WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, MAY 1977
Sponsored by the American Welding Society and the Welding Research Council

Arc and Pool Instability in GTA Welding

Preliminary study relates erratic welding of stainless steels to anode spot movements and identifies weld pool surface films that influence anode spot behavior

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ABSTRACT. The weldability of stainless steel with the GTA (gas tungsten arc) process is considered for those cases where there are heat to heat variations in the behavior of the arc and the weld pool. Industrial experience of lack of penetration, arc wander, excessively wide welds, lack of reproducibility and changes in welding behavior from one heat to another is collated and reviewed.

It has previously been postulated that the width/depth (w/d) ratio of a bead on plate weld indicates the weldability of that heat in terms of resistance to arc and pool instabilities. Calculations suggest that most of the heat input to the workpiece is in the region of the anode spot, and a model is proposed which relates the behavior of the anode spot to the weldability of the material.

It is postulated that, with heats on which welds have high width to depth ratios, there is a movement of the anode spot which distributes the heat input and hence produces a wide, shallow weld. Surface scum seen around the perimeter of the weld pool and which appears to be associated with anode spot movement is found to contain high concentrations of aluminum and titanium. Another form of scum has been observed floating over the surface of the weld pool either as lumps or as a film.

Experiments are described in which there were differences in the spectra and appearance of arcs on different heats. The formation of slags, their behavior and their effect on the arc are discussed together with changes in the anode spot produced by different concentrations of low ionization potential materials. These experiments are not yet completed, and no firm conclusions are drawn at this stage regarding the relationship between the composition of the heat and its weldability.

Introduction

There are three main welding faults classified together under the heading "arc and pool instability in GTA welding." These are:

1. Variable weld cross section, generally resulting in shallower penetration than anticipated.
2. Migration of the weld bead from the line of the joint.
3. Production of an asymmetrical molten region by an arc from an electrode positioned centrally on a joint between two pieces of apparently identical material.

These welding faults can persist even when all the usual causes, asymmetrical earth connections, disturbed gas flows, etc., have been eliminated. There is evidence from recent investigations which suggests that this misbehavior could be due to slight variations in the composition of different heats of nominally the same material.

This paper reviews previous work on variability in the GTA process, considers the heat input to the workpiece (anode) and demonstrates the impor-

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Paper presented at the 57th AWS Annual Meeting held in St. Louis, Missouri, during May 10-14, 1976.

tance of the anode spot. It also describes a series of experiments carried out at Marchwood and in collaboration with industrial concerns in the UK.

Previous Investigations

One of the first reports of variability in GTAW (Table 1) was that of Oyler *et al*[1] who investigated this problem with 20 heats of vacuum arc remelted Type 304L stainless steel. They initially identified their "troublesome" metals as ones on which the top of the weld bead was wider than expected and was a dark blue color instead of being straw colored. They state that when there was lack of penetration the arc "displayed bright sparking and other disturbances or flickering" and also that "these disturbances caused a growth to form on the tungsten electrode tip."

Some differences in the composition of the metal were noted and were attributed to different practices involved in the steel making process. These differences in composition were claimed to correlate with the changes in weldability, and preferred concentrations were proposed for silicon and manganese, but no quantitative evidence was cited in support of these proposals.

The conclusions were that if the silicon content is greater than 0.7% the fluidity of the molten metal is excessive, causing the pool to widen and give a consequential lack of penetration. If the silicon content is less than 0.3% and the manganese is less than 1.4%, a viscous and sluggish weld pool results with oxide entrapment as a possible result. Unspecified differences in the concentration of aluminum, sometimes used as an arc stabilizer in the furnace, were also reported but could not be clearly related to the variability in the welds.

Ludwig[2] noted differences in the penetration produced by welds carried out under nominally identical conditions on samples of 304 stainless steel obtained from two different heats. Metal from one heat had a weld with a wide, shallow cross section, whereas welds on the other heat were deeper and narrower. When making a butt weld between two plates from the different heats, the weld tended to be skewed towards the plate of the material which had previously produced a weld with a high width/depth (w/d) ratio.

