Stability of retained austenite in TRIP-assisted steels

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A theory is developed for the quantitative representation of the strain induced transformation of retained austenite in low alloy, TRIP-assisted steels of the type developed for the automobile industry. It is possible, therefore, to calculate the fraction of austenite as a function of the plastic strain, chemical composition, deformation temperature and the starting amount of austenite. The effect of composition and temperature is expressed through the free energy available for transformation. Good agreement has been obtained with published experimental data. The model can be used to investigate the stability of the austenite during plastic deformation.   **MST/5936**

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Introduction

The weight of an automobile can be reduced by using high strength steels as long as they have the ductility essential in metal forming operations.[1-3] One class of suitable alloys is known as the TRIP-assisted steels, in which the microstructure is frequently a mixture of allotriomorphic ferrite, bainitic ferrite and retained austenite; the term TRIP stands for transformation induced plasticity. The typical chemical composition is $Fe-0.15C-1.5Si-1.5Mn$ (wt-%); the silicon concentration is kept sufficiently high to ensure that cementite is not precipitated during the early stages of bainite formation. The carbon that is partitioned from bainitic ferrite stabilises the residual austenite, enabling it to be retained at ambient temperature. The final microstructure typically contains 20% bainitic ferrite, 10% retained austenite with the remainder being allotriomorphic ferrite.

There have been many publications on the microstructure – property relationships of TRIP-assisted steels. Most of these studies highlight the role of the retained austenite in achieving the required strength and formability. During plastic deformation the austenite tends to transform into martensite. This leads to the redistribution of stresses and a composite effect,[4,5] which is associated with the observed high uniform elongation.[6] The actual transformation strain as martensite forms is much smaller than the observed elongation so that the TRIP effect *per se* has only a minor role in determining the uniform elongation.[7]

The strain induced decomposition of austenite has therefore long been recognised to be important in contributing to the properties of TRIP-assisted steels. The fraction of retained austenite V_γ as a function of plastic strain ε is generally represented by the equation

$$\ln V_\gamma^o - \ln V_\gamma = k\varepsilon \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where V_γ^o is the fraction at zero strain. The constant k is derived by fitting to experimental data, which means that the equation has limited applicability since the chemical composition and test temperature are not explicitly included in the analysis. The purpose of the present work was to develop a more general theory in which the chemical composition of the austenite and the deformation temperature are accounted for, thereby allowing predictions to be made.

Theory

We begin by suggesting how the equation (1) might be derived. If the change in the fraction of martensite $dV_{\alpha'}$ for a given increment of strain $d\varepsilon$ is assumed to be proportional to the fraction of remaining austenite

$$\frac{dV_{\alpha'}}{d\varepsilon} = kV_\gamma \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

then since $V_{\alpha'} = V_\gamma^o - V_\gamma$, integration of equation (2) gives

