

# Inclusion Formation in Arc Welding

*Electromagnetically induced motion in the weld pool is the primary factor that determines the amount and distribution of inclusions in arc welds made in copper*

BY G. THEWLIS AND D. R. MILNER

**SYNOPSIS.** Inclusion formation and distribution have been investigated for the following GTA and GMA weld reactions using copper as base metal:

1. Oxidation at the weld pool surface.
2. Oxidation at the weld surface with deoxidant added to the filler metal.
3. Deoxidation of the base metal.

Arrays of inclusions arise from the freezing-in, by the advancing solidification front, of the circulation pattern of oxidation-deoxidation taking place within the weld pool. This pattern is brought about by the electromagnetically induced motion which circulates reacting constituents throughout the liquid metal.

The method of adding the filler metal can significantly affect the amount and rate of reaction. In GTA welding, the filler metal melts below the surface of the pool, and deoxidant is circulated throughout the weld. However, in GMA welding, the continual stream of filler metal droplets entering the pool creates a deoxidant enriched surface layer. Thus, in the case of gas-metal reactions, reaction product can prevent ingress of oxygen into the pool and limit further reaction.

The type of deoxidant influences material transport. Manganese and silicon form spheroidal inclusions which tend to float out but are transported with the motion and thereby largely retained within the weld pool. Aluminum as deoxidant tends to produce alumina films. These are more easily entrained by the fluid flow and retained within the pool.

If surface films are formed and/or the weld is the cathode, the arc root can become concentrated and unstable. This gives rise to intense jets from the surface into the weld pool which

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## Some Abbreviations Used in This Paper

A	—amperes
cm	—centimeter
GMA	—gas metal arc
GTA	—gas tungsten arc
O.F.H.C.	—oxygen-free high-conductivity (copper)
Q.T.M.	—Quantitative Television Microscope

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physically remove the reaction product from the surface and project it into the weld. Alternatively, material can be physically swept from the surface layers by the fluid circulation patterns within the pool.

## Introduction

A major problem in arc welding, particularly with steels, is the presence of inclusions which can have a marked effect on the mechanical properties. There is considerable knowledge of the types of inclusions that are found in welds, and there is a sound thermodynamic basis for the understanding of the chemical reactions by which they are formed.<sup>1-7</sup> However, there is very little knowledge of the factors which determine the amount and the distribution of the inclusions to be found in welds. This problem is essentially concerned with the rates of the reactions by which inclusions are formed and the rate at which they are transported into, or out of, the weld pool.<sup>2,4,6-11</sup>

Material transport processes and rates of reaction are extremely fast in arc welding because of the effect of the electromagnetic Lorentz force

which causes rapid fluid flow in the weld pool.<sup>10</sup> The objective of the present work has been to make a qualitative evaluation of inclusion formation and distribution in gas tungsten arc (GTA) and gas metal arc (GMA) bead-on-plate deposits, giving specific attention to the influence of the electromagnetic stirring forces in the weld pool.

While inclusion formation in steels is the primary inclusion problem in arc welding, the present investigation has been carried out with copper; this metal was chosen because it behaves very similarly to iron in terms of inclusion formation by oxidation and deoxidation, while the lack of complex transformation structures made it much easier to perceive metallographically the pattern of inclusion behavior. Additionally, in supplementary experiments in which specific features were isolated and examined in controlled melts in crucibles, the lower melting point of copper was a considerable advantage in getting the experimental system under control.

Three types of inclusion creating situations were examined:

1. Oxide inclusions arising from oxidation at the weld pool surface when there is oxygen in the welding atmosphere.

2. Inclusions arising when there is oxidation at the weld surface and deoxidants are added to the filler metal.

3. Inclusions formed when a deoxidizer is added to the filler metal to react with oxygen already present in the weld plate.

These reactions were carried to exaggerated levels so that the reaction products and their pattern of behavior and distribution could be clearly seen.

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G. THEWLIS and D. R. MILNER are with the School of Metallurgy, The University of Birmingham, Birmingham, England.

## Experimental Techniques

Reactions were investigated for GTA bead-on-plate welding, in which electrode holder movement and feeding of filler metal were both manually controlled, and for mechanized GMA bead-on-plate welding. The GTA welds were made with electrode negative over a current range from 100 to 200 amperes (A). The GMA welds were made with electrode positive at 300 A at a welding speed of 76 cm per min (30 ipm) and a filler metal feed rate of 500 cm per min (197 ipm). In both cases the weld plate was 3 mm (0.12 in.) thick, and the diameter of the filler metal was 1.5 mm (1/16 in.).

Oxygen was fed into the welding atmosphere of argon at a controlled rate, monitored by rotameter flow gauges. Two deoxidizing filler metals were used; the first contained 0.25% silicon, while the second contained 1% aluminum.

