A Study of Microstructural Progression in As-Deposited Weld Metal

Emission spectrographic analysis and electron microscopy are applied to submerged arc weldments wherein the range of alloying included 0.6 to 2.5% Mn, residual to 0.5% Mo and 0.1% carbon

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ABSTRACT. The effects of Mn and Mo on the transformation of ferrous weld metal during cooling have been studied over a range of compositions. Transformation begins with the emergence of boundary ferrite between 1000 and 750 C (1832 and 1382 F). This boundary ferrite may continue to develop as side plates which grow across the entire prior austenite grain between 750 and 650 C (1382 and 1202 F) or it may be arrested. In the latter case, intragranular acicular ferrite begins to form at about 600 C (1112 F).

These transformations are essentially complete by 500 C (932 F), except in the case of substantial alloying (2.2% Mn) when a shear product not unlike the side plates can form below 500 C (932 F). The transformation product exhibiting the best toughness was that of acicular ferrite with minimum boundary ferrite (1.4% Mn, 0.45% Mo).

Introduction

The microstructure of ferrous weld metal is known to have a significant influence on its toughness.[1,2] As yet no clear understanding has been developed of the transformation products obtained in weld metal. But such an understanding is critical to the development of improved welding consumables. This work was undertaken to investigate the effects of Mn and Mo on the transformation of carbon steel weld metal.

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Fig. 1—Typical weld metal microstructure showing large columnar grains in: A (top)—transverse and B (bottom)—longitudinal directions. See inserted letters in A for boundary Ferrite (B) Ferrite Matrix (M) and Island Phase (S). ×500

Experimental

Weldments were fabricated using the single electrode submerged arc process (750 A, 36 V DCRP, 76 cm/min) at a heat input of 22 kJ/cm. The base metal was 13 mm (½ in.) thick A36 steel, and the filler metal was 4 mm (5/32 in.) diameter 0.14 C-2.0 Mn wire. An experimental acid bonded flux was used to introduce alloying elements into the weld metal. These conditions resulted in a cooling rate of 40 C/s (72 F/s) in the temperature range 1300 to 500 C (2372 to 932 F) as measured by W-W 26% Re thermocouples immersed in the weld puddle.

Weld metal compositions were taken from the center of each weldment. Emission spectrographic analysis was used for determination of metallic elements. Combustion was used for determination of carbon.

Microstructural examination included both optical and electron microscopy. Thin foil and replica samples were studied using a 200 kV JEOL electron microscope.

The range of alloying studied included Mn from 0.6 to 2.5%, Mo from residual to 0.5% and carbon at 0.1%.

Results

Microstructure

The typical microstructure of as-deposited weld metal is shown in Fig. 1 in the transverse and longitudinal directions. It is characterized by boundary ferrite, an acicular ferrite matrix and a residual island phase. As the alloy content of the weld metal was altered, the distribution of these phases changed as shown in Figs. 2

Fig. 2—Microstructure of low Mn (0.8%) weld metal consisting of boundary ferrite (B), side plate ferrite (W) and pearlite island (P). View A (left) is optical light micrograph at ×500 and View B (right) is transmission electron micrograph at ×50,000 (reduced 40% on reproduction)

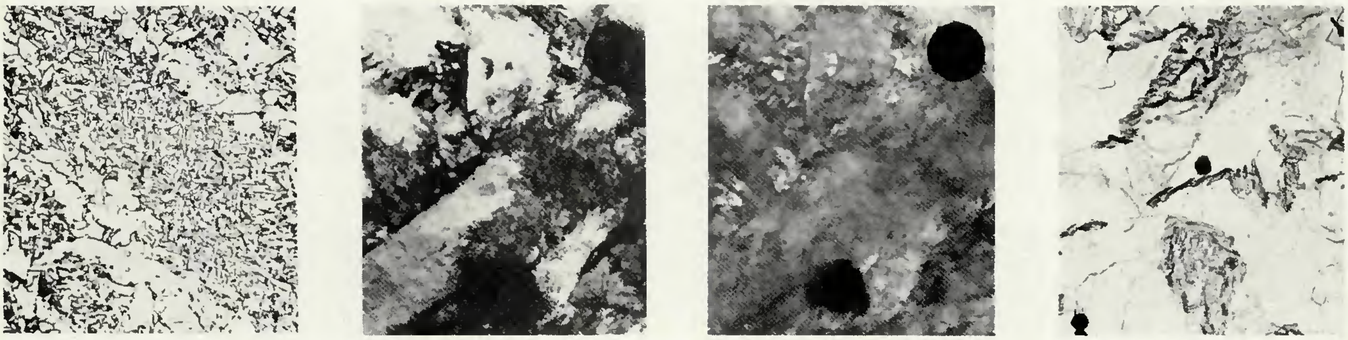


Fig. 3—Weld metal of 1.4% Mn. From left: A—light micrograph; B—transmission bright field; C—dark field; D—replica. A—×500; B, C and D—×50,000 (reduced 31% on reproduction)

through 5.

