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Fundamental Studies on Slag Adherence to Submerged Arc Weldment*

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Abstract

It is an important matter to make clear the mechanism of slag adherence to weldment in submerged arc welding. To examine the effect of condition of steel plate surface on the feature of the adherence, bead-on-plate welding was carried out using a weak acidic fused type flux and plates with polished, as-rolled and gas-cut surfaces.

It became clear that the slag adherence in bead-on-plate welding is liable to occur only near the bead edge. Slag adherence was rleatively significant in the as-rolled plate welding and was very scarce and almost absent in the polished and gas-cut plate weldings respectively. The cross sectional micro structures of the slag-metal interfaces near the bead edge were examined, because it was considered that the slag chips at the place can anchor the crusty slag over the bead by adhering themselves basically to the HAZ.

In the case of the polished plate, neither mechanical bonding nor intermediate layer was found in the slag-metal interface even by an electron microscope with a magnification of 5000×. In the case of the as-rolled plate, no mill scale was observed at the limited portion very near the bead edge under the slag, though a scale-bearing plate was used. And an uneven interface considerably rougher than the original scale-slag interface was formed. This seems to suggest the probable effect of mechanical bonding between slag and metal. Becsides, it was considered that in the case of the gas-cut plate, a greater detachability of the surface layers of the plate results in an equally greater detachability of the slag.

Key Words: Slag adherence, Slag removal, Mechanism of adherence, Slag/Metal interface.

1. Introduction

Slag adherence is recognized as a problem to be solved in submerged arc welding, because the adherence impairs welding workability, painting quality and also commercial value of the weldment. The adherence or removability of the slag has been invsetigated from the viewpoints such as epitaxial solidification at the slag-metal interface[1)-3)] and their expansion coefficients.[4)]

In this investigation, slag chips adhering near the bead edge were treated, because it was considerd that they can anchor the crusty slag over the bead by adhering themselves basically to the HAZ. Effect of oxide layers (scales) on the feature of the slag adherence was examined using plates with polished, as-rolled, and gas-cut surfaces. Cross sectional microstructures of the slag-metal interfaces were then investiagted using EPMA.

2. Experimental Procedure

SM41B type mild steel plates (25 mm thick) having three different surface conditions, a high manganese-low-silicon type electrode wire (4.8 mm dia.) and a weak acidic fused type flux (20×200 mesh, $B_L = -0.26$*1) were used in this experiment: Surface conditions of the plates are:

(i) Polished (with scale removed)*2.
(ii) As-rolled (without removing scale).
(iii) Gas-cut.

Table 1 Chemical compositions of steel plate and electrode wire (%).

	C	Si	Mn	P	S
Plate	0.12	0.21	1.09	0.018	0.003
Wire	0.12	0.01	1.97	0.012	0.007

Table 2 Chemical composition of flux (%).

SiO_2	MnO	CaO	MgO	Al_2O_3	TiO_2	FeO	CaF_2
39.2	20.2	19.6	4.1	2.6	3.7	1.4	8.0

Table 3 Chemical compositions of plate surfaces detected by X-ray diffraction test.

Polished	<u>α-Fe</u>
As-rolled	α-Fe, FeO, <u>α-Fe_2O_3, Fe_3O_4</u>
Gas cut	<u>α-Fe</u>, αFe_2O_3, Fe_3O_4

Components underlined: Strongly diffracted

The chemical compositions of the steel plates and electrode wire are shown in Table 1, and the chemical composition of the flux is shown in Table 2. The results of the X-ray diffraction analyses of the plate surfaces are shown in Table 3. Welding was performed using the bead-on-plate method, under the conditions of 500A, 30V (ac) and 30 cm/min.

Prior to examining the external appearances of the welds with fast stuck slag chips, the slag crusts over

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*1 Basicity $B_L = -6.31(SiO_2) + 4.8(MnO) + 6.05(CaO) + 4.0(MgO) - 0.2(Al_2O_3) - 4.97(TiO_2) + 3.4(FeO)$ where, (SiO_2), (MnO)……: Mole fraction of each component[5)].

*2 Finished by grinding machine with DA-46J abrasive wheel.

the beads were removed carefully and non-stuck slag-chips were blown off by compressed air. The specimens for microscopy were cut off by machines with cooling liquid supplied after the slag chips were covered with epoxy resin. The specimens were then embedded into hard resin for polishing after the epoxy resin was dissolved away by solvent.