The controlled crucible melts were made in crystallized alumina crucibles in which the copper was first melted by high frequency heating in an argon atmosphere and the metal allowed to become quiescent before introducing oxygen into the atmosphere and/or electromagnetically induced motion into the metal. The electromagnetically induced motion was brought about by an external field acting on the current flowing from an arc on the surface of the melt to an 8 mm (5/16 in.) diameter electrode cemented vertically into the base of the crucible. The external field was produced by an 8 turn coil from the crucible through which a current of 700 A was passed.

## Results

### Inclusions Arising from Oxidation at the Weld Pool Surface

To establish the effect of arc activity on the oxidation of copper, experiments were first carried out with small quiescent melts in crucibles; these then provided a basis for the subsequent evaluation of arc welding situations.

**Oxygen Absorption in Crucible Melts.** Samples of O.F.H.C. copper were melted in crucibles in an argon atmosphere by high frequency heating until a superheat of about 100 C (212 F) had been obtained. Heating was then stopped, and when the motion caused by heating had subsided, argon containing controlled proportions of up to 10% of oxygen was passed over the melt for 30 s at a gas flow rate of 6 litres per min (12.7 cfh), after which solidification took place under pure argon. The experiments were then repeated with a 100 A arc operating on the surface of the melt during the period that the argon-oxygen atmosphere was

flowing. The oxygen distribution in the ingot was then determined by optical microscopy and by Quantitative Television Microscope (Q.T.M.) scanning of the distribution of the copper-oxygen eutectic.

Without the arc action, there was no significant absorption of oxygen with up to 7% oxygen in the atmosphere—Fig. 1. However, at the 10% oxygen level there was a well-defined zone of oxygen absorption at the surface of the ingot—Fig 2. At the same time, there was also evidence of oxygen penetration into the bulk of the material—Fig. 1. By contrast, with arc activity there was marked oxygen absorption and transport of oxygen throughout the melt at all oxygen levels. In fact, there was a consistently higher oxygen level in the lower part of the ingot than near the surface—Fig. 1.

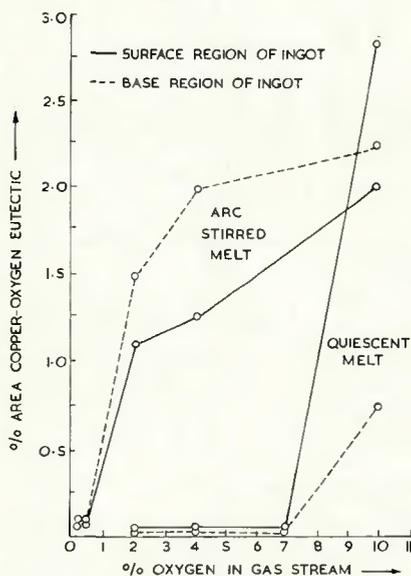


Fig. 1—Variation with oxygen content of atmosphere of the percentage area counts, by the Q.T.M., of copper-oxygen eutectic in the surface and base regions of small crucible melt ingots

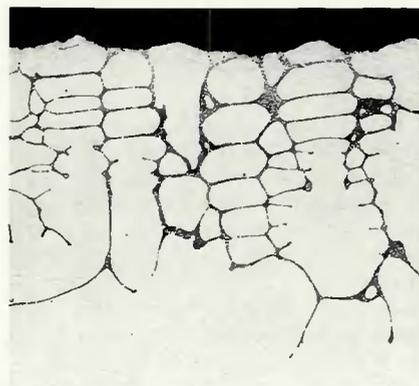


Fig. 2—Oxygen-rich surface layer in ingot produced from a quiescent melt over which a 10% oxygen-argon atmosphere was passed for 30 s.  $\times 30$  (reduced 30% on reproduction)

It was thus clear that the amount of oxygen absorbed into the molten metal was markedly increased. In fact, the amount of oxygen was virtually determined by the motion generated within the melt by the electromagnetic forces associated with the arc.

**Oxygen Absorption in GTA Welds.** Weld beads were manually deposited on O.F.H.C. copper plate using O.F.H.C. copper filler metal, in an atmosphere of argon containing 2% of oxygen at currents of 100, 150 and 200 A. Despite the much shorter life of the molten weld pool, compared with the 30 s oxygen absorption period used with the crucible melts, there was extensive oxygen absorption into all of the welds.

Metallographic examination of the 100 A welds showed a high concentration of oxygen in the region of the surface that had been under the arc (Fig. 3A), with bands of oxygen rich material in the depths of the weld (Fig.