Further tests with stationary arcs revealed a time dependence in the size of the anode root on material from each of the two heats. Variations in the arc voltage and associated changes in anode spot size were observed. Ludwig argued that this was brought

Table 1—Summary of Investigations Referenced in This Study

	Observed Phenoma		
Observer	In weld cross section	In arc	On weld pool surface
Oyler *et al*[1]	20 heats: no w/d values or compositions quoted. For satisfactory welds: $0.3 < Si < 0.7\%$ and $Mn > 1.4\%$	Arc flickered. Deposit formed on tungsten.	
Ludwig[2]	Two heats with w/d ratios: A = 3.7, B = 1.8 (no compositions quoted) In joints between A and B, arc preferentially moved to A	Size of anode spot varied with time and decreased when slag appeared.[a] Larger anode spot on A.[a] "Extraneous radiation from anode" in first minute of operation.[a] Size of anode spot increased and arc voltage decreased by addition of alkali elements.[a]	Lumps of slag (rich in Mg, Si and Bo) appear after 1 min in center of anode spot.
Chase and Savage[3]	w/d increase (amount unspecified) by adding 0.3% Al and Ti to Inconel 600.	Different arc shape (unspecified) seen when 50 mg of various additives (e.g., Al, Si, Mn, etc.) inserted in weld pool (estimated 0.5%).[b] Arc voltage increased by additives in weld pool.[b]	Slags seen on surface of weld pool (not identified).[b] Differences in pool contours reported (not specified).[b]
Bennett and Mills[4]	w/d varied from 1.7 to 4.8 on 11 heats. Increase in w/d occurs with change in Al from 0.003 to 0.019%. Al added to low w/d weld pool causes increase in w/d.	Arc more flared on high w/d heats. Blue zone in arcs on high w/d heats. Mn lines brighter in spectra of arcs with high w/d heats. Arc "flickered" and deposits formed on tungsten (occurrence related to gas content of heat varying from 0.2 to 0.4%).	
Paton *et al*[5]	Two heats with w/d ratios of 2.4 and 7.3. w/d decreased by adding thin flux layer of unspecified metal salts. Higher w/d on heat with higher Mn, Ni and Mo (Al contents not given).	Arc more flared on higher w/d heat.	

[a] Arc stationary. [b] Using pure nickel.

Table 2—Values Used to Calculate Electron Density in Arc Region

Parameter	Al	Mn	Si	Fe	Ti	Ar
Density of liquid (kg/m^3)	2700	7440	2420	7870	4500	–
Ionization potential (V)	5.96	7.41	8.12	7.83	6.81	15.6
Vapor pressure from weld pool at 2000 K (Pa)	867	18.7×10^3	4.0	46.7	10^{-2}	–
Contribution to electron density at 5000 K (m^{-3})	3.3×10^{21}	2.7×10^{21}	1.8×10^{19}	8.6×10^{19}	4.6×10^{19}	4.8×10^{17}
Percentage of total electron density	54	44	0.3	1.4	0.7	0.008

about by the preferential evaporation of the more volatile constituents in the weld pool; he associated this vaporizing process with "extraneous radiation" seen when the arc was first struck. This phenomenon may be more relevant than those occurring later, because normal welding conditions correspond to those which exist in the first few seconds of a stationary arc. Deliberate introduction of alkali elements caused an increase in the area of the anode spot and a drop of about 1 V in the arc voltage.

Chase & Savage[3] found that differences in the concentration of certain elements (particularly aluminum and titanium) produced variations in the depth and cross sectional area of welds on Inconel 600. In addition, they introduced small quantities of various elements into welds made on pure nickel; in most cases, these additions caused an increase in arc voltage, e.g., 0.7 V for aluminum. They also considered the possibility that the trace elements affect the surface tension of the molten metal, depending on whether they remain in solution or form a solid floating on the surface. They suggest that this would lead to different surface contours and could produce a change in the stirring pattern in the weld pool. They reported that such variations in surface contours and solids floating on the surface had been observed as well as changes in arc shape.

Differences in the w/d ratio of welds produced by identical weld procedures on steels which have been prepared by different processes have been examined by at least two groups of investigators.

Bennett & Mills[4] were concerned with high (9%) manganese steels which had been made by three processes—conventional air melting, vacuum arc remelting (VAR) and electroslag refining (ESR). ESR material produced much higher w/d ratios than the other two, and it was suggested that this was related to the amount of aluminum picked up during the remelting. Their eleven heats had concentrations of aluminum ranging from 0.003% to 0.019% with corresponding w/d ratios of 1.7 to 4.8. (These values are fully tabulated for comparison with our results in Table 3.)