3. Results and Discussion

3.1 *Location of slag adherence*

The external appearances of the welds are presented in Fig. 1. The following became clear.

(a) In the case of the as-rolled plate a comparatively remarkable slag adherence is seen near the bead edge extending from the weld metal to the plate. But, a substantial slag detachment can be seen on the beads in other cases, *i.e.* polished and gas-cut plates.

(b) In the case of the polished plate, thin slag specks are able to be seen on the base plate along the bead edge as shown in Fig. 2, but it is difficult to find such specks in the case of the gas-cut plate.

Regarding the poor adherence to the weld metal, the following possible causes were conceivable: Some gases such as CO, H_2, N_2 and so on prevent the adherence of the slag because of their continuous issuing from the weld metal during the solidification and cool-

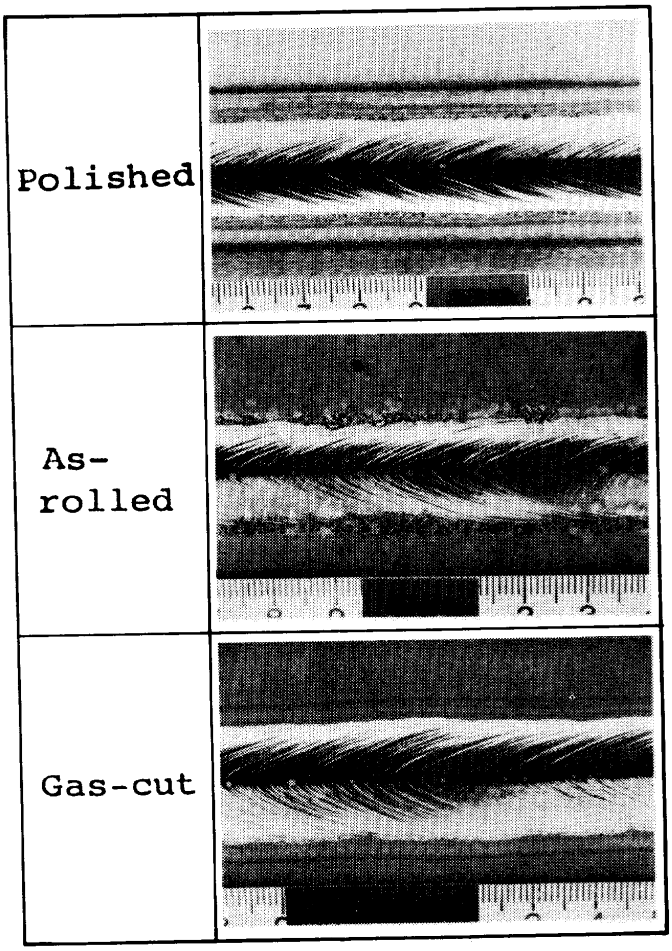


Fig. 1 External appearance of slag adherence for each plate surface condition.

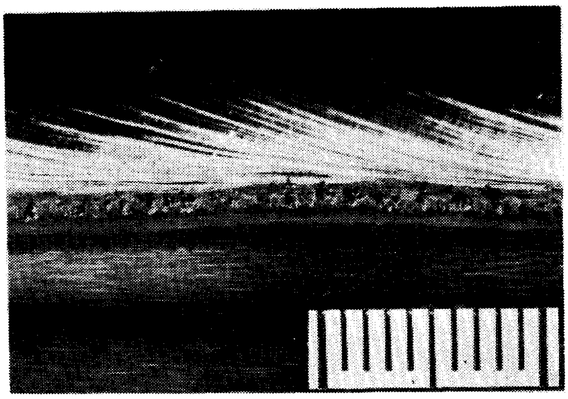


Fig. 2 Detailed appearance of slag adherence on the polished plate.

