Chapter 9
Gas Tungsten Arc Welding

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Abstract Gas tungsten arc welding (GTAW) utilises an intense electric arc formed between a non-consumable tungsten electrode and the workpiece to generate controlled melting within the weld joint. Essentially, the arc can be used as if it was an extraordinarily hot flame. The stability of the tungsten electrode and the option to use totally inert gas mixtures if desired means that the process can be very clean and easy to implement. It is also a process with the potential to deliver relatively high-power densities to the workpiece, and so can be used on even the most refractory metals and alloys. In this chapter, principles of GTAW including energy transport, momentum transport and weld pool behaviour which are required to understand and control heat source properties of GTAW are reviewed in detail. Furthermore, future trends of applications of GTAW are also described.

Keywords Arc welding · Tungsten · Arc plasma · Heat source properties

9.1 Introduction

Gas tungsten arc welding (GTAW) first made its appearance in the USA in the late 1930s, where it was employed for welding aluminium airframes. It was an extension of the carbon arc process, with tungsten replacing the carbon electrode. The new tungsten electrode, together with an inert helium shielding gas atmosphere, reduced weld metal contamination to the extent that highly reactive metals such as aluminium and magnesium could be welded successfully. For a time, the process was known as 'heliarc' in the USA. Other countries substituted the less expensive argon for helium and referred to the process as 'argon arc'. Later, these distinctions were dropped and the process became known as tungsten inert gas (or TIG)

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welding. More recently, the term gas tungsten arc (GTA) has been introduced to signify that the shielding gas may not necessarily be inert.

GTAW is known for its versatility and high joint quality. It can be used with a wide variety of materials, including highly reactive or refractory metals. It may be operated manually at lower currents (e.g. 50–200 A) for single-pass joining of relatively thin sections, or multi-pass welding of thicker sections that have appropriate V- X- or similar-type edge preparations.

During the 1960s, the process was extended to much higher current range, allowing the arc forces to play a significant role in increasing weld penetration. At currents above about 250 A, the arc tends to deform the weld pool surface, with the effect increasing as the current is increased further. This mode of operation is generally automated, and in its early manifestations gave rise to terms such as high current, buried arc, and subsurface arc TIG (or GTAW). Plasma arc welding also has its origins in the GTAW process. More recent innovations have included the introduction of active fluxes (A-TIG), dual shield GTAW, guided GTAW, keyhole GTAW, and laser-GTAW hybrid processes.

Understanding of the GTAW process involves input from many disciplines. Although appearing relatively simple, application of the process involves many choices including electrode size and composition, electrode tip geometry, power supply characteristics, electrode polarity, shielding gas, welding current, and voltage settings. Each of these will be related to the type of material and its joint geometry. The complexities and the importance of the GTAW process have stimulated research which is still very active more than 60 years after its introduction.

9.2 Principles

9.2.1 Energy Transport

GTAW utilises an intense electric arc ignited between a non-consumable tungsten electrode and the workpiece to produce controlled melting within the weld joint. Essentially, the arc can be used as if it was an extraordinarily hot flame. The stability of the tungsten electrode and the option to use totally inert gas mixtures if desired means that the process can be very clean and easy to implement. It is also a process with the potential to deliver relatively high-power densities to the workpiece, and so can be used on even the most refractory metals and alloys. It can be misleading to refer to arc temperatures as a measure of melting ability, but the intent can be captured in the measure of power density. Using this one finds that GTAW processes produce power densities at the weld pool of up to 100 W/mm^2. For comparison, this is at least an order of magnitude greater than is available from an oxyacetylene flame. The power density delivered to the workpiece is important in determining the process efficiency and can be a significant constraint when using with highly conductive metals such as copper.

Under standard conditions, all shielding gases are extremely good electrical insulators because of the small degree of ionisation of the gas. The current densities typical of welding arcs (of the order of tens of amps per square millimetre) can only be achieved if a high concentration of charged particles can be generated and maintained in the conducting channel. In arcs, the necessary populations of electrons and ions are maintained by thermal ionisation and this requires temperatures of about 10 000 K and above.

The degree of ionisation of a gas can be expressed as a function of temperature by the Saha equation [1]. The resultant conductivity is then determined from consideration of the charge mobilities, as can be found in standard texts, e.g. [2] and [3]. An example of dependence of conductivity of argon on temperature is shown in Fig. 9.1 [1].