The shape of the arc was different when producing these high w/d welds than it was on those with a low w/d. The arcs on welds with a high w/d ratio and a high level of aluminum flared out at the workpiece and had a dome of deep blue light surrounding the arc, but no description was given of the behavior of the anode. Spectroscopy showed this blue light to be emission from manganese. However, they were not able to identify the process by which arc shape, manganese emission, or w/d ratio were affected by an increased aluminum concentration. They made a further check by adding aluminum to a weld pool on a material normally producing a low w/d ratio. The weld pool instantly widened, and penetration decreased so that the w/d ratio increased and the arc shape changed to that normally associated with an arc on a high w/d material.

Paton *et al*[5] have compared the profiles of welds on steels from open-arc furnaces and on electroslag remelted steels. They do not present quantitative data on the differences in the welds but suggest that for the same conditions the welds in the refined steel have a small depth of penetration and a 50 to 100% increase in width (i.e., increase in w/d of at least 50% and up to more than 100%).

The analysis of the two metals used by Paton showed that the concentration of the minor elements was lower in the refined steel, except for nickel, molybdenum and manganese. No values are given for the aluminum concentrations. The arc profile was wider when making the welds (with high w/d ratios) on the refined steel. They were able to decrease the w/d ratio of welds on the refined steel by adding a flux containing an unspecified mixture of "metal oxides and salts" to the weld, either in the form of paste applied in a thin layer to the joint edges or as wire.

The patent application of Majetich and Yeo[6] claimed that a coating of metal oxides can increase the penetration of the GTA process on stainless steels. A similar improvement is claimed for an oxide film produced by heat treatment of the metal. It is not reported whether these treatments eliminate the variability in GTA welding between different heats of stainless steel. A similar increase in penetration was found by Simonik[7] with flux layers containing metal halides.

The w/d ratio of a weld cross section can also be affected by factors other than the composition of the metal or its surface contaminants. For example, gas composition and purity have been investigated by Glickstein *et al*[8] and Savage *et al*[9] respectively; electrode tip geometry by Savage *et al*[10] and Spiller and MacGregor[11]; and current level, arc length and welding speed by Glickstein *et al*[8]. The effects of these other factors are not considered here as these quantities have been maintained as constant as possible under the conditions considered in this paper.

Table 3—Results of First Series of Experiments

Weld Analysis		Steel Analysis (%)				Spectra
w/d	σ	Mn	Al	Ti	Si	MnII/MnI(a)
6.1	0.36	1.75	0.020	0.025	0.17	1.2
6.1	0.68	1.61	0.010	0.023	0.54	1.2
6.0	0.45	0.71	0.041	0.005	0.40	0.9
5.9	0.23	0.87	0.025	0.025	0.42	0.9
5.2	0.43	1.75	0.033	0.024	0.37	1.1
4.8	0.87	1.62	0.010	0.020	0.52	1.2
4.7	0.23	1.57	0.020	0.022	0.40	0.7
4.2	0.36	1.80	0.028	0.31	0.63	0.9
4.2	0.67	1.62	0.058	0.51	0.38	1.1
4.2	0.69	1.75	0.014	0.010	0.15	0.6
3.6	0.38	1.59	0.032	0.44	0.43	0.5
2.7	0.23	0.80	0.004	0.003	0.41	0.35

(a)Arbitrary units.

The investigators, whose work is summarized in this section and in Table 1, have suggested that small concentrations of trace elements can have a large effect on the penetration and weldability of stainless steels. So far it has been reported that variations in the levels of aluminum, titanium, manganese and silicon have been associated with changes in the w/d ratio of welds. Suggested explanations include changes in the fluid properties of the weld pool, in the arc voltage and in the arc root on the workpiece.

In the next section we consider the effect of these elements on the anode spot region of the arc and their consequential influence on the energy transfer from the arc to the weld pool. The processes taking place in the anode spot are examined because, as is shown, most of the heat input to the weld occurs in this region, but it is not intended in the long term that the other hypotheses should be disregarded.

