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The effect of prior austenite grain size on the transformation behaviour of C–Mn–Ni weld metal

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The influence of prior austenite grain size on the transformation behaviour and microstructural development of C–Mn–Ni weld metals was investigated. It was found that increasing the grain size depressed the start temperature of grain-boundary ferrite and slightly increased the acicular ferrite start temperature. The microstructural products also changed from a boundary-dominated effect in the small grain sizes, to an intragranular-dominated effect in the large grain sizes, and at the same time, the morphology of the acicular ferrite was seen to change to a larger aspect ratio.

1. Introduction

It is believed that a microstructure which possesses a high level of fine-grained acicular ferrite is beneficial to mechanical properties for low-carbon, low-alloy weld metals [1–6]. The factors which influence the transformation behaviour of the weld metals and the formation of acicular ferrite have been studied by many authors [7–13]. However, there are still some problems yet to be completely understood; for example, the role of prior austenite grain size.

Several investigators [14–16] have reported that a significant change in the continuous cooling transformation (CCT) diagrams of some steels was observed as a result of variation in the prior austenite grain size; little of the work, however, has related to weld metals. Harrison and Farrar [8] reported a similar variation of γ–α transformation temperature with grain size and discussed the possible reasons for weld metals. Recently, Dallam and Olson [17] carried out research both experimentally and with free-energy transformation calculations. These authors discussed the effect of austenite grain size on the γ–α transformation temperature and the nucleation rate of acicular ferrite.

The decomposition of supercooled austenite is a competitive process between the grain boundary and the intragranular transformations. If the austenite grain size influences the transformation behaviour of the weld metal, it will certainly change the proportions of the various transformation constituents. Previous workers have sought to model the reaction; Liu and Olson [18] used an Avrami equation approach and obtained an expression for the volume fraction of grain-boundary ferrite transformed, in which the prior austenite grain diameter is the main variation. Bhadeshia [19] and Bhadeshia and Svensson [20] have also carried out systematic modelling work and have presented a series of models for predicting the microstructure of the weld metals. Their expression for the fraction of either grain-boundary ferrite or Widmanstätten ferrite is seen to correlate with austenite grain size. Hence the grain size is considered to be important in determining the amount of acicular ferrite in the microstructure of the weld metals.

In this current investigation, a systematic study was undertaken using dilatometric techniques on a C–Mn–Ni weld metal. Using different prior austenite grain sizes, several CCT diagrams were produced. The fractions of different transformation products were assessed and the change in the morphology of the microstructure was observed. These experiments were designed to further our understanding of the role of the austenite grain size on the transformation behaviour and microstructural development of C–Mn–Ni weld metals.

2. Experimental procedure

Welding was carried out on En3B plate with 3.2 mm electrodes. The process conditions were 145 A, 18 V and a.c. polarity. A nominal heat-input of 1.2 kJ mm^{-1} was employed, and the interpass temperature was 150 °C. Welding was done in the horizontal position; three beads per layer were deposited using a 12° groove preparation. The total number of runs for the joint was 23.

The chemical composition of the weld metal used is listed in Table I. A theta quenching dilatometer was used to produce the continuous cooling transformation data. The specimens were extracted from the weld centre-line, well away from the dilution region. They were machined into standard dilatome-

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TABLE I Chemical composition of the weld metal

	C	Mn	Si	S	P	Ni
Wt %	0.048	0.782	0.660	0.008	0.015	5.530

try specimens, 5 mm outside diameter, 7 mm long and 1 or 0.5 mm wall thickness for the different cooling rates.

Three sets of peak temperatures and soaking times, i.e. 1150 °C × 10 s, 1350 °C × 10 s and 1350°C × 85 s were employed to obtain nominally different prior austenite grain sizes. Quantitative metallography was used to assess the relative microstructural constituents. Microhardness tests using 50 g loads were carried out for the microphase hardness assessment.

3. Results and discussion

3.1. Prior austenite grain sizes

Three austenite grain sizes (measured as mean linear intercept, m.l.i. and mean grain diameter, $\bar{d}$) produced by the different austenitizing procedures are shown in Table II.

