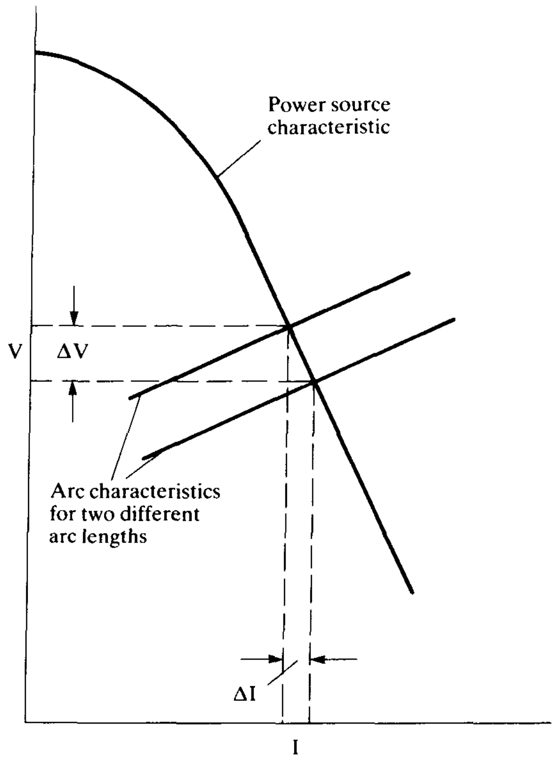
firstly the thyristor and later, high power transistors. So before discussing fusion welding processes, it will be convenient to describe these power source developments, particularly as they have also proved to be applicable to welding and cutting operations other than GMA.

Welding power sources

Simple machines consist of a transformer with, typically, a three-phase AC output with an open-circuit voltage of 65–100 V: a level which is usually considered low enough to be safe. Current control is obtained either by taking different tappings on the secondary coil or by moving the transformer core. Alternatively for site work, a rotating power source may be driven by an internal combustion engine. In the past, AC was more commonly used in Europe and Japan but US fabricators preferred DC for quality work. Almost all welding was carried out using stick electrodes and the machines were traditionally designed to have a drooping characteristic. In this way, the change in current produced by any inadvertent change in arc length (with corresponding change in arc voltage) is minimised, so helping to maintain steady welding conditions (Fig. 1.1).[2] The availability of solid state rectifiers has led to a more general use of DC, and simple transformer-rectifier sets are often employed for welding with coated electrodes.

More recent developments owe much to a need to improve the operating characteristics of pulsed arc welding (see later in this chapter). The first pulsed arc machines were only capable of pulse frequencies of either mains frequency or multiples thereof, and were dynamically slow, such that the process was difficult to use (Fig. 1.2a).[3] Variable frequency sources were required, and these became available as a result of the development of a transistor chopper controlled regulator in the early 1970s. Figure 1.2b illustrates a typical circuit. Such machines were however large and expensive, and largely used for research and development. An improved version, which became commercially available, utilised solid state power devices on the output side of the transformer to generate pulses.

The third generation of pulsed arc machines (Fig. 1.2c) is a radical departure. The three-phase power supply is first rectified, and then inverted to high frequency AC. The AC is fed to a transformer, the output of which is rectified and provides either a pulsed or steady DC source. For pulsed current, the switching is carried out using power transistors or thyristors on the primary side of the transformer, and this makes possible a nearly square wave shape for the pulse. When the switch is on the secondary side, however, the wave form is trapezoidal (Fig. 1.3).[4] The high frequency transformer requires a smaller core than a normal mains frequency type, such that the weight and volume of an inverter power source is about half that of a

