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Direct TEM observation of microstructures of the austenitic/carbon steels welded joint

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The successive alteration of the microstructure from the weld metal zone through weld bonds to the heat-affected zone of a $Cr_{18}Ni_{13}$ austenitic–0.45% C steels welded joint has been observed using transmission electron microscopy. A new type of microstructure, called pearlite-like structure, has been found and the microstructural details of the weld interface (or fusion line) have been studied. Based on the definition of various zones of the dissimilar steels welded joints under the optical microscope, the transmission electron microscopic characteristics, including microstructures and compositions, of each zone are described and discussed.

1. Introduction

Associated with the extensive application of dissimilar steel joints in modern industries, special attention has been focused on studies of the boundary of dissimilar steels welded joints. Savage *et al.* [1, 2] suggested that the so-called weld boundary is a region composed of an unmixed zone and a partially melted zone. Shi *et al.* [3] studied the microstructures of the dissimilar steels welded joints obtained by electric welding of a $Cr_{18}Ni_{13}$ electrode on the 0.45% carbon steel base metal by the optical metallographical method and electron probe microanalysis (EPMA). They further divided the unmixed zone into a weld metal fusion zone and a base metal fusion zone, and found that the carbon content in the weld metal fusion zone, which is approximately equal to that in the base metal (0.45%), is higher than in the base metal fusion zone.

In addition to these optical microscopic investigations, electron microscopic techniques have been widely used in this field. Dislocation structures [4], microcracking [5], nonmetallic inclusions [6], microsegregations [7] and precipitations [8] etc., in weld metal and heat-affected zones (HAZ) were investigated mainly using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Ikawa *et al.* [9] studied the weld bond of dissimilar steels welded joints using TEM by means of a heat-simulation technique and found a new microstructure, the martensite-like structure. Nonetheless, so far no TEM observations on the directly sampled weld bond, especially that of dissimilar steels welded joints, have been reported.

In the present work, the weld bond has been observed using TEM on specimens sampled directly from the dissimilar steels welded joints and the qualitative and quantitative information about the microstructures and the variation of the compositions in various zones of the weld bond is reported.

2. Experimental techniques

The dissimilar austenitic/carbon steels welded joint was made by single-pass surfacing of the 0.45% carbon steel base metal with $Cr_{18}Ni_{13}$ austenitic electrode. The chemical compositions of the original materials are shown in Table I.

An automatic weld machine, type S-11, was used at a welding current of 160 A, an arc voltage of 26 V, and a travel speed of 130 mm min^{-1}. Cross-sections of specimens 0.6 mm thick were cut perpendicular to the welding direction using a spark machine. The positions of the four TEM discs studied, each 3 mm diameter, in the cross-section are schematically illustrated in Fig. 1. Preparation of the thin foils for TEM by the conventional electropolishing technique was unsatisfactory because of the difference in polishing rate for different regions across the weld junction. Thus the discs were mechanically ground to 40 μm thick and then ion thinned. Foils were examined using 200 kV

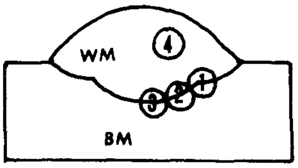

Figure 1 Cross-section diagram of the $Cr_{18}Ni_{13}$–0.45% C steels welded joint showing the positions of TEM discs (WM = weld metal, BM = base metal).