It is now known that the current density in an arc column has a limiting value under normal conditions. Once this limit is reached further increases in total current only distribute the current over larger areas of the anode, with no appreciable change in peak current density on the arc axis [4]. In the case of argon, the conductivity increases until doubly ionised argon appears at about 22 000 K. At this point, the resistance provided by the doubly charged ions outweighs the benefit of the increased number of electrons and so conductivity reaches a local maximum (see Fig. 9.1). Once this temperature has been reached in a particular region, further increases in current will tend to expand the current distribution into the adjacent, slightly low-temperature regions [5].

For a very preliminary research of the welding arc, its main section can be treated as one-dimensional, i.e. as a function of radius, r, only. Such an approach, introduced by Glickstein in 1981, began with a simple model for the positive column in which ohmic heating was balanced against radial thermal conduction:

$$\sigma E^2 = \frac{-1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right)dr \tag{9.1}$$

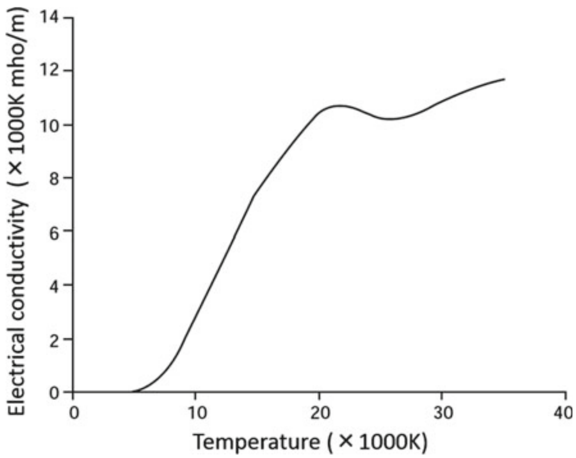

Fig. 9.1 Dependence of the electrical conductivity of argon on temperature from 3000 to 30 000 K

In the above equation, σ is the electrical conductivity, E is the electric field, r is the radius from the arc axis, k is the thermal conductivity and T is the temperature. Equation (9.1) is known as the Elenbaas–Heller equation. This equation can be corrected for additional energy losses through radiation, S(T), [1] and it is then known as the 'corrected Elenbaas–Heller', Eq. (9.2):

$$\sigma E^2 = \frac{-1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right)dr + S(T) \tag{9.2}$$

Since the electrical and thermal conductivities of shielding gases have complicated temperature dependencies, as shown in Fig. 9.1, these equations can only be solved numerically. Nevertheless, the view of an arc in which radial conduction and radiation balance ohmic heating is easily visualised and so is useful in developing a qualitative understanding of arc behaviour. For example, Glickstein's solutions predicted that helium arcs should be much broader than those of argon despite peak temperatures and current density distributions being similar. Consequently, helium arcs should require higher voltages than argon arcs do—as is observed—since the energy is derived from the electric field. Similarly, it can be appreciated that vapour contamination or minor additions of a gas of lower ionisation potential should significantly alter the arc configuration.

An appreciation of the welding arc with the Elenbaas–Heller equation has two fundamental limitations: there is no consideration of the regions connecting the plasma to the electrodes and the omission of convection within the arc.

The very narrow regions between the electrode surfaces and the arc proper are known as sheath regions. In these regions, the high temperatures (∼10 000 K) needed for good electrical conductivity in the gas cannot be sustained due to the cooling provided by the cold electrodes (even the boiling temperature of iron is thousands of degrees below that required for argon to conduct well). Consequently, the electrical conductivity of the gas will be extremely low. Because of the high resistivity close to the electrodes the electric field of the arc will be very much stronger in these regions than elsewhere. This is equivalent to saying that the field has a nonzero divergence and according to Maxwell's equations must be associated with the presence of net electric charge:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \tag{9.3}$$

Or, in one dimension:

$$\rho = \varepsilon_0 \frac{dE}{dx} \tag{9.4}$$

Consequently, sheath regions will be bounded by regions of charge, one on the electrode surface and the other at the interface with the plasma. This latter constitutes a region of space charge. The corresponding voltage drops are sometimes known as 'fall' voltages (see Fig. 9.2).

