Some Influences of Slag Composition on Heat Transfer and Arc Stability

Limited study sheds some light on the complex field of arc physics in the presence of slags

BY B. M. PATCHETT

ABSTRACT. The effect of simple fluxes on heat transfer and arc stability has been investigated for both nonconsumable and consumable electrode arc processes using mild steel plate material. One and two component fluxes were made by sintering chemicals in the solid state to avoid composition alterations due to agglomeration or fusion.

Weld bead penetration and surface condition were used as the criteria to assess heat transfer and arc stability characteristics, and the performance of each flux was judged by comparison with a weld pass made with argon gas shielding.

Chemical compounds used in flux formulations have individual effects on heat transfer and heat balance which depend on electrode polarity and electrode emission characteristics. Arc instability is also greatly affected by flux composition, and in extreme cases can lead to individual "spots" of molten metal rather than a weld bead. The time spent on one weld area is therefore variable, and affects penetration consistency and possibly ripple formation and weld bead uniformity. There are indications that these effects are linked with the nature of electron emission of coated substrates, and with the effect of ion additions from fluxes to the anode and cathode fall areas, but the pattern is only consistent over a narrow range of simple materials.

B. M. PATCHETT is Senior Research Officer, Department of Materials, Cranfield Institute of Technology, Cranford, Bedford, England.

Introduction

In recent years some attention has been focussed on the effect of impurities in shielding gases and residual elements in base metals on heat transfer and arc stability in arc welding processes.

In gas tungsten arc-welding (GTAW) small amounts of oxygen in argon shielding gases affect heat transfer by causing increased penetration in aluminum (Ref. 1) and reduced penetration in nickel alloys (Ref. 2), possibly by affecting the anode drop. Residual elements in base metals can also affect heat transfer, and Ludwig (Ref. 3) found that penetration increased as the residual chlorine level increased from 6 ppm to 32 ppm in refined zirconium alloys. He attributed this to the increased anode drop created by a negative space charge of Cl ions at the anode. Chase and Savage (Ref. 4) also found that controlled additions of trace elements in a pure nickel base metal caused both increases and decreases in gas tungsten-arc (GTA) weld penetration, but they could find no adequate correlation with physical properties or chemistry to account for their observations.

Ludwig (Ref. 5) investigated random variations in gas tungsten-arc heat transfer which has been observed in stainless steels. He found that easily ionized chemical compounds added to the base metal led to variations in anode spot size and reductions in arc voltage, leading in turn to decreased penetration. He postulated that similar effects in commercial plate material could be caused by slag inclusions picked up from refractory furnace linings during the steel manufacturing process. Deliberate additions of fluxes have been exploited by Gurevich et al (Ref. 6) to increase gas tungsten-arc weld penetration in titanium alloys. They also reported similar effects in stainless steels, molybdenum and niobium, and apparently had no difficulty with variations in penetration which Ludwig observed when slag compounds were entrained in the base metal.

Arc instabilities caused by fluxes occur in consumable electrode arc processes, and Hazlett (Ref. 7) found that this led to variations in penetration and bead shape when individual chemical compounds used in electrode manufacture were used as submerged arc fluxes (e.g. Na_2SiO_3, $CaCO_3$). Moreover, particles of slag-like compounds (e.g. oxides) on metal surfaces can cause arc instability leading to alterations in heat transfer due to anode plasma jets, as observed by Wilkinson and Milner (Ref. 8). Pintard (Ref. 9) has shown that coatings on the base metal or on the electrode affect both the weld penetration and the electrode melting rate.

Electrode polarity is another variable in consumable electrode welding, and Pintard found that the electrode melting rate decreased and penetration remained constant as flux emissivity increased on electrode positive polarity, while penetration decreased and the electrode melting rate was approximately constant as flux emissivity increased with electrode negative polarity.

The physical complexity of electric

welding arcs has led to great difficulty in analyzing the effect of chemical elements or compounds which enter the arc plasma region from a shielding gas, base metal, or flux. For fluxes and slags in particular, there is little information concerning the effect of an individual chemical compound on arc stability and heat transfer. Commercial fluxes are the result of long formulation experience, and even experimental fluxes like those of Gurevich (Ref. 6) are the result of empirical experimentation. Fundamental information on flux formulation is very nearly nonexistent, and much work remains to be done in this field. The gradual trend towards the use of automated arc welding processes serves to emphasize the fact that any random variations in arc stability and heat transfer due to impurities or slag compounds must be minimized by obtaining a good working knowledge of their causes.

In this investigation the effect of simple one and two component fluxes on heat transfer and arc stability has been studied using non consumable and consumable electrode systems with mild steel base metal.

Experimental

The basic consideration for this work was the simplification of slag systems in order to achieve a fundamental assessment of heat transfer in arc welding.

The fluxes used in all of the experimental work (see Table 1) were sintered in the solid state in order to avoid any changes in chemical composition due to reactions with crucibles during fusion or the addition of binding agents in agglomeration processes. The sodium silicate used in the latter process is known to have a beneficial effect on arc stabilization, and its presence could easily alter the inherent arc stability of a simplified flux mixture.

The initial flux compounds were chosen for high thermodynamic stability, suitable melting and boiling points, and a minimal tendency to react or alloy with the mild steel base material and electrode metals. These conditions were best satisfied by the alkaline earth fluorides, which also provided a progressive series of cations (from Mg to Ba) having varying atomic weights, thermionic work functions, etc.

A second series of more complex fluxes used the alkaline earth fluorides with the greatest differences in properties (MgF_2 and BaF_2) as bases for alkaline earth oxide additions. Oxide additions were made at a level of 30 mo1 % to maintain a constant cation balance despite variations in atomic weight. Finally two fluxes, NaF and MgO-NaF, were made with an alkali fluoride, NaF, to assess the effect of a fluoride from a different chemical group.

