Acicular ferrite transformation in alloy-steel weld metals

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In this paper, the morphology of acicular ferrite in alloy-steel weld metals has been investigated. The effect of the grain size of prior austenite on acicular ferrite transformation has also been studied. It is found that acicular ferrite can form in reheated weld metals when the austenite grain size is relatively large. On the other hand, classical sheaf-like bainite will form at the same temperature if the austenite grain size is kept small. Further results strongly suggest that acicular ferrite is in fact intragranular bainite rather than intragranular Widmanstätten ferrite.

1. Introduction

Acicular ferrite has been known to be the most desirable microstructural constituent in steel weld metals because its presence directly correlates with improved toughness [1–6]. However, acicular ferrite is not included in the Dubé classification [7], and is not in general found in wrought steels. Although the transformation temperature range of acicular ferrite is around that of Widmanstätten ferrite and bainite, the morphology of acicular ferrite differs from that of either bainite or Widmanstätten ferrite. There has been a considerable amount of work on the nature of this important phase in the past decade. Many researchers [2, 8–11] suppose acicular ferrite to be a new phase, distinct from conventional steel microstructures. Some authors [12, 13] conclude it to be intragranularly nucleated Widmanstätten ferrite. The classification of microstructures on the basis of morphology is of considerable use in the study of structure–property relationships, but the prediction of microstructure requires a deeper understanding of the transformation mechanism. Further studies are therefore needed to establish the exact growth mechanism of acicular ferrite.

In this paper, we present results concerning the detailed morphology of acicular ferrite and the grain size effect on acicular ferrite transformation in alloy-steel weld metals. A complete study of its transformation mechanism has been carried out by means of high-speed dilatometry, optical microscopy and transmission electron microscopy.

2. Experimental methods

The specimens studied were taken from the top layer of a manual metal arc weld of chemical composition Fe–0.06C–0.27Si–1.84Mn–2.48Ni–0.2Mo (wt %). The weld also contained the following trace elements: 0.04Cr–0.01V–0.005S–0.008P–0.01Al–0.02Ti–0.01Nb–0.0317O–0.0098N. This weld is one of a series of high-strength weld deposits in which the primary microstructure consists essentially of acicular ferrite together with a small quantity of martensite and retained austenite [14, 15]. The chemical analysis was carried out using a spectroscopic technique, though the concentrations of oxygen and nitrogen were measured using Leco furnaces (Ro-17 and Tn-15), with 50 g of material for each determination to ensure representative results. The welds were made using 4 mm diameter electrodes (E10016-G type as defined by the American Welding Society), the joint geometry being designed according to BS639 in order to avoid dilution from the base plate. The welding was carried out in the flat position using the stringer bead technique, the parent plate thickness being 20 mm. The welding current and voltage used were 180 A and 23 V (d.c. +), respectively (nominal arc energy 2 kJ mm^{-1}), the weld consisting of some 21 runs with 3 runs per layer, deposited at a speed of about 0.002 m sec^{-1}; the interpass temperature was typically 250 °C.

Specimens for dilatometry were machined from the homogenized weld metal (1200 °C for 3 days while sealed in a quartz tube containing a partial pressure of pure argon). The specimens were 3 mm diameter cylindrical rods of length 20 mm, electroplated with a 7 μm layer of nickel, to provide constraint and avoid surface nucleation or surface degradation effects. After austenitization in an atmosphere of pure helium (carried out in a Theta Industries high-speed dilatometer) at 950 or 1200 °C for 10 min, the specimen chamber was evacuated to facilitate the quench to the isothermal transformation temperature, by means of a controlled high-pressure helium jet directed both radially and axially at the specimen, giving quench rates averaging 250 to 300 °C sec^{-1}.
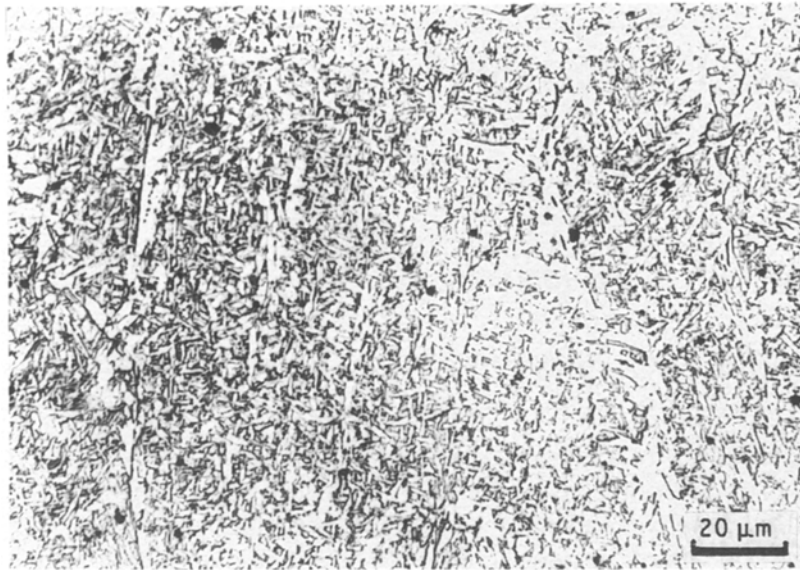
Transmission electron microscopy samples were