The Anode Spot and Heat Transfer

It is well known that the cross section of the arc diminishes close to the anode and also that anode spots are sometimes seen.[12] Where the arc diameter reduces very sharply at the anode, there is a significant reduction in visible luminous intensity. Under this region there may then be a blue diffuse glow and sometimes an anode spot.

It is also well known[13,14] that most of the heat transfer to the workpiece in the GT arc occurs in the anode spot. Quigley *et al*[15] calculate that for a short arc (9.5 V arc drop) 80% of the total heat input is transferred to the workpiece, and this has been experimentally confirmed by Lancaster[14]. Also, of the heat reaching the workpiece, about 80% is transferred within the anode spot region; the remaining 20% reaches the workpiece by convection or radiation from the rest of the arc.

The main consequence of this concentration of heat is that the position of the anode spot is a major factor determining the point of application of the heat. It is reasonable to expect, therefore, that if a mechanism exists that moves the anode spot this will effectively move the point of heat input and hence the weld pool. Thus, it is postulated that during welding in which there is lateral movement of the arc root, the weld will have a more distributed heat input and hence be wider than one on which the arc root stays stationary relative to the line of the joint. For this reason, variation in the stability of the arc root is advanced as one possible cause of the variability in w/d ratio and penetration.

The arc root is the region in which electrode material, which has a low ionization potential, enters the arc. We can calculate the contribution to the total ionization from these elements using a version of Saha's equation adopted by Suits[16]:

$$\log_{10} (T^{1.5}) - 5040\ V/T = \log_{10} (n_e^2/n_a 10^6) - 15.38$$

where V is the ionization potential, T is the temperature, n_e is the electron density and n_a is the atomic density of the gas in question.

The latter may be calculated from the vapor pressure of each of the elements, and n_e may then be found for any temperature; in this case, an arc temperature of 5000 K (8540 F) was chosen as being typical for this region[13].

Table 2 shows that most of the ionization is provided by aluminum and manganese, assuming that a saturated vapor of these elements is present just above the pool. There is some support for this assumption from Bennett and Mills[4] who say they determined that the alloy constituent elements were present in their arc roughly in proportion to their vapor pressures. However, the formation of oxides could reduce the vapor pressures; also, transients in the weld pool could disturb this balance in the vapor composition.

Despite these uncertainties, aluminum or manganese could have an influence on the ionization in the arc, and hence the anode spot would tend to move to regions from which these elements were vaporizing. Unequal concentrations of the elements in two heats put together to form a joint would by the same process cause the arc to be biased to one side.

Experimental Investigations

Preliminary Tests: Observation of Anode Spot Region with a Stationary Arc

Relatively simple experiments were set up for the purpose of observing the anode spot region in a GT arc. A moderate power microscope with camera attachments and neutral density filters was used to examine and photograph the area in the arc close to the weld pool surface. In this region a bright blue glow, containing the anode spot, could be seen moving around the surface of the pool. A distinctive behavior pattern was clearly observed in which, even with an apparently clean material, some scum would appear almost instantaneously on the surface of the weld pool, to be followed by the anode spot moving to the edge of the scum.

Motion of the anode spot appeared to be produced by the spot anchoring itself to the scum until the latter was consumed, at which point the spot would move on to the next available patch of scum. Clearly the scum played an important role in determining the behavior of the anode spot.

The phenomenon was investigated further by manipulating the workpiece to collect an appreciable amount of scum and centering it and the anode spot in the middle of the weld pool. By switching off the arc the material was trapped in the center of the solidified weld pool for subsequent chemical analysis. The duration of each test was about 20 seconds.

The results of these first investigations showed that the material was composed primarily of titanium with, in addition, large quantities of vanadium and molybdenum. All these elements were present in very much higher proportions (at least one hundred times greater) than was found in the base metal.

A second series of experiments was undertaken in which the metal was polished with abrasive paper and cleaned with acetone. The same experimental procedure was adopted to scavenge a significant part of this scum into the center of the weld pool. Analysis of the solidified scum was then carried out as before, but this time titanium and aluminum were the dominant elements. Since aluminum was not present in the weld metal, at more than 0.005%, it is concluded that it came from the abrasive paper; further analysis confirmed that the paper contained aluminum oxide as its abrasive constituent.

The later experiments demonstrated how surface contaminants and preparation can influence the constitution of the solids on the surface of the weld pool. Figure 1 shows electron microscope photographs which indicate the accumulation of the specific elements in the scum.