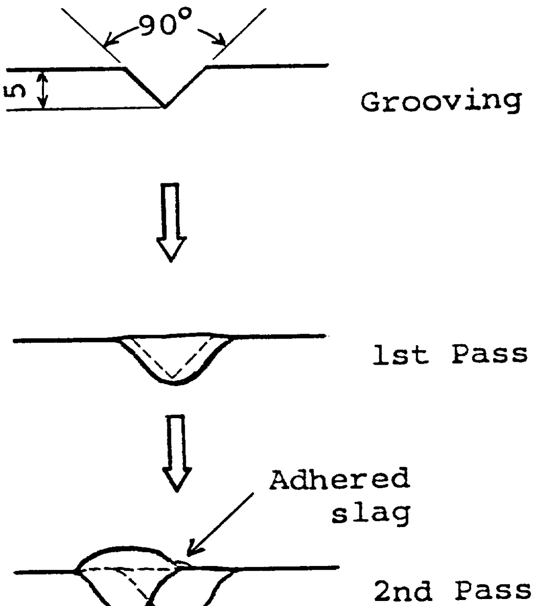


Fig. 3 Experimental procedure to ascertain possibility of slag adherence to the cold weld metal.

ing processes of the metal. On the other hand, the difference in the thermal expansion coefficient between slag and metal makes them slip.

Among these hypotheseses, the former was ascertained by the authors by means of the following experiments (see Fig. 3).

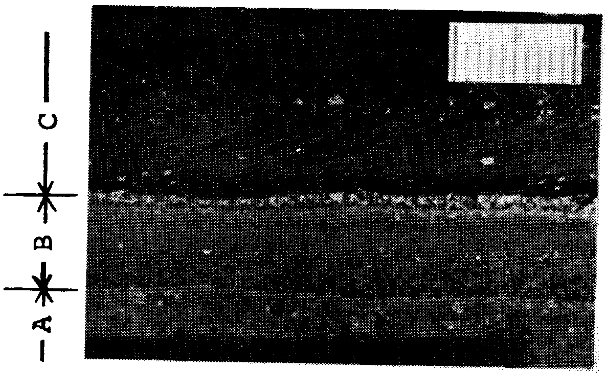
(i) A 90° V groove was formed on the as-rolled plate.

(ii) Welding was done on this groove in such manner that the bead face was flush with the plate surface.
Welding conditions: 550 A, 35 V (ac), 47 cm/min.

(iii) The weld was allowed to cool down in the air to the room temperature for degassing, and heated again to 150°C and kept for 48 hours at this temperature, then allowed to cool down to the room temperature in the air.

(iv) Using the bead formed in the 1st pass as the base metal, the 2nd pass was done under the same conditions as above.

As a result, adherence also occurred, as shown in Fig. 4, on the weld metal which was used "as the base



A : Base plate

B : 1st Pass

C : 2nd Pass

Fig. 4 Appearance of slag adhering to the weld metal "as the base metal".

metal" and cooled down once in the air, along the bead edge of the 2nd pass. This can be said to be evidence supporting the above-mentioned hypothesis.

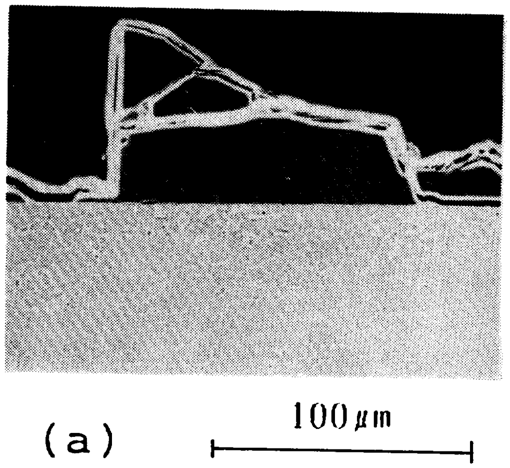
Incidentally it was considered that the slag adherence to the base metal near the bead edge is essentially located on the HAZ. Such an idea is supported from the following fact, *i.e.* the width of the adhering zone on the plate almost corresponds to the width of the HAZ, because the portion of the plate heated higher may be possibly favorable for adhering of the slag. For example, the width of the HAZ, extending from the bead edge to the end of the HAZ, was estimated to be about 1.3 mm in the case shown in Fig. 5 (this weld was obtained under the conditions of 500 A, 30 V (ac) and 30 cm/min).

3.2 *Observation of slag-metal interfaces*

In order to clarify the reasons why the slag is liable to adhere to the HAZ and why the degree of adherence varies with the surface conditions of the base metal, the authors then examined the cross sectional microstructures of the slag-metal interfaces.

(1) Polished plate

Electron micrographs of the boundaries between the base metal and the slag adhering to the HAZ are shown in Fig. 6 (a) and (b), where, (a): 500×, (b): 5000×. In the photographs, any slag-metal engagement (or meshing) resulting in probable mechanical bonding is not found. And neither gap nor intermediate layer was able to be detected even in the observation with 0.5 μm resolution as shown in Fig. 6(b).