prepared from 0.25 mm thick discs cut from the dilatometric specimens. The discs were mechanically ground down to a thickness of 0.05 mm on 1200 grit SiC paper; the specimens were then twin-jet electro-polished using a mixture of 5% perchloric acid, 25% glycerol and 70% ethanol at ambient temperature, and 45 V. They were examined using a Philips EM400T transmission electron microscope operated at 120 kV.

3. Results and discussion
3.1. The morphology of acicular ferrite

The primary microstructure of as-deposited weld metal, consisting mainly of acicular ferrite (volume fraction $\simeq 0.9$) with very little allotriomorphic and Widmanstätten ferrite, is illustrated in Fig. 1. The latter constituents arise simply because of the presence of chemical segregation in the weld, which cools under non-equilibrium conditions. The detailed morphology of acicular ferrite in as-deposited weld metal studied by transmission electron microscopy is presented in Figs 2 to 5. Fig. 2 shows that due to hard impingement the non-parallel plates of acicular ferrite are arranged in an interlocking pattern, and small amounts of microphases are located among the acicular ferrite plates. In other cases, several acicular ferrite plates can grow from one inclusion to give a star-shaped cluster as shown in Fig. 3. It has also been found that small platelets of acicular ferrite apparently nucleate "sympathetically" [16] on the austenite/ferrite interface as displayed in Fig. 4.

During the initial stages of transformation, nucleation occurs heterogeneously at non-metallic inclusions
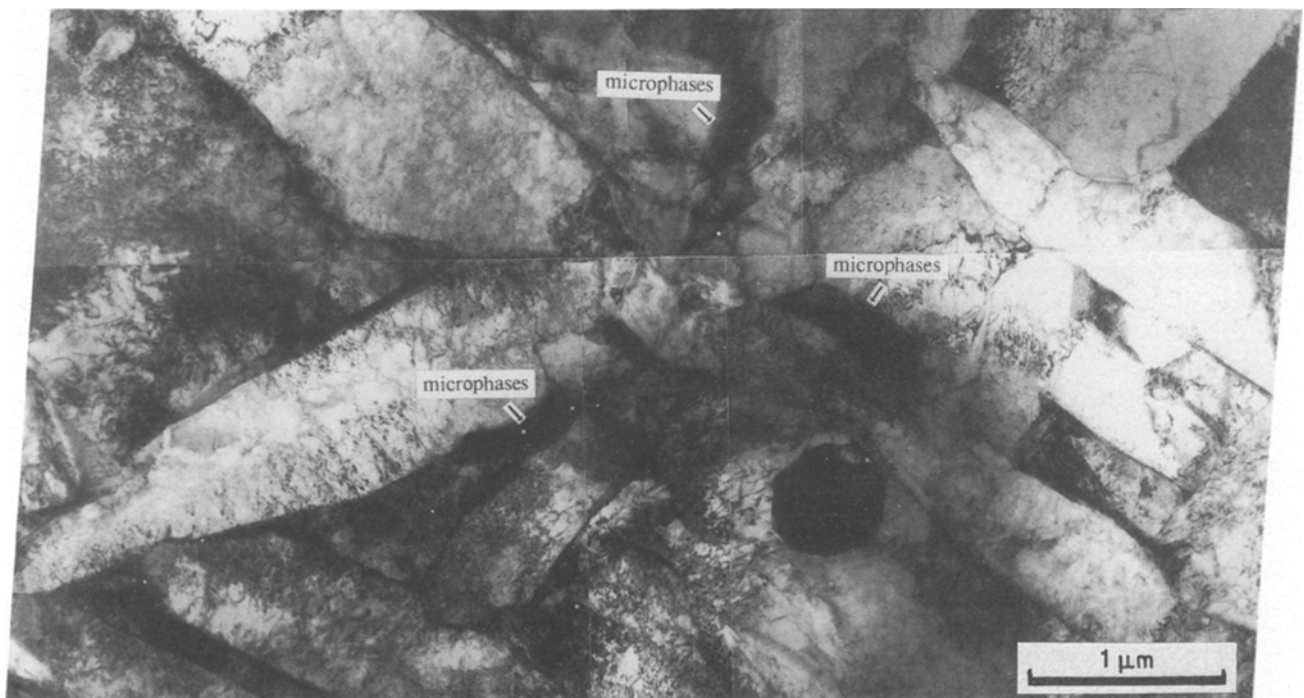