$$\ln V_\gamma^o - \ln V_\gamma = k\varepsilon$$

This equation has been applied widely for the transformation of austenite during deformation above the martensite start temperature. In order for it to be more generally applicable, it is necessary to express k as a function of the chemical composition of the austenite and of the deformation temperature. It is obvious that anything which stabilises the austenite, e.g. higher concentrations of elements such as Mn, C, or deformation at higher temperatures, must make it more resistant to plastic strain. Both of these effects are inherent in the chemical free energy change $\Delta G^{\gamma\alpha'} = G^{\alpha'} - G^\gamma$ for the transformation of austenite to ferrite of the same composition (without considering stored energy due to the shape deformation). This quantity is negative for transformation to be possible, and its magnitude is henceforth written $\Delta G^{\alpha'\gamma} = -\Delta G^{\gamma\alpha'}$. A larger value of $\Delta G^{\alpha'\gamma}$ makes it easier to form martensite. The simplest assumption is to assume that k is proportional to the driving force
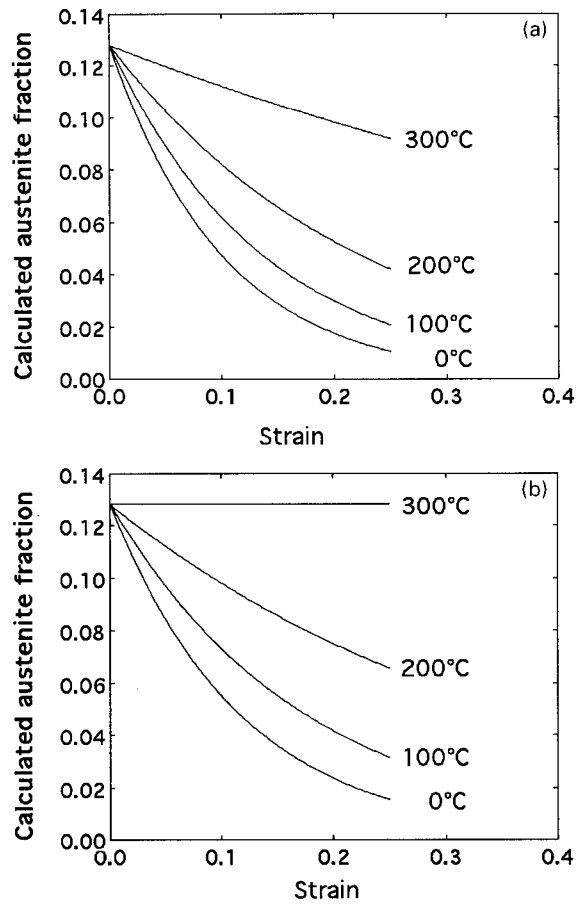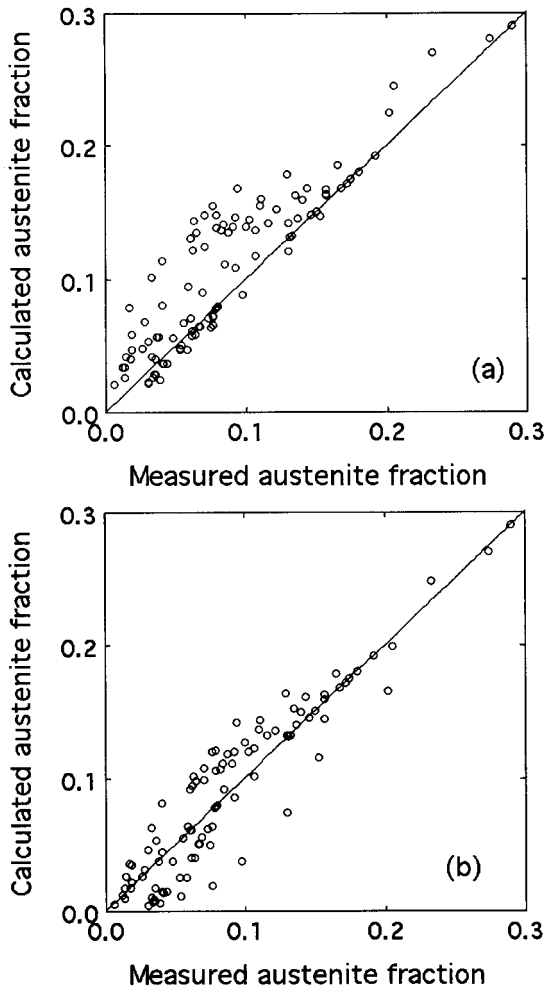
$$k = k_1 \Delta G^{\alpha'\gamma}$$

so that

$$\ln V_\gamma^o - \ln V_\gamma = k_1 \Delta G^{\alpha'\gamma}\varepsilon \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

To test this, experimental data were collected from the published literature;[6,8-13] in each case, the $\Delta G^{\alpha'\gamma}$ ($J\ mol^{-1}$) values were calculated for the stated chemical composition of the retained austenite and the deformation temperature. The free energy calculations were carried out using MTDATA with the NPL-plus database for steels.[14] The concentration and temperature ranges covered by the published data are given in Table 1.

It was possible, by plotting all the accumulated values of $\ln V_\gamma^o - \ln V_\gamma$ versus $\Delta G^{\alpha'\gamma}\varepsilon$ to obtain a best fit value of $k_1 = 0.002017\ mol\ J^{-1}$. Figure 1*a* compares the predicted and measured values of retained austenite for the entire dataset. The extent of agreement is reasonable given the range of compositions and temperatures involved, but the theory seems to consistently overestimate the austenite content.