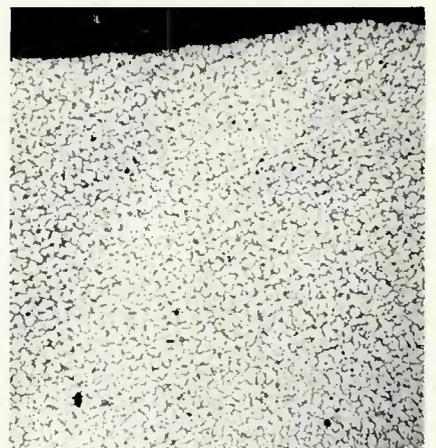


Fig. 3—Oxygen absorption in a GTA weld made in a 2% oxygen-argon atmosphere at 100 amperes. A (top)—high oxygen concentration in surface region, B (bottom)—band of oxygen-rich material, in otherwise low oxygen zone, at base of weld pool.  $\times 60$  (reduced 30% on reproduction)

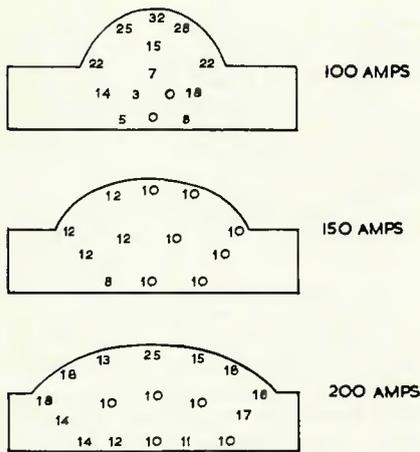


Fig. 4—Q.T.M. percentage area counts of copper-oxygen eutectic throughout the fusion zone of weld beads deposited by GTA welding at different currents in a 2% oxygen-argon gas stream

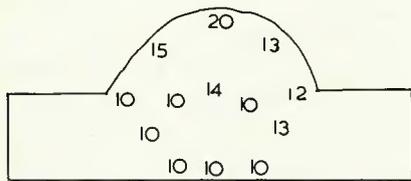


Fig. 5—Q.T.M. percentage area counts of copper-oxygen eutectic throughout the fusion zone of a weld bead deposited by GMA welding at 300 A in a 2% oxygen-argon gas stream



Fig. 6—Layered structure in oxygen-rich surface region of GMA welding.  $\times 150$  (reduced 50% on reproduction)



Fig. 7—Oxygen absorption in surface layer of metal at the base of the droplet formed on the end of the filler-metal electrode in GMA weld.  $\times 400$  (reduced 50% on reproduction)

3B). The bands or "sweeps" of oxygen-rich material gave the impression of arising from a pattern of circulation from the surface-rich zone, which was frozen-in by the advancing solidification front.

At 150 and 200 A, there was a more general dispersion of oxygen throughout the weld and no evidence of discrete frozen-in "sweeps" arising from the circulation pattern. However, there was still a considerable degree of non-homogeneity in the oxygen distribution, in that there was a tendency for the surface layers to be higher in oxygen, as shown by the Q.T.M. counts of the copper-oxygen eutectic—Fig. 4.

**Oxygen Absorption in GMA Welds.** Weld bead-on-plate deposits were made with the same O.F.H.C. filler metal at the higher current of 300 A, again in a 2% oxygen-argon atmosphere. Q.T.M. examination showed the amount of oxygen absorption and the oxygen distribution throughout the weld to be generally similar to that observed with the GTA welds—Fig. 5. Metallographic examination at a more detailed level showed, however, a difference in the distribution of the

oxygen in the surface layers compared with the GTA welds.

Noting that the GTA welds, particularly at low currents, had shown a uniform and relatively high concentration of oxygen in the surface, the GMA weld showed a non-homogeneous "layered" structure in the surface region—Fig. 6. Sections of droplets which had solidified on the end of the electrode showed a surface layer of oxygen absorption, with much less penetration of oxygen into the bulk of the drops—Fig. 7. Thus, the surface non-homogeneity was attributed to the advancing solidification front freezing-in the pattern of dispersal of the last droplets to be deposited in the surface of that section of the weld.

#### Inclusions Arising from Oxidation in the Presence of Deoxidants

The series of oxygen absorption experiments described in the previous section was repeated for both GTA and GMA welding, again in a 2% oxygen-argon atmosphere, but using the deoxidized filler metals.