Figure 2 Transmission electron micrograph showing non-parallel plates of acicular ferrite arranged in an interlocking pattern.
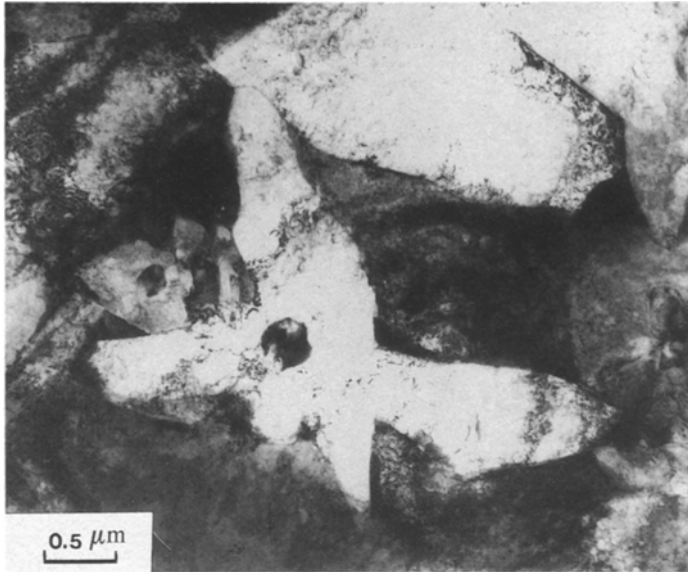
Figure 3 Transmission electron micrograph showing acicular ferrite plates growing from one inclusion to give a star-shaped cluster.
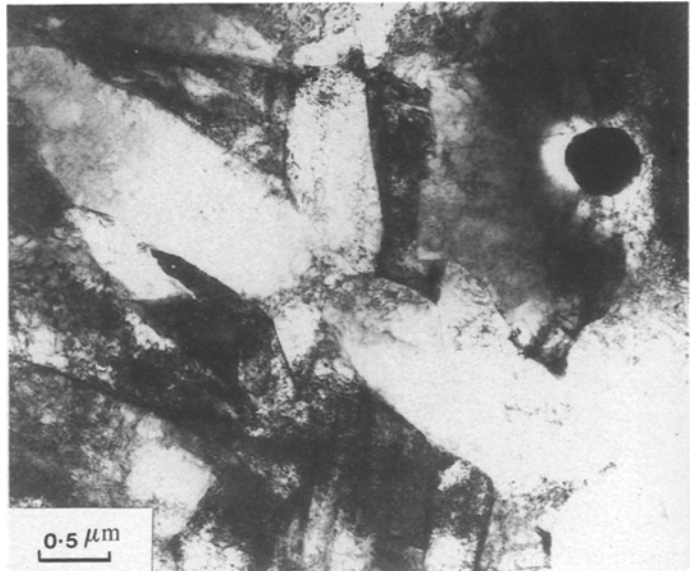

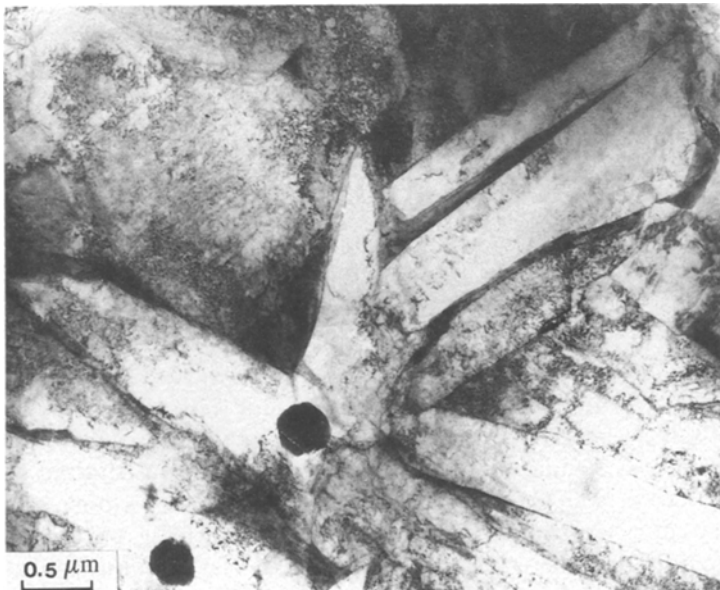*Figure 4* Transmission electron micrograph showing sympathetic nucleation of acicular ferrite