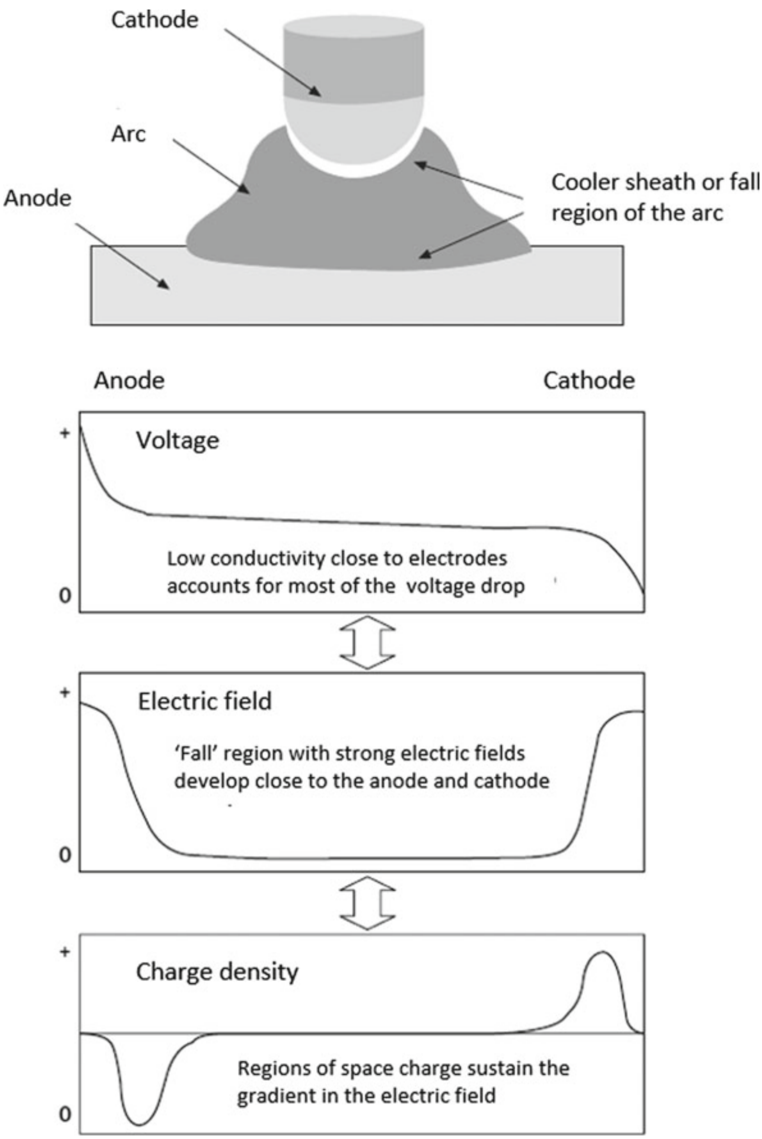

Fig. 9.2 Schematic illustrations of the variation in voltage, electric field and charge densities with position along an arc discharge

The sheath regions are extremely important to determine the particular characteristics of an arc and to establish the overall energy balance. In welding arcs, the predominant charge carriers are electrons and these must be continually replenished by being drawn out of the cathode and across the cathode sheath. Liberating electrons from a metal surface requires a considerable amount of energy—each electron absorbing at least an amount eϕ where ϕ is the work function of the surface (typically 2–4 V). If the metal is suitably refractory (such as tungsten or hafnium), this can be provided by the high temperature of the electrode and is then known as thermionic emission. In this case, the electrons effectively evaporate from the surface. If the temperature of the electrode is not high enough, the electrons must gain their energy from the very high-strength field between the surface and the surrounding space charge. This is termed field emission. GTAW is generally operated in the thermionic emission mode. Electron emission is aided by the presence of oxides and other surface impurities.

The electrons leave the arc by crossing the anode sheath and entering the anode, which is usually the workpiece. The anode sheath is believed to be of the order of one electron mean free path in width, to be consistent with its relatively low temperature. In crossing this and entering the anode, the electron transports a considerable portion of the total energy flux. The energy contribution of each electron to the anode includes its thermal energy, the energy it absorbs from the anode fall, and its energy of condensation, eϕ. In some cases, this can amount to as much as 80% of the total energy flow into the anode. The other major source of energy transport to the anode is conduction and here the characteristics of the shielding gas become important. For example, helium is far more conductive than is argon and consequently delivers more heat—hence, the perception that it makes an arc 'hotter'. Gases such as hydrogen and nitrogen exhibit what is known as 'reactive thermal conductivity'. They dissociate at high temperatures with the absorption of significant amounts of energy, only to recombine and release this energy in the cooler regions such as the anode sheath. So these gases are also associated with 'hot' arcs. In addition to electron absorption and conduction, convection and radiation also transport energy. Convection in particular becomes very important as currents rise above 40 A or so [6] and may be the dominating transport mechanism outside the sheath regions. Convective flow is powered by Lorentz forces associated with the passage of the high welding currents and has an impact on the momentum as well as on energy transferred to the weld pool. Present numerical models of welding arcs endeavour to incorporate all these effects [6, 7] but there is still much development to be done.