TABLE II Austenitization procedure and resultant grain sizes

Procedure	$\bar{l}_{ml}$ (μm)	γ grain size, $\bar{d}$ (μm)	ASTM no.
1150 °C × 10 s	18	32	6.67
1350 °C × 10 s	53	93	5.19
1350 °C × 10 s	119	208	2.87

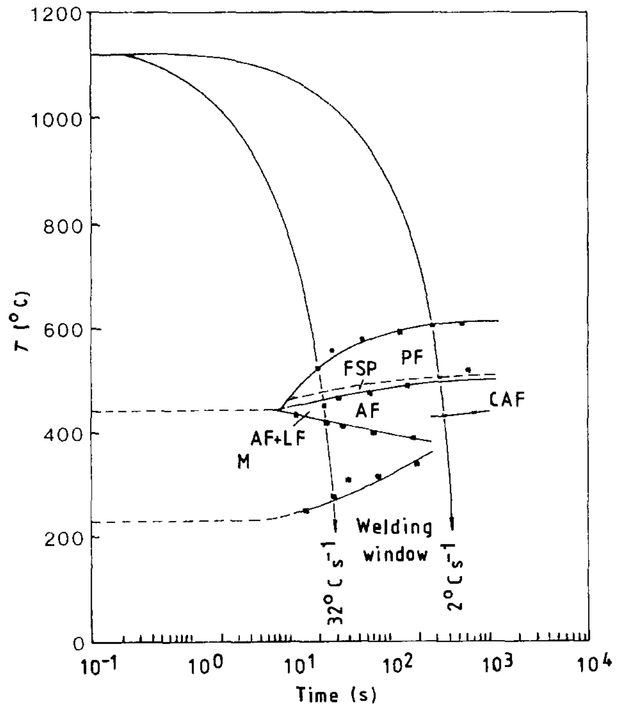

Figure 1 The CCT diagram of the weld metal with smaller prior austenite grain size (32 μm): austenitized at 1150 °C, 10 s, ASTM grain size 6.67 $\Delta T = 800$–500 °C; (– – –) estimated.

3.2 Change of transformation behaviour

Figs 1–3 show the continuous cooling transformation (CCT) diagrams of the weld metal obtained with different prior austenite grain sizes. From the CCT diagrams, it is obvious that the prior austenite grain size has a profound influence on the transformation behaviour of the weld metal. This is clearly shown by

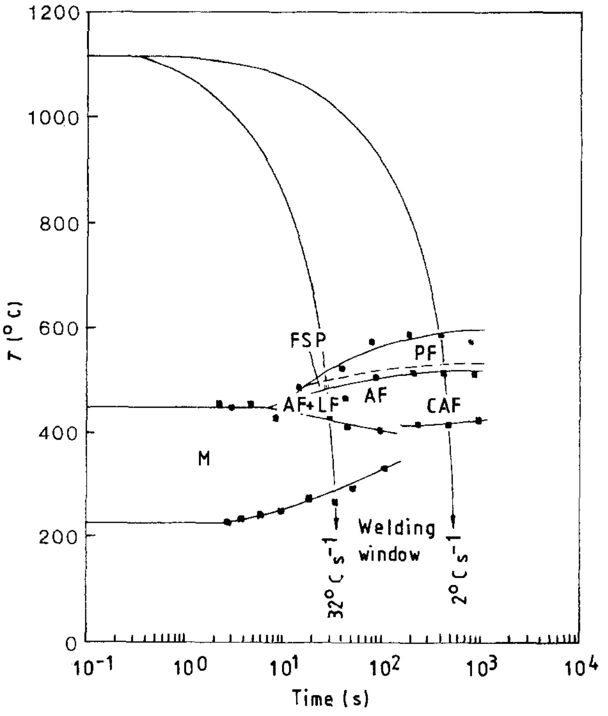

Figure 2 The CCT diagram of the weld metal with medium prior austenite grain size (93 μm): austenitized at 1350 °C, 10 s, ASTM grain size 5.19, $\Delta T = 800$–500 °C; (– – –) estimated.