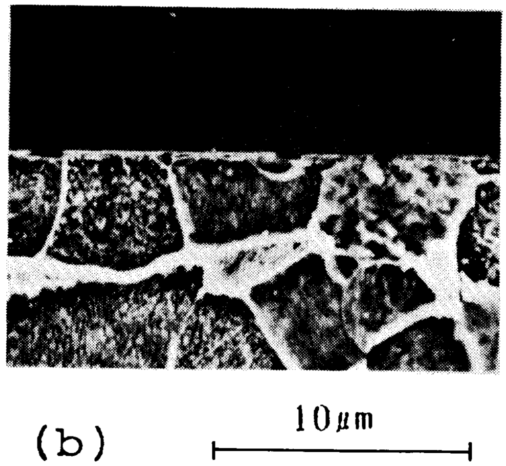


Fig. 6 Electron micrographs showing the boundary between slag and base metal taken with magnification of (a) 500×, (b) 5000×.

An experiment on the glass-to-iron sealing similar to the slag-metal bonding described in this work, indicates that a sealing of good quality can also be obtained when the sealing has such an intermediate layer as not to be detected even in the observation of 3000× magnification.[6] The above-mentioned results, however, cannot provide a logical evidence of an ionic bond, though it might be said that neither the intermediate layer nor the mechanical bonding such as "engagement" is always absolutely required in the

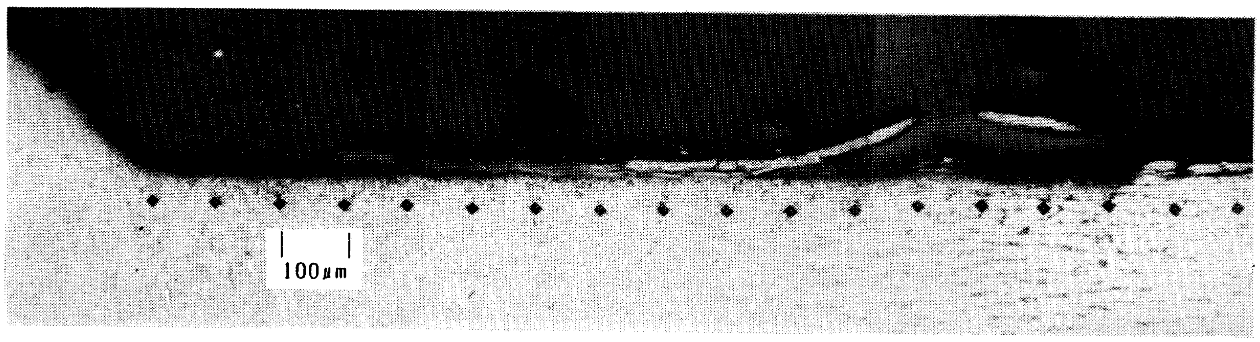


Fig. 5 Cross sectional microstructure of HAZ.

slag-metal bonding.

(2) As-rolled plate

Fig. 7 shows schematically the phenomena occurring with the slag at the bead edge. Fig. 8 shows X-ray images near the slag tip being dissolved in the slag and the result of analysis by EPMA. Fig. 9 shows a microstructure of the bead edge. Fig. 10 shows a detailed structure of the slag-metal interface under higher magnification and the result of anlaysis by EPMA. The following could be inferred from the results of Figs. 7~10.

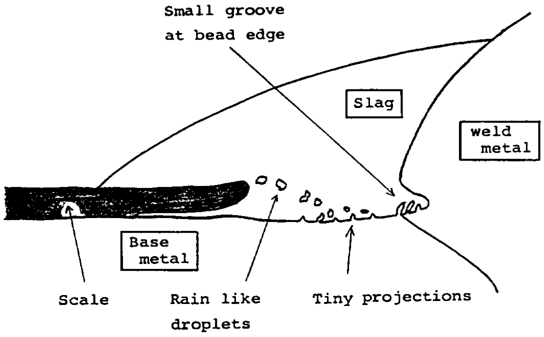


Fig. 7 Schematic illustration showing phenomena occurring under the slag at the bead edge in as-rolled plate welding.

