# Mechanical stabilisation of eutectoid steel

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Martensitic transformation involves the translation of a glissile interface, whose motion can be retarded by defects introduced into the parent austenite. Quantitative measurements of this process of mechanical stabilisation in a eutectoid steel have been compared successfully against a recent theory for the phenomenon.

**Keywords:** Mechanical stabilisation, Interface, Martensite, Dilatometry, Dislocations

## Introduction

Displacive transformations involve the coordinated movement of atoms. Such movements cannot be sustained against strong defects such as grain boundaries. Thus, martensite plates do not traverse austenite grain boundaries. Defects such as dislocations also hinder the translation of the martensite/austenite interface. It has been known for some time that the plastic deformation of austenite before its transformation retards the growth of martensite, a phenomenon known as mechanical stabilisation.[1–5] This can be expressed quantitatively by balancing the force driving the transformation interface against the resistance from dislocation debris in the austenite.[6] Eutectoid steels, particularly in wire form, often involve transformation from deformed austenite. In the present work, the authors examine both experimentally and theoretically, the extent of mechanical stabilisation with respect to martensitic transformation in a eutectoid steel.

## Experimental

The chemical composition of the steel studied is 0·75C–1·02Mn–0·28Si–0·11Cr–0·05Ni–0·015S–0·009P–0·08Cu (wt-%).

A Gleeble–1500 thermomechanical simulator was used for the experiments. Two cylindrical samples, 12 mm diameter and 110 mm length, were machined for thermomechanical simulation using a Gleeble–1500. They were heated at a rate of 100K $\mathrm{s}^{-1}$ to 1100°C and were kept for 1 s before allowing them to cool. In one case, the sample was deformed in compression along the longitudinal direction, within the range 1000–900°C at constant load (120 MPa stress at the beginning of deformation), the strain being implemented within 3 s. The samples were then cooled to produce martensite when the change in diameter was monitored; the cooling period between 800 and 500°C was 8 s.

Compressive deformation can be heterogeneous. A finite element analysis using the commercial software DEFORM was performed as illustrated in Fig. 1, showing a variation in effective strain of between 0·4 and 1 along the horizontal centreline.

Dilatometric data presented in Fig. 2 reveal two effects. The martensite start temperature $M_S$ of the deformed austenite is depressed by ~10°C. Second, the temperature range over which martensite forms is greater for the deformed austenite. These observations should in principle be explained by the theory of mechanical stabilisation[6] as explained in the following section.

## Analysis

The theory for mechanical stabilisation relies on balancing the force required to move the austenite/martensite interface through a forest of dislocations, against the force owing to the chemical free energy change $\Delta G^{\gamma\alpha}$ driving the interface[6]

$$\frac{\mu b \rho^{1/2}}{8\pi(1-v)} = \Delta G^{\gamma\alpha} \tag{1}$$

where $b=0{\cdot}252$ nm is the magnitude of the Burgers vector, $\mu=8\times10$ Pa is the shear modulus of the austenite, $v=0{\cdot}27$ is its Poisson's ratio and $\rho$ is the dislocation density.

$\Delta G^{\gamma\alpha}$ for transformation without a composition change was calculated using MTDATA.[7] For the steel used, this gives

$$\begin{aligned} &\Delta G^{\gamma\alpha} = 7.0337T - 5218\ \mathrm{J\,mol^{-1}} \\ &\text{or}\quad \Delta(\Delta G^{\gamma\alpha}) \equiv 7.0337\Delta T \end{aligned} \tag{2}$$

where $T$ is the absolute temperature and the equation applies over the range 450–510 K. The deformed and undeformed samples transform at different temperatures, i.e. at different driving forces, so that

$$\Delta(\Delta G^{\gamma\alpha}) = \Delta G^{\gamma\alpha}_{235\,^\circ\mathrm{C}} - \Delta G^{\gamma\alpha}_{225\,^\circ\mathrm{C}} = 70\ \mathrm{J\,mol^{-1}}$$

where $\Delta(\Delta G^{\gamma\alpha})$ is the magnitude of the change in available driving force owing to the presence of dislocations in the austenite, and $\Delta T$ is the corresponding reduction in $M_S$ temperature.

Using equation (1), the following can be obtained

$$\frac{\mu b}{8\pi(1-v)}\left[\rho^{1/2} - \rho_0^{1/2}\right] = \Delta(\Delta G^{\gamma\alpha}) \equiv 7{\cdot}0337\Delta T \tag{3}$$

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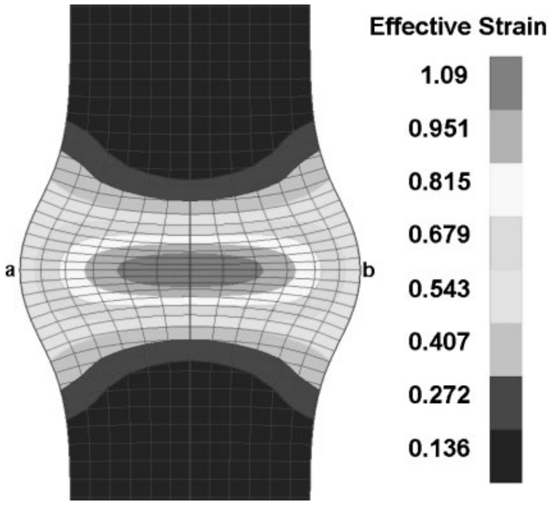


**1 Strain distribution calculated as described in text: effective strain is calculated using von Mises criterion; dimensional changes during transformation were measured along horizontal line ab**

The dislocation density $\rho$ has a value $\rho_0$ at zero plastic strain.