For both the nonconsumable and consumable electrode work, dc power was used and argon shielding gas flowing at 15 l/min protected the molten flux-metal from the atmosphere. Weld runs in argon only (using no flux) were used as references for each system.

The runs were sectioned transversely and longitudinally (for 25 - 30 mm) to assess penetration characteristics.

To minimize any compositional variables in the consumable electrode, all submerged arc runs were made with one reel of electrode. All of the base plate test sections used for welding were cut from one large mild steel plate for the same reason. The chemical composition of the steel plate and electrode is given in Table 2.

GTA welds were made without filler metal on plates 50 mm × 180 mm × 5 mm (2 × 10 × 3/16 in.) thick, clamped to a moving carriage. A standard argon tungsten arc torch carrying a 3.2 mm diam electrode was clamped above the plates, and runs were made with a 5 mm arc gap on electrode negative polarity at a nominal voltage of 17 V and current of 300 A. All arcs were initiated in argon on bare plate, and then traversed across an area 150 mm long (6 in.) covered with flux to a depth of 3 mm (1/8 in.). The traverse speed was fixed at 300 mm/min (12 ipm). Bead width and penetration were measured as criteria of heat transfer characteristics.

Submerged arc runs were made on similar plates 100 mm × 250 mm × 5 mm (4 × 10 × 3/16 in.) thick with flux spread on the surface to a depth of 25 mm (1 in.). Electrode stickout was kept constant at 20 mm (3/4 in.) and traverse speed at 600 mm/min (24 ipm). The wire feed speed was nominally 226 m/hr (175 ipm) for electrode positive operation, and 495 m/hr (325 ipm) for electrode negative operation with a 1.6 mm (1/16 in.) diam mild steel electrode. The welding conditions are given in Table 3. In the cases where the flux would not support the nominal electrode melting rate, the electrode feed rate was reduced until a stable deposition condition was achieved. Penetration of a sectioned weld bead, and bead surface regularity, were taken as criteria of heat transfer and arc stability characteristics.

Results

Fused Zone Runs

Weld bead widths, although reduced about 10% in comparison with the argon reference run, did not vary very much. However, penetration varied not only from flux to flux (as shown in Table 4), but also on occasion along the length of the weld bead. Voltage and current varied slightly during the runs, indicating some arc instabilities. (Changes in arc voltage are important, since they may be indicative of changes in the

Table 1 — Flux Compositions

Flux	Fluoride, wt %	Oxide, wt %	Oxide, mol %
NaF	100	—	—
MgF_2	100	—	—
CaF_2	100	—	—
SrF_2	100	—	—
BaF_2	100	—	—
MgO-MgF_2	78.2	21.8	30
MgO-BaF_2	91.0	9.0	30
BaO-MgF_2	48.7	51.3	30
BaO-BaF_2	72.8	27.2	30
MgO-NaF	71.8	28.2	30

Table 2 — Base Plate & Consumable Electrode Composition

Material	C, wt %	Mn, wt %	Si, wt %	S, wt %	P, wt %
5mm mild steel plate	0.22	0.74	0.035	0.028	0.022
1.6mm diam electrode	0.11	1.82	0.78	0.03 max	0.03 max

Table 3 — Welding Conditions for Submerged Arc Welding

	Electrode negative			Electrode positive		
Flux	Electrode feed rate, m/h	Volts, V	Current, A	Electrode feed rate, m/h	Volts, V	Current, A
Ar	380	25	225	266	23	250
NaF	266	20	300	266	22	240
MgF_2	380	25	250	266	25	240
CaF_2	380	18	325	266	24	250
SrF_2	380	19	325	266	24	240
BaF_2	380	15	350	266	24	250
MgO-MgF_2	266	24	200	266	22	250
MgO-BaF_2	205	20	225	205	19	225
BaO-MgF_2	266	10	325	230	24	225
BaO-BaF_2	205	19	240	205	20	200
MgO-NaF	230	28	150	205	1B	250

Table 4 — Heat Transfer Characteristics

	GTAW		SAW			
	Electrode negative		Electrode negative		Electrode positive	
Flux	Avg. penetration, mm	Bead appearance	Avg. penetration, mm	Bead appearance	Avg. penetration, mm	Bead appearance
Ar	2.5	Smooth	1.0	Smooth	3.0	Smooth
NaF	2.5	Smooth	0.5	Irregular	4.0	Irregular
MgF_2	4.0	Heavy Ripple	1.5	Irregular	2.5	Undulating
CaF_2	2.5	Ripple	1.5	Irregular	2.5	Smooth
SrF_2	1.5	Smooth	3.5	Smooth	2.5	Undulating
BaF_2	1.0	Smooth	4.0	Smooth	2.0	Smooth
MgO-MgF_2	3.0	Heavy Ripple	1.0	Smooth	1.0	Smooth
MgO-BaF_2	3.0	Ripple, Pockmarks	2.5	Smooth	1.5	Smooth
BaO-MgF_2	3.0	Ripple	0.5	Irregular	2.0	Smooth
BaO-BaF_2	2.0	Slight Ripple	3.5	Undulating	3.0	Irregular
MgO-NaF	2.0	Very Irregular	1.5	Undulating	2.0	Undulating

anode and cathode fall regions, but the observed variations of about one volt could not be recorded accurately enough to be used as experimental evidence.)

The average penetration using the alkaline earth fluorides varied from above the Ar reference value with MgF_2 (Fig. 1) to well below it with BaF_2 (Fig. 2). The bead surfaces also differed widely, as shown in Fig. 3, where the irregular surface of the MgF_2 bead is indicative of a less stable arc, which is also evident in the greater variation of penetration shown by the MgF_2 run. The NaF flux reduced the bead width compared to the reference run, but the penetration was unaltered.