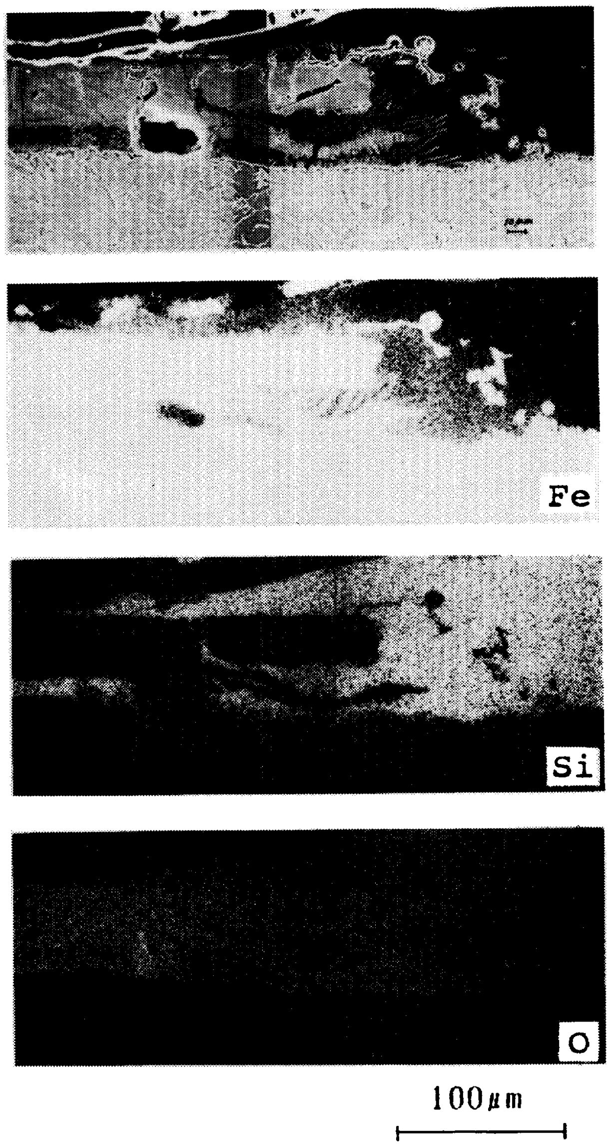


Fig. 8 Electron micrograph near the scale tip being dissolved in the slag and result of analysis by EPMA.

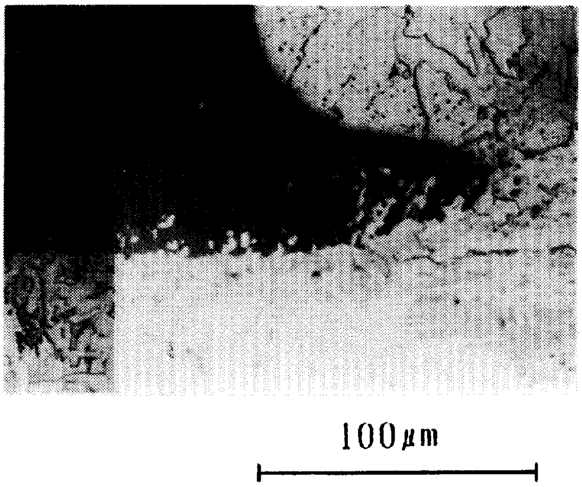


Fig. 9 Groove observed at the lower end of the bead edge in as-rolled plate welding.

(i) The slag and the base metal make direct contact partially in the portion between the scale end and the bead edge (the slag is conventionally considered to lie on the scale, but this is not proved by this experiment).

(ii) The scale end and its lower portion appear to dissolve into the slag (slag penetration to the underside of the scale can be confirmed by detection of Si; Fig. 8).

(iii) It appears that small droplets fall down over the base metal like raindrops from the tip of the scale end (these droplets contain much Fe and less O, hence they can be considered metallic iron).

(iv) A number of very small projections are formed on the surface of the base metal (these tiny projections are also of metallic iron, like the droplets mentioned above).

(v) The shape of the slag-metal interface is considerably uneven (Fig. 10) compared to the scale-metal interface which is still free of slag penetration shown in Fig. 11.

(vi) A groove is formed at the lower end of the bead edge, and tiny projections are also found inside of it (Fig. 9).

These phenomena, such as roughening of the metal surface, formation of the tiny projections and formation of the small groove at the bead edge, suggest that slag and metal are bonded to each other mechanically.

