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The observation of interphase precipitation in association with the lateral growth of Widmanstätten ferrite

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This paper describes the observation of interphase precipitation in association with the isothermal decomposition of austenite to ferrite in two particular iron-base alloys. Specifically, it is shown that the interphase precipitates are arranged in sheets parallel to the broad faces of the Widmanstätten plates such that it may be inferred that this precipitate dispersion nucleates on the low-energy austenite/ferrite interface. It is also shown that precipitation from supersaturated solid solution often occurs in the Widmanstätten ferrite plates.

1. Introduction

The formation of Widmanstätten ferrite has been the subject of many investigations for some considerable time (e.g. [1–3]). Although some doubt still exists concerning the early stages of the transformation [4, 5], it is generally accepted that the lateral growth of Widmanstätten ferrite occurs by the movement of "disordered" ledges along a relatively low-energy immobile interface [5]. A variety of studies have shown that this ferritic product is related to the austenite into which it is growing by the Kurdjumow–Sachs [6], orientation relationship [1] and that the broad faces of the Widmanstätten plates (i.e. the low-energy interfaces) are close in crystallographic index to the $(1\,1\,1)_\gamma/(1\,1\,0)_\alpha$ planes.

In many low-alloy steels and iron-base alloys, the decomposition of austenite can lead to a ferritic product which is supersaturated with respect to one or more precipitate phases. This supersaturation can lead to the development of a ferrite/precipitate aggregate, the precipitate forming on the advancing transformation interface. One such precipitate dispersion is termed interphase precipitation [7] and consists of planar sheets of precipitates parallel to the ferrite/austenite interface. A number of studies [7–11] have suggested that this mode of precipitation is associated with the lateral movement of ledges along a low-energy interface which implies a Kurdjumow–Sachs orientation between austenite and ferrite, and a $(1\,1\,1)_\gamma/(1\,1\,0)_\alpha$ interfacial plane.

Although this "coherent interphase precipitation" has been widely reported in association with the formation of equi-axed ferrite (e.g. [8,9]) little information exists concerning the development of precipitate dispersions in association with the growth of Widmanstätten ferrite.

In this paper, the structure of Widmanstätten ferrite is examined in terms of its associated precipitation reactions. It is shown that interphase precipitation can develop during the lateral growth of this ferritic product and that the planar sheets of precipitates so formed are closely parallel to the broad faces of the Widmanstätten plates. This observation supports the current theories of the development of interphase precipitation [8–10], i.e. this precipitate type is associated with the ledge-type growth mode of low-energy immobile interfaces.

2. Experimental details

Two particular alloys have been investigated: Fe–0.3%V–0.05%C and Fe–2%Cu–5%Ni.* These alloys were chosen since it has been established [11,

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* wt %.

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12] that in both instances, Widmanstätten ferrite can be produced on isothermal transformation.

Both alloys were made from high-purity base materials, melted in an argon arc furnace and fully homogenized under a partial pressure of argon before heat treating in a molten tin bath. The transformation temperatures selected for the two alloys were such that a high proportion of the ferrite formed by isothermal decomposition of austenite was Widmanstätten in nature.

The resultant structures were examined both optically and by electron microscopy of thin foils in either a Phillips EM300 or EM400 electron microscope.

3. Results

A typical example of the overall ferrite morphologies examined is shown in Fig. 1, which shows the microstructure of a Fe–Cu–Ni specimen transformed at 615° C for 80 min. The ferritic product is typically Widmanstätten in nature and nucleation has occurred almost exclusively on the austenite grain boundaries. The fine scale morphology of the individual Widmanstätten ferrite units is shown in Fig. 2 which is an electron micrograph of the Fe–V–C alloy transformed at 740° C for 150 min.* As can be seen, the Widmanstätten ferrite plates tend to be parallel sided and in general the misorientation between adjacent plates was found to be small. In common with a variety of other studies, the Widmanstätten ferrite in both alloy systems was observed to contain a fairly high dislocation density (e.g. see Fig. 2).

Precipitation was observed in association with Widmanstätten ferrite in both alloy systems. In the Fe–2Cu–5Ni alloy this precipitate was identified as fcc ϵ–Cu which had an orientation relationship with the ferrite of the form

$$(1\,1\,1)_{\epsilon\text{-Cu}} \parallel (1\,1\,0)_\alpha$$

$$[\bar{1}\,1\,0]_{\epsilon\text{-Cu}} \parallel [\bar{1}\,1\,1]_\alpha \qquad (11)$$

which is the Kurdjumow–Sachs [6] orientation relationship.