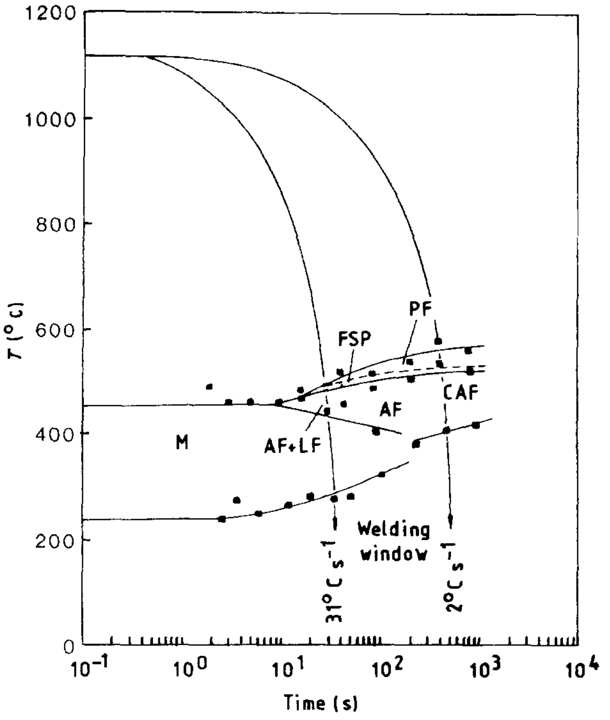

Figure 3 The CCT diagram of the weld metal with larger prior austenite grain size (208 μm): austenitized at 1350 °C, 85 s, ASTM grain size 2.87, $\Delta T = 800$–500 °C; (– – –) estimated.

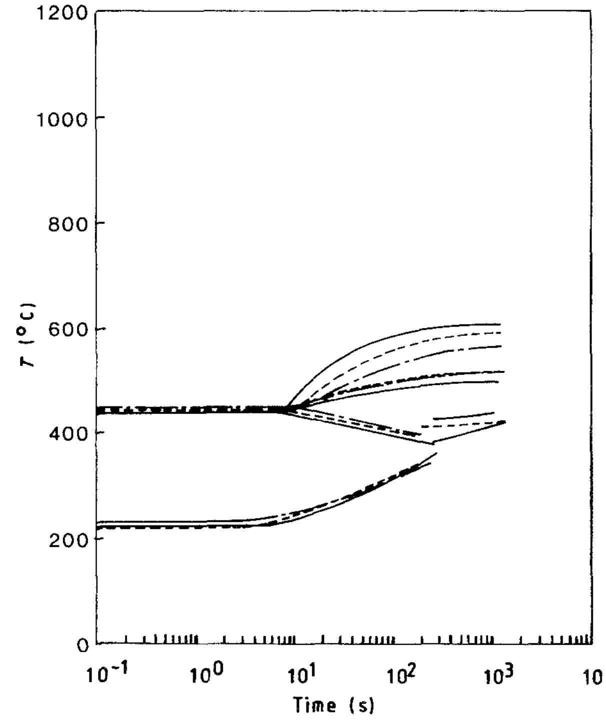

Figure 4 The influence of the prior austenite grain size on the weld metal transformation behaviour, (—) 1150 °C, 10 s, ASTM 6.67; (– – –) 1350 °C, 10 s, ASTM 5.19; (·–·–·) 1350 °C, 85 s, ASTM 2.87.

superimposing the three constituent diagrams as illustrated in Fig. 4.

When the austenite grain size was increased, the polygonal ferrite (PF) start temperatures were reduced significantly. When the average diameter of the austenite grains was increased from 32 μm to 93 μm, then to 208 μm, the corresponding PF start temperatures decreased by about 25 °C, respectively, at almost every cooling rate.

The acicular ferrite (AF) start temperature, on the other hand, increased slightly with grain size. When the prior grain size increased from 32 μm to 93 μm, the AF_s temperatures increased by about an average at 20 °C, with a further increase in grain size, the change in the AF_s temperature became rather scattered and fell in a range of ± 20 °C. The PF_s and AF_s temperatures for the three grain sizes at some typical cooling rates are listed in Table III.