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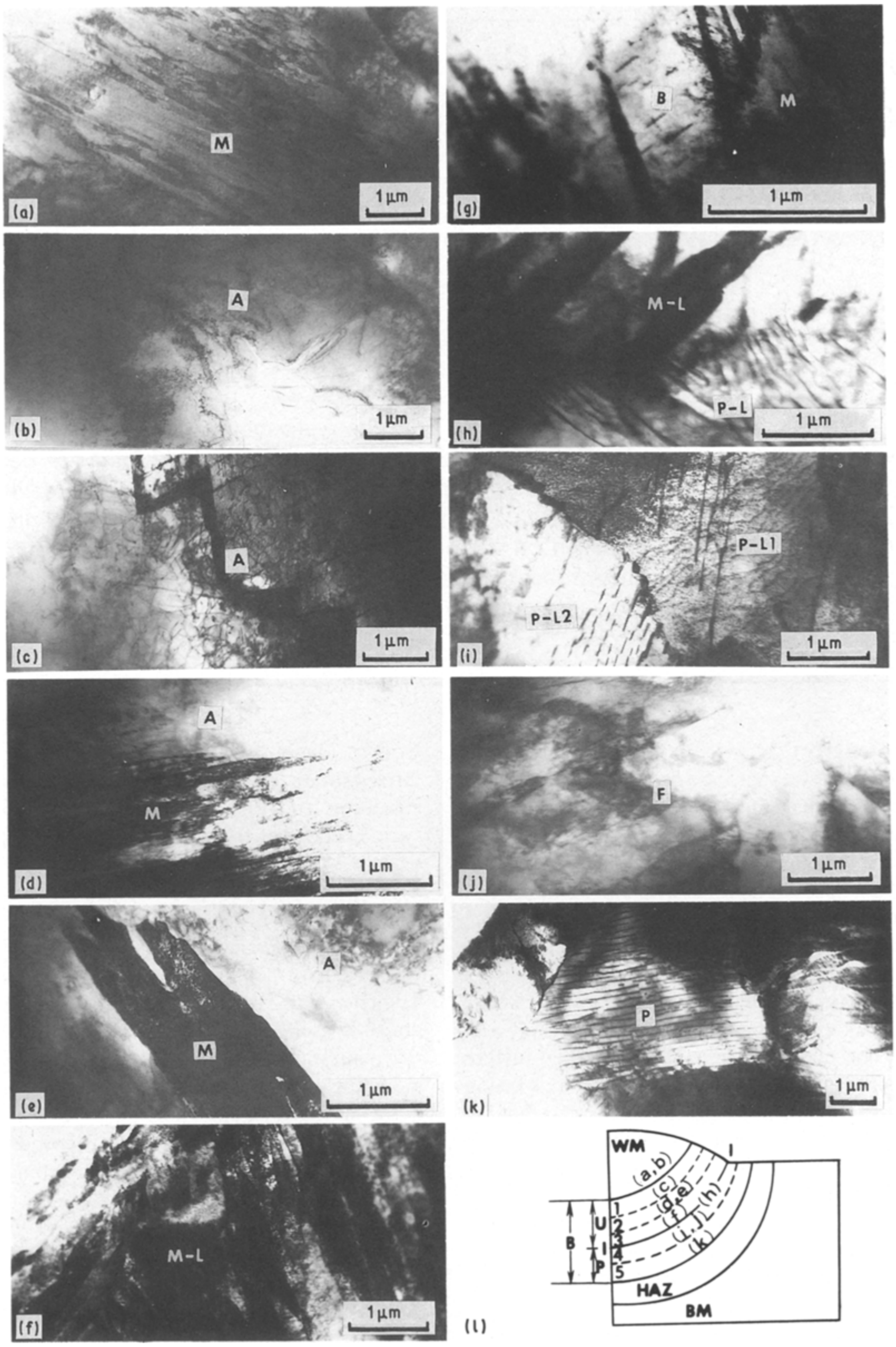

Figure 2 TEM microstructures of a $Cr_{18}Ni_{13}$–0.45% C steels welded joint (WM, weld metal; B, weld bond; U, unmixed zone; P, partially melted zone; HAZ, heat-affected zone; BM, base metal; 1, austenite single-phase zone; 2, austenite and martensite mixture zone; 3, martensite-like structure zone; 4, ferrite and pearlite-like structure zone; 5, small-grained fine pearlite zone; I–I, weld interface).

TABLE I Chemical compositions of the original materials (wt %)

Material	Element									
	C	S	P	Mn	Si	Cr	Ni	Mo	N	Fe
$Cr_{18}Ni_{13}$	0.048	0.013	0.022	1.40	0.40	18.40	13.06	2.40	0.048	Bal.
0.45% C steel	0.46	0.009	0.015	0.67	0.25	–	–	–	0.009	Bal.