The oxide-fluoride mixed fluxes reduced bead widths by about 20% on average, and produced uneven penetration values with fluxes containing MgO (Fig. 4). The fluxes containing barium oxide produced penetrations of about the same depth as the Ar reference run. One noticeable difference in behavior was the effect on cathode heat input. Very high heat inputs to the tungsten electrode and housing occurred when fluxes containing compounds based on more than one metal atom were used — ie, *Mg*O-*Ba*F_2, *Ba*O-*Mg*F_2, and *Mg*O-*Na*F. The arc in these cases was "harsh", in contrast to the behavior when fluxes with compounds based on only one metal atom were used (ie, *Mg*O-*Mg*F_2 and *Ba*O-*Ba*F_2), where the arcs were very quiet. The MgO-NaF flux produced the most erratic run, with very large variations in penetration due to a highly unstable arc (Fig. 5).

Submerged Arc Runs

In the electrode negative runs, all of the pure fluoride fluxes except NaF supported the reference electrode melting rate, but there was some decrease in voltage and increase in current drawn during submerged arc welding (SAW). All of the oxide-fluoride fluxes required electrode feed rate reductions on electrode negative polarity. There were virtually no differences at all in conditions between the reference run and the pure fluoride runs on electrode positive polarity. Of the oxide-fluoride fluxes, only the MgO-MgF_2 composition could support the reference electrode feed rate and electrical parameters, and electrode feed rate reductions had to be made for the rest.

Electrode Negative Operation

The results listed in Table 4 show that the most notable difference between the consumable and nonconsumable runs on electrode negative polarity occurred with the pure alkaline earth fluoride fluxes, where penetration increased through the range from MgF_2 to BaF_2. This behavior is the reverse of the fused only runs using a tungsten electrode. Figure 6 shows the difference in cross-section between the MgF_2 and BaF_2 runs. The bead surface appearance and regularity was better with the SrF_2 and BaF_2 runs; this is consistent with the fused only run behavior. Penetration with the NaF flux was low and irregular, and the bead itself had a very irregular surface (Fig. 7).

The oxide-fluoride mixtures again demonstrated a separation in behavior, but in this case the change was apparently based on the nature of the fluoride base. Both fluxes containing MgF_2 maintained relatively high electrode melting rates, but had greatly reduced penetration compared with the BaF_2 based fluxes. This behavior is consistent with pure fluoride results, if the fluoride dominates the situation. The increased penetration with the BaF_2 based fluxes was accompanied by a decrease in the electrode melting rate, which indicated that there had been a displacement in the heat distribution between the cathode and the anode. Figure 8 shows how the bead cross-section changed between the fluoride bases for fluxes with MgO additions.

The MgO-NaF flux slightly increased the penetration over the reference level, and produced an undulating bead surface. The very erratic behavior of the fused only experiment was absent.

Electrode Positive Operation

The results listed in Table 4 show that penetration with the pure alkaline earth fluorides was slightly less than the reference run and virtually the same for all of them. This is consistent with the virtually identical

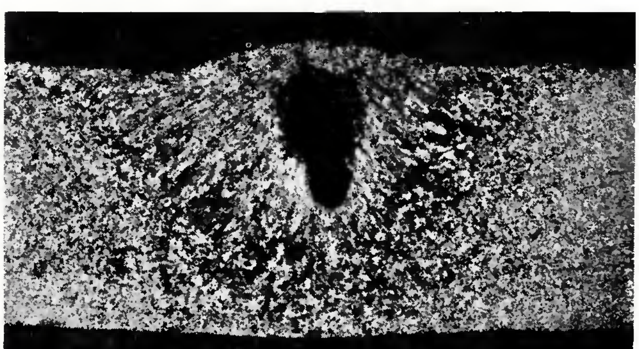


Fig. 1 — GTAW penetration in mild steel with pure MgF_2 flux

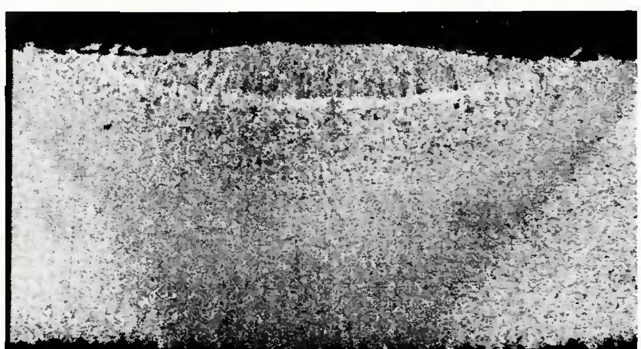


Fig. 2 — GTAW penetration in mild steel with pure BaF_2 flux

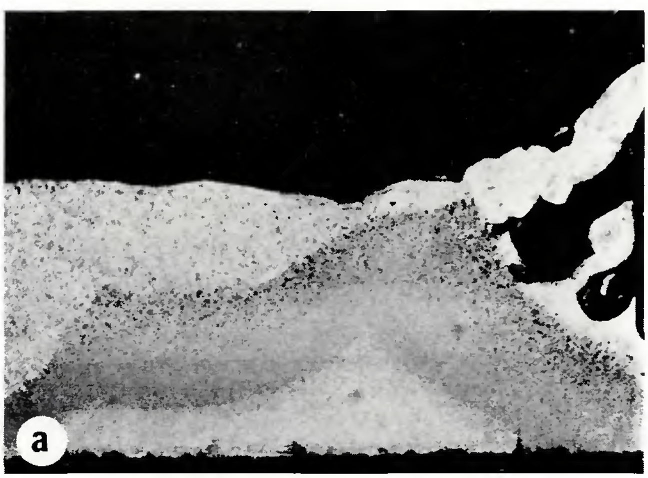
Fig. 3 — (a) Surface of GTAW weld in mild steel with pure MgF_2 flux; (b) surface of GTAW weld in mild steel with pure BaF_2 flux