For the Fe–0.3 V–0.05 C alloy the precipitate was identified as vanadium carbide which was crystallographically related to the ferrite by the Baker–Nutting [13] orientation relationship (e.g. [12, 14]):

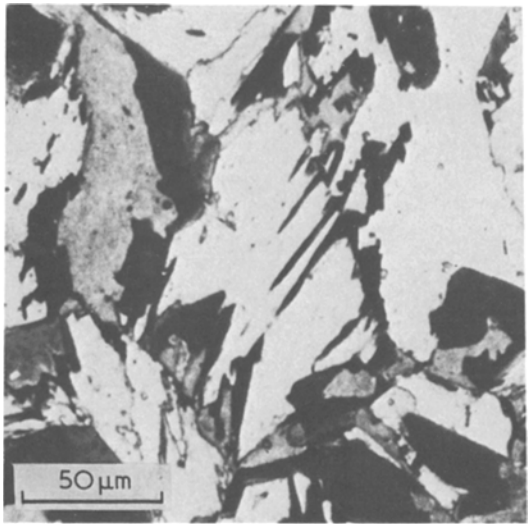

Figure 1 An optical micrograph of a partially transformed Fe–Cu–Ni specimen showing the overall morphology of the Widmanstätten ferrite. Nucleation has occurred almost exclusively at the austenite grain boundaries.

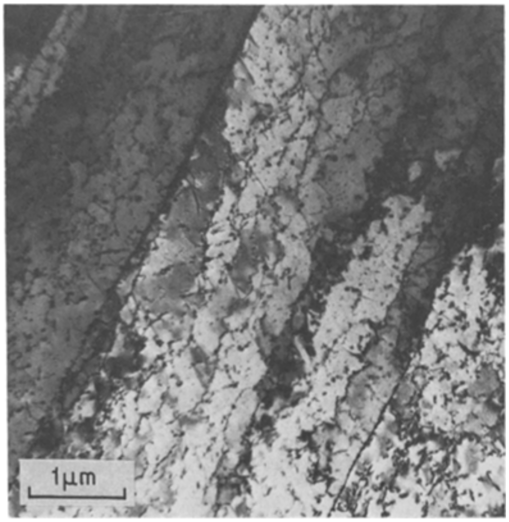

Figure 2 A low magnification transmission electron micrograph of a fully transformed Fe–V–C specimen illustrating the structure of individual ferrite plates. A relatively high dislocation density is apparent.

$$(1\,0\,0)_{VC} \parallel (1\,0\,0)_\alpha$$

$$[0\,1\,1]_{VC} \parallel [0\,0\,1]_\alpha.$$

In both alloy systems two dissimilar precipitate dispersions were observed in association with Widmanstätten ferrite:

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* The two heat treatments were taken as standard for the two alloys, and the results detailed in this paper relate to these two particular treatments.