TABLE III The change of the transformation temperatures

$\bar{d}$ (μm)	Cooling rate (ΔT = 800–500 °C) (°C s^{-1})	Transformation temperatures	
		PF_s T (°C)	AF_s T (°C)
32	2	604	506
	4	589	489
	10	579	474
	32	524	450
93	2	584	515
	4	587	514
	10	572	504
	32	487	461
208	2	576	532
	4	537	502
	10	514	487
	31	491	481

The difference in transformation behaviour due to the variation in prior grain size can be explained in terms of nucleation site density and supercooling. This was elucidated previously by Harrison and Farrar [8].

In the case of extremely small austenite grains, there is a large grain-boundary area which contains a high density of favourable primary heterogeneous nucleation sites. The supercooled austenite tends to be less stable, and a high rate of grain-boundary nucleation occurs with small amounts of supercooling (i.e. at higher temperature). In the case of coarse-grained austenite, there is a smaller grain-boundary area fraction and therefore it will transform at a relatively lower temperature because it contains less nucleation sites for the high-temperature product (PF).

Accompanying the grain-boundary transformation, the diffusion of alloying elements, mainly carbon, will occur from the grain-boundary regions towards the intragranular regions. Because the PF forms at a different temperature when the prior grain size is changed, the extent of carbon diffusion will also change. The calculated average carbon diffusion coefficients in the retained austenite at average PF transformation temperatures with a cooling rate of 4 °C s^{-1} are as follows for the three grain sizes: $\bar{D}^{\gamma}_{(\bar{d} = 32\,\mu m)} = 2.31 \times 10^{-10}\,cm^2 s^{-1}$ (at $\bar{T} = 539\,°C$); $\bar{D}^{\gamma}_{(\bar{d} = 93\,\mu m)} = 3.08 \times 10^{-10}\,cm^2 s^{-1}$ (at $\bar{T} = 550.5\,°C$); $\bar{D}^{\gamma}_{(\bar{d} = 208\,\mu m)} = 1.39 \times 10^{-10}\,cm^2 s^{-1}$ (at $\bar{T} = 519.5\,°C$).

The total times for diffusion and growth were measured as ~24 s for 32 μm grain, 18 s for 93 μm grain and 8.5 s for 208 μm grain at the same cooling rate. This means that during the polygonal ferrite reaction, the diffusion of carbon in the smaller austenite grain is faster and a longer time is available than in the larger grains. Therefore, the retained austenite in the small-grained metal will be enriched by carbon in the intragranular region. This process is illustrated in Fig. 5; where C_0 is the original carbon content and C_0+ is the enriched level. This enrichment of carbon will depress the AF_s temperature to a lower value compared with the coarse-grained material.

Assuming that during the grain-boundary ferrite reaction, the influence of the chemical potential due to the carbon redistribution at the γ–α interface on the succeeding carbon diffusion profiles can be neglected, the carbon content of the newly formed grain-boundary ferrite can be approximated to 0%, and the carbon content of the retained austenite to be transformed will be constant at the average level of the weld

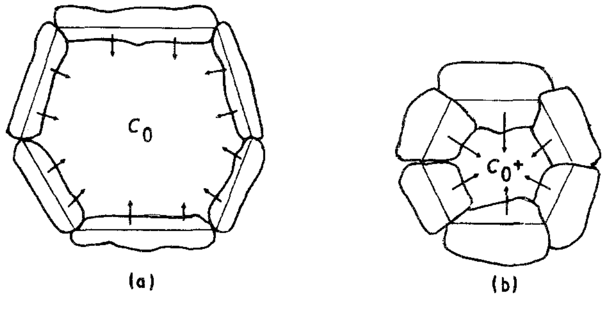

Figure 5 The situation of carbon diffusion in different grains: (a) large grain, (b) small grain.