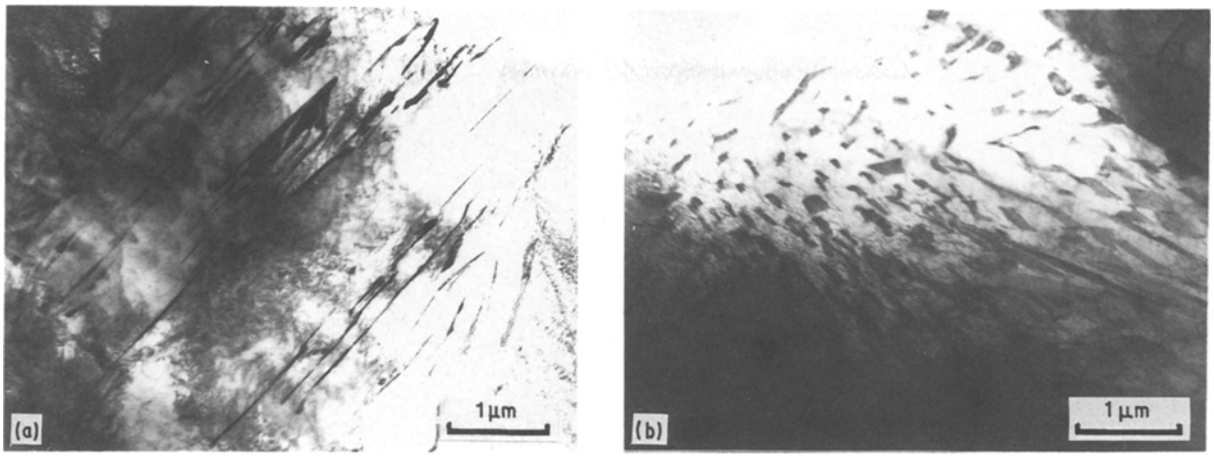

Figure 3 TEM morphologies of the pearlite-like structure in the partially melted zone.

H-800 and 120 kV JEOL JEM-100CX(II) electron microscopes.

3. Experimental results

3.1. TEM direct observation of the weld bond microstructures

Specimens 1 to 4 in Fig. 1 were observed using TEM. Some common characteristics of the variation in the microstructures in the weld bond and weld metal zone are shown in Fig. 2.

The microstructure in the weld metal zone is a mixture of austenite and martensite. Compositions and microstructures in this zone are inhomogeneous: in the region with the composition 11% Cr and 3.8% Ni, the martensite is more than the austenite (Fig. 2a); in the region of 11.6% Cr and 8.3% Ni, the austenite is more than the martensite (Fig. 2b). The microstructures in the weld bond vary according to the following sequence.

1. Austenite single-phase zone (Fig. 2c) which lies near the weld metal zone and contains 9% to 11.6% Cr and 7.5% to 8.5% Ni.
2. Austenite and martensite mixture zone (Figs 2d, e) in which the element content is about 9% Cr and 6.4% Ni, lower than that of the austenite single-phase zone; two types of martensite were observed. i.e. the twinned martensite (Fig. 2d) and the lath martensite (Fig. 2e).
3. Martensite-like structure zone (Figs 2f, g): its composition varies from 8.3% Cr and 5.7% Ni to 3.8% Cr and 2.9% Ni, lower than that of the austenite and martensite mixture zone. In the present observations the morphology of the martensite-like structure is nearly the same as that observed by Ikawa *et al.* [9], except that the structure is inhomogeneous; some regions are the mixture of fine lath martensites and carbides (Fig. 2f), the others near the base metal are the mixture of fine lath martensites, bainites and carbides (Fig. 2g).
4. Pearlite-like (Fig. 2i) and ferrite (Fig. 2j) zone: for details see Section 3.2. From the martensite-like to pearlite-like or ferrite zone, the contents of the alloy elements and the microstructures are changed abruptly. The boundaries between them are called the weld interface or the fusion line (Fig. 2h).
5. Small-grained fine lamellar pearlite zone (Fig. 2k): this is situated between the pearlite-like and ferrite structures, on the one hand, and the coarse-grained pearlite structures in the heat-affected zone (HAZ), on the other hand.

