Transformation induced plasticity assisted steels: stress or strain affected martensitic transformation?

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Transformation induced plasticity (TRIP) assisted steels contain a small quantity of carbon enriched retained austenite, which transforms into martensite during the course of plastic deformation. Transformation of this kind can be induced by both stress and plastic strain. The detailed mechanism by which the martensite is induced is different for these two scenarios. An attempt is made here to discover the relative importance of these mechanisms and it is found that stress affected transformation can explain much of the variation in retained austenite content as a function of plastic strain.

Keywords: TRIP, Transformation plasticity, Martensite, Stress affected transformation, Strain induced transformation

Introduction

Transformation induced plasticity (TRIP) assisted steels have a microstructure in which the major phase is allotriomorphic ferrite, with the residue consisting of a mixture of bainitic ferrite and carbon enriched retained austenite.[1–11] The quantity of retained austenite is usually in the range 10–20 vol.-% and it transforms into martensite during the course of plastic deformation. This enhances both the strength and ductility of the steel so the phenomenon is important to understand.

Most investigations into TRIP assisted steels are based on tensile tests involving large plastic strains. It seems reasonable therefore to assume that the martensite that forms is strain induced. In this mechanism, the dislocations introduced in the austenite during plastic deformation assist in the nucleation of martensite.[12] In contrast, stress affected transformation occurs because the interaction of the applied stress with the shape deformation of martensite contributes a mechanical component ΔG_{mech} to the free energy change driving the transformation.[13] It is not straightforward to decide on the dominant mechanism because of the following reasons:

(i) it has been demonstrated that the carbon enriched retained austenite is in fact the hardest phase in the microstructure.[14–16] The austenite is therefore elastically loaded for a large portion of the overall deformation strain

(ii) dislocation debris accumulating in the austenite can retard or prevent martensitic transformation by a phenomenon known as mechanical stabilisation, in which the debris interferes with the translation of the transformation front. The phenomenon has recently been expressed theoretically.[17] An important outcome of this work is that the critical value of the plastic strain required to suppress martensitic transformation becomes smaller as the austenite becomes more stable, as is the case for carbon enriched austenite

(iii) the yield strength of the retained austenite is typically in excess of 800 MPa.[14,16] ΔG_{mech}, which is the quantity that expresses the tendency for stress induced transformation, should therefore be large before the austenite starts to undergo permanent deformation.

The purpose of the present work was to quantitatively investigate the roles of stress and strain induced martensitic transformation of the retained austenite in TRIP assisted steels. The authors begin by calculating the critical strain ε_c required to suppress martensitic transformation.

Critical plastic strain

The dislocation density created during the plastic deformation of austenite interferes with the motion of the glissile austenite/martensite interface. A strain ε_c is eventually reached where this resistance to interface motion becomes equal to the force driving the interface, bringing the latter to a halt[17]

$$b\Delta G=\frac{1}{8\pi(1-\nu)}Gb^{3/2}\left(\frac{\varepsilon_c}{L}\right)^{1/2}+\tau_s b \tag{1}$$

where b (=0·252 nm) is the Burgers vector, ν (=0·27) the Poisson's ratio, G (=8×10^{10} Pa) the shear modulus of austenite, L a parameter related to the austenite grain, ΔG the free energy change driving the interface and τ_s the resistance to interface motion due to solid solution hardening. The last two quantities can be calculated given the composition of the austenite.

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Published by Maney on behalf of the Institute
Received 19 December 2006; accepted 5 February 2007
DOI 10.1179/174328407X226536