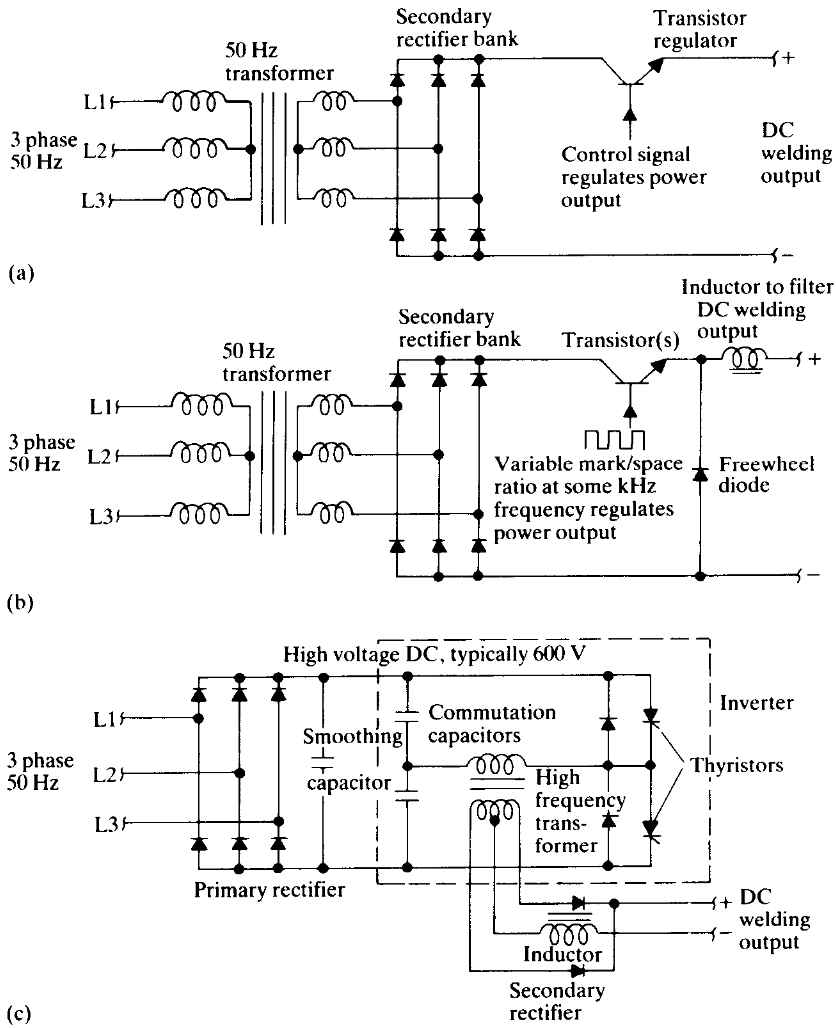


1.1 Effect of changing arc length on welding current.[2]

conventional type, whilst the price, although higher, may well be justified by improved performance.

Apart from pulsed arc welding, current pulsing may be useful in gas tungsten arc (GTA) or plasma welding, in short circuiting and flux-cored GMA welding, and in high speed plasma cutting. Inverter power sources may also be used primarily for portability, for example in low current (below 50 A) plasma cutting machines and for site welding.

Thus the number of types of welding power source has multiplied remarkably, as has the number of welding processes. Figure 1.4 shows a classified list of power sources used in Japan, in which the listing relates to the control system.[5] Within such general categories, there are various types adapted to particular processes or to a range of processes; for example, in 1989 one company listed seven types of inverter source[3], whilst the old moving core or stepped voltage AC welding set was at that time still available. The general tendency with all power sources however is towards electronic control both on the input side (to compensate for fluctuations in mains voltage) and on the

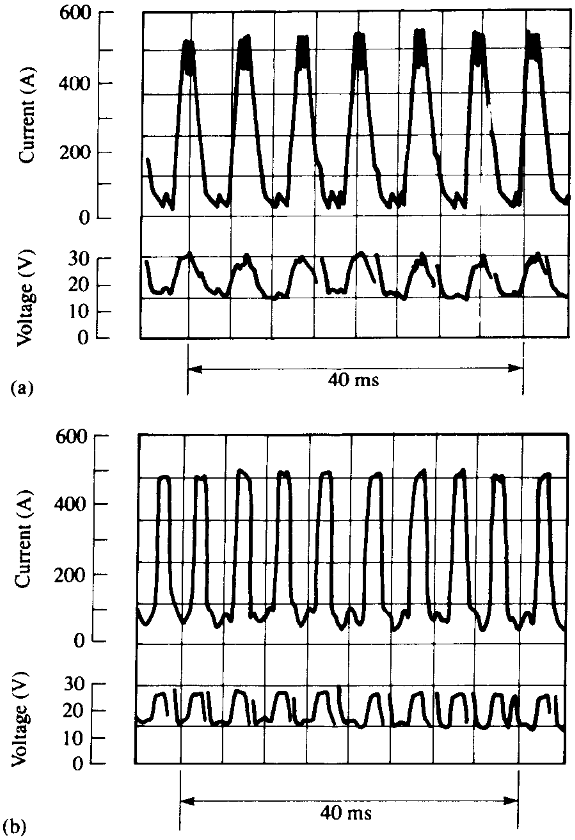


1.2 Various types of pulsed GMA welding power sources:[3] a) 50 Hz secondary transistor regulator; b) Secondary transistor switched mode regulator; c) Primary switched inverter.

output side to provide a minimum stepless control of both current and voltage.