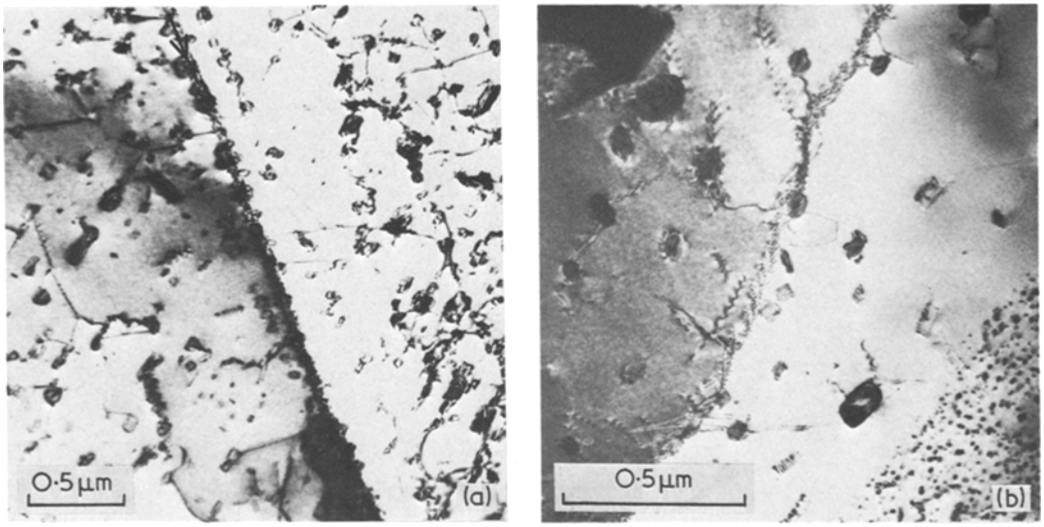

Figure 3 Examples of precipitation from supersaturated ferrite. (a) The Fe–V–C alloy. Precipitation is observed on the ferrite/ferrite grain boundary (arrowed) and within the matrix (mainly on dislocations). (b) The Fe–Cu–Ni alloy. Both grain boundary and dislocation precipitation is evident.

(a) precipitation from supersaturated solid solution, typically on dislocations,

(b) precipitation formed on the advancing Widmanstätten ferrite–austenite interface, i.e. interphase precipitation.

3.1. Precipitation from supersaturated solid solution

In both alloys, precipitation from supersaturated solid solution was observed on dislocations and on grain boundaries (Fig. 3a and b). Such precipitation characteristically displayed several variants of the appropriate orientation relationship discussed above. The development of this type of precipitate dispersion is discussed in Section 4.

3.2. Interphase precipitation

Although precipitation from supersaturated solid solution was often the predominant dispersion, interphase precipitation was observed in association with the growth of the Widmanstätten plates. Fig. 4a shows interphase precipitate (arrowed) in the Fe–Cu–Ni alloy. As may be seen, the precipitate sheets are closely parallel to the Widmanstätten ferrite/austenite interface. Precipitation from supersaturated solid solution is also observed as is a virtually precipitate free zone in the vicinity of the interface which most probably formed during the quench from the isothermal transformation temperature. In Fig. 4b (from the Fe–V–C alloy) two planar sheets of interphase precipitate are arrowed. These sheets are closely parallel to the adjacent Widmanstätten ferrite grain boundary. Two further examples of the observation of interphase precipitation, and their relationship to the broad faces of the adjacent Widmanstätten plates are given in Fig. 4c (Fe–Cu–Ni alloy) and Fig. 4d (Fe–V–C alloy).

4. Discussion

The observation of planar sheets of interphase precipitates, closely parallel to the broad faces of the Widmanstätten ferrite plates implies that the precipitates formed in association with the lateral growth of these ferrite plates. This provides supportive evidence for the postulate [7–10] that this interphase precipitate nucleates on the low-energy immobile austenite/ferrite interface which is constrained to grow via a ledge mechanism. Similarly these observations intimate that the planar interphase precipitation dispersions, observed at higher temperatures in alloys of this type are also associated with the ledge-type growth of partially coherent interphase boundaries even though the resultant ferrite morphology is, in general, equiaxed.

In many cases it was found that precipitation from supersaturated ferrite was the dominant precipitation mode and often no evidence of interphase precipitation was observed. In these instances it is most likely that the kinetics of the transformation at these temperatures prohibited either