Collaborative Investigations

Collaborative investigations have been set up with other industrial establishments which are concerned about the form of weld instability discussed here. In one series of experiments it has been found that when two materials from heats of AISI 304L (each producing welds of different width to depth ratios) are put together, an under-penetrated or a skew weld can result (Goodman and George, private communication).

The w/d ratio of a number of weld samples was measured. It was found that in general by pairing off materials of roughly equal w/d, good weld joints were produced. When joints were made from samples, of which one had a w/d, for example, of about 4 and the other 2, unacceptable welds

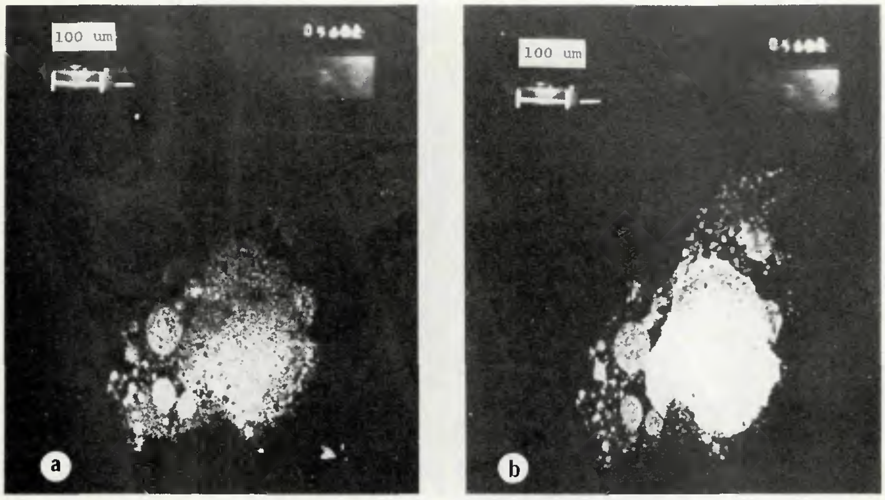

Fig. 1—Electron microscope photographs showing accumulation of aluminum and titanium in the weld pool scum

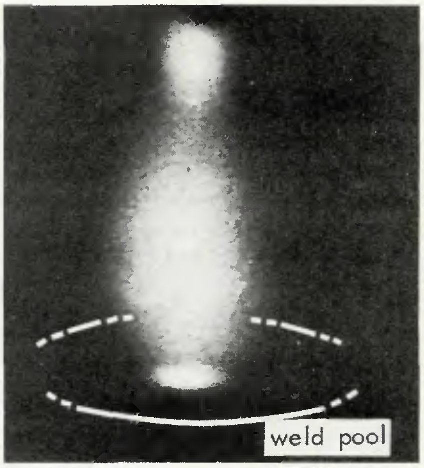

Fig. 2—GT arc showing anode spot on weld pool. (Reproduced on blue sensitive film to show up anode spot—hence only central core of arc can be seen)

were obtained.

Analysis of the metal from two heats at the extremes of the w/d range showed that the heat with the lower w/d (1.9) had the higher concentration of chromium (20.3% compared with 19.4%), manganese (0.86% compared with 0.67%) and silicon (0.41% compared with 0.39%). The heat on which the trial welds had shown a w/d of 6.4 had a higher level of nickel (12.2% compared with 11.8%) and a very much higher level of aluminum (0.037% compared with 0.007%). There was no significant difference in the concentrations of the other constituents.

The chemical analyses of the metal in the weld beads were also obtained for comparison with those of the base metal. For all the constituents except aluminum there was no significant difference between the concentrations of the various elements in the weld bead or in the base metal. However, the percentage of aluminum for the sample with w/d = 1.9 was 0.003 in the weld metal, and for the sample with w/d = 6.4 it was 0.028, both of which are significantly lower than the concentrations in the base metal. Metal from these heats is included in our present laboratory investigations.

Another collaborative program concerns tube-to-tube welds in AISI 321, for which one of the two tubes had been formed from a helically welded strip. In this case a satisfactory weld had been produced for the majority of the 600 mm (24 in.) circumference, but for a length of about 75 mm (3 in.) the weld bead went off-line erratically and increased in width. This deviation occurred in the region where the helical seam weld intersected with the circumferential joint.