Gas tungsten arc (GTA) welding

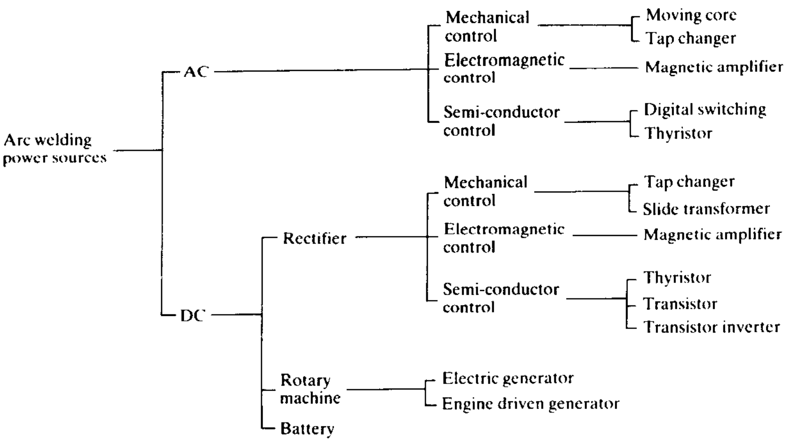
This process became established in industry after the Second World War, mainly for welding austenitic chromium-nickel steels and



1.3 Oscillograms of voltage and current for: a) Conventional pulsed power source (trapezoidal wave): b) Inverter type (rectangular or square wave) (source: Daihen Corporation).[4]

non-ferrous metals, particularly aluminium. It provides a heat source only and filler metal must be added separately. In this and other respects it resembled the oxyacetylene and carbon arc welding processes which it rapidly displaced. Originally called tungsten inert gas (TIG) welding, it was redesignated gas tungsten arc welding by the American Welding Society because for some purposes argon-hydrogen, argon-nitrogen or pure nitrogen gas shields are used. However in the UK and in Europe the title tungsten inert gas welding is still employed.

An argon gas shield containing 2–5% hydrogen may be employed in welding austenitic stainless steels and nickel alloys to reduce oxidation and obtain higher welding speeds. Nitrogen and argon-nitrogen mixtures may be used for copper and provide a higher heat input rate for any given current. Helium-argon mixtures (typically 76He 25Ar) also



1.4 Classification of arc welding power sources.[5]

increase the heat input rate and are applicable to most metals, particularly aluminium, stainless steel and nickel-base alloys. Pure (99.95%) argon is the most commonly used shielding gas.

The process is operated by striking an arc between the tungsten electrode and the workpiece, with shielding gas flowing through a nozzle disposed circumferentially around the electrode. In the majority of applications the current is DC, electrode negative (straight polarity, as opposed to reverse polarity which is electrode positive). For aluminium it is normal to use AC because during the electrode positive part of the cycle the cathode removes oxide from the surface of the weld pool. However if a helium or argon-helium mixture is used for the gas shield it is possible to obtain good fusion of aluminium with electrode negative. This process is used for the automatic seam welding of irrigation tubes, and also for welding seams in vessels where a high quality weld free from porosity is required, as in the nuclear industry. With DC the heat input to the workpiece per ampere is substantially greater than with AC so that the DC automatic process is faster and capable of welding thicker material: up to 25 mm. For descriptive purposes it is convenient to consider the process in three parts: the electrode, the arc column and the weld pool.

The tungsten electrode

In DC operation the electrode is typically a rod 1.5–3.5 mm diameter ground to a conical tip. Pure tungsten is not used because the tip of the cone melts and the cathode spot moves over the molten drop, making the arc difficult to control. The most common electrode material is thoriated tungsten; this contains 1.5–2.0% ThO_2 and operates (at normal welding currents of say 200 A and below) without melting. At the high temperature of the electrode tip the thorium oxide is reduced by tungsten to form thorium, which diffuses to the electrode surface. Thorium-coated tungsten has a lower electron work function than the pure metal and therefore can emit the required electron current density (which is of the order of 10^7 A/m^2) at a lower temperature.