**GTA Welds with Manganese and Silicon in the Filler Metal.** Oxygen

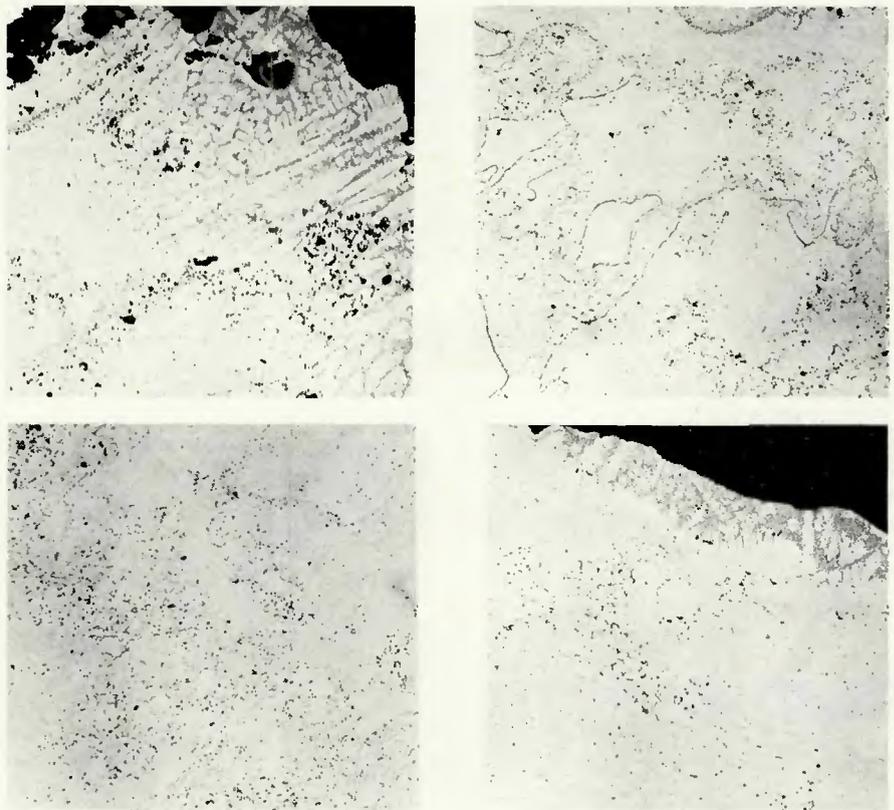


Fig. 8—The four types of inclusion zones observed in GTA welds made in a 2% oxygen-argon atmosphere with manganese-silicon deoxidized filler metal. A (top left)—area that had been immediately beneath the arc showing turbulent mixture of copper-oxygen eutectic and deoxidation products; B (top right)—central zone of frozen-in circulation pattern; C (bottom left)—lower region of weld in which inclusion material has become more uniformly dispersed; D (bottom right)—surface edge of weld in which oxygen absorption has occurred comparatively undisturbed by weld pool motion.  $\times 100$  (reduced 30% on reproduction)

absorbed from the surface and swept into the weld pool reacted with deoxidant from the melting filler metal to give rise to a complex pattern of oxygen absorption and deoxidant interaction, the characteristics of which changed with depth in the weld pool:

1. In the region that had been immediately beneath the arc, there was a turbulent zone where oxygen had been absorbed into the surface layers which had partially reacted with deoxidant from the filler metal. This zone contained a mixture of copper-oxygen eutectic and deoxidation product. There were also streamers of inclusion material from the surface regions into the pool and considerable porosity—Fig. 8A.

2. There was a central zone where the inclusion distribution followed the circulation pattern by which material from the surface regions had been swept into the body of the weld pool. In this zone, the absorbed oxygen had been further converted to manganese and silicon inclusions—Fig. 8B.

3. Further into the depths of the weld pool, the well-defined circulation pattern had dispersed to give rise to a more general distribution of inclusions—Fig. 8C.

4. There was a band along each edge of the surface of the weld bead, which appeared to have been zones of comparative quiescence; here oxygen absorption had gone on largely unaffected by the weld pool turbulence—Fig. 8D.

**GMA Welds with Manganese and Silicon in the Filler Metal.** At the higher current used with the GMA process (300 A compared with 100 to 200 A used with the GTA process) and with the electrode material acted on by (and transferred through) the arc, there was in fact much less oxygen absorption and inclusion formation in the body of the weld pool. There was, however, a marked surface layer in which there was clear evidence of reaction and inclusion products—Fig. 9A.

This layer was attributed to the continuous supply of deoxidant-rich droplets entering the surface, prior to



Fig. 10—Reaction layer on droplet surface.  $\times 600$

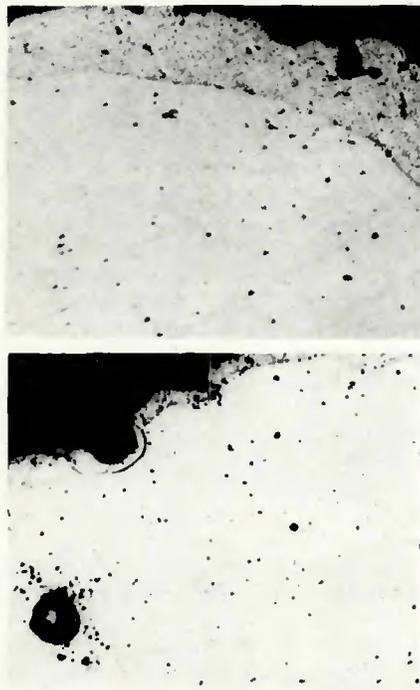


Fig. 9—GMA weld made with manganese-silicon deoxidized filler metal in 2% oxygen-argon atmosphere. A (top)—reaction predominantly in surface layers; B (bottom)—inclusions apparently "projected" into the weld from the surface layer of reaction product.  $\times 600$  (reduced 39% on reproduction)

being swept into the bulk of the weld pool. The droplets created a surface-rich layer of deoxidant that prevented ingress of oxygen into the body of the weld. Examination of droplets which had solidified on the end of the electrode clearly showed the effect of the deoxidant was to confine the reaction to the surface. Thus, the droplets were surrounded by a skin of reaction product, with no oxygen or reaction product within the droplet metal—Fig. 10.