Material analysis showed that there was relatively little variation in the concentrations of titanium and silicon on either side of the joint (Thomas, private communication), but significant differences were found in the concentrations of manganese and aluminum. The seamless tube had approximately twice the level of aluminum of the seamed tube and approximately 1.4 times the level of manganese. There was no obvious change in these concentrations where the weld first went off center. Where the weld became skewed, it moved towards the material with the higher levels of aluminum and manganese.

Present Investigations

Experimental Arrangements. The experimental program which we are carrying out at present is concerned principally with monitoring GTA welds carried out under closely controlled conditions. These bead-on-plate welds are being made on a selection of stainless steel heats which have a range of concentrations of elements which appear to cause variability in the welds, i.e., aluminum, manganese and titanium. The samples include 10 heats of AISI 304L obtained from the first of the two collaborative exercises referred to above and six heats (one 304, two 316 and three 321) made available by the special steels division of the British Steel Corporation, and which have been produced by either the arc remelting or the AOD steel making process.

The same welding conditions are being used for all samples. They are such that they produce on any heat a greatest penetration of just under 50% of the thickness of the plate. The welding current is 100 A (straight polarity), and the electrode is 2.4 mm (0.094 in.) diameter 2% thoriated tungsten, with a tip ground to a 30 deg included angle and with a point of 0.3 mm (0.012 in.) spherical radius.

The torch is set and maintained in a position with the electrode vertical to the workpiece. The gap between electrode tip and the workpiece is set at 3 mm (0.12 in.) before the start of a weld, and the tip protrudes 3 mm from the nozzle of the torch. A new electrode is used for each weld. The welding speed for all the tests is 4.2 mm/s (9.8 in./min).

The shielding gas is argon of normal welding quality with a nominal maximum impurity level of 100 ppm. However, in view of the experience reported by Savage *et al*[9], the precaution is being taken of analyzing the contents of each cylinder used. So far, although the impurity levels (i.e., the oxygen and nitrogen content) have been very much higher than specified, they are reasonably constant (Smalley, private communication). The gas lines to the torch are purged before each weld to reduce the effects of any entrainment of air within the hoses. A gas flow of 10 liters/min (21.2 ft^3/h) is used, through a ceramic nozzle of 16 mm (0.63 in.) internal diameter, which incorporates a gauze "gas lens" to stabilize the flow.

Each weld is monitored by a number of methods. Cine-photography is used to record the behavior of the arc and weld pool surface. This is done by placing a camera on the axis of the weld looking at a shallow angle across the pool. The film is run at 250 frames/s, and neutral density filters are used to reduce the light intensity without altering the color balance.

In addition to measuring the arc current on a moving coil ammeter (0.1% accuracy), the signal from a second current shunt and the voltage between the torch input and the workpiece are monitored on a chart recorder. The experimental operations (e.g., start and stop of traveling table, isolation of the instrumentation during arc initiation, etc.) are carried out by means of a sequence controller in an endeavor to reduce manual variations. Light emission from a central vertical slice of the arc is recorded on a Hilger and Watts medium quartz spectrometer.

The surfaces of the weld samples are cleaned in one of two ways. A "reasonably" clean surface is produced by manual washing of the plates at least twice in acetone, rubbing the surfaces during the first wash with paper tissues to remove any stubborn deposits. For the sake of consistency a "very" clean surface is prepared by ultrasonic agitation in acetone, both before and after electrostripping the sample in a solution containing phosphoric and sulfuric acid and chromium trioxide.

Preliminary Results. During the first part of this series of experiments, analyses were obtained of the following elements: C, Si, Mn, P, S, Cr, Mo, Ni, Al, B, Co, Cu, Nb, Sn, Ti, W and O_2 and compared with w/d ratios. For most of these elements there appeared to be no correlation between their levels and w/d ratio; however, there seemed to be a possible correlation between w/d and Mn, Al, Ti, and Si, and as these were the elements thought by previous workers to be important, they were examined more closely and discussed in this paper. It is these latter elements which are the main subject of present investigations although the others are monitored to detect any significant variations.