Fig. 4 — Longitudinal penetration characteristics of GTAW welds in mild steel: (a) 30 mol % MgO in MgF_2 flux; (b) 30 mol % MgO in BaF_2 flux

voltage and current levels drawn by these fluxes, but contrasts with the variations of the electrode negative results. The MgF_2 bead surface was quite irregular, and longitudinal variations in penetration were present, as shown in Fig. 9. The bead surfaces with the heavy metal fluorides were again more regular, as shown in Fig. 10 for BaF_2. The NaF flux, on the other hand, produced a bead exceeding the penetration of the reference run, and again produced a very irregular bead surface. The trend observed with the oxide-fluoride fluxes was that penetration tended to increase and the electrode melting rate tended to decrease as the amount of heavy Ba cation increased. The MgO-NaF flux in this case slightly reduced the penetration in comparison to the reference run, and produced an undulating bead similar to the one in the electrode negative submerged arc run.

Discussion

The aim of this work was to establish a pattern of the behavior of welding arcs in the presence of slags, by



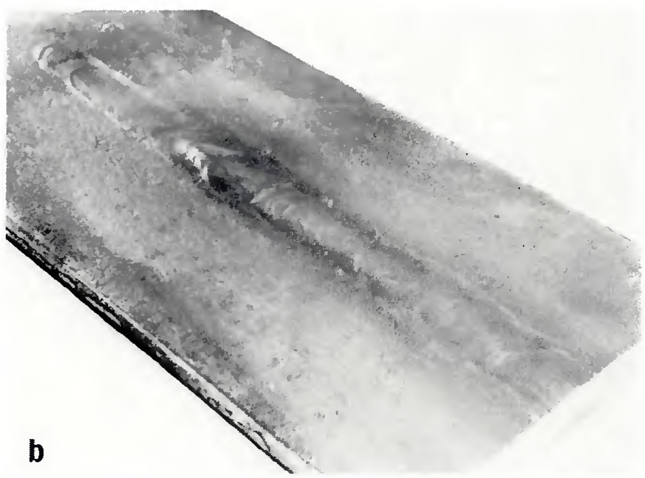


Fig. 5 — (a) Longitudinal penetration characteristics of GTAW welds in mild steel with 30 mol % MgO in NaF flux; (b) surface of GTAW weld in mild steel with 30 mol % MgO in NaF flux, showing the effect of arc instability

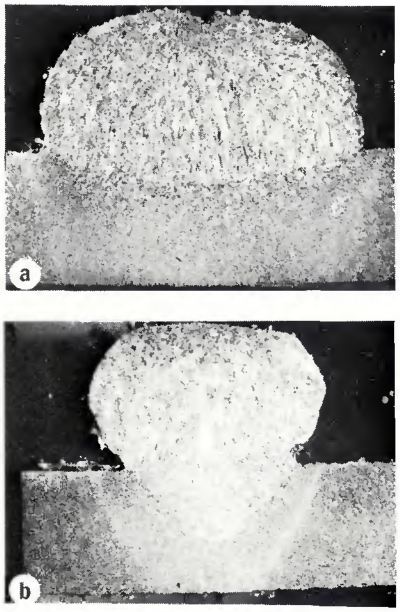


Fig. 6 — Cross-sections of SAW welds in mild steel (electrode negative): (a) pure MgF_2 flux; (b) pure BaF_2 flux

Table 5 — Physical Properties of Electrode and Flux Materials

Element or compound	Atomic or molecular wt	Melting point, C	Boiling point, C	Ionization potential, eV	Thermionic work function, eV
W	183.85	3380	~5900	8.1	4.53
Fe	55.9	1536	~3070	7.83	4.31
Na	23.0	98	883	5.12	2.35
Mg	24.3	650	1107	7.61	3.64
Ca	40.1	843	~1350	6.09	2.80
Sr	87.6	770	~1350	5.67	2.35
Ba	137.3	710	1638	5.19	2.11
F	19.0	—	—	17.34	—
O	16.0	—	—	13.55	—
Ar	39.9	—	—	15.68	—
NaF	42.0	995	1700	—	n.a.
MgF_2	62.3	1263	2239	—	n.a.
CaF_2	78.1	1418	>2250	—	n.a.
SrF_2	125.6	1400	>2250	—	n.a.
BaF_2	175.3	1320	2137	—	n.a.
MgO	40.3	~2600	>2800	—	3.1 - 4.4
BaO	153.3	1923	>2000	—	1.4 - 1.6

n.a. = not available.