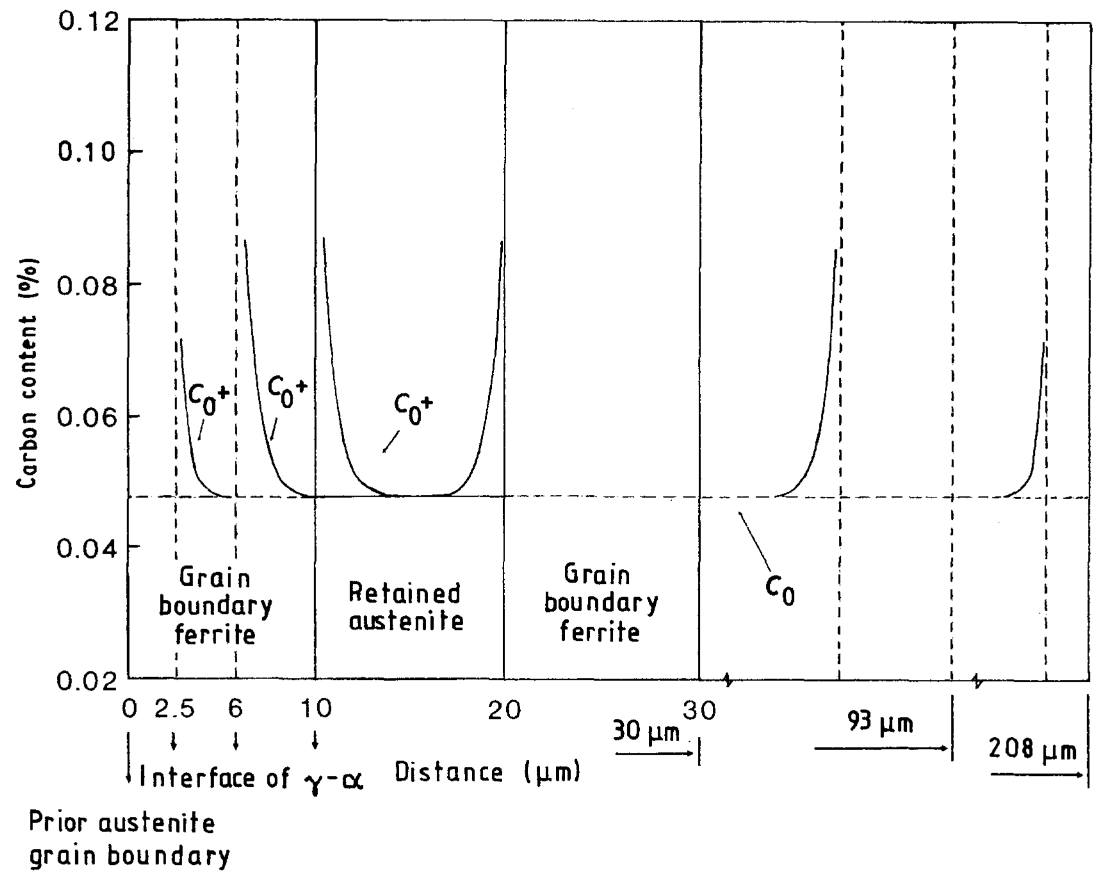

Figure 6 Redistribution of carbon after grain-boundary transformation.

metal, i.e. C_0 (0.048%). The carbon redistribution C_0 + for all three austenite grain-size structures at the moment just after the grain-boundary transformation (at 4 °C s^{-1} cooling) can then be calculated using the error function equation. The results are illustrated in Fig. 6. It is shown that the carbon enrichment caused by high-temperature reaction associated with the small austenite grain size is significant and it will increase the stability of the retained austenite and therefore encourage supercooling. This confirms the earlier comments on the temperature at which acicular ferrite forms.

While investigating the effect of grain size, it was also found that although smaller austenite grain sizes favoured the formation of PF, it also promoted martensite, M, to form at lower cooling rates (i.e. reduced the critical cooling rate for martensite). The effect is thought also to be the result of the local enrichment of carbon in the centre of the transforming austenite.

The change of transformation behaviour would cause the proportions of microstructural constituents to vary significantly as shown in Table IV.

The results show that with the smaller grain sizes, the weld metal transforms into PF-dominated structures, whereas with larger grain sizes, AF was the dominant phase. It also should be noted that higher cooling rates (i.e. > 10 °C s^{-1}) led to more martensite being formed in the intragranular areas for larger grain sizes. For example, 56% martensite at 32 °C s^{-1}) for 32 μm grain size compared with 79% martensite at 31 °C s^{-1} for 208 μm grain size.

