The role of oxygen rich inclusions in determining the microstructure of weld metal deposits

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The influence of the deoxidation product size distribution in determining the prior austenite grain and the subsequent balance between inter- and intragranular nucleation has been studied in C–Mn–Nb weld metals. The growth of austenite appears to be controlled by pinning of the grain boundaries by the deoxidation inclusions, and follows the classical Zener precipitate–boundary interaction equations. Some evidence of the direct nucleation by inclusions of the acicular ferrite phase has been obtained.

1. Introduction

A number of recent investigations have indicated that the relationship between the number, type and distribution of deoxidation products and the final microstructure in carbon manganese weld metals is highly complex.

Ito and Nakanishi [1] reported a discontinuous dependence of the Charpy-V transition temperature with varying oxygen contents. They observed that both high (> 500 ppm) and very low (< 200 ppm) oxygen contents produced brittle microstructures, whereas the intermediate levels (200 to 500 ppm) produced tough acicular ferrite structures.

Recently, Cochrane and Kirkwood [2] produced a series of weld metals of nearly identical composition, with the exception of the oxygen level, and were able to conclude that the major effects concerned the inclusion size distribution and the surface energy of the inclusion/matrix interface. They also felt that if the austenite boundaries were pinned by inclusions an extra volume fraction of inclusion/grain boundary interface would become available for nucleation. These small grain sizes would favour intergranularly nucleated ferrite side plates.

Harrison and Farrar [3], who employed high-speed dilatometry, concluded that the austenite-to-ferrite transformation temperatures could be altered by the interaction of inclusions with the austenite grain boundaries. Higher inclusion contents tended to reduce austenite grain sizes and hence favour transformation products such as, polygonal ferrite and Widmanstätten secondary side plates.

These authors also concluded that the nucleation of acicular ferrite was directly aided by inclusions, as their complete removal led to the development of lower temperature lath-like microstructures.

Abson *et al.* [4] have also postulated that oxygen-rich inclusions can directly nucleate acicular ferrite, and that the absence of these inclusions leads to the formation of lath-like structures similar to those observed by Ito and Nakanishi [1].

Clearly there is still considerable confusion as to the precise role played by the deoxidation products; do they alter the microstructure by providing direct nucleation sites for intragranular products such as acicular ferrite, or do they alter the balance of the inter- and intragranular nucleation by changing the austenitic grain-growth kinetics?

The present investigation was therefore designed to alter the deoxidation inclusion population in a niobium bearing carbon manganese weld metal which normally exhibited a fine grained acicular ferrite microstructure [3].

TABLE I Chemical analyses of weld metals

Sample code	C (wt%)	Mn (wt%)	Si (wt%)	Nb (wt%)	O (ppm)
EO	0.10	1.33	0.28	0.03	305
0 Fe	0.08	0.98	0.39	0.03	390
5 Fe	0.09	0.93	0.31	0.03	470
15 Fe	0.08	0.40	0.20	0.02	1200

2. Experimental procedure and results

Three submerged arc-weld metals were produced at a nominal heat input of $3.4 \, kJ \, mm^{-1}$, using a C—Mn—Nb base plate, an agglomerated carbonate flux and a 3.2 mm diameter wire, EMK-6, containing 0.1% C, 1.0% Si and 1.4% Mn. The high silicon content of the wire was chosen in order to balance the vigorous oxidation reactions produced by the carbonate flux. For comparison purposes, an earlier [3] weld deposit, EO, was added to the present study to act as a control.

In order to modify the oxygen content and inclusion content of the weld deposit, pure magnetite (Fe_3O_4) was mixed with the carbonate flux in the proportions 5 and 15 wt%, respectively.

The chemical analyses of the weld deposits are reported in Table I.

Each sample was examined by optical microscopy and the results obtained are illustrated in Fig. 1a to c. The control weld, EO, had a very similar microstructure to the weld 0 Fe.

The size distributions and inclusion densities of the deoxidation products (Table II) were determined by using two-stage plastic—carbon extraction replicas, as shown in Fig. 2. The cumulative distribution curves (Fig. 3) were constructed from the measurement of approximately 800 particles in each weld sample.

Suitably polished samples were subjected to a thermal etching cycle of 5 min at 1250° C in a Theta dilatometer to determine the prior austenite grain size (Fig. 4). Subsequently these samples were allowed to transform at typical submerged arc-cooling rates of 5 to 8° C sec^{-1}. The results of the prior austenite grain size measurements and the thermal arrest transformation temperatures are given in Table III.