The results available at the time of writing showed that the selection of heats provided a significant range of w/d ratios in the welds. Table 3 shows the average w/d ratios for each heat, the standard deviation in the observed values, the concentrations of manganese, aluminum, titanium and silicon and details from the arc spectra. It can be seen that the mean values vary from 2.7 to 6.1 with the standard deviations ranging from 0.23 to 0.87. The lowest and highest values of w/d obtained in the tests were 2.1 and 7.0.

The photographs showed that there were variations in the arc profiles on different heats. At one extreme the arc was, apart from the region close to the cathode, a uniform white color. On the other hand some records show arcs in which there was a distinct blue region close to the surface of the weld pool (Fig. 2). In some cases this blue zone stayed relatively central, in others it moved around, and in some cases it extended as far as the edge of the weld pool.

The first interesting spectroscopic result is that in all cases the spectrum near the anode is totally different from that higher up in the arc. A typical spectrum appears in Fig. 3 which shows that in the body of the arc the dominant lines are those of argon. However, approaching within about a millimeter of the workpiece these fade and metal vapor lines, especially manganese, show very strongly.

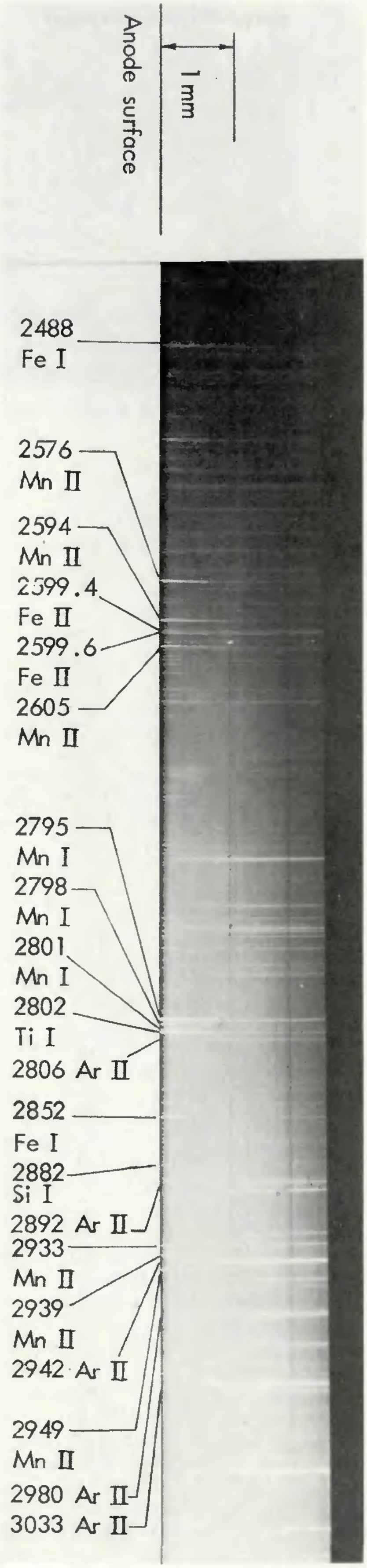

Fig. 3—Spectrum of GT arc showing metal vapor lines near the weld pool

The spectra from almost all the arcs contain the same lines, but there are differences (Table 3) in their intensities, particularly in the ratios of the line intensities from the ionized and un-ionized states of manganese. For heats with a high w/d ratio the ratios of ionized to un-ionized manganese lines (at 294.9 and 279.5 nm respectively) are high, whereas for low w/d ratios the MnII/MnI ratios are lower.

This loose correlation between w/d and the relative intensity of the ionized manganese line suggests that a high w/d ratio is associated with a higher arc temperature close to the weld pool. One consequence of a higher arc temperature would be a greater proportion of heat transferred to the weld by convection, and as this is more distributed than the heat dissipated at the anode spot it might be expected to produce a wider weld and hence the higher w/d found.

The cine observations of the weld pools have revealed differences in the surface conditions. In some instances, quite large lumps of slag have been seen floating around on the surface of the molten metal. Generally only a few of these "islands" are seen, and they appear to be solid although that has not been confirmed. Another form of surface contaminant seen on other welds consists of a thin layer which looks dark in contrast to the reflecting surface of the molten metal. This thin scum is more mobile than the previously mentioned slag, and it gives the impression of being either a liquid or a fine powder which is easily moved by the surface currents on the weld pool. Also, a more tenacious form of scum has been seen adhering to the sides of the weld pool, and in our preliminary experiments the arc root showed a tendency to anchor on this scum.