Figure 5 Transmission electron micrograph showing that after initial nucleation events at inclusions, subsequent plates can form sympathetically.
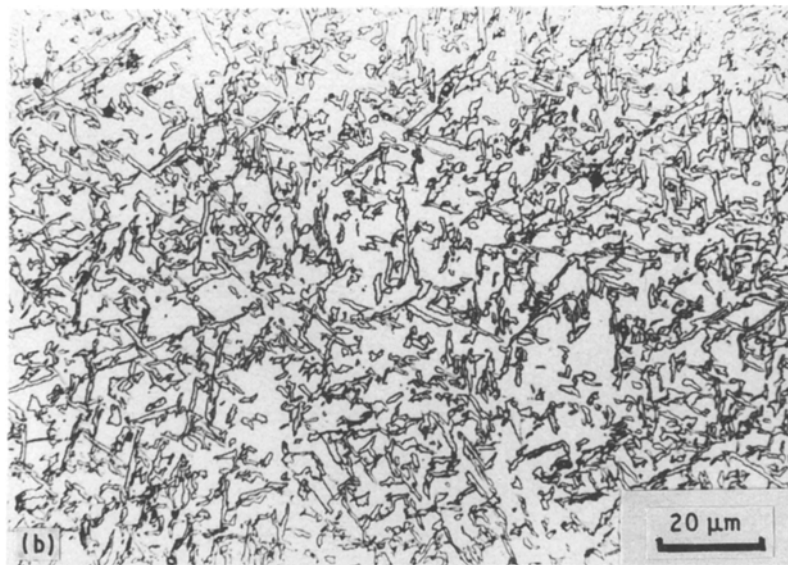
841

present in weld deposits [1–3, 17]. It appears that after the initial nucleation events at inclusions, subsequent plates can form sympathetically (as shown in Fig. 5) so that a one-to-one correspondence between inclusions and acicular ferrite plates is not expected. Since the lenticular shape of acicular ferrite is always observed, it is suggested that acicular ferrite has in three dimensions a thin-plate morphology. The tips of the acicular ferrite plates are also found to be smoothly curved. These morphological observations are consistent with a shear mechanism [18] in which the lenticular plate shape of acicular ferrite arises through the need to minimize the strain energy associated with the accompanying shape deformation.

3.2. The grain size effect

It is difficult to resolve the nature of acicular ferrite in wrought steels, simply because of the absence of suitable intragranular heterogeneous nucleation sites and because the austenite grain size of such steels is deliberately kept small; transformations initiated at austenite grain boundaries thus swamp the interior regions as well. However, if after deposition a weld is

reheated into the austenite phase field to generate large austenite grains, then these new grains still contain the inclusions which were present in the original deposit. Isothermal transformation of this structure in a temperature range where acicular ferrite usually forms in welds should then lead to the intragranular nucleation and growth of plates, whose morphology should be identical to that of the acicular ferrite observed in weld deposits.