3. Discussion

The microstructural changes observed within this series of weld metals, confirm the trends observed by previous workers [2, 3]. The proportion of intragranularly nucleated acicular ferrite was drastically reduced with increasing volume fractions of deoxidation products and higher oxygen contents (Table III).
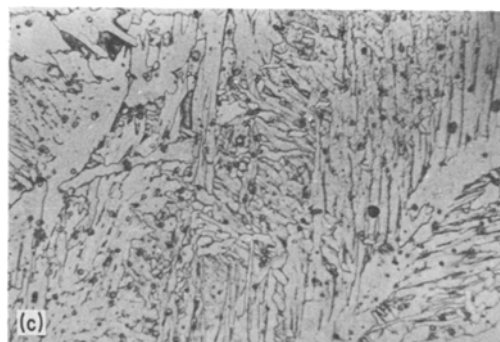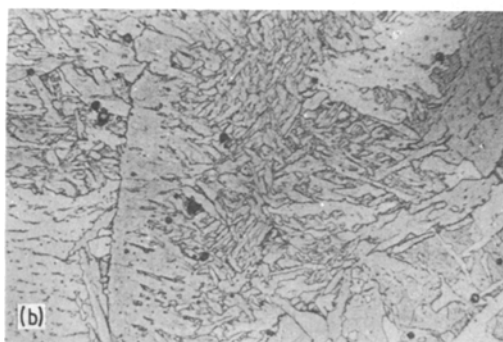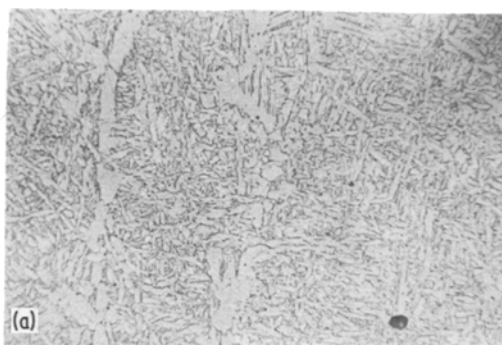

Figure 1 Microstructure of the as-welded samples ($\times$ 405). (a) 0 Fe; 390 ppm oxygen; (b) 5 Fe; 470 ppm oxygen; (c) 15 Fe; 1200 ppm oxygen.
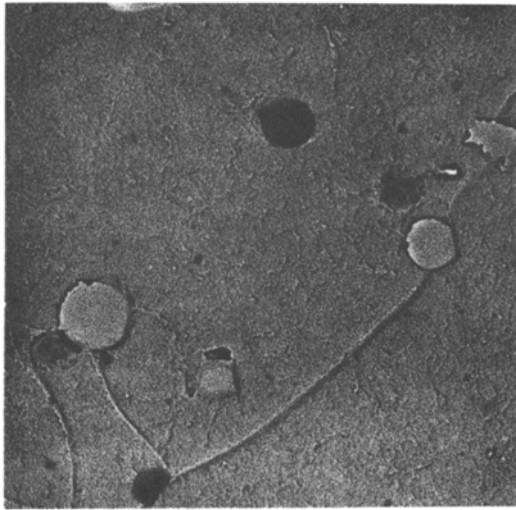
Figure 2 Typical deoxidation products interacting with austenite grain boundary in weld 5 Fe (X 11700).

Figure 4 Austenitic grain size delineated by vacuum thermal etching in weld 5 Fe (X 150).

The changes in the various proportions of the microstructural constituents are illustrated in Fig. 5, where they closely follow the results obtained by Wilson [6], who studied a similar system.

The increasing amounts of Fe_3O_4 in the welding flux formulation appears to shift the equilibrium deoxidation reactions and lead to a change in the volume fraction of the deoxidation products and to a change in the size distribution, as shown in Fig. 3.

The effect of second-phase particles on the growth of grains was first studied by Zener [7].
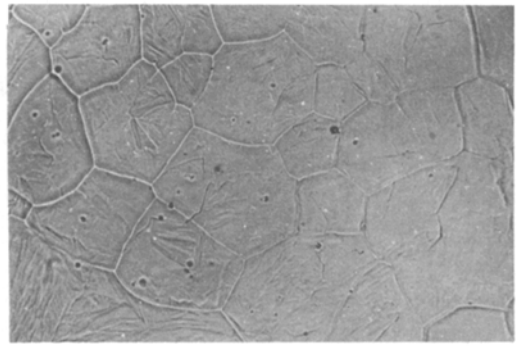
Hellman and Hillert [8] extended Zener's equations to introduce a correction factor, β, which depended upon the volume fraction of the second-phase particles. Following these authors we may write:

$$\frac{R_0}{r} = \frac{A}{\beta f}, \tag{1}$$

where, $2R_0$, is the austenite grain diameter, r is the mean inclusion radius, f is the volume fraction of inclusions and β is a correction factor which depends on the relative position of the inclusions and the nearest austenite boundary.

