Stress-affected transformation to lower bainite

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Experiments have been conducted on the formation of lower bainite under the influence of an externally applied stress. It was found that both the ferritic and cementite components of the microstructure respond to the stress. The ferrite plates that grow appear to comply best with the applied stress, leading to an aligned microstructure. Within any given ferrite plate, the stress was found to favour the formation of a single variant of cementite. The results are consistent with a displacive mechanism of transformation, and provide an explanation for the frequent observation that cementite precipitates in a single orientation within any given plate of lower bainite ferrite.

1. Introduction

The tempering of martensite in steels leads to the precipitation of carbides, even when the tempering temperature is so low as to prevent the diffusion of iron during the heat treatment. This led to early suggestions that the carbides precipitate by a mechanism in which the iron atoms (and substitutional solutes) are displaced into positions they occupy in the carbide structure, with carbon diffusion enabling the necessary composition change [1–3]. This amounts to a displacive, paraequilibrium [4, 5] mechanism of transformation, which has been supported by recent atomic resolution experiments [6]. The experiments demonstrate that substitutional solutes do not partition during cementite growth even on the finest conceivable scale.

The cementite particles grow in the form of thin plates, and it is believed that the change in shape, as they grow by a displacive mechanism, can be described as an invariant-plane strain with a large shear component [7]. Consequently, the precipitation of cementites becomes sensitive to stress, which favours the formation of those variants which comply with the stress. The mechanical interaction between the stress and the shape change contributes a mechanical driving force [8] which may compliment or oppose the usual chemical driving force for precipitation. If the mechanical driving force dominates, then only that crystallographic variant of carbide which complies best with the stress will precipitate [9]; otherwise, even variants which do not comply with the stress will form, although the favoured variant is likely to dominate. Hence, a decrease in stress, or an increase in the carbon concentration (i.e. increased chemical driving force) favours the precipitation of multiple variants (refer to the martensite in Fig. 1). Notice that the stress need not be externally applied, because each plate of martensite has its own associated stress field. Thus, a single carbide variant is observed in low-carbon martensite which is tempered without externally applied stress [9].

Indeed, it may be the case that the classical microstructure of lower bainite can be explained as discussed above (Fig. 1). Lower bainite forms above the martensite-start temperature, with a microstructure in which the plates of ferrite usually contain just one crystallographic variant of carbide [10]. Martensite in the same alloy may temper to give multiple variants of carbides. It is argued that this is because only some of the carbon that is in lower bainitic ferrite precipitates as carbides, whereas the rest escapes into the surrounding austenite. Thus, the driving force for carbide precipitation is reduced; only the carbide variant which complies with the self-stress of the plate of ferrite then precipitates, giving the classical microstructure of lower bainite.

The purpose of the present work was to show, for the first time, that the number of variants of carbide that form in lower bainite can be reduced by the application of stress, in order to confirm the mechanism of transformation. Work like this has already been published for the tempering of martensite [9], but never for lower bainite.

2. Experimental procedure

The experiments were carried out using an alloy containing a large silicon and carbon concentration: Fe–0.46C–2.10Si–2.15Mn wt %. The silicon suppresses the precipitation of carbides from austenite [11]. The large carbon concentration increases the driving force for the precipitation of carbide from supersaturated ferrite [9, 12]. This, in turn, stimulates the precipitation of more than one variant of carbide in any given plate of ferrite, even though the self-stress of the plate favours just one variant. This is because the chemical driving force of carbide precipitation becomes large when compared with the mechanical

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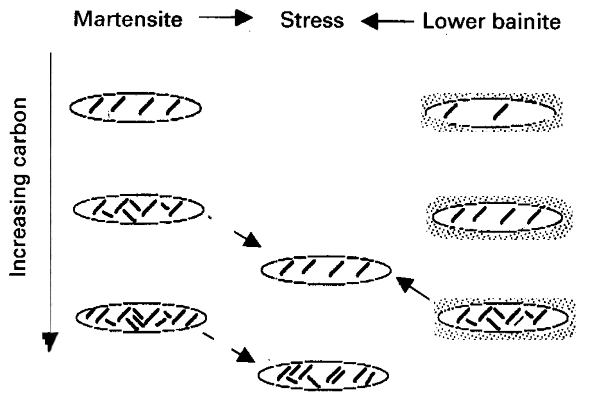

Figure 1 The left and right hand sides represent the tempering of martensite, and formation of lower bainite, respectively, without any applied stress. The central region of the diagram shows how the microstructure might change when the process occurs under the influence of a uniaxial applied stress. Note that all the effects observed with martensite are shifted to higher carbon concentrations for lower bainite, because some of the carbon in the lower bainite escapes into the residual austenite, as illustrated by the shading. In general, an increase in the carbon concentration, or a decrease in stress favours the precipitation of multiple variants of cementite during the tempering of martensite [9].

driving force due to stress, when the carbon concentration is high [9, 12]. Hence, from experience, it was expected that the lower bainite would form with multiple variants of cementite. The effect of the applied stress would then be obvious if it reduced the number of variants.