At low Mn content (0.8%) the microstructure (Fig. 2A) is dominated by boundary ferrite which has developed into side plates crossing the prior austenite grain. The side plate ferrite is characterized by low dislocation density, pearlite and coarse boundary ferrite, clearly indicating that this structure formed at high temperature.

At higher Mn content (1.4%) the formation of side plates was suppressed (Fig. 3A), although boundary ferrite was still present. This structure change occurs above 1.2% and has also been reported by Widgery[3] in GMA weld metal. A rather high dislocation density is associated with the acicular ferrite matrix—Fig. 3B. The residual phase exhibits fine carbides similar to those observed in lower bainite.[4] These features indicate a lower transformation structure than that associated with the low Mn weld metal.

At high Mn content (2.2%) the structure is qualitatively similar to the low Mn weld metal (Fig. 4A), but an extremely high dislocation density is associated with the laths—Fig. 4B. No boundary ferrite is observed in this structure which is characterized by fine ferrite laths growing side-by-side with intervening carbide precipitates. The laths are separated by low angle (<13 deg) boundaries. The residual phase etches yellow-brown and is similar to that identified as martensite/austenite by Cryderman[5] and Widgery.[3]

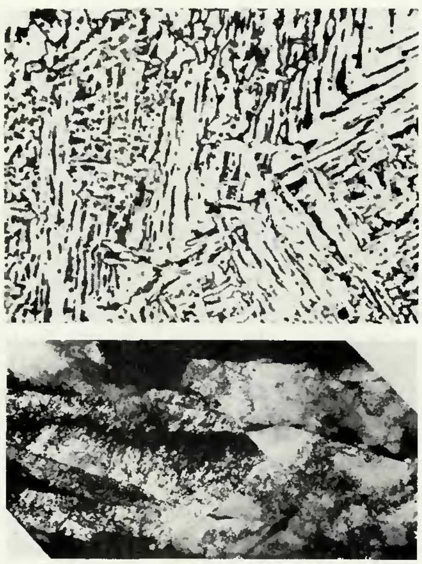


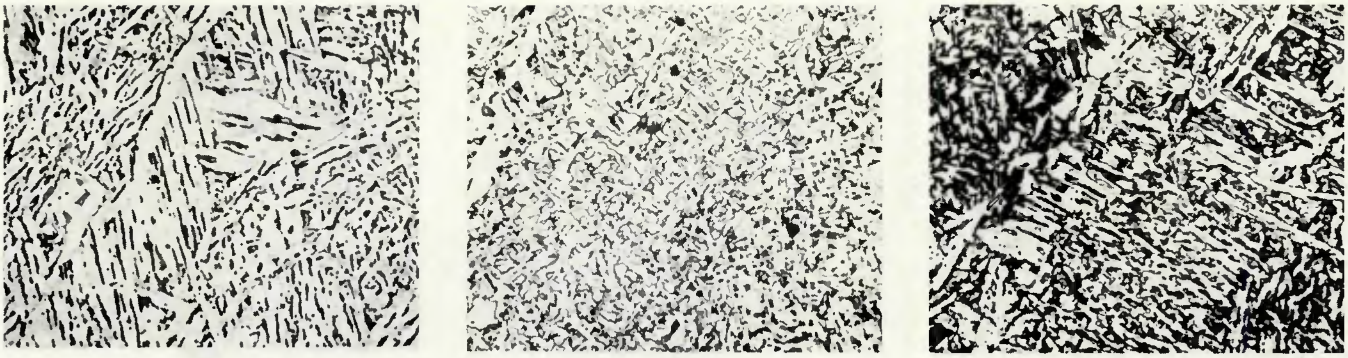
Fig. 4—Lath type structure found in the 2.2% Mn weld metal: A (top)—light micrograph; B (bottom)—electron micrograph. A—×500 (no reduction); B—×65,000 (reduced 57% on reproduction)

The presence of Mo (0.45%) at various Mn levels significantly reduced the presence of boundary ferrite but had little effect on the interior structure—Fig. 5.