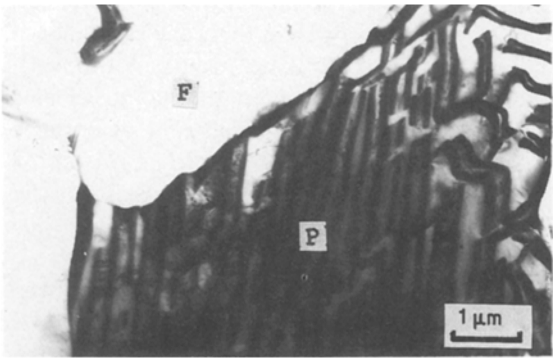

Figure 4 TEM morphologies of the ferrite (F) and pearlite (P) in the 0.45% C steel base metal.

3.2. TEM morphologies of the pearlite-like microstructure

On the pearlite steel (base metal) side of the weld interface, a new special structure was observed in this work with two characteristic morphologies: (1) a few Fe_3C plates in large ferrite grains (P-L1 in Figs 2i and 3a); (2) larger Fe_3C plates precipitated at ferrite grain boundaries and smaller and broken Fe_3C plates in the middle of grains (P-L2 in Figs 2i and 3b). Such a structure has some similarities with the conventional pearlite of the base metal (Fig. 4) and with the bainite. For simplicity we call it pearlite-like structure. It contains neither chromium nor nickel.

3.3. TEM observation of weld interfaces

When crossing the ferrite/martensite-like boundary (Fig. 5) or the pearlite-like/martensite-like boundary (Fig. 6), both microstructures and compositions show an abrupt change. These boundaries thus correspond to the weld interface. Most of the weld interface is the ferrite/martensite-like type. When crossing the boundary, the chromium content increases from 1.5% to 4.6% and the nickel from 0.6% to 3.8% abruptly. In the case of the pearlite-like/martensite-like boundary, the chromium content increases gradually from 1.4% to 3.4%, and the nickel content increases abruptly from 0.9% to 2.0%.

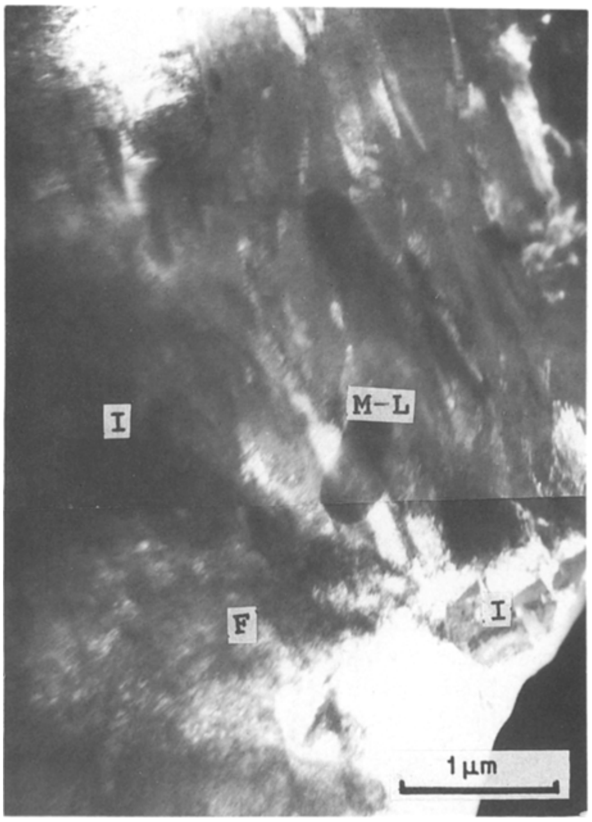

Figure 5 Martensite-like (M-L)/ferrite (F) weld interface (I–I). Dark field.

4. Discussion

Savage *et al.* [1, 2] and Shi *et al.* [3] divided the weld bond into some smaller regions from metallographical observation and EPMA measurement. From direct TEM observation and the higher space resolution measurement of the contents of the alloy elements in this work, we can subdivide the unmixed zone into (Fig. 2): (1) single-phase austenite zone, (2) austenite and martensite mixture zone, and (3) martensite-like structure zone, and the partially melted zone into: (1) ferrite and pearlite-like zone, and (2) small-grained fine pearlite zone. The characteristics and the formation of these zones together with the weld metal zone are discussed below.