The value of the constant A in Equation 1 is uncertain, and values ranging from 1.33 [7] to 0.44 [8] have been quoted in the literature. The correction factor, β, is given by Hellman and Hillert as being equal to $0.124 \ln 40\rho/r$, where ρ is the undisturbed grain-boundary radius.
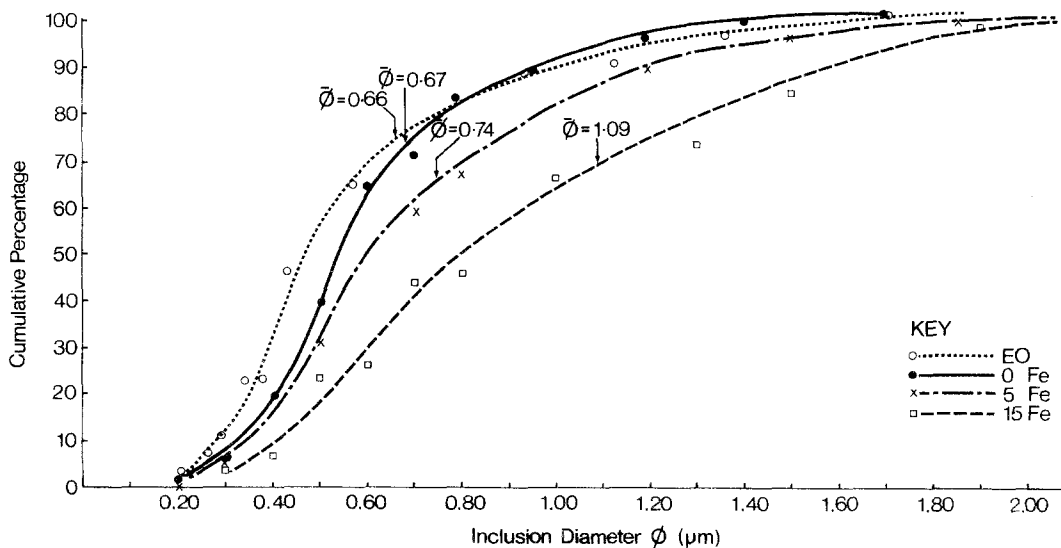

Figure 3 Cumulative particle-size distribution.

Sample code	Inclusion density (Number mm^{-3})	Volume fraction, f	Mean inclusion diameter, $\bar{\phi}$ (μm)
EO	3.2×10^7	4.8×10^{-3}	0.66
0 Fe	3.3×10^7	5.2×10^{-3}	0.67
5 Fe	4.1×10^7	8.6×10^{-3}	0.74
15 Fe	3.0×10^7	2.1×10^{-2}	1.09

In order to apply Equation 1 to the current experimental data, we use the total volume fractions, f, as shown in Table II, which were calculated from the volume fractions for each size interval of the inclusion distribution. The value of the undisturbed grain size, ρ, can be calculated from the expression developed by Alberry et al. [9] for heat-affected zone grain sizes.

Following Alberry et al. [9], the undisturbed grain size, ρ, after holding at 1250° C for 300 sec is calculated to be $\sim 850\,\mu$m.

The results of the calculation using Equation 1 with $A = 1.33$ are shown in Table III. With the exception of sample 15 Fe, the predicted values follow the experimental trend. If we allow for the uncertainty in the value of A, a better fit to the

first three samples is obtained with $A = 1.05$. Obviously further studies are needed to check the exact value of A for these weld microstructures.

In the case of the high-oxygen sample 15 Fe, it is likely that the mean inclusion size is now too large to produce efficient pinning and rapid austenite grain growth can occur. Another significant difference with the sample was the much lower manganese content which gave rise to the higher transformation start temperature, 724° C. This change in hardenability will enhance the nucleation of grain-boundary phases such as polygonal ferrite and ferrite side plates.

During the examination of the microstructure, a few instances were observed (Figs 6 and 7) in which there was evidence for the direct nucleation
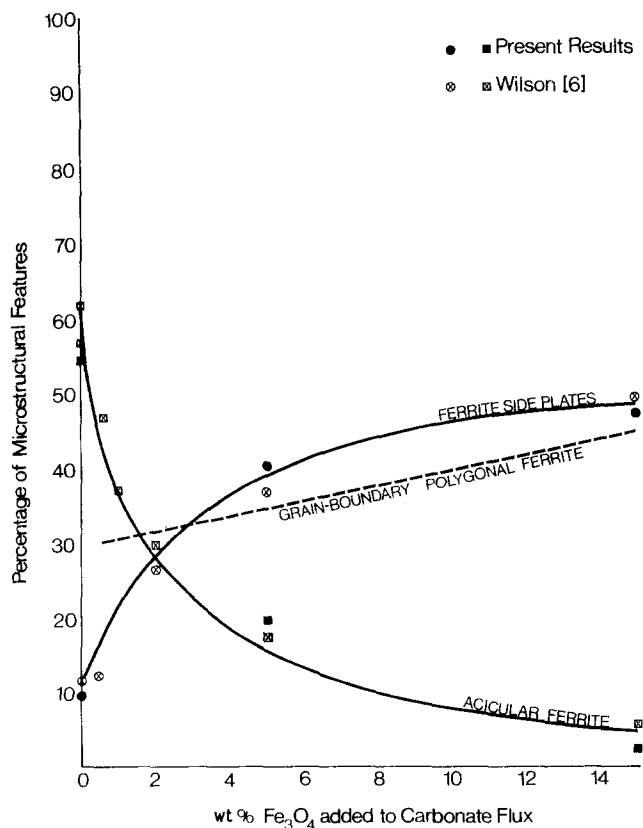