The alloy, in the form of a 10 mm diameter steel bar was sealed in a quartz tube containing pure argon, for homogenization at 1300 °C for 3 days. The bar was then machined into cylindrical samples, 8 mm diameter and 12 mm long.

Transformation experiments were performed in a thermomechanical simulator, Thermec-master-Z, which is equipped to enable the simultaneous recording of the diametric and longitudinal length changes (strain), in addition to time, temperature and load data. The specimen was heated using a radio-frequency coil and the temperature was measured with Pt/Pt–10% Rh thermocouple spot welded to the sample. The temperature variation along the length of the sample was checked to be within 4–5 °C. The sample was heated to 1000 °C for 10 min for austenization in a vacuum chamber, then quenched using a helium jet to a temperature where lower bainite could form. For experiments involving an applied stress, a uniaxial compressive load was applied via silicon nitride discs, at the instant the sample reached the isothermal transformation temperature. The level of stress was chosen to be 700 MPa, in order to ensure a mechanical driving force which is large enough to influence cementite precipitation [9, 12]. The stress is certainly larger than the yield strength of the austenite, and this should affect the kinetics of bainite formation; however, this was not the prime purpose of the study and not a matter of concern, because the carbides grow from ferrite and not from the austenite.

Optical, scanning and transmission electron microscopy were all used to characterize the microstructures. Samples for SEM were ground, polished down to 1 μm and then examined using a *Camscan* 200 microscope operated at 20 kV. Thin foils were prepared by electropolishing discs in a mixture of 5% perchloric acid, 25% glycerol and 70% ethyl alcohol. The polishing potential was 55 V at a current of 20–30 mA, at a temperature of about −10 °C. The thin foils were examined using a Philips EM-400ST transmission electron microscope operated at 120 kV.

3. Results and discussion

3.1. Aligned microstructure

Typical electron micrographs, for specimens transformed with and without external applied stress (700 MPa), are shown in Fig. 2; the micrographs are longitudinal sections containing the stress axis, in the direction indicated.

These micrographs show the effect of the stress on the development of the bainitic microstructure. As expected [13, 14], the stress has caused a high degree of alignment of the bainite platelets, which tend to form close to the planes of maximum shear stress. These results are not in themselves unusual, because it is well known that the growth of bainite causes a change in the shape of the transformed region. This shape deformation is an invariant-plane strain with a large shear component, so that the transformation is expected to be sensitive to applied stress [15].

3.2. Carbide precipitation

The transmission electron micrographs discussed in this section are representative samples of quite extensive studies.

For the steel studied, the upper/lower transition temperature (LB_s) and martensite-start (M_s) were established metallographically to be 295 and 260 °C, respectively. Fig. 3 shows the lower bainitic microstructures obtained at two different transformation temperatures (295, 270 °C). There are a number of interesting features in Fig. 3 and other similar micrographs generated in the studies. Firstly, the carbide precipitates in any given plate of lower bainite could be found to be in a single orientation, or multi-variant. The intensity of the precipitation became larger, and the tendency to obtain several variants of carbide greater, as the transformation temperature was reduced. As discussed earlier, many variants are favoured when the carbon concentration is large (Fig. 1). The same applies when the transformation temperature is reduced, because less carbon then has an opportunity to partition into the austenite; this also explains the greater intensity of carbide precipitation as the transformation temperature is reduced.

Because the purpose of the work was to cause a change from a multi-variant precipitation morphology to a single variant, the transformation temperature was fixed in subsequent experiments at 270 °C, with identical austenitization conditions. The two examples illustrated in Fig. 4 show clearly that when lower bainite grows under the influence of a large enough stress, the number of variants of cementite to be found in any given plate of ferrite noticeably decreases.