9.2.2 Momentum Transport

At currents below about 200 A, the gas tungsten arc has many characteristics of an ideal flame. It can be chemically inert, it produces very high heat fluxes to the workpiece, and it appears to produce almost no disturbance to the molten metal it produces. But despite the absence of metal transfer, the arc does transport momentum and this becomes important at higher currents. The momentum transfer and several of the resultant forces on the weld pool are due to Lorentz forces generated within the arc. These forces can give rise to high-velocity plasma jets. Similar forces also occur within the pool and are one of the drivers for circulation within it. The strength of these forces is dependent on the magnitude of the welding current ($F \propto I^2$) and its geometric distribution. The latter dependency is in turn related to variables such as electrode composition and geometry, and choice of gas shield composition. In order to model a welding arc, one might begin by considering the motion of an individual element of the plasma. Thus, each element of the arc fluid is accelerated in proportion to the net force acting on it:

$$\rho \frac{dv}{dt} = \rho\left(\frac{dv}{dt} + v \cdot \nabla v\right) = \text{net force per unit volume} \quad (9.5)$$

where ρ is the (incompressible) fluid density, v is its velocity and t is the time. The net force per unit volume in an arc will include the Lorentz term $J \times B$, the pressure gradient—∇P, and a 'diffusion' term that accounts for viscous damping, $\eta\nabla 2v$. The resultant equation is a modified Navier–Stokes equation for an incompressible fluid, and reads

$$\rho \frac{dv}{dt} = -\rho v \cdot \nabla v - \nabla P + J \times B + \eta \nabla^2 v \quad (9.6)$$

Solving this equation for an arc is challenging since the parameters are strongly coupled, rendering the system non-linear. In general, several different equations must be satisfied simultaneously (e.g. conservation of mass, energy, charge and momentum) and numerical methods must be used for their solution. The work of [6] provides a comprehensive treatment of this problem.

However, as is often the case, much can be learned by considering simplified approximations. One such approximation is to ignore viscosity, as done by [8]. He treated the arc as a truncated cone with the welding current, I, flowing between the two electrodes, a tungsten tip with an emission area of cross-sectional radius R_e and the weld pool surface of larger radius R_a. With the assumption that the current density is constant over any chosen radial cross section, the net force normal to the pool was found to be

$$F = \frac{\mu I^2}{8\pi}\left(1 + 2\ln\frac{R_a}{R_e}\right) \quad (9.7)$$

The ratio R_a/R_e is known as the arc expansion ratio.

Converti identified the two $J \times B$ components contributing to the net Lorentz force acting on the arc. Current flowing through an arc generates a circumferential magnetic field, $B_\theta(r)$, perpendicular to both the axial and radial vectors. Consequently, both axial and radial components of the arc current will interact with this field to give rise to forces. The axial component ($J_z \times B_\theta$) generates a compressive, or pinch force while any radial component ($J_r \times B_\theta$, due to arc expansion) results in an axially directed force. These two forces give rise to a radial pressure gradient and a fluid flow (the plasma jet), respectively. The radial pressure gradient produces a static pressure that squeezes the plasma against the terminating electrodes. On the other hand, the fluid flow contributes to a dynamic pressure that acts only on surfaces that change the velocity of the fluid stream.

Evaluation of Eq. (9.7) indicates that the arc force increases with the square of the welding current. Furthermore, experimental observation [9] and calculations based on reasonable estimates of the arc expansion ratio [10] show that the magnitude is of the order of $3 \times 10^{-5} I^2$ grams weight. So, for example, an arc carrying 100 A would exert a relatively insignificant force of about 300 mg weight, whereas at 500 A the force would be nearer 7.5 g weight. The latter is sufficient to displace a significant volume of weld metal, molten stainless steel having a density of about 7 g/cm^3.