So far, the only chemical analysis of these slags and scums has been in our preliminary tests when they were found to contain higher than normal levels of aluminum and titanium. To date we have insufficient evidence to clearly identify the role of these surface contaminants, and further investigation is planned to clarify this.

Discussion

We have found that, for the heats available to us at present, our tests produced a range of width/depth ratios from 2.7 to 6.1. Bennett and Mills[4] considered that the w/d ratio is an increasing function of the aluminum content over the range from 0.003 to 0.019%, as shown in Table 4. Our results have not confirmed this relationship, although the single heat in our tests which has a very low aluminum content also has by far the lowest w/d ratio. All of our other heats have at least 0.01% aluminum which is at the higher end of the Bennett and Mills data; however, it could be important that their heats had a much higher level of manganese (9%) than ours.

We have not found a relationship between w/d ratio and any other elements; the only correlation we have identified so far is a loose one showing that w/d is an increasing function of the intensity ratio of spectral lines from ionized and un-ionized manganese which could indicate a dependence of w/d on local arc temperature. We confirm the presence of the blue glow region close to the workpiece and scum on the weld pool. Both could play some part in the processes which occur, but so far our results are not sufficient to interpret unambiguously the roles of these phenomena.

Ludwig[2] as well as Goodman and George (private communication) found that, when joining two heats of different w/d ratios, a skewed weld can result with the weld generally being biased towards the material of higher w/d. Analysis of skew or off-center welds suggests that the weld pool exhibits a propensity to move to a region of higher aluminum and manganese.

No clear picture has yet emerged from our tests. The simple model proposed earlier may be inadequate, because it does not take into account the role of the oxide slags which these elements can form on the weld pool surface. It is known (Wolstenholme, private communication) that aluminum and titanium are more likely to form stable oxides than manganese and silicon. If, for example, a $MnO.SiO_2$ slag exists on the surface of the weld pool, any aluminum suddenly appearing would tend to form alumina at the expense of the manganese silicate. This would change the metal vapor proportions in the arc.

The SiO_2, TiO_2 and MnO slags have low melting points (about 1900 K or 3000 F), with that of $MnO.SiO_2$ being even lower (1600 K or 2400 F). Alumina (Al_2O_3), however, has a melting point of 2300 K (3700 F), higher than the weld pool temperature, and will give a crystalline slag rather than the thin glassy slag of $MnO.SiO_2$. There may, therefore, be an interaction between the formation of slags involving aluminum and manganese and the presence of these elements in the arc where they affect ionization.

Table 4—Experimental Results of Bennett and Mills (at 200 A; Mn = 9.0% nominal)

Al	w/d
0.003	2.1
0.003	2.2
0.003	1.8
0.003	1.8
0.004	1.7
0.018	4.0
0.019	4.8
0.010	4.2
0.009	3.3
0.004	3.8
0.003	2.2

An aspect which we have not taken into account at this stage is the electromagnetically induced circulation of molten metal in the weld pool. It is known that circulation takes place on the surface, and experiments by Woods and Milner[17] and others have indicated that it takes place below the surface also. Circulation of the molten metal can modify the distribution of elements such as aluminum and also affect the heat flux pattern throughout the bulk of the weld pool. For a fixed anode spot there may be a number of stirring patterns which could give different w/d ratios.

In our experiments we have seen a moving anode spot. It could be a fairly complex interaction between spot movement and circulation which determines the final w/d ratio. Theoretical work on this subject, until recently, has been concerned with circulation from a single spot. Work at the Marchwood Laboratories by Andrews and Craine (private communication) is in progress with the intention of obtaining a solution for the moving spot case.

Conclusion

The results of earlier workers, and our calculations, suggest that small levels of impurities in heats of stainless steel can influence the behavior and characteristics of the GT arc, and so possibly affect the w/d ratio of welds.

Our recent experimental results do not support this latter hypothesis. It is suspected that the processes determining weldability are complex and may involve interactions between the effect on the arc of material of low ionization potential, such as aluminum, slags or scum on the weld pool surface and electromagnetic stirring effects within the pool.

Acknowledgment

This work was carried out at Marchwood Engineering Laboratories and is published by permission of the Central Electricity Generating Board.

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