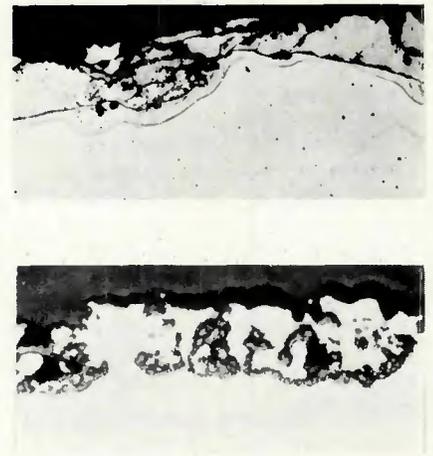
Fig. 11—GTA weld in 2% oxygen-argon atmosphere with 1% aluminum in the filler metal, showing how the reaction becomes more confined to the surface with increasing current: A (left)—100 A,  $\times 80$ ; B (top right)—150 A,  $\times 120$ ; C (bottom right)—200 A,  $\times 200$  (all reduced 30% on reproduction)

A further feature was that in places the surface appeared "indented." This was associated with a spherical inclusion in the adjacent weld metal which gave the impression of having been projected into the weld pool from the surface—Fig. 9B.

**GTA Welds with 1% Aluminum in the Filler Metal.** The use of aluminum as deoxidant in GTA welding gave better weld cleanliness, compared with manganese and silicon. At 100 A the region that had been under the arc root showed a pattern of frozen-in turbulence, comprising general circulation bands and also localized projections, or streamers, of inclusion material—Fig. 11A (similar to that observed with manganese and silicon in the filler metal—Fig. 8A). However, with aluminum the inclusions were in more film-like formations; also, there was less tendency for them to be swept into the depths of the weld pool and to degenerate into a homogeneous dispersal.

With increasing current, the tendency of the aluminum to form inclusion films and to restrict the reaction to the surface became more pronounced—Fig. 11B and C. At the highest current of 200 A, the surface reaction was particularly marked and was associated with a very rough "puckered" surface—Fig. 11C. As the reaction became more confined to the surface, the body of the weld was more inclusion-free, compared with that observed with manganese and silicon in the filler metal (compare Figs. 11 and 8). There was still, however, evidence of the localized streamers of inclusion material projected from the surface into the weld—Fig. 12.

**GMA Welds with 1% Aluminum in the Filler Metal.** The behavior of aluminum in GTA welds in which a protective surface layer was formed



and became more pronounced with increasing welding current was not carried over into GMA welds. Instead the GMA weld contained more inclusion material than the GTA welds. There was, in particular, a layered surface structure (Fig. 13A) as observed with the other GMA welds. Also, there were regions where oxygen was absorbed to form copper-oxygen eutectic (Fig. 13B) together with patches of film-like inclusion material within the body of the weld (Fig. 13C).

Droplets which had solidified on the end of the electrode showed an almost continuous surface layer of reaction product, similar to that observed with manganese and silicon in the filler wire (Fig. 10), with the body of the drop free from inclusions. It appeared that the greater amount of inclusion material in the GMA welds, compared with the GTA welds, resulted from the droplet impinging on, and breaking up, the protective surface oxide layer. This allowed oxygen absorption to take place and, at the same time, caused surface oxide films to be transported into the depths of the weld.

#### Inclusions Arising from Deoxidation of the Weld Plate

In this series of experiments the situation was investigated in which the role of the deoxidant in the filler metal was to react with oxygen already present in the base metal. Thus, tough pitch copper weld plate was employed, with the same deoxidizing filler metals as used for the previous experiments.

The GTA and GMA welds showed the same pattern of behavior so that both systems are considered together.

*GTA and GMA Welds with Manganese and Silicon in the Filler Metal.* In all of the welds the deoxidizing filler material had penetrated to the boundary of the fusion zone. Thus, there was a clear demarcation between the oxygen present as copper-oxygen eutectic at the grain boundaries of the

unmelted tough pitch copper and that present as individual inclusions in the fusion zone—Fig. 14. Around much of the fusion zone there was a semi-continuous line of inclusion product; this could have marked the limit of the static liquid boundary layer adjacent to the solid weld plate, with reaction product on the fusion zone side being removed by the motion in the weld pool. Most of the metal in the weld pool had been deoxidized, although there were some isolated regions where the oxygen had solidified as copper-oxygen eutectic—Fig. 15A. However, the welds were comparatively clean, considering the amount of oxygen initially present in the tough pitch copper. Because of this, it was apparent that the deoxidation product had been largely removed from the bulk of the weld. There was, however, again a pronounced region that had been beneath the arc which showed a frozen-in turbulent pattern of deoxi-

dation product—Fig. 15B.

*GTA and GMA Welds with 1% Aluminum in the Filler Metal.* The behavior of the GTA and GMA welds in tough pitch copper with the 1% aluminum in the filler metal was similar to that observed with manganese and silicon in the filler metal, in that the deoxidant appeared to have penetrated throughout, and fully deoxidized, the weld pool. There was, however, an important difference: the aluminum oxide deoxidation product was not removed from the weld pool but remained within the welds which were full of film-like inclusion material—Fig. 16.