The difficulty arises from the fact that all the steels were analysed in a single dataset; alloys associated with larger

a analysis based on $k_1 = 0.002017$ mol J^{-1}, correlation coefficient is 0.91, standard error 0.026; *b* analysis based on $k_1 = 0.00446$ mol J^{-1}, correlation coefficient 0.93, standard error 0.023

1 Plot of the predicted versus measured values of retained austenite, using equation (3): line represents ideal case, where measured and calculated values are identical; dataset in each case consists of some 97 points

a 0.5 wt-%Mn; *b* 2.5 wt-%Mn

2 Example calculations using equation (5) and $k_1 = 0.00446$ mol J^{-1} for steel of base composition Fe–Mn–2Si and $C_\gamma = 1.2$ wt-% with $V_\gamma^o = 0.1282$

quantities of data would therefore bias the value of k_1. To avoid this, individual steels were analysed in isolation to obtain several values of k_1, and the average of these (i.e. $k_1 = 0.00446$ mol J^{-1}) was found to give much better results, as illustrated in Fig. 1*b*. This procedure gives equal prominence to each experiment and therefore leads to a better representation of the bigger picture.

Some example calculations are illustrated in Fig. 2, which shows that either increasing the manganese content, or raising the temperature, makes it more difficult to transform austenite by deformation. In the case of the 2.5 wt-%Mn alloy, deformation at 300°C fails to produce transformation. The methodology has therefore been able to predict the M_d temperature[15] beyond which it is impossible to induce martensitic transformation by stress or strain.

Notice that these effects of composition and temperature are included via the free energy $\Delta G^{\alpha'\gamma}$; thus, to study the

effect of an alloying element which has not been investigated experimentally (for example, cobalt), simply involves the application of MTDATA to calculate the free energy.

Finally, it is interesting to note that Pyshmintsev *et al.*[16] used the equation

$$\ln V_\gamma^o - \ln V_\gamma = (k - \beta P)\varepsilon$$

in representing the effect of hydrostatic stress on the strain induced transformation of austenite in TRIP assisted steels, where β is an empirical constant and P is the hydrostatic compression. It is well known that the effect of hydrostatic compression is to oppose martensitic transformation (which leads to a volume expansion). Thus, the free energy of transformation at ambient pressure, is modified[2] to $\Delta G^{\gamma\alpha'}\{1\}$ as

$$\Delta G^{\gamma\alpha'}\{P\} - \Delta G^{\gamma\alpha'}\{1\} = \int_1^P \Delta V_m dP'$$

where ΔV_m is the change in molar volume on transformation, equivalent to the term β if it is a constant over the pressure range of interest. The equation used by Pyshmintsev *et al.* is therefore equivalent to the present approach (equation (3)) with $\Delta G^{\gamma\alpha'}$ altered by the pressure.

Table 1 Composition range (wt-%) of steels analysed: C_γ is measured carbon concentration of retained austenite, whereas $\bar{C}$ is average carbon concentration in steel: sources of data described in main body of paper

C_γ	$\bar{C}$	Mn	Si	Cr	Ni	T, K
0.73–1.83	0.13–0.60	0.80–1.66	0.38–2.00	0–0.17	0–0.16	293–423

Alternative model

It has been proposed that strain induced martensite is stimulated by introducing martensite nucleation sites.[17,18] Each nucleus then transforms into a plate of martensite of a specified volume $\bar{V}$. Autocatalysis is also possible, in which the formation of one plate stimulates others, but this is normally taken into account using a constant autocatalysis factor. The importance of $\bar{V}$ in the present work is that the thickness of a plate is known to decrease when $\Delta G^{\alpha'\gamma}$ increases.[19] The practical effect is that the volume per plate will decrease at large driving forces, thereby leaving more austenite untransformed. This variation in plate volume has not been taken into account in equation (3).