Following observations were made about the changes on the metal surface:

(a) In the molten slag which is an electrolytic solution, the anode parts of the base metal are dissolved with formation of pits and tiny projections are deposited on the cathode side, causing uneven interface to be formed; In the glass-to-iron sealing[6] and enamelling[7)-9)] technologies, formation of the similar interface and the local cell men-

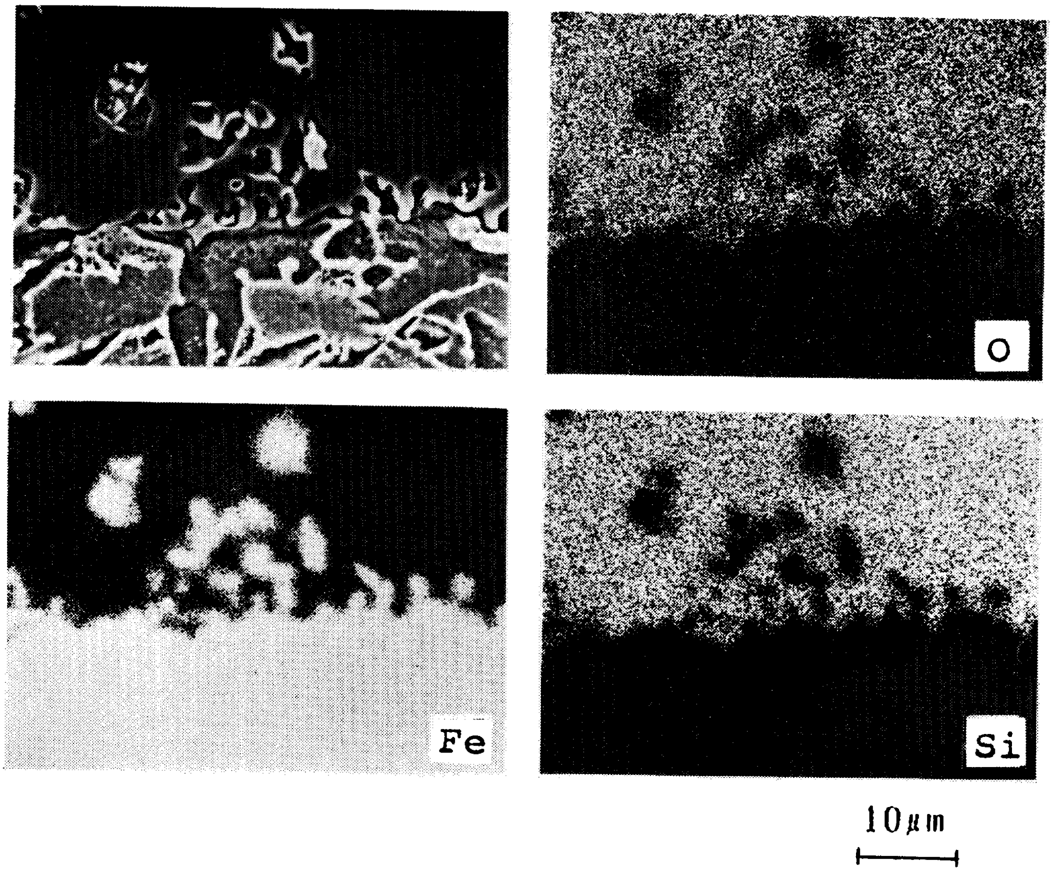


Fig. 10 Detailed structure of the slag-metal interface and result of analysis by EPMA.

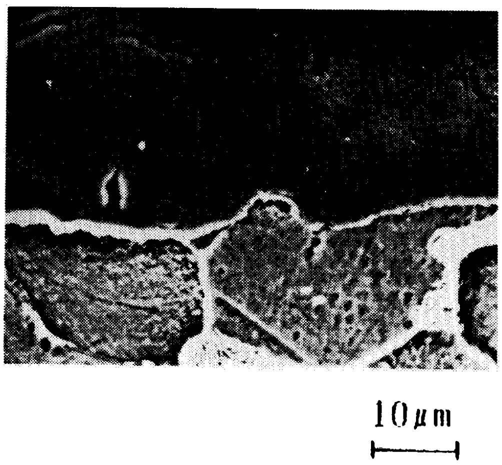


Fig. 11. Scale-metal interface free of slag penetration.

tioned above have been reported.

(b) Projections may also be formed by deposition of metallic iron on the base metal as the result of reduction or decomposition of the scale containing wüstite in the molten slag.