Evidently, the larger portion of the arc force derives from the dynamic pressure term $(\mu/4\pi) \ln (R_a/R_e)$. Consequently, changing the arc expansion ratio will alter the arc force generated at a given current. Now, in the case where the tungsten electrode is the cathode, there is good evidence that the emission current is approximately proportional to emission area. In fact, measured values for emission current densities vary slightly around about 150 A/mm^2, depending on electrode composition [11] and welding current [12]. Consequently, the arc expansion ratio can be increased by measures such as reducing the angle of the electrode taper or changing the electrode composition. Other factors, such as choice of shielding gas and electrode diameter can also alter the expansion ratio by changing the thermal balance at either electrode.

The arc pressure is a measure of the arc force per unit area at any given point over the weld pool. Generally, arc pressure is a maximum on or close to the arc axis and is often modelled as having a Gaussian distribution. Arc pressure is sensitive to changes in the distribution of the arc force and so is significantly altered by factors such as redistribution of the current and changes in gas viscosity. For example, the arc pressures in a helium arc are significantly lower than those in an argon arc at the same current because high-temperature helium is more viscous than argon and therefore distributes the arc force over a wider area.

9.2.3 Weld Pool Behaviour

To complete a model of the GTAW process, it is necessary to consider the behaviour of the liquid weld metal. The weld pool can be a very active part of the welding process, with significant energy and momentum transport taking place within it. In addition to Lorentz forces, the weld pool is subjected to variations in surface tension, buoyancy, Marangoni and 'aerodynamic' plasma drag forces. Finally, at higher currents, the pool surface can be highly distorted and this can modify current and gas flow within the arc, as well as produce another surface tension-based driver for the flow of the liquid metal (see below). In general, however, forces associated with gradients in surface tension are believed to dominate flow within the pool.

The flow resulting from gradients in surface tension is often referred to as Marangoni flow [1]. Normally, surface tension decreases with increasing temperature, so that the weld pool surface will have a higher surface tension at the edges than at the centre. As a result, the hotter weld metal at the centre is drawn across the surface to the edges, thereby establishing a circulation that transports heat directly to the edges of the pool, favouring the formation of a wide, shallow weld puddle. Under appropriate conditions, this effect can be reversed by surface-active elements such as sulphur, phosphorus and selenium. These elements lower the surface tension in the cooler regions of molten metal, but are dissipated at higher temperatures. In such circumstances, the temperature coefficient of surface tension can become positive (that is, surface tension could increase with temperature) and reverse the expected direction of flow. This circulation transports heat to the bottom of the pool rather than to the edges, to produce deep, narrow weld pools. In this way, the performance of specific welding procedures can be compromised by heat-to-heat variations in sulphur content within a given type of stainless steel, for example. Lorentz forces also promote 'centre-down' circulation within the pool (see Fig. 9.3).

When the arc current exceeds about 150 A, the weld pool surface becomes noticeably concave in response to the arc forces. The degree of metal displacement increases with increasing current and becomes an important influence on process