In automatic welding operations electrodes may be required to operate for extended periods of time and the thoria content may be reduced due to evaporation, so that the arc may become unstable. To improve electrode life various alternative additions have been made to tungsten, notably the oxides of cerium, lanthanum and yttrium. Such rare additions react with tungsten to form tungstates or oxy-tungstates, which also diffuse to the electrode surface. Here they have two effects; firstly to reduce the electron work function and secondly to increase the thermal emissivity.[6] Table 1.2 shows the results of measurements suggesting that rare earth additions could indeed improve GTA electrode performance, and that in particular lanthanated electrodes should perform well.

Other factors that may contribute to longer electrode life are tungsten grain size and tip shape. Diffusion of both thorium and rare earths is largely intergranular, and both are exhausted more slowly in coarse-grained material. The cone angle, if too small, may result in overheating and disintegration. A cone angle of 60° appears to be a good choice.

These considerations do not necessarily apply to welding with AC which is normally used for aluminium. For any given arc current the rate of heat liberation at the electrode is greater when it is anodic than when it is a cathode; consequently all these materials melt at the tip although thoriated tungsten may still have some advantage. Using say a 6 mm diameter electrode gives better cooling and normally permits stable operation but there is a limiting current above which drops of tungsten may be emitted by the electrode, giving rise to tungsten inclusions in the weld.

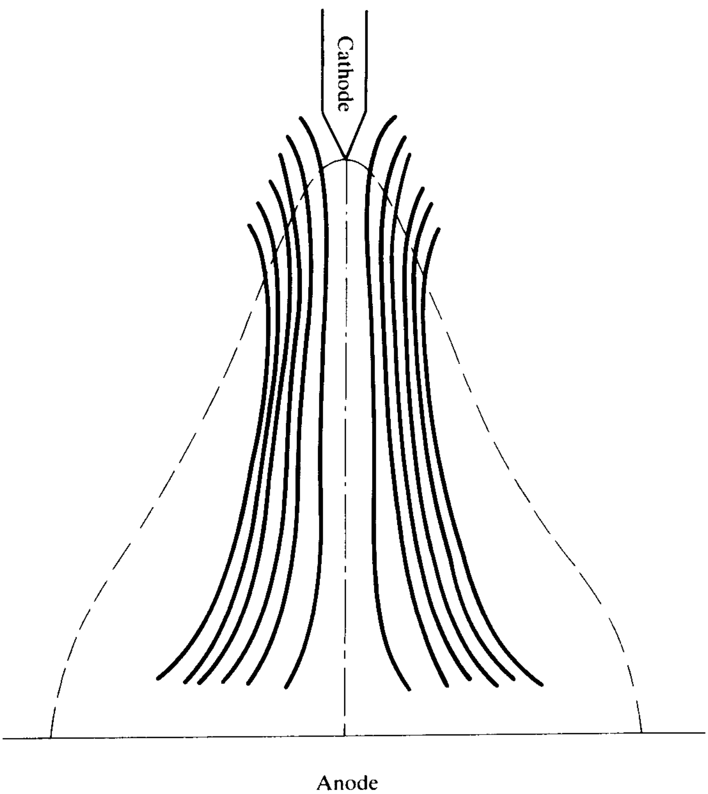
Table 1.2 Tip temperature, emissivity value and work function for several electrodes after 30 min of arcing at 150 A in pure argon[6]

	Electrical material		
	W/ThO_2	W/CeO_2	W/La_2O_3
Tip temperature, °C	3340	2800	2440
Emissivity	0.18	0.22	0.30
Work function, eV	2.38	2.14	2.0