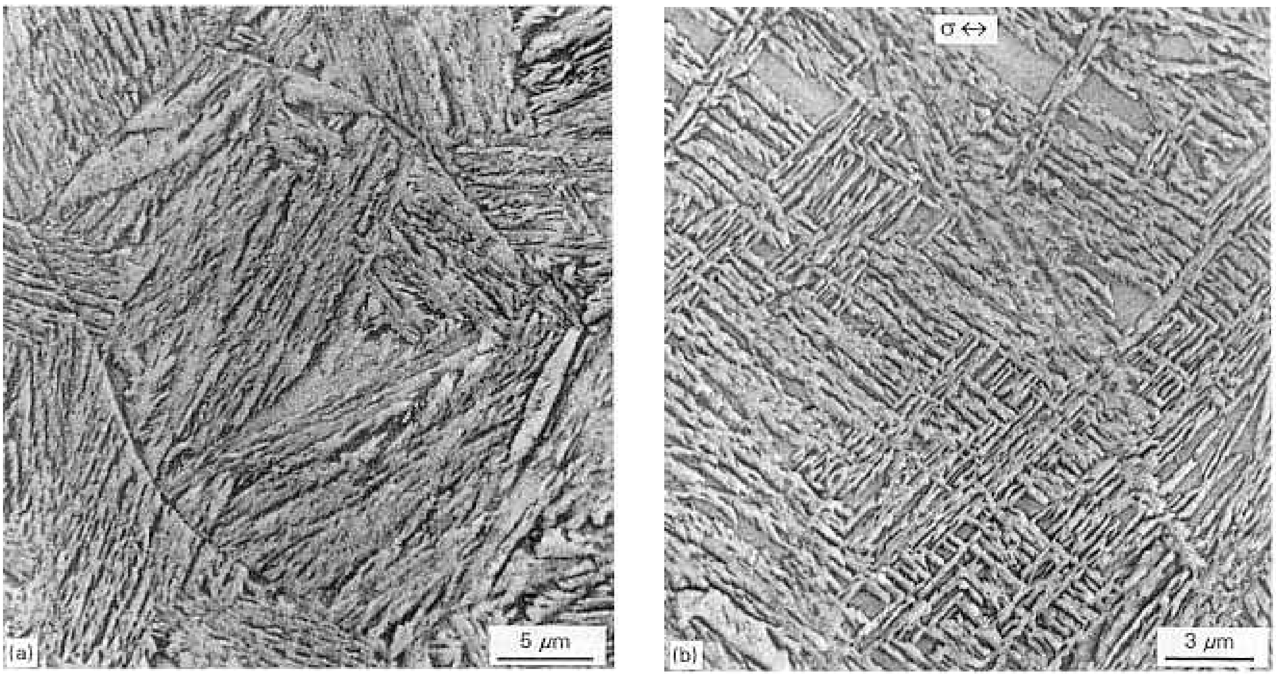

Figure 2 Scanning electron micrographs of samples austenitized at 1000 °C for 600 s, and isothermally transformed at 270 °C for 2500 s before quenching to ambient temperature. (a) Zero applied stress; (b) compressive stress of 700 MPa during transformation.