Owing to the strong convection and stirring effect, the alloying elements in the molten pool are distributed homogeneously at the moment when the electrode moves away and their contents take the mean values of those in the filler metal and in the base metal (dilution effect). Thus the nickel and chromium contents in the weld metal zone are much lower than those in the austenitic stainless steel (see Table I). The microsegregation during the solidification process makes the chemical compositions and hence the microstructures in this region inhomogeneous. According to the Schaeffler weld structure map [10], an inhomogeneous mixture structure of the austenite and martensite forms.

After the electrode has moved away, the heat in the overheated molten pool is transferred to the base metal which causes the liquid–solid interface to be moved in the base metal direction and the other base metal remains in solid state with some partially melted region in the neighbourhood of the interface. Then with the overall decrease in the temperature, the liquid–solid interface is moved back. During these processes of redistribution, increase and decrease of temperature, the substitutional alloying elements chromium and nickel diffuse from the weld metal zone to the base metal zone with much greater diffusion coefficients in the liquid than in the solid state, and the interstitial solute element C diffuses from the base metal zone to the chromium-rich zone owing to the larger affinity between carbon and the carbide-formed element.

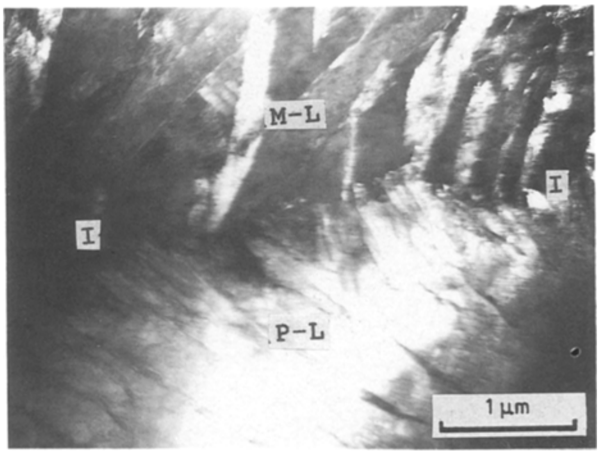

Figure 6 Martensite-like (M-L)/pearlite-like (P-L) weld interface (I–I). Dark field.

Because of the difference in the equilibrium solute compositions in the liquid, C_l, and in the solid, C_s, (the partition coefficient $k = C_s/C_l$ is not equal to unity), there exists a true weld interface across which the solute compositions and hence the microstructure experience an abrupt change, as described in Section 3.3. Although the region between the weld metal zone and the weld interface was completely melted, the solute distribution in this region is mainly determined by diffusion owing to the stagnation in this region, hence the term "unmixed zone" results [1, 2]. The gradient of nickel, chromium and carbon contents determines the variety of the microstructure in the unmixed zone in accordance with the Schaeffler map [10]. In the region with higher nickel, chromium (and hence carbon) contents, the austenite single-phase zone results; in the region with lower nickel and chromium contents, martensite-like structure results; in between is an austenite and martensite mixture zone. On the other side of the weld interface, the base metal is partially melted. The presence of the melted region inhibits the grain growth in this zone [1, 2], hence the small-grained pearlite zone results. Moreover, the rapid migration of the interstitial solute element C from this region to the unmixed zone determines the formation of the ferrite-rich zone. The reason for the formation of the pearlite-like structure is not clear.

5. Conclusions

1. TEM direct observation of the $Cr_{18}Ni_{13}$ austenitic–0.45% carbon steels welded joints has revealed that the weld bond, which lies between the weld metal zone and the heat-affected zone, may be subdivided into the following zones: austenite single-phase zone,

austenite and martensite mixture zone, martensite-like structure zone, ferrite and pearlite-like structure zone, and small grained fine pearlite zone.

2. The principal reason for the formation of these zones together with the austenite and martensite structures in the weld metal zone is the alloy element distribution determined by the convection and stirring effect and the diffusion process during the welding cycle. The observed microstructures and the measured alloy element contents coincide with each other rather well in accordance with the Schaeffler map.

3. There exist abrupt changes of both microstructures and chemical compositions when crossing the martensite-like/ferrite or pearlite-like boundary. This boundary is thought to be the true weld interface.

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