Austenite grain sizes for homogenized specimens austenitized at 950 °C for 10 min and 1200 °C for 30 min have been investigated. Using the linear intercept method, austenite grains were measured on a Quantimet 720 image-analysing computer. The average grain size for the former is about 15 μm, and for the latter about 45 μm. The results of isothermal transformation experiments on reheated weld metal are illustrated in Figs 6 to 8. Fig. 6 demonstrates the results of isothermal transformation at 460 °C for 30 min; in one case the weld was reaustenitized at 950 °C for 10 min (Fig. 6a) and another sample was austenitized at 1200 °C for 30 min (Fig. 6b) before isothermal transformation. It is clear from Fig. 6b that isothermal transformation with the larger austenite
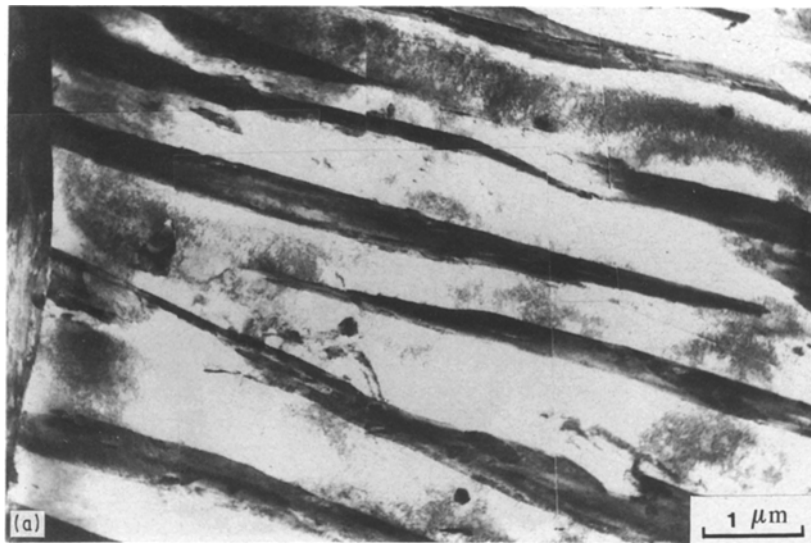
Figure 7 Transmission electron micrographs, confirming the morphologies of (a) upper bainite and (b) acicular ferrite for the corresponding optical micrographs shown in Fig. 6.

grain condition has led to the intragranular nucleation of plates of ferrite which can be identified morphologically with the acicular ferrite found in welds. On the other hand, in the specimen reaustenitized at 950 °C, the smaller austenite grain size has prevented intragranular nucleation. However, the ferrite plate nucleated at the austenite grain boundaries and has grown by a sub-unit mechanism to give the morphology of sheaves of upper bainite (Fig. 6a).

The striking transmission electron micrographs in Fig. 7a and b distinctly confirm the morphologies of upper bainite and acicular ferrite in weld metal for the corresponding optical micrographs shown in Fig. 6a and b. In order to investigate the morphologies for higher volume fraction of bainite and acicular ferrite in weld metal, the isothermal transformation was carried out at 440 °C for 30 min. The results are shown in Fig. 8. Fig. 8a displays the large amount of bainite obtained after austenitization of weld metal at 950 °C for 10 min followed by isothermal transformation at 440 °C for 30 min. The micrograph clearly demonstrates that the sheaves of bainitic ferrite grow from grain boundaries, swamp the interior region of austenite grains, and then impinge with the opposite austenite grain boundaries.

Fig. 8b shows the high volume fraction of acicular ferrite obtained after austenitization at 1200 °C for 30 min followed by isothermal transformation at 440 °C for 30 min. This optical micrograph shows the interlocking nature of acicular ferrite, which arises because acicular ferrite nucleates intragranularly at inclusions within large austenite grains, and because of hard impingement between plates nucleated on adjacent inclusions. Intragranular nucleation on inclusions has a higher activation energy compared with grain boundary nucleation [19] so that the number of grain boundary sites must be minimized to obtain acicular ferrite. It is clear that acicular ferrite requires the presence of inclusions to initiate intragranular nucleation, and will only form when the austenite grain size is relatively large, so that events originating from the grain boundaries do not swamp those occurring intragranularly.