Figure 5 Influence of per cent Fe_3O_4 additions to the welding flux on the proportion of microstructural planes, after Wilson [6].

TABLE III Transformation start temperatures and prior austenite grain sizes

Sample code	Transformation start temperature (°C)	Grain size (μm)	
		Experimental	Predicted by Equation 1 with $A = 1.33$
EO	660	90	125
0 Fe	645	83	120
5 Fe	667	71	80
15 Fe	724	98	50

of acicular ferrite on or by oxygen-rich deoxidation products. These observations appear to confirm the suggestions made by Abson *et al.* [4] and the recent work by Barritte and Edmonds [10]. These latter authors froze in the $\gamma \rightarrow \alpha$ reaction, by quenching partially transformed samples and concluded that intragranular nucleation can occur on inclusions, and that this nucleation may be aided by the localized stress distribution associated with these inclusions.

To summarize, the current studies indicate that the degree of inter- and intragranular nucleation may be changed by altering the prior austenite grain size. The grain growth appears to be controlled by pinning of the austenite grain boundaries by the inclusions and that this follows classical precipitate—boundary interaction equations.

4. Conclusions

(1) A good correlation has been found between the as-welded microstructure and the number of oxygen-rich inclusions. High-temperature transformation products, such as proeutectoid ferrite and ferrite side plates becoming dominant when the oxygen level is greater than 400 ppm.

(2) There is evidence, that oxygen-rich inclusions pin the prior austenite grain boundaries and therefore influence the grain-growth kinetics and transformation temperatures. A small grain size favours high-temperature transformation products, whilst grain sizes larger than $45 \mu m$ tends to produce acicular ferrite.

(3) A limited amount of evidence was obtained which indicated that acicular ferrite may be directly nucleated on or by deoxidation products.

(4) When the mean size of the inclusions increases, the pinning of the austenite grain boundaries may no longer occur and grain growth takes place. If this occurs in a low hardenability weld, the resultant microstructure will consist of high-temperature products such as ferrite side plates.
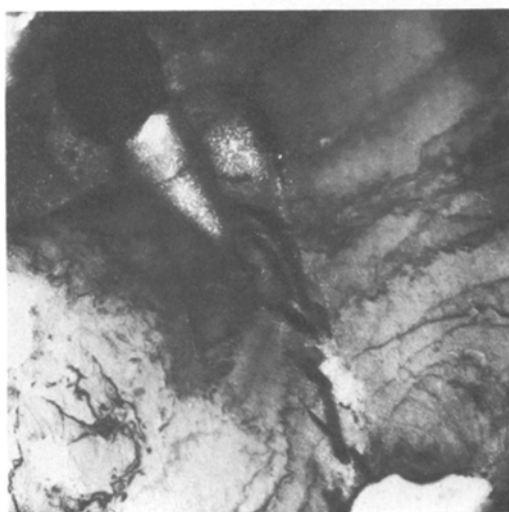
Acknowledgements

Figure 6 Deoxidation product and associated acicular ferrite (× 18 000).
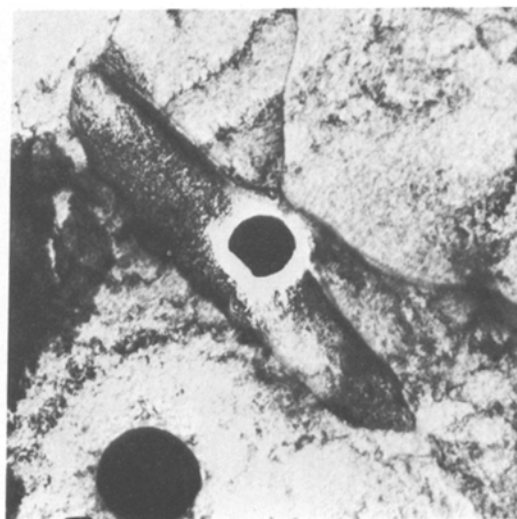
Figure 7 Acicular ferrite nucleated on a deoxidation product (× 14 400).

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