#### Surface Transport into the Weld Pool

Many of the results showed a turbulent pattern of oxygen absorption and deoxidation product in the region that had been immediately beneath the arc. In other cases, e.g., Figs. 9B and 12, there appeared to be clear evidence for localized projection from the surface film of reaction product into the weld pool.

These phenomena raised the problem of whether the electromagnetically induced motion in weld pools was able to physically entrain material from the surface into the molten metal. To seek further evidence on this point, an experiment was carried out with the crucible melt system. In this



Fig. 12—Aluminum oxide "inclusion streamer" projected into the weld pool from the surface of a GTA weld at 150 A.  $\times 200$  (reduced 30% on reproduction)



Fig. 14—Weld plate-fusion zone interface in weld made in tough pitch copper with manganese and silicon in the filler metal.  $\times 170$  (reduced 50% on reproduction)

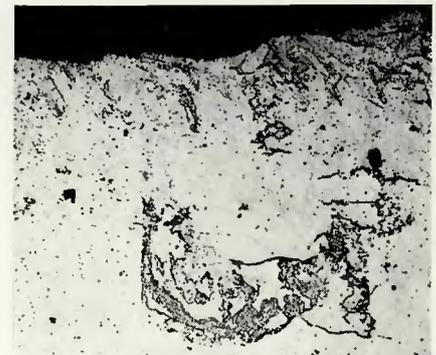
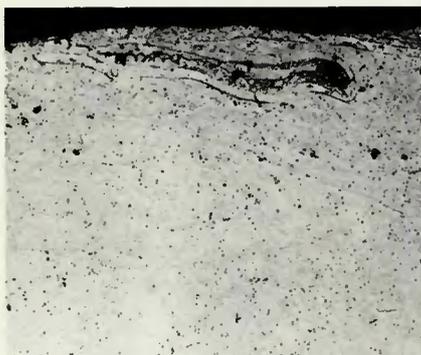


Fig. 13—GMA weld in 2% oxygen-argon atmosphere with 1% aluminum in the filler metal: A (left)—layered surface structure; B (center) region of oxygen absorption at the surface; C (right)—patches of film-like inclusion formations in the body of the weld.  $\times 120$

experiment O.F.H.C. copper was melted under a blanket of inert flux comprising 15 wt-% calcium fluoride, 15 wt-% magnesium fluoride and 70 wt-% barium fluoride. The melting point of this flux mixture was about 870 C or 1598 F. It was impossible to operate an arc through this flux layer, so the electromagnetically induced motion was brought about in the melt by dipping into the surface a 6.5 mm (¼ in.) diameter tungsten electrode through which 100 A was passed to generate motion while the metal solidified.

On sectioning and metallographic examination, clear evidence was

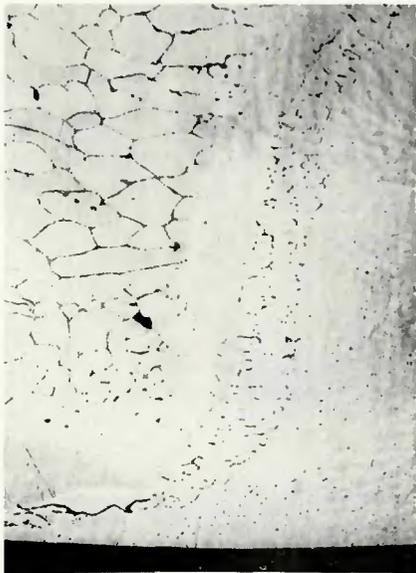


Fig. 15—Deoxidation of tough pitch copper with filler metal containing manganese and silicon: A (top)—region of partial deoxidation in depths of weld,  $\times 100$ ; B (bottom)—surface region, that had been immediately beneath the arc, showing frozen-in turbulent pattern of deoxidation product,  $\times 200$  (A and B reduced 30% on reproduction)

found for the inert insoluble layer of surface flux being carried into the melt. It appeared particularly to have been swept to, and trapped in, the peripheral zone of the ingot—Fig. 17.

### Discussion

Considerable work has been done in the past to identify the inclusions in welds and to establish the reactions by which they are formed. However, comparatively little attention has been given to the factors that determine the amount and the distribution of inclusions in welds. Where a high concentration of inclusions has been found, the tendency has been to attribute this to segregation. The present work has shown, however, that the dominant factor in determining inclusion distribution is the electromagnetic motion in the weld pool which transports the reacting constituents and the reaction products that make up the inclusions. The resulting inclusion array then arises by the advancing solidification front freezing-in this pattern of circulation and dispersal.

The experimental work has shown that the effect of the electromagnetic motion on inclusion formation has to be considered in relation to three factors:

1. The transport of the reactive constituents, i.e., oxygen, deoxidants and reaction products, to and from the surface of the weld pool.
2. The method by which the filler metal is added to the weld.
3. The nature of the reaction product.