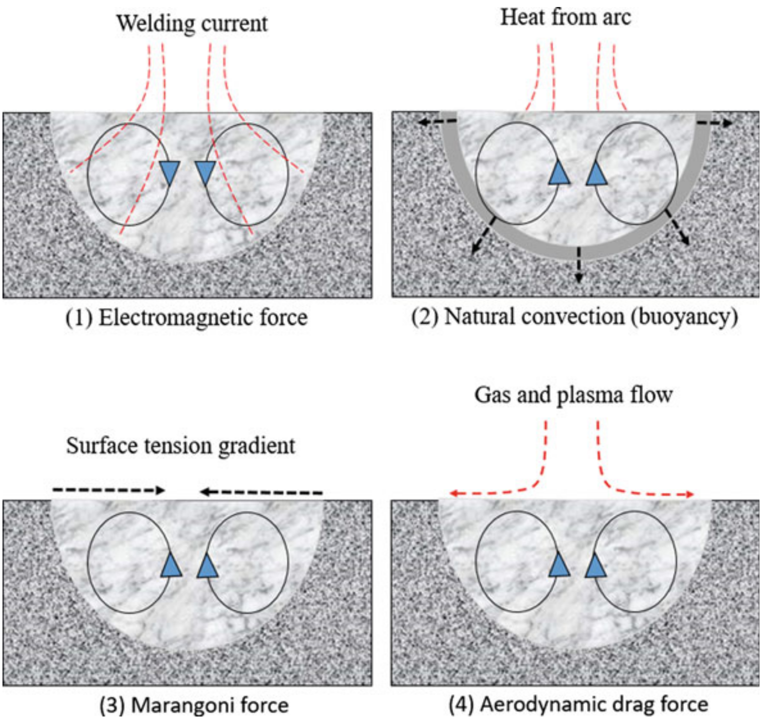

Fig. 9.3 Flow directions induced by four possible motive forces in arc welding

performance above about 250 A. The displacement of the weld pool is visible as a terminating crater if the weld is abruptly terminated. Such craters are interesting for several reasons. For example, their presence indicates that the liquid displaced by the arc forces does not simply accumulate around the edges of the pool but actually gets frozen into the weld bead. The amount of material required to fill the crater has been referred to as the 'deficit' [10]. Although the shape of the crater may differ from the depression of the pool during welding, it is evident that the deficit is conserved. Hence, measurement of the deficit, via the terminating crater, can be used to provide useful insights into the weld pool dynamics.

The use of measurements of deficit is illustrated by the data presented in Fig. 9.4. The data is from experiments involving GTA bead-on-plate welds on stainless steel using alternately argon and helium shielding gas. What is evident in each case is an abrupt and large increase in deficit over small changes in current. These changes correspond to similarly large changes in penetration (Fig. 9.5). The implication is that an inadvertent choice of welding parameters near such transition regions could result in serious weld inconsistencies.

Models that balance arc forces against the combined effects of buoyancy and surface tension [10] could explain sudden changes in deficit. Essentially, the argument is as follows. If the width of a weld pool is fixed and the arc force is gradually increased from zero, surface distortion will be resisted by buoyancy and by surface tension. These forces increase as the curvature increases, and hence deficit rises relatively slowly. However, the resistance provided by surface tension has a maximum value ($2\mu\ r\gamma$) that corresponds to the surface becoming vertical at some radius r. Further increase in arc force beyond this value causes proportionately much greater displacement as it is now only limited by the weaker buoyant forces.

Models that can describe weld pool surface geometry begin with the assumption of a 'free surface'. This means that the pool surface moves until the net pressure change across it is zero. Pressures arise from surface tension, buoyancy and arc pressure. Because the net pressure is zero everywhere, the surface is at a local

