Short Communication

Quantitative evidence for mechanical stabilisation of bainite

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Metallographic observations have in the past demonstrated conclusively that the bainite transformation is susceptible to mechanical stabilisation. This means that the growth of bainite can be hindered when the transformation occurs in austenite which is plastically deformed, although the rate of heterogeneous nucleation may be accelerated. In the present work we report dilatometric measurements to confirm the earlier metallographic observations and include an interpretation of the effect of prestrain on the martensite that forms from the carbon enriched residual austenite that remains after bainite. MST/3616

Introduction

Displacive phase transformations and mechanical twinning involve the coordinated movement of atoms during the glide of glissile interfaces. Such movements cannot be sustained against strong defects such as grain boundaries. Thus, martensite, bainite, or mechanical twin plates cannot cross grain boundaries. Defects such as dislocations also hinder the progress of any glissile interface in much the same way that ordinary slip is made more difficult by the presence of dislocation forests.

It follows that displacive transformations can be suppressed by prestraining the parent phase. This effect is known as 'mechanical stabilisation', first established for martensitic transformations where transformation can be hindered by prestraining the austenite. Similar observations have been reported for mechanical twinning in many metals,[1] and for the bainite transformation in steels.[2–10]

The detailed effect of prestrain on the bainite or martensite transformations is more complex than has been described above. Although the crystallographic discontinuities in the austenite, caused by prestrain, clearly interfere with the progress of plates of transformation products, the same discontinuities provide heterogeneous nucleation sites. There is therefore an enhancement of nucleation on defects but at the same time a hindrance to growth. Consequently, prestrain can lead to an acceleration of the bainite transformation though the fraction of bainite obtained may be reduced since each nucleated plate will grow to a smaller limiting size.

Effects like these were demonstrated metallographically and using hardness measurements for a bainitic steel.[2] The purpose of the present work was to confirm those observations using dilatometry, which monitors the progress of transformation as it happens.

Experimental

The alloy studied has the chemical composition (wt-%): Fe–0·12C–2·03Si–2·96Mn. The alloy contains a relatively large silicon concentration, which suppresses the precipitation of cementite from austenite.[3] Consequently, carbide free upper bainite can be obtained which consists of just bainitic ferrite and retained austenite, allowing the observation of transformation without interference from the secondary formation of carbides. The alloy also has sufficient hardenability to avoid the formation of other high temperature transformation products during heat treatment.

A number of cylindrical samples (8 mm dia., 12 mm length) were machined from the alloy after homogenisation at 1200°C for 2 days (while sealed in a quartz tube containing pure argon). The overall size of the sample is suitable for heat treatment in an adapted Thermecmaster Z simulator. Using this, the polished sample was heated by induction in a high vacuum (4×10^{-2} mbar), with a Pt–PtRh (type *R*) thermocouple attached to the centre of one of the curved sides. The samples were heated to 1200°C at 10 K s^{-1} and held there for 180 s before cooling to the deformation temperature. The sample was strained longitudinally at 1 s^{-1} to a predetermined value of the compressive strain. It was then cooled rapidly to a selected isothermal transformation temperature as illustrated in Fig. 1 using helium as the quenching gas. A number of deformation temperatures, strains and isothermal transformation temperatures were tested. The specimen was finally helium quenched to ambient temperature after the isothermal transformation to bainite.

The compressive plastic deformation of cylindrical samples tends to be inhomogeneous, as described elsewhere in detail.[2] The dilatometric data reported here represent changes in sample diameter due to the formation of bainite. They were measured using a laser transducer directed half way along the length of each sample. Different samples can therefore be compared, but the absolute magnitudes of the measured transformation
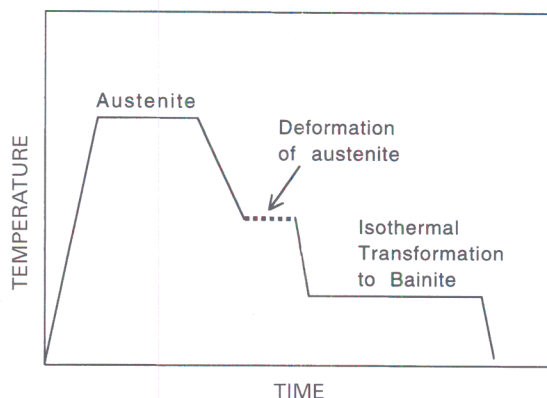
1 Schematic illustration of heat treatment and deformation schedule: all austenitisation heat treatments were carried out at 1200°C for 180 s
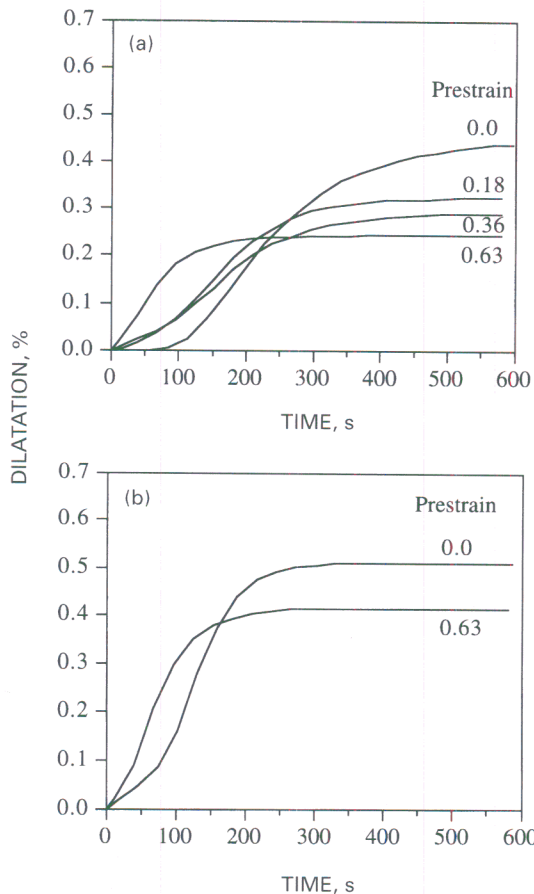
a during isothermal transformation at 475°C following prestrain at 700°C; b during isothermal transformation at 450°C following prestrain at 700°C
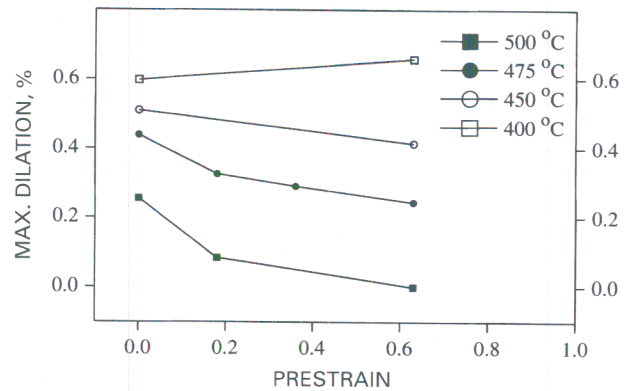
2   Change in radial dilatation during isothermal transformation to bainite as function of time and prestrain: values of prestrain are indicated next to individual curves