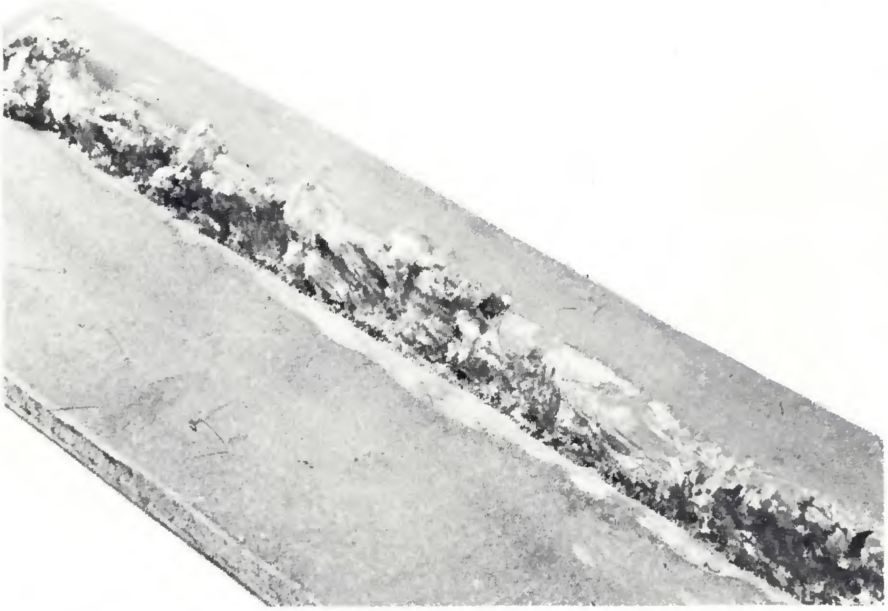


Fig. 7 — Surface of SAW weld in mild steel with pure NaF flux (electrode negative)

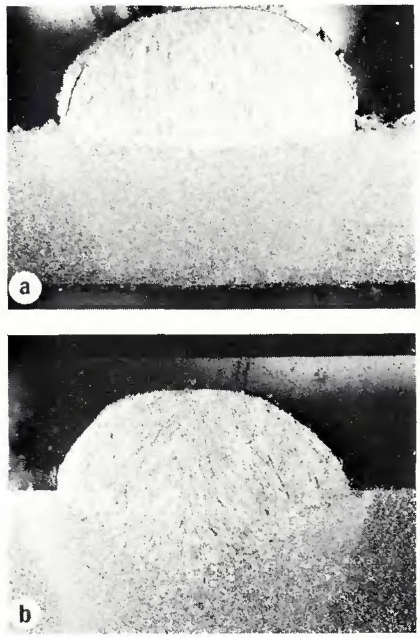


Fig. 8 — Cross-sections of SAW welds in mild steel (electrode negative): (a) 30 mol % MgO in MgF_2 flux; (b) 30 mol % MgO in BaF_2 flux

using very simple slags and minimizing welding variables as much as possible. The results show that individual chemical compounds and their combinations have a measurable effect on heat transfer and on arc stability which is dependent on the physical and chemical properties of the compounds, the electrode polarity, and the physical nature of the electrode metal.

The effects of materials introduced into a welding arc are difficult to isolate, but the most profound influences are likely to be those affecting the production of electrons at the cathode, and those affecting the reentry of the electron stream at the anode, since these provide the bulk of the energy used in melting metal at the anode.

Conditions at the anode are better understood at present, and the melting heat developed by the electron stream can be considered to be (to a first approximation) a function of three major variables: the anode work function, the anode drop (caused by a negative space charge) and the thermal energy of the electron stream.

Thus,

$$H_{anode} = I(\phi + V_a + 3kT/2e)$$

where ϕ = anode work function

V_a = anode drop

$3kT/2e$ = average thermal energy of one electron in the arc column

The thermal energy of electrons in the arc plasma is unlikely to be affected by slags, leaving the anode work function and space charge induced anode drop as the major anode variables.

Cathode conditions are more complex, and two types of electron generation are probably involved in high current welding arcs. Cathode metals with very high melting points, e.g. tungsten, produce electrons thermionically over a relatively large area and at a low current density (~ 10 A/mm^2). Tungsten welding electrodes, especially when doped with thoria or zirconia, have very low work functions and produce electrons easily. Metals with lower melting points, sometimes called "cold cathode" materials, are more difficult to extract electrons from, and emission generally occurs from small, rapidly moving cathode spots at very high current densities.

This form of electron generation is called field emission, and the state of matter at the cathode spots (where current densities may be as high as 10^4 - 10^5 A/mm^2) is very difficult to assess theoretically or experimentally. Any element or compound with a low work function which comes into contact with such a cathode will encourage electron emission and tend to change the cathode into a thermionic emitter. Positive ions in the arc column migrate to the cathode, and aid cathode heating and electron emission through collision with the cathode material. Plasma or vapor jets originating at the anode can also affect cathode heating if they are powerful enough to overcome any cathode plasma jet.

The simplest behavior observed in this work involved the alkaline earth fluorides. Only one anion and one cation source needs to be considered, and the physical properties listed in Table 5 (Refs. 11-13) show that melting and boiling points are very similar for the constituent metal and the fluorides, so that their assimilation into the arc atmosphere should be very nearly identical. Their thermodynamic properties are also very similar, e.g. free energy of formation, so that dissociation in the arc plasma should be of similar extent with all four compounds.

A reasonably consistent pattern of results is established if penetration is plotted as a function of the thermionic work function of the metal atom of the alkaline earth fluorides (Fig. 11). The GTAW system shows a linear increase in penetration with increasing work function, and the results fall on either side of the reference run penetration where no flux was present. If the assumption is made that flux additions do not affect the thermal energy of the electrons in the arc plasma, then the work function of the anode and the anode drop are the most likely items to be affected by the flux. The tungsten cathode work function is too low to be affected by the fluxes, and this probably accounts for the relatively constant current observed. Also in the GTAW runs, the flux was vaporized in the anode spot area, leaving a molten ring of slag around the periphery of the arc region, thus offering no physical barrier to the passage of current. Only a very thin layer of slag could have been present on the metal surface, probably as a film formed during constant condensation and vaporization at the molten metal surface.