It follows that the depression of transformation temperature can be calculated as a function of the change in the dislocation density of the austenite. However, it would be useful to be able to estimate the change in $M_S$ as a function of plastic strain rather than dislocation density. It is necessary therefore to derive a relationship between plastic strain $\varepsilon$ and dislocation density. Such a relationship will necessarily be approximate, so two alternative methods were attempted. The first is labelled empirical since it relies on measurements carried out on different steels, and the second physical because it begins with an assumption about stored energy.

For the empirical method, data from[8] are used to obtain

$$\rho = \underbrace{2\times10^{13}}_{\rho_0} + 2\times10^{14}\varepsilon \qquad \mathrm{m}^{-2} \tag{4}$$

In the alternative approach it is assumed that only 5% of the plastic work is stored in the material, both owing to changes in the austenite grain surface per unit volume, $\Delta S_V$, and owing to the expected change in dislocation density. By balancing the plastic work stored against the energy of defects created, the following can be obtained

$$0{\cdot}05\sigma_y\varepsilon \simeq \sigma_{\gamma\gamma}\Delta S_V + \phi\Delta\rho \tag{5}$$

where $\sigma_y$ is the yield stress of austenite (measured to be 30 MPa at 1000°C), $\sigma_{\gamma\gamma}$ is the austenite grain boundary energy per unit area, taken to be 0·6 J $\mathrm{m}^{-2}$ (Ref. 9) and $\phi \simeq 0{\cdot}5\mu b^2$ is the dislocation energy per unit length.

For axisymmetic compression[10]

$$\frac{S_V}{S_{V_0}} = \frac{\left(8e^{\varepsilon}+4e^{-2\varepsilon}\right)^{1/2} + 1/3\left[e^{-\varepsilon}+2(e^{\varepsilon})^{1/2}\right]}{1+2(3)^{1/2}} \tag{6}$$

The value of $S_V$ at zero deformation is given by $S_{V_0} = 2/d_\gamma$, where $d_\gamma = 26\pm3$ μm is the mean lineal intercept defining the austenite grain size.

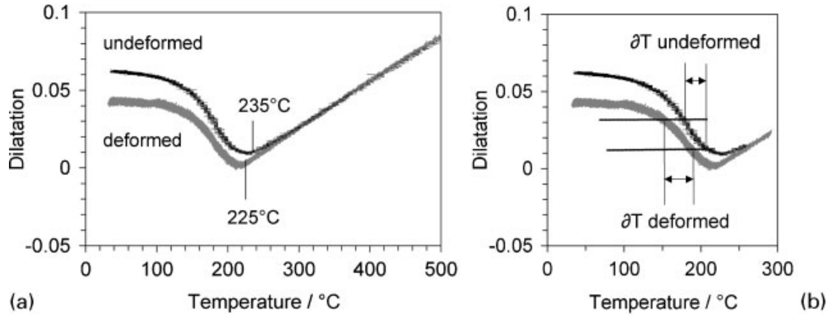
The stored energy owing to deformation is simply calculated using the term on the left hand side of equation (5). Removing the component owing to the change in $S_V$ (equation (6)) from equation (5) gives the change in dislocation density.

In the plastically deformed sample, transformation is expected to begin at the point which has undergone the smallest plastic strain, i.e., 0·4 (line ab in Fig. 1). The predicted depression in the martensite start temperature using equations (3)–(5) is shown in Fig. 3. The calculated values compare well with the measured value.

The fact that the sample does not deform homogeneously has a consequence which is reflected in the measurements. The effective strain within the region of measurement varies from 0·4 to 1·0 (Fig. 1). Calculations using this range of strains show that the $M_S$ temperature should vary as a function of position, from 225°C at the surface to ~217°C in the centre of the sample (Fig. 3). The transformation therefore occurs over a greater range of temperatures when compared with the undeformed specimen, as shown in Fig. 2*b*.

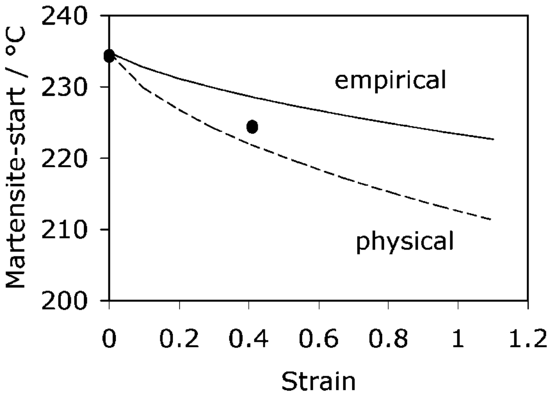
## Summary

It has been demonstrated that the change in martensite start temperature when the phase grows in deformed austenite can be estimated quantitatively using the theory of mechanical stabilisation, in which the chemical free energy change driving the transformation front is opposed by the resistance to interface motion from deformation defects. An interesting outcome is that the range over which martensite forms is extended when the deformation in the austenite is heterogeneous.



***a*** **depression of** $M_S$ **when martensite forms in deformed austenite;** ***b*** **increased temperature range over which transformation occurs in deformed sample**

**2 Dilatometric data**



**3 Calculated changes in $M_S$ as function of plastic strain in austenite before its transformation**

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