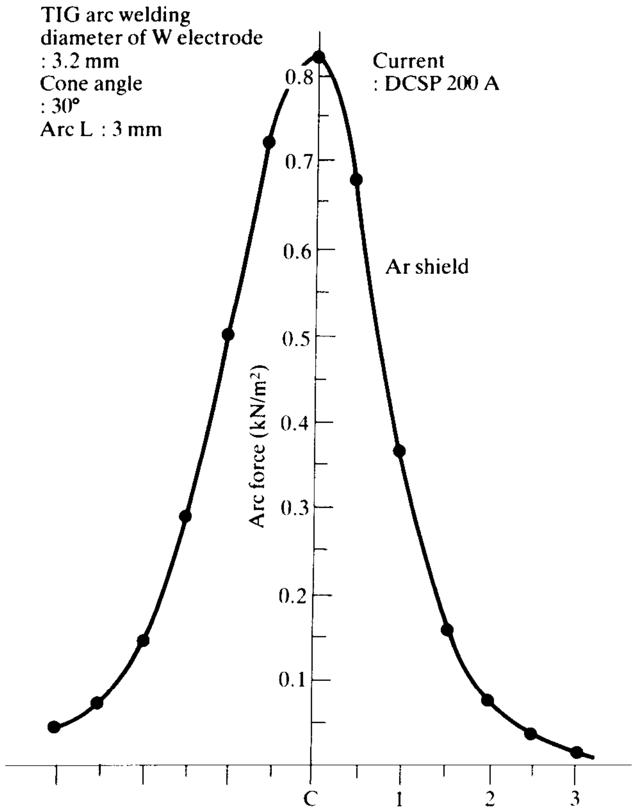
The GT arc column

Axial flow rate in the GT arc column are of the order of 100 m/s for currents in excess of 100 A, and lend the quality of stiffness to the arc. The flow is from electrode to workpiece as shown in Fig. 1.5 and is jet-like.[7] It is caused by the electromagnetic forces induced by the interaction between the arc current and its own magnetic field. Impingement of this jet on the weld pool results in a stagnation pressure. Figure 1.6 gives the pressure distribution on the anode for a 200 A argon-shielded TIG arc.[8] The total force due to this condition is about 5×10^{-3} N, and it is not sufficient to cause the deep depression of the weld pool surface (the crater) that is characteristic of submerged-arc or manual metal arc welding (MMA). The arc force may be reduced by using helium as a shielding gas or by increasing the cone angle of the electrode tip. It may be increased (to obtain greater stiffness) by using a pulsed current in the range 5–10 kHz. This effect may be useful for welding at currents below 100 A.

Except for welding in an enclosed chamber there is always some degree of oxidation of the weld pool in argon-shielded GTA welding.



1.5 Streamlines of electromagnetically induced flow in the column of a GT arc.[7]



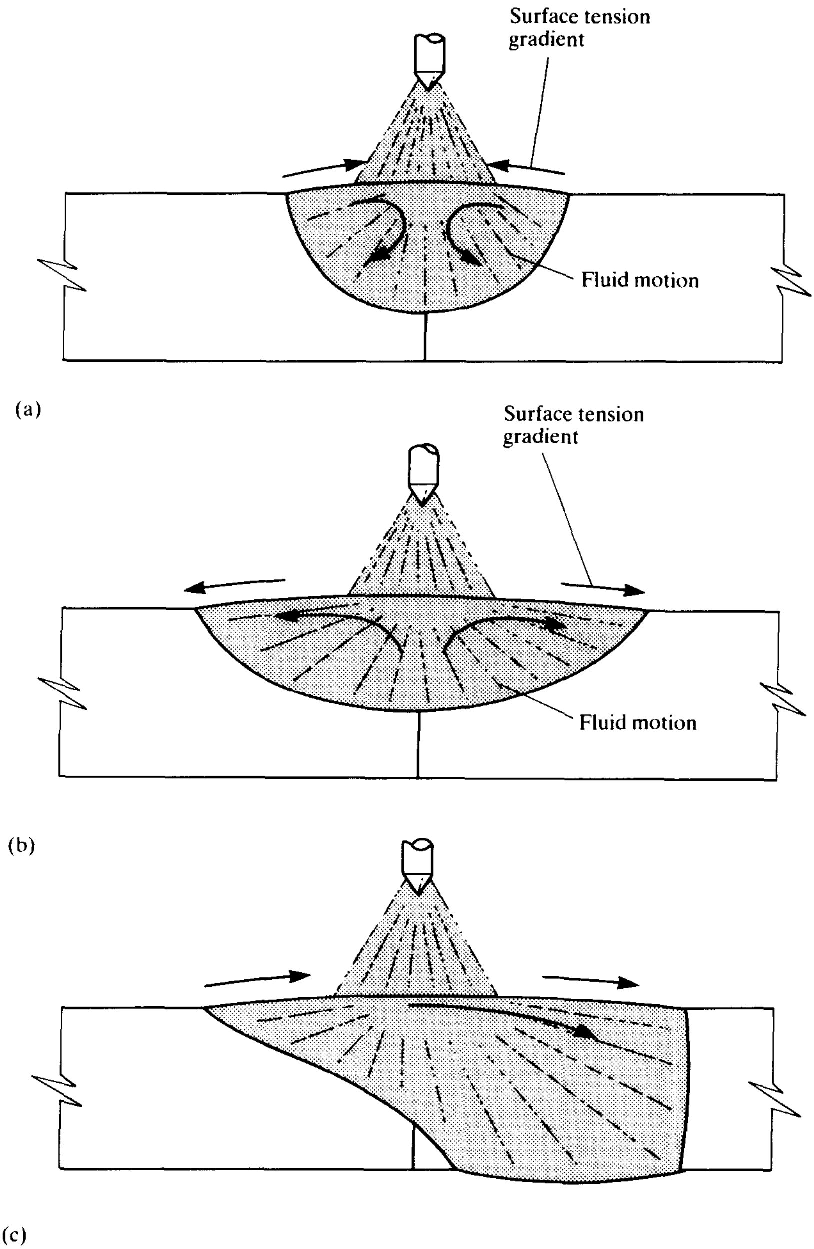
1.6 The pressure distribution on the anode of a 200 A arc in argon.[8]