3.3. Thermodynamic evidence

The details of thermodynamic investigations of the acicular ferrite transformation mechanism have been presented elsewhere [14, 15, 20]. It has been shown that the transformation mechanism of acicular ferrite
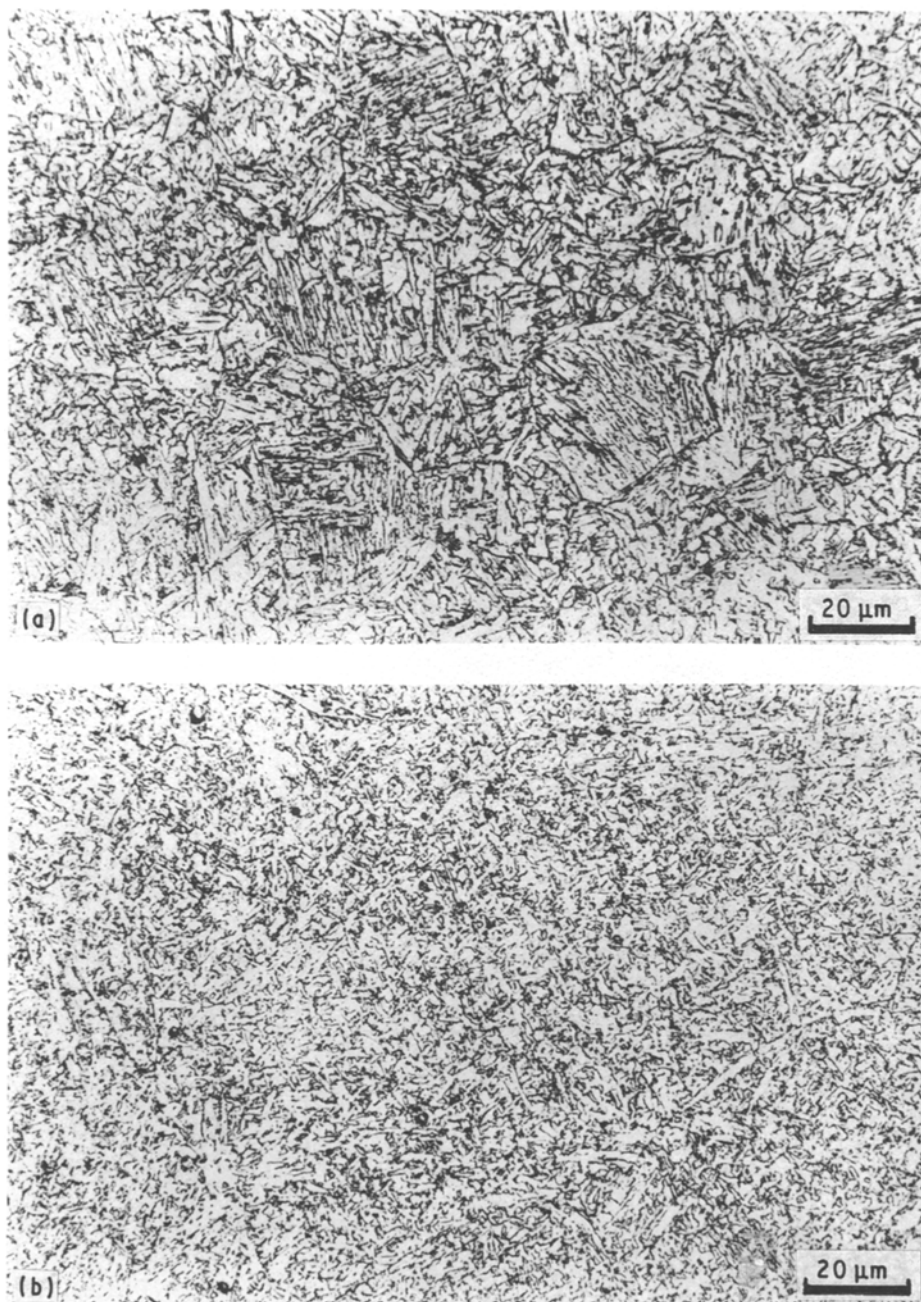
843

Figure 8 Optical micrographs: (a) high volume fraction of bainite obtained after austenitization of weld metal at 950 °C for 10 min followed by isothermal transformation at 440 °C for 30 min; (b) high volume fraction of acicular ferrite obtained after austenitization of weld metal at 1200 °C for 30 min followed by isothermal transformation as in (a).

is the same as that of bainite: the plates form by a diffusionless and displacive transformation mechanism, and immediately after plate growth, carbon is partitioned into the residual austenite. The transformation does not therefore obey the lever rule and exhibits a classical incomplete reaction phenomenon [21, 22] in which reaction ceases well before the residual austenite achieves its equilibrium carbon concentration. In fact, the transformation stops when the carbon concentration of the residual austenite reaches the T_0' curve* on the phase diagram.

4. Conclusions

Acicular ferrite is not a new transformation product, but is simply intragranularly nucleated bainite. Its morphology differs from classical sheaf-like bainite merely because it nucleates intragranularly at point sites within large austenite grains, and is also limited by hard impingement with other plates which form on neighbouring sites.

Acknowledgements

*The T_0' curve [23, 24] is defined such that at any specific isothermal temperature, austenite and ferrite of the same composition (with a certain amount of stored energy associated with transformation strains) have equal free energy. The corresponding curve for stress-free austenite and ferrite of identical composition is conventionally called the T_0 curve.

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