TABLE IV The change of the microstructure

d (μm) (ASTM no.)	Cooling rate (ΔT = 800–500 °C (°C s^{-1})	Microstructure (%)			
		PF	FSP	AF	M
32	2	72	3	25	
(6.67)	4	46	4	30	20
	10	40	5	24	31
93	2	46	7	47	
(5.19)	4	25	11	64	
	10	11	12	49	28
208	2	24	6	70	
(2.87)	4	10	10	80	
	10	6	6	50	38

3.3. Change of microstructure morphology

Figs 7–9 show typical optical microstructures of the weld metal with the three prior austenite grain sizes at a cooling rate of 4 °C s^{-1} (ΔT = 800–500 °C). A full growth of PF can be seen in the microstructure with the smallest grain size. The measured average width of the grain-boundary ferrite is about 20 μm. For the largest grain size, the width of grain-boundary ferrite was reduced to only 5 μm.

Another important microstructural change was the variation in the acicular ferrite morphology. The results indicate that with increasing prior austenite grain size, the acicular ferrite constituent became larger and

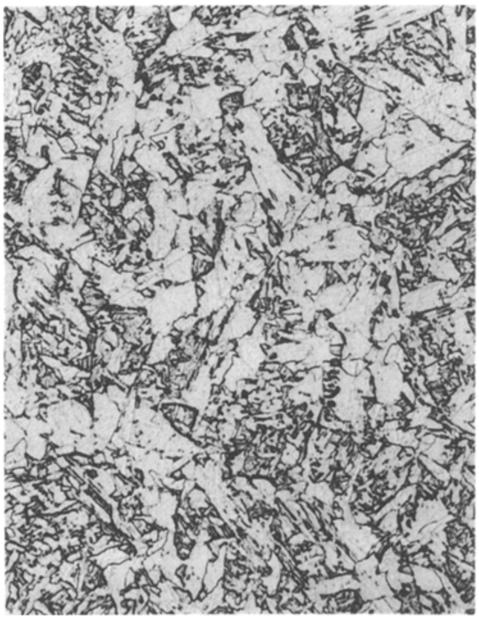

Figure 7 Microstructure of the weld metal with smaller prior austenite grain size at 4 °C s^{-1} (32 μm). × 500

Figure 8 Microstructure of the weld metal with medium prior austenite grain size at 4 °C s^{-1} (93 μm). × 500

its aspect ratio increased as well, whereas, with a smaller grain size, the intragranular products were refined (Figs 7–9). This contradicts the results of Dallam and Olson [17], who reported a coarsening of the structure.

Generally, the morphology of a microconstituent depends on the following factors: (1) rate of nucleation, (2) rate of growth, and (3) area and available time for growth. When the prior grain size was comparatively large, AF formed at a higher temperature. This implies a lower nucleation rate and higher growth rate, together with a larger growth area and a smaller rejection of carbon by diffusion. The result of this is an AF structure with a high aspect ratio. However, in the case of a small grain size, because of the full development of grain-boundary ferrite and local enrichment of carbon, AF formed at a lower temperature with a higher nucleation rate and lower growth rate. In addition, due to the limited retained austenite area the growth of the intragranular ferrite structure was restricted to a smaller aspect ratio.

Figure 9 Microstructure of the weld metal with larger prior austenite grain size at 4 °C s^{-1} (208 μm). × 500

TABLE V Microhardness of the acicular ferrite

$\bar{d}$ (μm)	32	93	208
VPN (50 g load)	314	282	263

The results of microhardness testing confirmed the hypothesis. Table V indicates that AF hardness increased with decreasing prior austenite grain.

4. Conclusion

From the experimental results and the discussion above, it is concluded that the prior austenite grain size has a profound influence on the transformation behaviour of C–Mn–Ni weld metal. It not only changes the formation temperatures of grain-boundary products, but varies the condition at which intragranular structures form, and hence changes the proportions of the microstructural constituents. It also influences the morphology of the products formed.

The reasons are thought to be the availability of grain-boundary nucleation sites and the elemental redistribution into the intragranular areas of the retained austenite.

Controlling the prior austenite grain size is, therefore, important in terms of both microstructure and the toughness of low-alloy weld metals. If the austenite grain is too small, it leads to a polygonal ferrite-dominated structure. A large grain size will depress the

PF formation and increase the percentage of acicular ferrite at lower cooling rates, but would increase the amount of martensite when the cooling rate is sufficiently high.

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