Data on the effect of surface films on substrate work function are sparse, but those available show that both metals and compounds of the alkali and alkaline earth series reduce the work function of most metals (Ref. 11). Therefore some drop in the heat of electron condensation at the anode is possible if the anode drop and electron temperature are *rela-*

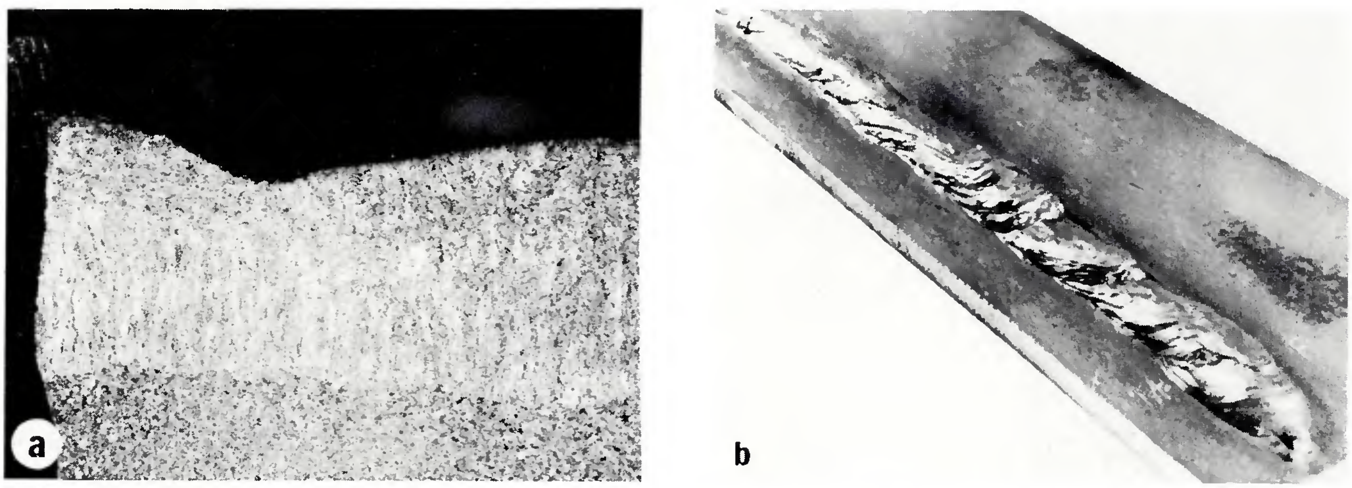


Fig. 9 — (a) Longitudinal penetration characteristics of SAW welds in mild steel with pure MgF_2 flux (electrode positive); (b) surface of SAW weld in mild steel with pure MgF_2 flux (electrode positive)

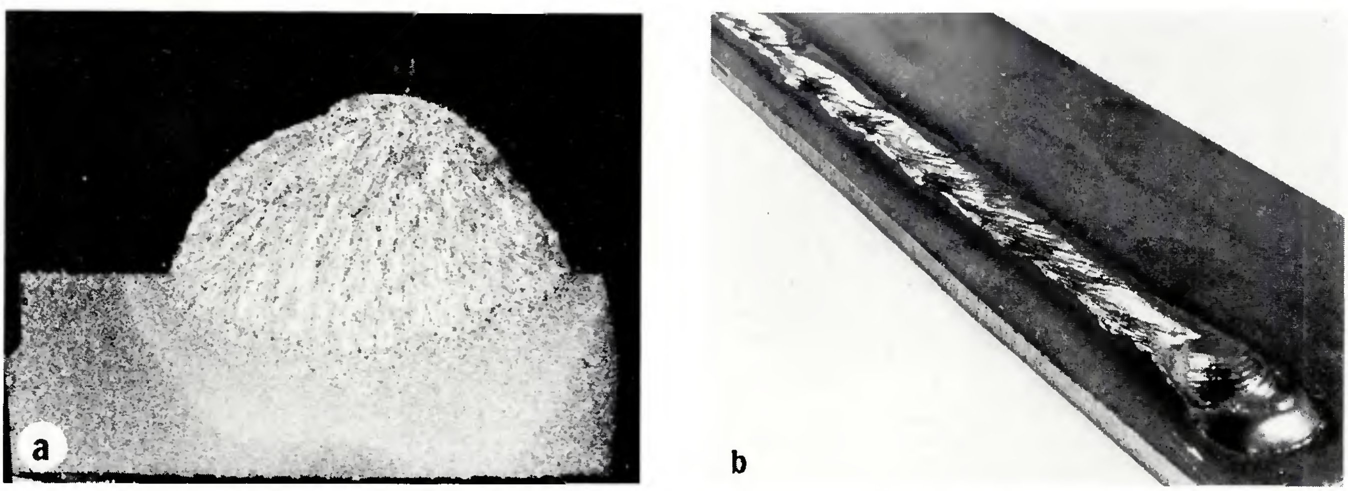


Fig. 10 — (a) Cross-section of SAW weld in mild steel with pure BaF_2 flux (electrode positive); (b) surface of SAW weld in mild steel with pure BaF_2 flux (electrode positive)

tively unaffected, and the reduced penetration of the SrF_2 and BaF_2 welds with the GTAW process conform to such a model (Fig. 11).

However, the MgF_2 and CaF_2 results show respectively an increase in penetration and no change in penetration, and demonstrate that heat balance effects are complex even with the simplest of fluxes and welding processes. The "harsher" arcs noticed with these latter fluxes are possibly due to an increased activity in the arc, e.g. more pronounced vapor or ion streams from the anode. The lower atomic weight of Mg and Ca compared to Sr and Ba could increase ion mobility and the tendency to form ion streams, and give rise to an increase in the anode drop which nullifies or overrides any decrease in anode work function, thus restoring or augmenting the anode heat input.