(c) A small groove may be formed at the bead edge initially as the result of over-lapping of the weld metal onto the scale originally existing on the plate. But the groove may be enlarged further because of dissolving by the hot slag.

By the way, in other technologies mentioned above, the preheating of the base metal is desirable to obtain excellent adherence of the glass to the metal. And in the enamelling technology, the preheating is considered a necessary treatment to obtain an oxide film

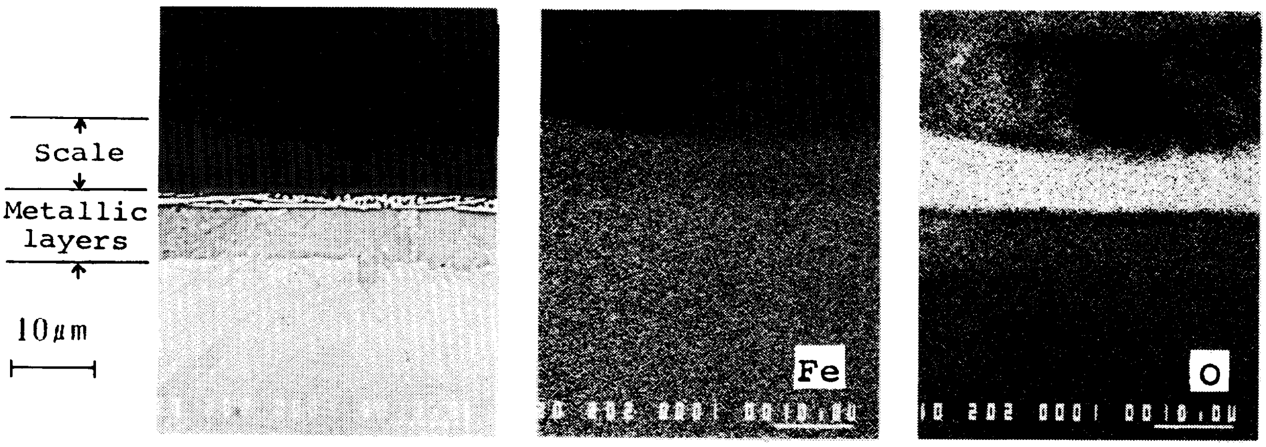


Fig. 12 Microstructure near the gas-cut surface.

by which iron ion is supplied to the interface, resulting in formation of an ionic bond. Therefore, it seems that the scale on the welding plate also plays a similar role to that played by the oxide film.

(3) Gas-cut plate

The gas-cut plate seldom causes slag adherence as shown in Fi.g 1, and this seems to be attributable to a peculiar structure of the gas-cut surface. On the gas-cut surface, the outermost oxide layer and two metallic layers, each of which can be regarded as a part of the base metal, are observed as shown in Fig. 12. These metallic layers as the base of the slag adherence can be detached from the base metal so easily. Therefore, it is considered that the slag to adhere is hardly allowed to remain on the plate surface, even though the formation mechanism of slag adherence is similar to that of the as-rolled plate. This greater detachability of the surface layers of the gas-cut plate can also be recognized in a polishing work of the microstructure specimen, as reported by Ohnishi et al.[10]

4. Conclusions

As a part of the basic study on the slag adherence in submerged arc welding, bead-on-plate welding was conducted on three different surfaces of mild steel plates, that is, polished, as-rolled, and gas-cut surfaces, using a fused type flux, and the location of slag adherence and the slag-metal interface on HAZ were examined. The results obtained can be summarized as follows:

(1) Crusty slags did not adhere essentially to the bead in any steel plate, but chiplike ones were found on the portion near the bead edge. *i.e.* only on the base metal (substantially on the HAZ) or both sides of the edge. No slag adherence was observed even to the HAZ on the gas-cut plate.

(2) The adherence varied with the surface conditions of the steel plate: In the polished plate, slight adherence occurred on HAZ near the bead edge, and in the as-rolled plate, marked adherence was formed near the bead edge extending from the weld metal to the base metal.

(3) The following differences were noted in the slag-metal interface between the polished plate and the as-rolled one: In the polished plate, a straight boundary between slag and metal was noted, and neither mechanical bonding nor intermediate layer was observed. In the as-rolled plate, the scale was lost near the bead edge, and the slag and metal made direct contact via roughened interface, and a number of tiny projections were found on the metal surface.

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