Transformation

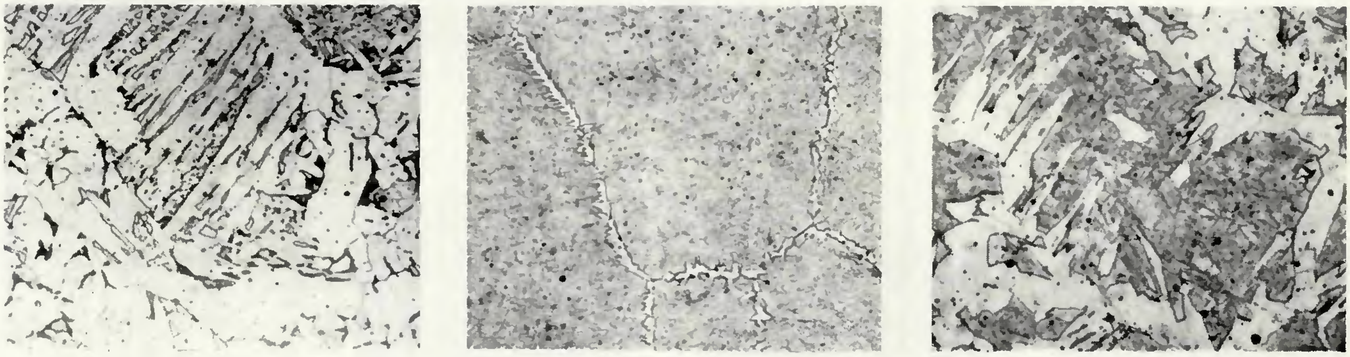
A special technique was developed to study transformation products. A thin specimen of weld metal was very rapidly heated (>80 C/s, and >144 F/s) to 1300 C (2372 F) and then cooled at the same rate as in the weldment to a predetermined temperature from which it was quenched. Each specimen was used only once.

At low Mn content (0.8%) it is observed that the boundary ferrite begins to appear as high as 1000 C (1832 F)—Fig. 6. Some evidence of side plate development is also seen at this temperature. By 750 C (1382 F) nearly 40% of the structure is transformed to sideplates. At 650 C (1202 F) the transformation is complete: no further

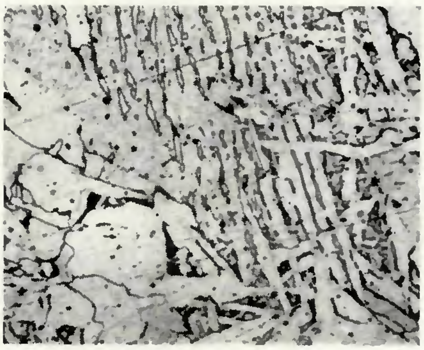


A B C

Fig. 5—Microstructures of the 0.5% Mo weld metal containing: A (left)—0.8% Mn; B (center)—1.4% Mn; C (right)—2.2% Mn. ×500



A B C



D

Fig. 6—Sequence of structure development in 0.8% Mn weld metal: A—as-welded condition; B, C, D, E—heated above 1300 C followed by continuous cooling down to 1000 C, 750 C, and 650 C and 550 C respectively and water quenched. ×500

E

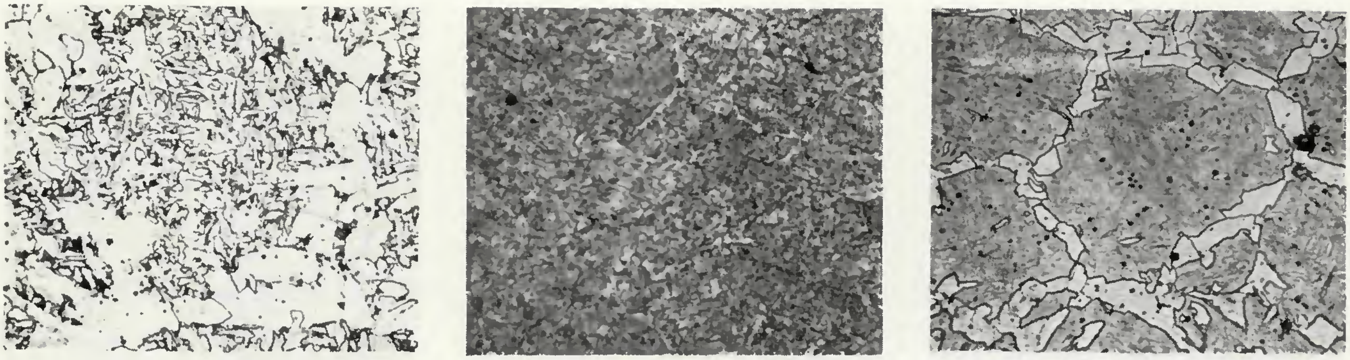
transformation occurs on cooling to 550 C (1022 F). The close association of the two ferrite species—boundary and side plate—indicates that they are kinetically continuous products of austenite decomposition and that their growth is controlled by diffusion. Since a major fraction of the side plate growth occurred at 750 C (1382 F), some undercooling of austenite is important. It was discovered that austenite grain size is important in side plate development; smaller austenite grain size inhibits side plate formation.