The evidence in other welding research partially contradicts this view. Chase and Savage (Ref. 4) found that Ca alone dropped the total arc voltage with a nickel anode in the GTAW process, but the effect on anode heat input was not given, and the exact location of the voltage drop is unknown. The fluorine present as a constant factor in the fluoride fluxes probably does not affect the relative performance of the alkaline earth metals, but its presence or absence alter the absolute effect of Ca or any other metal on arc characteristics.

The change to a consumable electrode on negative polarity resulted in a complete change in behavior. Penetration decreases with an increase in alkaline earth work function, and is always in excess of the Ar reference level (Fig. 11). This can be attributed to the change in cathode emission characteristics caused by the flux additions, which result in lower voltages and greatly increased currents at a constant electrode feed rate, due to the electrical characteristics of the power source. The ferrous electrode metal is probably altered from a field emitter towards a thermionic emission mode without measurably affecting the cathode heat input (melting rate).

This lack of effect on cathode heat input is demonstrated again in the results for a consumable electrode on positive polarity, where the penetration is nearly constant for all the alkaline earth fluorides, and is always slightly less than the Ar reference level. This reduction may be caused by a reduction in anode drop due to the tendency towards thermionic emission by the ferrous base metal. The minimal extent of the effect may be attributable to the nature of cathode spots, where the intense current densities and high temperatures could keep the quantity of flux in these regions to very low levels.

GTAW and SAW results using oxide-fluoride fluxes on both electrode polarities are more difficult to discuss since no clear pattern of behavior emerged. There are none of the consistent correlations observed with the pure fluoride fluxes on curent-voltage changes, and apparently the addition of oxides to fluorides even of the same chemical group complicates consumable behavior to a greater extent than present knowledge of arc physics can account for. For example, the effect of mixed oxide-fluoride fluxes on substrate emission characteristics is unknown. The effect of ion and/or vapor

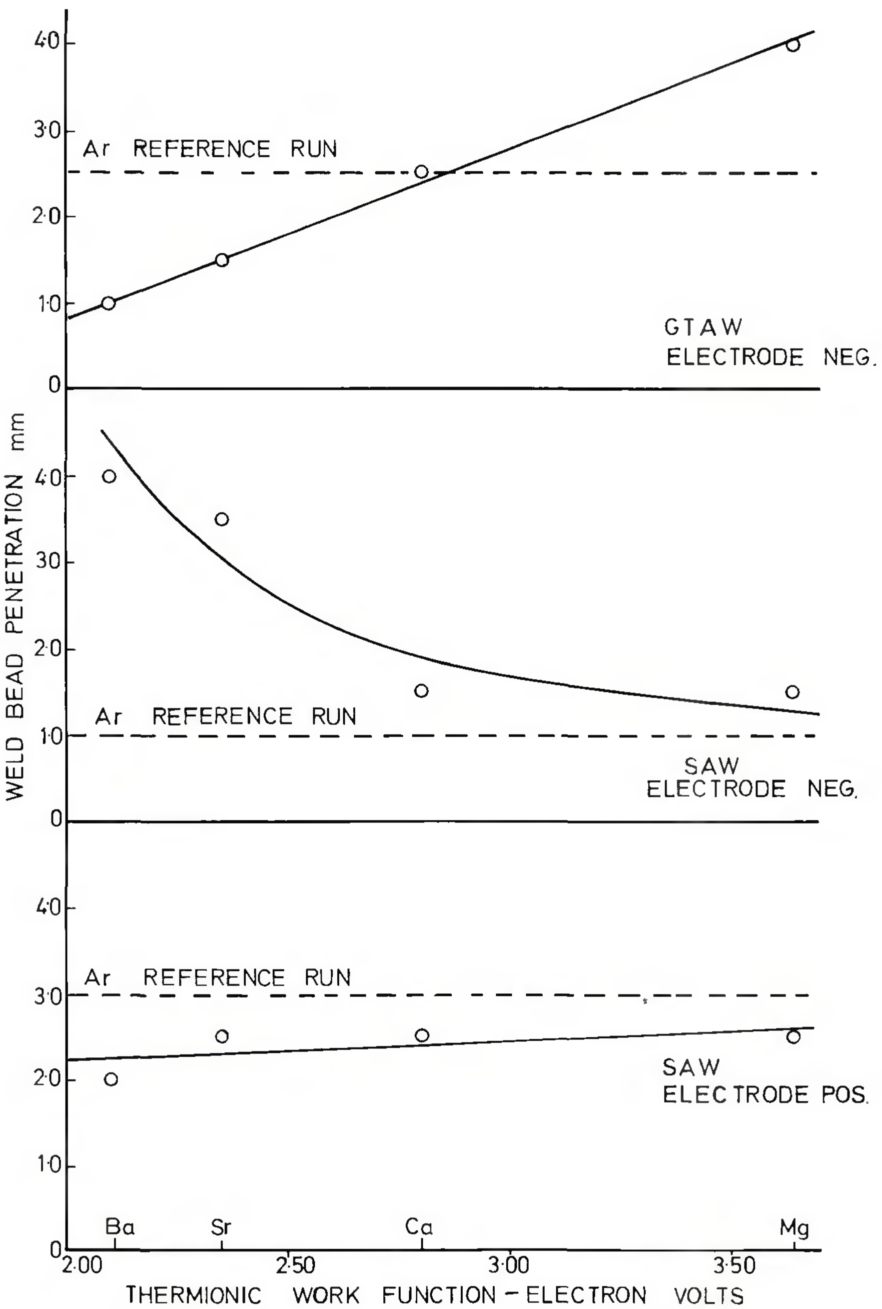


Fig. 11 — Weld penetration in mild steel vs alkaline earth work function for GTAW and SAW welds