### Material Transport

In the simplest quiescent situation that was approached by the crucible melt, the surface of the metal was converted to metal oxide, and penetration of oxygen into the metal was then determined by diffusion of oxygen from this surface oxide layer into the body of the metal, as portrayed diagrammatically in—Fig. 18A. These quiescent conditions never occurred in the weld pool. However, they did appear to pertain more to the reactions at the surface of the droplet on the tip of the electrode, where an oxygen-rich surface layer was observed, with comparatively little penetration of oxygen into the bulk of the droplet.

With an arc there is a constriction of the current flow by the arc root at the weld pool surface (compared with the broad current path through the weld metal), and the associated Lorentz force sets up a fluid flow within the weld pool. Oxygen and deoxidants are

then rapidly transported into the weld from the surface so that there is a greater rate of absorption while, at the same time, the reacting constituents penetrate throughout the weld pool—Fig. 18B. This situation gives rise to a generalized circulation in the weld pool; it occurred when there was a stable arc, i.e., in GTA welding with electrode negative, and a comparatively clean metal surface.

A more localized and intense jet-like projection of material from the surface layer of reaction product into the weld pool was also observed. This occurred with electrode-positive GMA welding where the current was emitted from cathode spots on the metal surface; it also occurred with GTA welding with a



Fig. 16—Weld in tough pitch copper made with filler metal containing 1% aluminum.  $\times 25$  (reduced 30% on reproduction)



Fig. 17—Inert, insoluble, fluoride flux that has been carried from the surface by the electromagnetically induced motion and trapped in the solidifying ingot.  $\times 100$  (reduced 26% on reproduction)

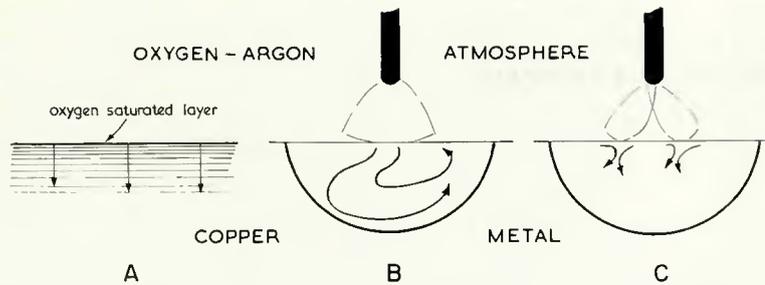


Fig. 18—Modes of transportation from the surface: A—quiescent situation, transport governed by diffusion; B—transport by motion electromagnetically induced by current flow from stable and comparatively large arc root; C—intense, intermittent “jetting” brought about by unstable constricted arc root

film on the surface, when the arc root tended to become unstable. Under these conditions the arc root tends to move, localizing for short periods of time on small areas which support a high current density. This leads to intense fluid flow away from the points of constriction giving rise to a series of intermittent surface jets—Fig. 18C.

The jets are apparently capable of carrying surface reaction product into the weld pool. This situation occurred particularly when a layer of reaction product was formed at the surface which interfered with the current flow from the arc into the weld metal. Because the experimental conditions used in the present work were specifically designed to intensify the deoxidation reaction, it is difficult to hypothesize about the extent to which this mechanism operates in practical welding situations.

#### Method of Adding the Filler Metal

There was comparatively little difference in the amount of oxygen absorption with the GTA and the GMA welding systems, but there was a considerable difference in their behavior in deoxidation. With the GMA process, there is a continual stream of droplets entering the surface layers which are subsequently transported into the body of the weld by the weld pool motion—Fig. 19A. This would make the surface layer rich in deoxidant which reacts with the oxygen that is being absorbed into the surface to form films; the films in turn limit the ingress of the oxygen into the weld pool.

With the GTA welding system, the filler metal is added by dipping it into the weld pool. The super-heated weld metal circulates around the filler rod below the surface and melts it away, at the same time carrying it into the body of the weld pool where it is diluted by the weld plate material. The oxygen being absorbed into the weld metal from the surface penetrates deeper

into the weld pool and reacts with the deoxidant—Fig. 19B. In this way there tended to be more reaction, and more deoxidation product, in the body of the GTA welds than in the GMA welds.

This pattern of behavior was altered when the deoxidation reaction was intense and aluminum was used as the deoxidant. Under these circumstances, a substantial film of alumina formed on the surface of the weld (as opposed to alumina inclusions being formed by reaction within the weld pool, or discontinuous alumina films formed at the surface but broken up and swept into the pool, as occurred at low currents). Where the substantial surface film remained intact, as with GTA welding at 200 A, it prevented oxygen ingress and thereby the formation of inclusions within the weld metal. With the droplet transfer in GMA welding, the film was fragmented and carried into the weld pool, and further oxidation then proceeded at the weld surface.

In GTA welding, the rather paradoxical situation arose in which the weld metal became cleaner as the inclusion forming reaction became more intense. This result could, however, be specific to the present work in which the experimental conditions were arranged to exaggerate the inclusion forming reaction. Normal welding conditions would probably conform more to the less intense reaction situation in which alumina inclusions formed in, or discontinuous alumina films were transported from the surface into, the weld pool.