At higher Mn content (1.4%) some suppression of boundary ferrite occurs—Fig. 7. Even at 750 C (1382 F) only a fraction of prior austenite boundaries are transformed. Moreover between 750 and 650 C (1382 and 1202 F) further transformation was retarded. Acicular ferrite begins to appear at 650 C; apparently it is nucleated at inclusions—Fig. 7D. The transformation to acicular ferrite is essentially complete by 600 C (1112 F). Mn seems to act to permit substantial undercooling of austenite to a point at which relative nucleation of acicular ferrite is high but growth is low. This results in a finely sized ferrite.

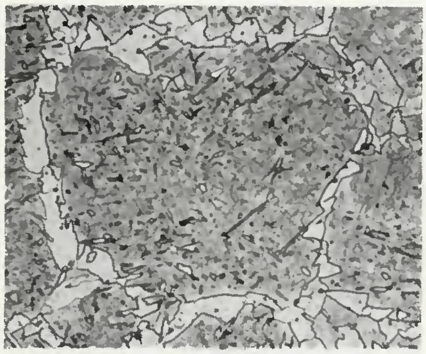
The high degree of dimensional freedom associated with the acicular ferrite results in a small mean free path for cleavage as contrasted with that of the side plate ferrite. Consequently, the acicular ferrite has superior fracture toughness at temperatures in the transition range. Furthermore, it is clear that minimization of boundary ferrite with an acicular matrix will yield optimum toughness.

The addition of Mo (0.45%) to weld metal containing 1.4% Mn suppresses the formation of boundary ferrite—Fig. 8. Although boundary ferrite forms between 750 and 650 C (1382 and 1202 F) as it does without Mo, no further boundary ferrite develops below 650 C. Figure 8D shows strong evidence for nucleation of acicular ferrite at inclusions. Presumable Mo affects the transformation kinetics of boundary ferrite, because of its strong interaction with carbon. Aaronson[6] suggests that the formation of Mo-C precipitates at carbon with interphase boundaries between austenite and ferrite may be responsible for retardation of boundary ferrite growth.

At high Mn content (2.2%) no apparent transformation occurs above 550 C (1022 F)—Fig. 9. Between 550 and 450 C (1022 and 842 F) the remaining austenite transforms completely to the highly stressed lath structure. The high dislocation density, presence of carbide film and apparent transition tempera-