The relationship between plate thickness and $\Delta G^{\alpha'\gamma}$ is almost linear,[19] and hence can be described using an equation of the form

$$\bar{V} = \bar{V}_0 + \frac{\partial \bar{V}}{\partial(\Delta G^{\alpha\gamma})} \Delta G^{\alpha\gamma} \quad \ldots \ldots \ldots \quad (4)$$

where $\bar{V}_0$ and $\partial \bar{V}/\partial(\Delta G^{\alpha'\gamma})$ are constants. Since the effect of strain within equation (3) will be proportional to $\bar{V}$, a more general expression of the stability of retained austenite should be

$$\ln V_{\gamma}^{\circ} - \ln V_{\gamma} = k_2 \bar{V} \Delta G^{\alpha\gamma} \varepsilon$$
$$\equiv k_2 \left[\bar{V}_0 + \frac{\partial \bar{V}}{\partial(\Delta G^{\alpha\gamma})} \Delta G^{\alpha\gamma} \right] \Delta G^{\alpha\gamma} \varepsilon$$
$$= \phi \varepsilon \quad (5)$$

where

$$\phi = \left[k_2 \bar{V}_0 \Delta G^{\alpha\gamma} + k_2 \frac{\partial \bar{V}}{\partial(\Delta G^{\alpha\gamma})} (\Delta G^{\alpha\gamma})^2 \right]$$

For a given alloy i and test temperature, a plot of $\ln V_{\gamma}^{\circ} - \ln V_{\gamma}$ versus ε gives a value of ϕ_i. Using all the values of ϕ_i, and corresponding values of $\Delta G_i^{\alpha'\gamma}$, the linear equation

$$\frac{\phi_i}{\Delta G_i^{\alpha\gamma}} = k_2 \bar{V}_0 + k_2 \frac{\partial \bar{V}}{\partial \Delta G^{\alpha\gamma}} \Delta G_i^{\alpha\gamma}$$
$$= k_3 + k_4 \Delta G_i^{\alpha\gamma}$$

was solved to give $k_3 = 0.008478$ mol J^{-1} and $k_4 = -2.42 \times 10^{-6}$ mol J^{-1}, so that all the unknowns in equation (5) are solved. Predictions made using this equation are shown to be in excellent agreement with the experimental data, as shown in Fig. 3. However, it is important to emphasise that this alternative model, although it indicates the role of martensite plate size, is limited to $\Delta G_i^{\alpha'\gamma}$ values less than about 2500 J mol^{-1} because the relationship described in equation (4) is essentially empirical.

We would in general recommend the simpler model described by equation (3), given that the standard error of the analysis is probably comparable with the experimental error in measuring retained austenite content using X-ray diffraction. It is likely that all the alloys studied are not chemically homogeneous and will typically contain manganese segregation. This will add to the uncertainties in measured data, reinforcing the case that a simple analysis that gives a realistic scatter in the predictions is probably justified.

Conclusions

With the assumption that the increment of martensite per unit plastic strain is proportional to the fraction of austenite and to the volume per plate of martensite, it has been possible to develop a quantitative theory for the strain
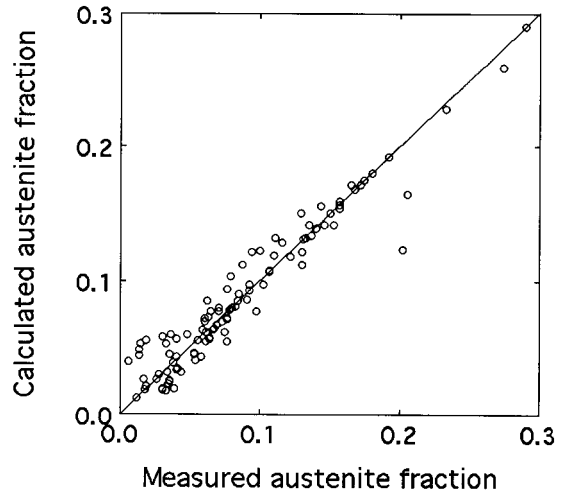
3 Plot of predicted versus measured values of retained austenite, using equation (5): correlation coefficient is 0.96 with standard error ± 0.015; line represents ideal case, where measured and calculated values are identical

induced transformation of retained austenite in a class of TRIP-assisted steels destined for the automobile industry.

The models allow the progress of austenite transformation to be followed as a function of the plastic strain, chemical composition and the temperature at which the deformation is carried out. The effect of the latter two variables is expressed through the chemical driving force for transformation, which has been introduced into a simple equation for strain induced transformation.

Acknowledgements

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