Such oxidation is probably due to the action of the plasma jet in drawing in contaminated argon from the outer region of the gas shield.

The weld pool

The pool is subject to electromagnetic, buoyancy and surface tension forces, as well as shear forces due to the outward spread of the plasma jet. For short (say 2–4 mm) arcs used in welding the surface tension force is potentially the strongest. In a pure metal surface, tension decreases with increasing temperature, and in a weld pool with a negative temperature gradient from centre to edge, this could result in a shear force at the surface acting in an outward direction. This in turn may generate an outward flow of metal across the surface, giving a relatively wide, shallow pool (Fig. 1.7 illustrates the mechanism).

In practice weld metals are not pure and in particular are contaminated



1.7 Flow in a GTA weld pool induced by a gradient of surface tension:[9] a) Inwardly-directed surface flow, associated with the presence of surface-active elements; b) Outwardly-directed surface flow, as in a pure metal; c) A combination of normal sulphur steel on the left with low sulphur steel on the right.

with oxygen (from the plasma jet) and, in steel, with sulphur. In steel both these elements are surface-active, and in their presence the surface tension gradient with temperature becomes zero or positive. Normally, therefore, the flow in the weld pool is relatively sluggish and the profile of the fusion boundary is more or less semicircular, as would be expected in the absence of flow.

Abnormal conditions, however, may prevail in welding austenitic stainless steels. These alloys are aluminium killed and when the residual aluminium content is 0.01% by mass or greater, the oxygen content of the liquid metal is very low, even when there is oxide on the surface. Thus, if the sulphur is also low (say below 50 ppm) the alloy behaves like a pure metal, and there is an outward flow across the surface of the weld pool which convects heat in a radial direction. In this way the depth/width ratio of the fused zone may be reduced from a normal value of about 0.5 to as low as 0.2. Also, welding a normal-sulphur to a low-sulphur steel can give an asymmetric fused zone, as shown in Fig. 1.7.[9]

Such conditions can be avoided by specifying a lower limit for the sulphur content. Too much sulphur makes the alloy susceptible to hot-cracking during welding, and it has been proposed that the sulphur content of austenitic stainless steel be maintained between 0.01% and 0.02% by mass.

Similar effects have (exceptionally) been observed with ferritic steel. Using the oxygen converter it is practicable to manufacture steel of very low impurity content, and although this may improve the notch-ductility of the unwelded material it may not benefit welded joints. Apart from loss of control of penetration, such steels may suffer greater hardening in the heat affected zone. Calcium-treated steel is particularly subject to variable penetration because calcium reacts with sulphur and removes it from solution, as does aluminium with oxygen.

Except for AC welding of aluminium, the weld pool forms the anode of the arc. In argon or helium this is normally a diffuse region and, unlike the cathode, is not fixed to any point on the metal surface. At low currents and at high welding speeds, however, a fixed anode spot may form and cause the arc to move forward discontinuously. This defect can be overcome by applying a pulse of 5–10 kHz to the arc current.

Anode spots may also be formed around patches of oxide on the weld pool surface; these move along with the weld pool but may distort the heat flux distribution and modify the fused zone profile.

AC welding

During the electrode positive part of the current cycle the workpiece becomes the cathode and emits electrons. The mechanism of electron