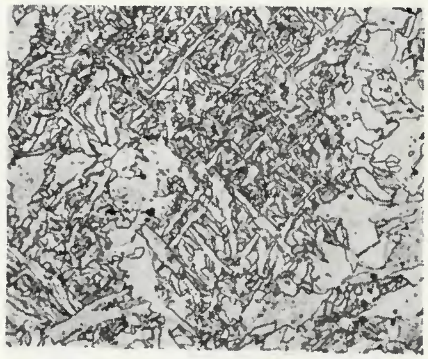


A B C

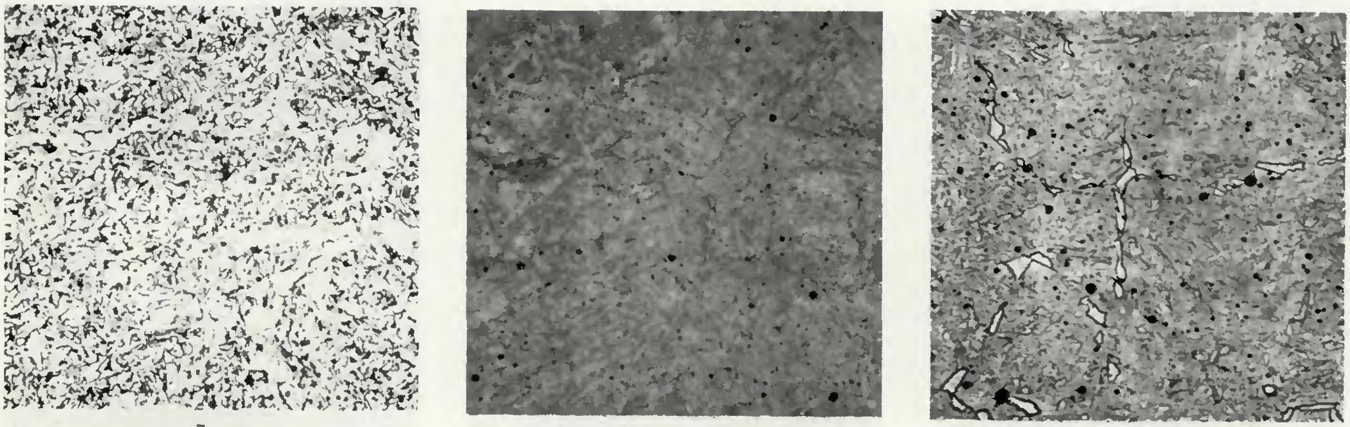


D

Fig. 7—Sequence of structure development in 1.4% Mn weld metal: A—as-welded; B, C, D, E—heated above 1300 C, cooled to 1000 C, 750 C, 650 C and 550 C respectively and water quenched. ×500



E



A B C

D E F

Fig. 8—Sequence of structure development in 1.4% Mn-0.45% Mo weld metal: A—as-welded; B, C, D, E—heated above 1300 C, cooled to 1000 C, 750 C, 650 C, 550 C and water quenched; F—continuously cooled to R.T. ×500

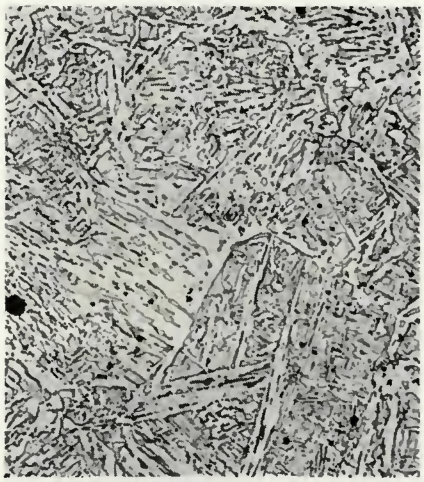
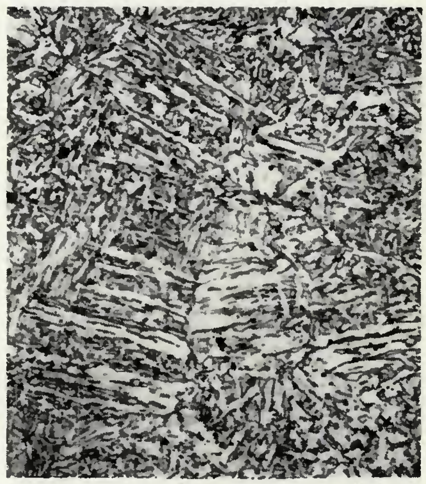


Fig. 9—Sequence of structure development in 5.5% Mn weld metal: A—as-welded; B, C, D—heated above 1300 C cooled to 700 C, 550 C, 450 C and water quenched; E—continuously cooled to R.T. ×500



ture range suggest that this is bainite.[7]

Summary and Conclusions

The transformation and structure of C-Mn-Mo ferrous weld metal has been characterized over a range of composition. Four structural types are observed:

1. Boundary ferrite which forms between 1000 and 750 C (1832 and 1382 F) and whose growth is controlled by diffusion.

2. Ferrite sideplates which form between 750 and 650 C (1382 and 1202 F) and which are separated by low angle boundaries.

3. Acicular ferrite which forms below 600 C (1112 F) and which results in a finely divided structure.

4. Lath ferrite, which is most probably bainite, which forms below 500 C (932 F) and which is highly stressed.

The structure with optimum toughness in the transition range is acicular ferrite with minimum boundary ferrite achieved with 0.1 C–1.4 Mn–0.45 Mo.

Acicular ferrite nucleation is apparently influenced by inclusions present in the austenite. Whether morphology is important or whether stress considerations are important are unanswered questions.

Control of composition will apparently allow control of transformation products. If care is exercised, an acicular structure can always be achieved in low carbon weld metal of this kind. This is not the case in weld metal containing Cb as an alloying addition.[2]

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