3   Maximum observed radial dilatation as function of prestrain and isothermal transformation temperature

strains reflect the average degree of transformation in the cross-section at half sample height.

Results and discussion

Figure 2 shows that the effect of prestrain is to accelerate the formation of bainite, but with a reduction in the total amount of transformation. This is because there is an increase in the nucleation rate but each nucleus leads to a smaller degree of transformation in plastically deformed austenite. Plates of bainite grow in clusters called sheaves. The growth of each platelet is accompanied by a change in the shape of the transformed region, a change which can be described as an invariant plane strain with a large shear component. Because bainite forms at relatively high temperatures, the invariant plane strain causes plastic deformation in the adjacent austenite.[11] The resulting local increase in dislocation density stifles the growth of the bainite plate, so that each plate only achieves a limited size which is much less than the size of the austenite grain. Prestraining has the effect of reducing this limiting size even further, so that the total amount of bainite can be reduced even though the nucleation rate might be increased.

The results illustrated in Fig. 2b are from experiments at a lower isothermal transformation temperature. The driving force for bainitic transformation is therefore larger, so it is not surprising that the maximum extent of transformation

observed is larger for both levels of strain. Metallographic studies were conducted to supplement the dilatometric data but are not reported here since the trends are exactly the same as reported previously.[2]

Further data are summarised in Fig. 3. Prestrain is seen to have a much lower effect at lower transformation temperatures, because of the larger driving force available for the growth of bainite. Indeed, for transformation at 400°C, it is evident that the increase in nucleation rate caused by prestrain overrides the decrease in plate size so that the net extent of transformation is increased in deformed austenite. At all other bainite formation temperatures, the extent of reaction clearly decreases with increasing prestrain, though the changes observed are smaller as the isothermal transformation temperature is reduced.

It was possible for the higher bainite transformation temperatures to measure the martensite start M_s of the residual austenite (i.e. the carbon enriched austenite that is not transformed to bainite), as the samples cooled to ambient temperature. The M_s temperature in the present circumstances depends on two factors: the change in the carbon concentration caused by the formation of bainite and the effect of prestrain with respect to mechanical stabilisation of both bainite and martensite.

As expected, Fig. 4 shows that in all cases, the measured M_s temperature is reduced relative to the sample without any bainite or prestrain. Prestrain initially causes an increase in the M_s of the residual austenite as the extent of bainitic transformation is reduced (Fig. 2). However, it then decreases with increasing prestrain because the martensite itself will become mechanically stabilised.
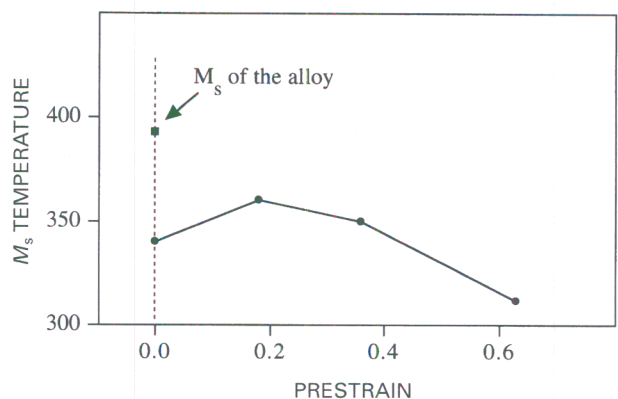
4   Measured martensite start M_s temperature of austenite left untransformed after formation of bainite at 475°C as function of prestrain

Conclusions

Consistent with published data, it is found that bainite is mechanically stabilised by plastically deforming the austenite. The plastic deformation accelerates the formation of bainite by enhancing the nucleation rate, but each nucleus then transforms to a smaller amount of bainite so that the overall extent of transformation can be reduced. The martensite that forms from the carbon enriched austenite after bainite is also mechanically stabilised by prestrain.

Acknowledgements

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