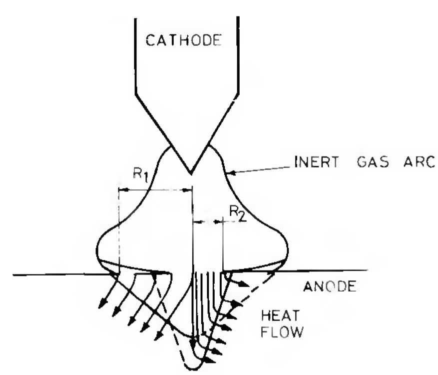


Fig. 12 — Two dimensional model of the relationship between penetration and anode spot size (after Ludwig, Ref. 5)

streams emanating from the anode is clearly demonstrated in the mixed oxide-fluoride fluxes. The cathode heat input in GTAW welding was greatly increased with the $MgO-BaF_2$ and $BaO-MgF_2$ fluxes. These and particularly the MgO-NaF flux also clearly showed the effect of arc stability on heat transfer.

The arc in the MgO-NaF experiment jumped around on both the anode and cathode surfaces enough to concentrate heat in fixed areas for widely varying lengths of time, which resulted in a series of weld "spots" of varying sizes rather than a weld bead. A similar but less marked effect in GTAW welding stainless steel was attributed by Ludwig (Ref. 5) to variations in anode spot size caused by easily ionized slag-like materials in the base plate, where weld penetration is inversely proportional to anode spot size (Fig. 12).

However, evidence in this area is not entirely consistent, since the easily ionized impurities (which were distributed inhomogeneously in small quantities) generally led to decreases in penetration in stainless steel in Ludwig's experiments, while slags used by Gurevich (Ref. 6) in GTAW welding titanium (which saturated the weld area) generally led to increases in penetration, apparently by reducing anode spot area. The evidence in the present work (using large quantities of slags) shows that the variation in time spent on a given anode spot area is also important, and that this time is greatly influenced by arc stability.

One consistent effect throughout the fused only submerged arc runs was the tendency toward more irregular bead shape and variations in penetration with the lighter fluorides, MgF_2 and CaF_2. Since this occurred with relatively unstable arcs, it is likely that the nonaxial arc column caused by variations in time spent at certain cathode or anode spots in unstable arc systems influences not only penetration but also rippling in fused only runs and the "humping" and irregular bead shape observed where metal transfer occurs.

The results reported in this work can only scratch the surface of the enormously complicated field of arc physics in the presence of slags and much more work remains to be done in this field. The ultimate aim of this type of investigation must be to lead to a rational system of flux design based on accurate knowledge of physical and chemical behavior. At present commercial fluxes must be made empirically by analyzing the performance of possibly hundreds of combinations (Ref. 14), and although the results are in most cases satisfactory, it is hoped that further work on fundamentals will help to solve some of the more difficult problems of flux design by prediction rather than chance.

Acknowledgments

The author wishes to record his indebtedness to the late Professor E. C. Rollason of the Department of Industrial Metallurgy, University of Birmingham, for providing laboratory facilities. He also wishes to thank Dr. D. R. Milner for his advice and encouragement, and the Ministry of Defense (Navy) for financial sponsorship.

References

1. Cresswell, R. A., Discusson on Paper No. 20. *Physics of the Welding Arc,* p. 233. Unwin, London, 1966.

2. Savage, W. F., Lundon, C. D. and Goodwin, G., "An Effect of Shielding Gas on Penetration in Inconel Weldments,-- *Welding Journal,* Vol. 47, (7), Research Suppl., p. 313s, 1968.

3. Ludwig, H. C., "Arc Welding of Vacuum and Inert Atmosphere Melted Zircaloy," *Welding Journal,* Vol. 36, (7), Research Suppl., p. 335s-341s, 1957

4. Chase, T. F. and Savage, W. F., "Effect of Anode Composition on Tungsten Arc Characteristics," *Welding Journal,* Vol. 50, (11), Research Suppl., p. 467s-473s, 1971.

5. Ludwig, H. C., "Current Density and Anode Spot Size in the Gas Tungsten Arc," *Welding Journal,* Vol. 47, (5), Research Suppl., p. 234s-240s. 1968.

6. Gurevich, S. M., Zamkov, V. N. and Kushnirenko, N.A., "Improving the Penetration of Titanium Alloys when they are Welded by Argon Tungsten Arc Process," *Automatic Welding,* 18, (9) p. 14, 1965.

7. Hazlett, T. H., "Coating Ingredients' Influence on Surface Tension, Arc Stability and Bead Shape," *Welding Journal,* Vol. 36, (1), Research Suppl., p. 18s-22s, 1957.

8. Wilkinson, J. B. and Milner, D. R., "Heat Transfer from Arcs," *British Welding Journal,* 7, (2), p. 115-128, 1960.

9. Pintard, J., "Some Experimental Data on Short-Circuit Transfer," Lecture 3, Session 3, *Physics of the Welding Arc,* p. 92-97, Unwin, London, 1966.

10. Milner, D. R.,Salter, G. R. and Wilkinson, J. B., "Arc Characteristics and their Significance in Welding," *British Welding Journal,* 7, (2), p. 73-88, 1960.

11. Fomenko, V. S., *Handbook of Thermionic Properties,* Plenum Press Data Division, New York, N.Y., U.S.A., 1966.

12. *Handbook of Chemistry and Physics,* 46th Edition, Chemical Rubber Publishing Company, Cleveland, Ohio, U.S.A., 1965.

13. Smithells, C. J., (Ed), *Metals Reference Book,* 4th Edition, Butterworths, London, 1967.

14. Smith, D. C. and Johannes, K. P., "Development of a Notch-Tough Self-Shielded Flux-cored Electrode," *Welding Journal,* Vol. 47, (3), p. 207-214, 1968.