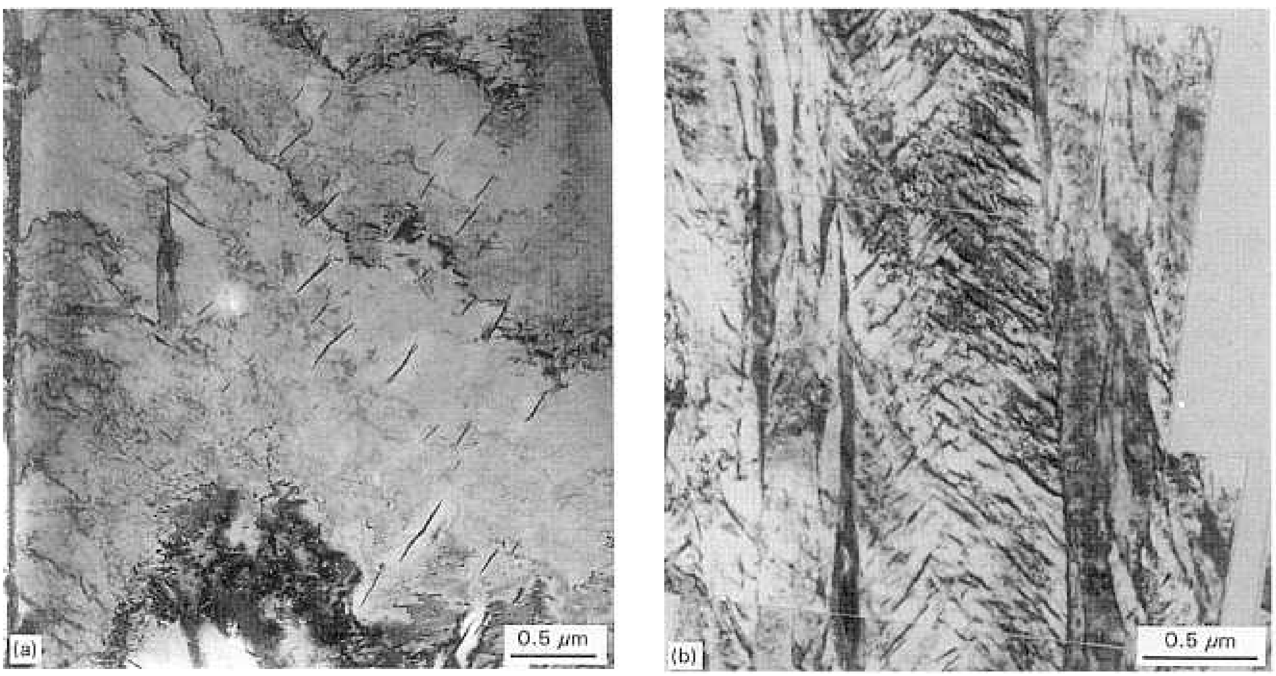

Figure 3 Transmission electron micrographs of lower bainite obtained by austenitization at 1000 °C for 600 s, followed by isothermal transformation at (a) 295 °C for 2500 s and (b) 270 °C for 2500 s. The samples were quenched to ambient temperature after transformation to bainite.

The results are all consistent with previous work on the proposed mechanism of cementite precipitation at low temperatures [16, 17]. They also support the hypothesis [18] that the single variant of carbide frequently observed in lower bainite is because the precipitation is influenced by the self-stress of the plate of bainite. This stress favours the growth of a particular variant over other less optimum orientations. It remains to measure directly the shape deformation due to cementite precipitation.

4. Conclusion

It has been demonstrated that it is possible to change a lower bainitic microstructure, in which each plate of bainite contains many orientations of cementite, into a classical microstructure in which the plate contains just one characteristic orientation. This can be achieved by growing the bainite under the influence of a uniaxial stress. The fact that the applied stress can cause such a change, is consistent with a mechanism in which the cementite particles grow by displacive

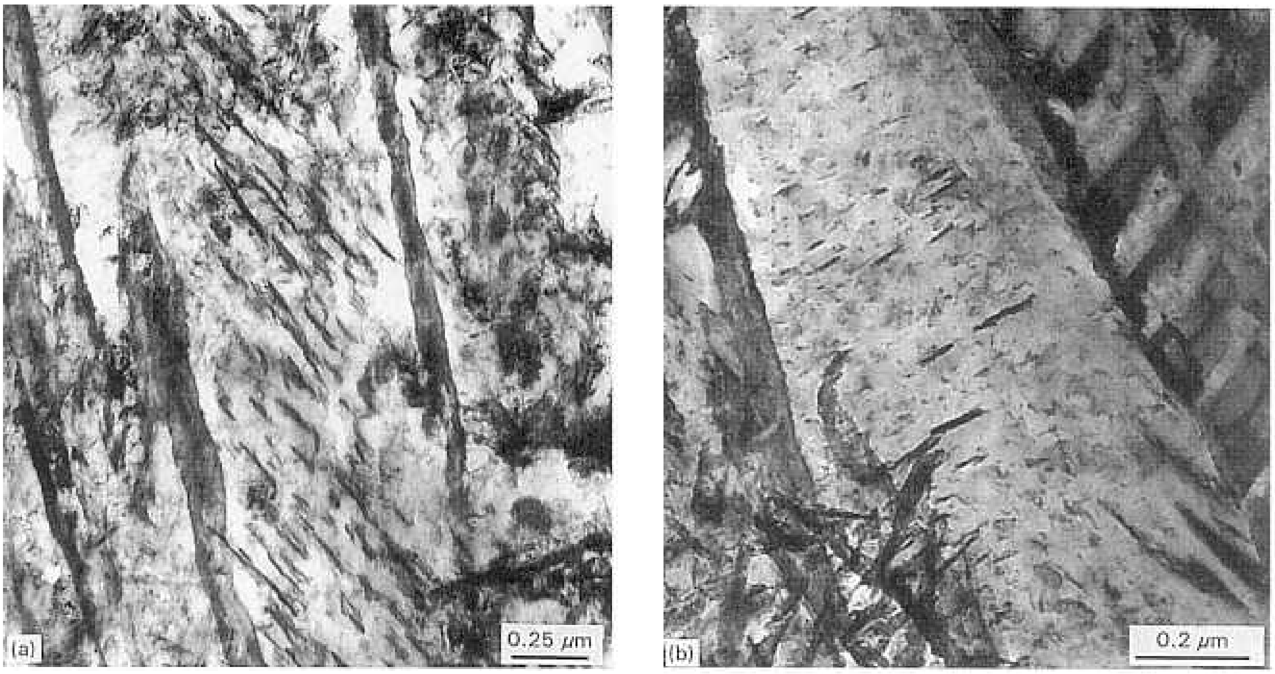

Figure 4 Two examples of lower bainite that has formed under the influence of a compressive stress of 700 MPa. Both cases show a clear tendency for the carbides to precipitate in a single orientation. These micrographs should be compared with Fig. 3b.

paraequilibrium transformation. It is likely that when, in the absence of an externally applied stress, lower bainite is found with a single variant of cementite, it is the self-stress of the ferrite plate which prevents the precipitation of many cementite variants.

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