#### Nature of the Reaction Product

The nature of the reaction product was significant where arc instability occurred and intense surface jets projected material from the layer of reaction product on the surface into the bulk of the metal. Where the reaction product was liquid, as with the use of manganese and silicon as deoxidizers, the projected material formed

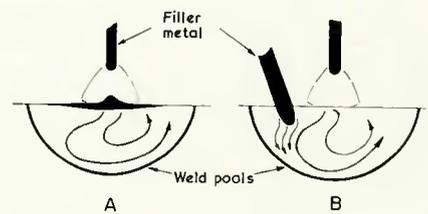


Fig. 19—Proposed significance of the difference between the methods of adding the filler metal: A—the GMA welding system with droplets forming a deoxidant-rich surface layer; B—GTA system in which filler metal melts directly into, and circulates in, the body of the weld pool

spherical inclusions. Where the reaction product was a solid surface film, the film formation was largely retained in the structure of the inclusion that was projected into the weld metal. It could be that these two inclusion formations—one round and with small surface area, the other having a large surface area, flake-like form—could have markedly different effects on the mechanical properties of the weld metal.

Another aspect in which the nature of the reaction product was significant was the extent to which it was removed from the molten weld pool. This showed up particularly clearly in the experiments with the tough pitch copper in which the reaction took place entirely within the body of the weld pool. With both the manganese-silicon and the aluminum deoxidized filler metals, the reaction product has a lower density than the metal and would therefore be expected to float out. On the other hand, the motion of the metal within the weld pool exerts a viscous drag force on the inclusion material which tends to carry it along with the metal flow and thereby to keep it within the weld pool.

The flotation process was significant with manganese-silicon as deoxidizers, since the lower zones in the welds were comparatively free from inclusions. With aluminum as deoxidizer, alumina films provided a large surface area over which viscous drag would occur; the result was that the metal circulation retained the inclusions within the weld pool.

#### Preliminary Nature of the Work

In the present work it has been shown that weld pool motion plays a major role in determining the amount and the distribution of inclusions to be found in welds. This is an aspect of inclusion formation that does not appear to have received much attention and which merits further study.

It would not be advisable to generalize much on the findings of the present investigation, in which the

copper-oxygen system was chosen specifically for its favorable characteristics for an initial study. Here inclusion formation was exaggerated to make it easier to observe the processes taking place. Other systems also need to be investigated so as to develop a fuller understanding of the problem.

## Conclusions

1. The primary factor that determines the amount and the distribution of inclusions in arc welds in copper, for a given oxygen concentration in the welding atmosphere, is the electromagnetically induced motion in the weld pool. This motion produces a rapid rate of transport of oxygen from the surface into the weld pool. It also rapidly circulates the deoxidants in the filler metal that is added to the weld. The array of inclusions then found in the weld comes about by the advancing solidification front freezing-in this pattern of circulation and interaction between the oxygen and the deoxidants.

2. Where inclusions arise from oxidation of GTA welds in copper—and manganese and silicon are added as deoxidizers to the filler metal—the oxygen circulates from the surface into the body of the weld pool and reacts with the deoxidizers circulating from the melting filler rod. The product of reaction then tries to float out but to some extent is retained by the weld pool motion.

3. With aluminum used as the deoxidizer in the filler metal in the GTA welding of copper, a similar pattern of

behavior to that observed with manganese and silicon prevails at low reaction intensity. But if the deoxidation reaction becomes sufficiently intense, e.g., as at high currents and a high oxygen content in the welding atmosphere, a protective alumina film forms on the surface and prevents ingress of oxygen into the weld pool.

4. With GMA welding the continuous stream of droplets entering the surface layers of the weld pool produces a high surface concentration of deoxidants which react with the absorbing oxygen and thereby limit oxygen ingress. On the other hand, the impinging droplets break up any protective surface film that may otherwise form and expose the metal surface to further oxidation. GTA welding, therefore, produces cleaner welds when a protective surface film forms, whereas GMA welding produces the cleaner welds at lower reaction levels.

5. The physical nature of the reaction product markedly affects the inclusion content of the welds. This was shown particularly clearly in deoxidation of welds in tough pitch copper. With manganese and silicon as deoxidizers, the reaction product tended to become spherical and to float out, whereas, with aluminum as the deoxidizer, alumina films that formed were swept along by the weld pool motion and thereby retained in the weld.

6. When the arc root at the weld pool surface becomes unstable (as, for example, when surface films form and/or the weld pool is the cathode), it then moves around on the surface

taking up a sequence of constricted locations of high current density. A series of high velocity metal jets are generated from the weld surface into the weld pool. These jets physically detach material from the layer of reaction product on the surface and transport it into the body of the weld pool. Surface reaction product can also be physically transported into the weld by the less intense, stable, weld pool motion that generally occurs under welding conditions.

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by A.W. Schueler

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