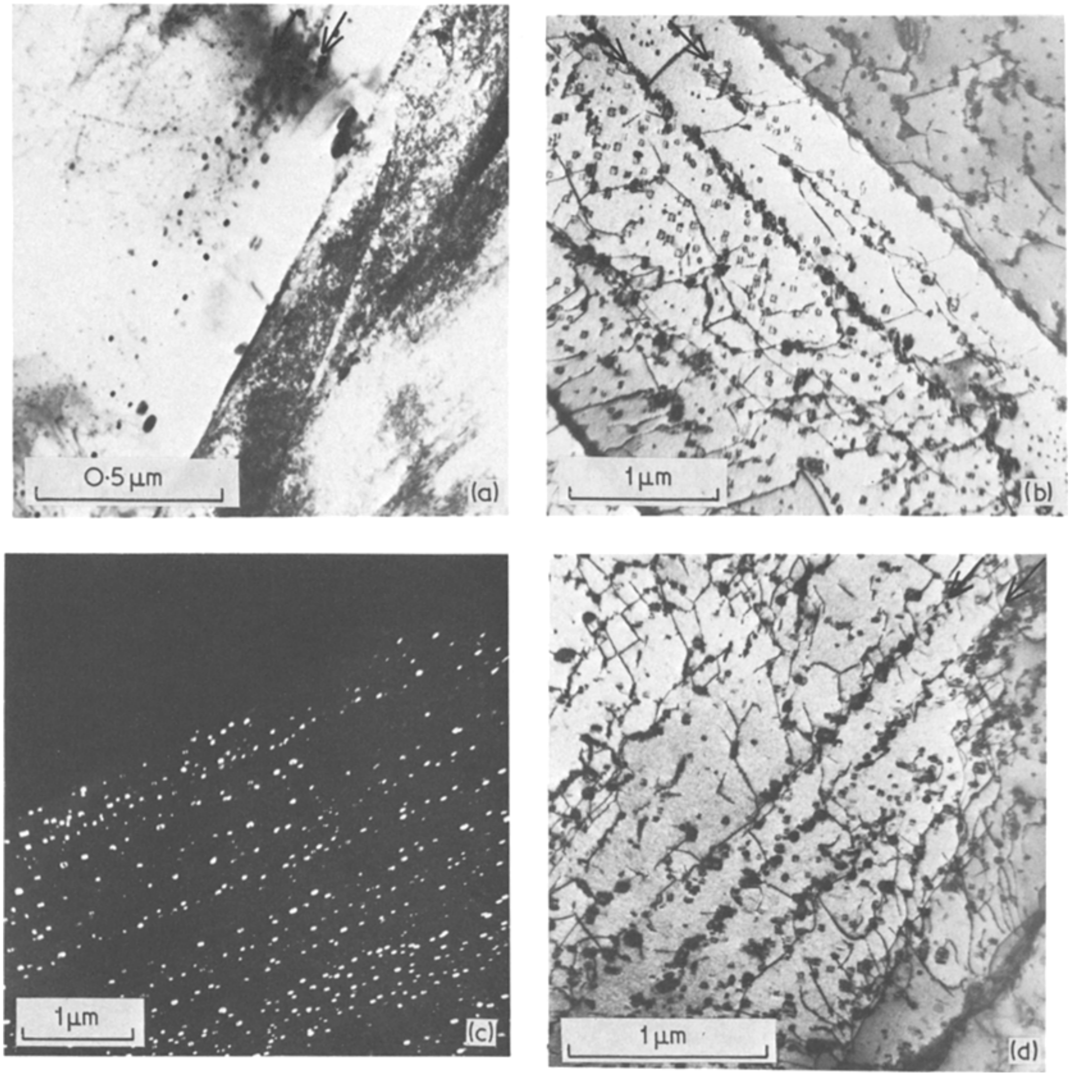

Figure 4 Examples of the observation if interphase precipitation in association with Widmanstätten ferrite. (a) Fe–Cu–Ni. The sheets of interphase (arrowed) are seen to be closely parallel to the ferrite/austenite interface. A rim of clean ferrite is seen adjacent to this interface and this most probably results from the quench. (b) Fe–V–C. Two sheets of interphase (arrowed) are in a parallel orientation to the ferrite/ferrite grain boundary. Precipitation from supersaturated ferrite is also observed. (c) Fe–Cu–Ni. A further example of the association between interphase precipitation and the broad faces of the Widmanstätten plates. (d) Fe–V–C. Three sheets of interphase precipitation, these being parallel to the average trace of the Widmanstätten plate.

diffusion of solute in the interphase boundary or nucleation on the immobile boundary facets (and see [10]). Where the transformation kinetics are such that there is a finite probability of producing precipitation either on the advancing interface, or from the supersaturated ferritic phase alone, then any variation in either ledge height or spacing will promote one precipitation reaction rather then the other since an increase in either ledge height or spacing will favour interphase precipitation. Hence, it is to be expected that both dispersions may be found in the same Widmanstätten ferrite plate as is often observed (see Fig. 4a to d).

5. Conclusions

(1) Widmanstätten ferrite can form in association with either interphase precipitation or precipitation from supersaturated solid solution in Fe–Cu–Ni and Fe–V–C alloys.

(2) Interphase precipitate sheets are closely parallel to the broad faces of the Widmanstätten ferrite plates.

(3) Interphase precipitation forms in association with the lateral growth of Widmanstätten ferrite, which is by movement of disordered ledges along a low-energy immobile interphase boundary.

(4) Supersaturated Widmanstätten ferrite may form if the solute diffusion in the boundary or the nucleation of precipitates, is prevented by the kinetics of the reaction. Such supersaturated ferrite can decompose to ferrite + precipitate during the isothermal heat treatment.

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