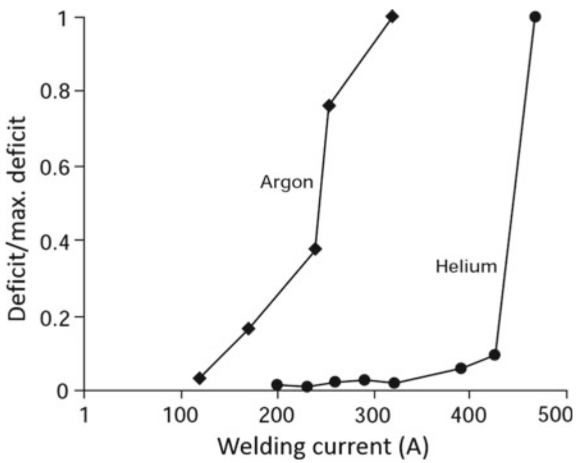

Fig. 9.4 Variation in deficit with current for melt-in mode GTAW

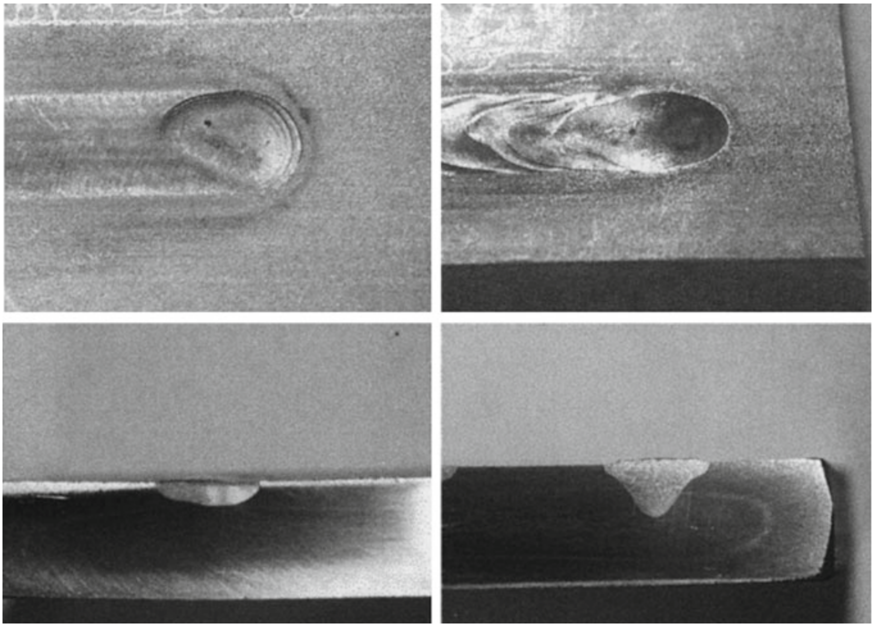

Fig. 9.5 Visual evidence of abrupt changes in deficit for bead-on-plate welds on stainless steel. Both welds were made using argon shielding and at the same welding speed and voltage. Left 240 A, right 255 A

minimum in energy. Of course the surface is attached to the parent material at the boundary of the pool. It follows that when the boundary moves as the heat source moves along the joint, the distorted surface moves with it (If it did not then its shape would change, its surface energy increase and it would experience a restoring force acting to realign it with the moved boundary). This automatically drives liquid metal from the leading to trailing edge of the pool and so is another potential driver for fluid flow within the pool.

9.3 Future Trends of Applications

There are a number of misconceptions and genuine limitations relating to GTAW and these must be addressed if the process is to retain its relevance in the future. The ‘basic’ GTAW process has been hampered by its low penetration and consequent poor productivity. As a production tool, it tends to be used when quality or other overriding issues demand it. It is argued that the process has much more to offer and has illustrated this with the detailed description of two of its many variants. It is suggested that this realisation that GTAW has ‘more to offer’ will be increasingly appreciated, particularly as fabrication operations become more integrated and mechanised. One of the historical impediments to the seamless integration of welding into production lines has been poor joint fitup and the consequent need for a degree of adaptability that was only available with manual intervention. This impediment is rapidly being removed as component tolerances improve, welding processes become more tolerant and control systems are made more intelligent and responsive. This trend will suit the lower deposition welding processes such as GTAW and should renew the search for innovative ways of exploiting this very elegant process.

Many of the changes to GTAW over recent times have been forecast correctly to be in the area of the equipment used to implement the process [13, 14]. This area covers power sources, control systems, monitoring, viewing and data acquisition [14]. This trend is expected to continue in the future, with the increasing availability of significant computational power driving the process in the direction of greater adaptability and user-friendliness. Occupational health and safety as well as environmental issues is also becoming more important and concerns about electromagnetic radiation and its potential to interfere with computerised equipment, metal fume and overall power requirements will all lead to further changes in equipment and practices.

However, the opportunity for new variants is expected to continue and to produce some very productive processes. One example of this is the recent research into hybrid processes and particularly laser plus GTAW [15, 16]. Hybrid welding refers to a situation where two processes (in this case, laser welding and GTAW) are coupled together to act as a single point. The coupling between the laser beam and the gas tungsten arc produces a number of synergistic effects that enhance the best features of each process. For example, the laser not only provides deep penetration but also stabilises the anode spot of the arc. As one result, the gas tungsten arc then can be operated in the more efficient DCEN mode, even when welding aluminium. At the same time, the arc broadens the weld pool at the plate surface, improves the laser to material coupling and relaxes the very high joint tolerances required for laser welding. It also provides additional heat input and an improved weld profile with reduced notch angles. In one set of trials on a 2 mm aluminium 3% magnesium alloy, [15] reported an increase in welding speed from 5 m/min for the laser to 8 m/min with the hybrid process. The GTAW operated alone could only be operated in the ac mode at 2 m/min.

Another innovation, in GTAW, is the newly reported guided GTAW or GGTAW process [17]. In this variant, the main arc is established between a short, hollow tungsten electrode and the workpiece. However, a separately powered electrode positioned above the main electrode provides a lower current ‘pilot arc’. This arc is constricted in passing through the hollow main electrode. The result is two concentric arcs, the inner of which has a high energy density and is relatively stiff. The inner arc has the effect of stiffening or ‘guiding’ the main arc, hence the name of the process. This process is anticipated to have some advantages over both GTAW and plasma arc.

In summary, GTAW is a particularly elegant welding process because of its apparent simplicity and appeal to fundamental physical principles. It is also becoming far more productive and versatile than popular images of the process suggested. The likely scenario is that this process will continue to be developed in new and imaginative ways for many years to come.

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