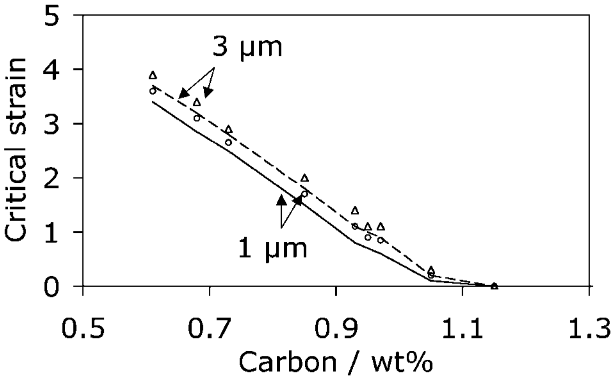
Although the carbon concentration of the austenite is usually reported in experimental studies of TRIP assisted steels, its substitutional solute concentration is rarely reported. The steel is usually produced by intercritical annealing to generate a mixture of allotriomorphic ferrite α and austenite γ, followed by the partial lower temperature transformation of the latter phase into a mixture of bainitic ferrite α_b and carbon enriched retained austenite γ_r. The intercritical anneal can in principle lead to the partitioning of all solutes between the α and γ phases. It is impossible to calculate this partitioning but its upper and lower limits are defined by equilibrium and paraequilibrium respectively, between the α and γ phases.

Several complete sets of experimental data suitable for analysis, including the carbon concentration of the retained austenite, are available in the literature.[18–21] The steel compositions are listed in Table 1. For these cases, MT-DATA[22] with the SGTE database was used to calculate the equilibrium and paraequilibrium states at the reported intercritical annealing temperature. Calculations for the alloys studied in Refs. 18 and 19 are listed in Table 2, which shows that the concentrations for the equilibrium and paraequilibrium cases are not substantially different. The analysis indicated that one of the alloys[21] was fully austenitic at the intercritical annealing temperature; although inconsistent with experimental data, the retained austenite in this particular case contained a very large concentration of carbon (1·473 wt-%). As will be seen later, in this circumstance, the partitioning of substitutional solutes does not affect the conclusions and their concentrations were assumed to be the average values in the alloy. Tomita and Morioka's[20] alloy was heat treated into a fully austenitic condition before the formation of bainite.

The thermodynamic driving force ΔG_{chem} for transformation of the retained austenite to martensite was calculated using MT-DATA for each of the austenite composition as determined above. The free energies obtained from MT-DATA were reduced by 600 J mol^{-1} to account for the stored energy of martensite.[23] The grain size of retained austenite in these steels is reported to be about 1–3 μm. Figure 1 shows the values of ε_c plotted as a function of the carbon concentration of the austenite. It is evident that significant strain induced martensitic transformation is unlikely when the carbon concentration exceeds ~1·1 wt-%.

Table 1 **Chemical composition of steels used for present calculations, wt-%**

Reference	C	Si	Mn	S	P	Al
18	0·14	1·94	1·66	0·015	0·008	0·025
19	0·13	1·5	1·42	0·009	0·013	2·22
19	0·16	0·3	1·3	0·012	0·013	0·027
20	0·6	1·52	0·8			
21	0·4	1·5	1·5	0·002	0·015	0·036



1 Plot of ε_c versus carbon concentration of retained austenite: lines were calculated using ΔG assuming equilibrium and points assume paraequilibrium; continuous line and circular points are for austenite grain size of 1 μm, dashed line and triangles for grain size of 3 μm; calculations are for retained austenite carbon concentrations reported in Refs. 18–21 and 24

Stress affected transformation

The interaction of an external stress with the shear s and dilatational strains δ of the shape deformation of martensite adds a mechanical component ΔG_{mech} to the total driving force as follows[13]

$$\Delta G_{\mathrm{mech}} = \sigma_{\mathrm{n}}\delta + \tau s \tag{2}$$

where σ_{n} is the normal component of the applied stress on the martensite habit plane and τ is the shear component of the applied stress σ, resolved along the direction of the shear displacement of the shape deformation. For uniaxial loading, the ΔG_{mech} per MPa is ~0·86 J mol^{-1} (Ref. 25). Given the value of the applied stress, ΔG_{mech} can be added to the chemical term calculated using MT-DATA after removing the 600 J mol^{-1} of strain energy to give the total free energy change ΔG.

Figure 2 illustrates ΔG for martensitic transformation in austenite of the composition Fe–1C–2Mn–2Si (wt-%) for three levels of uniaxial tensile stress. It is estimated from this that the increase in M_s per unit of tensile stress is ~0·1375 K.

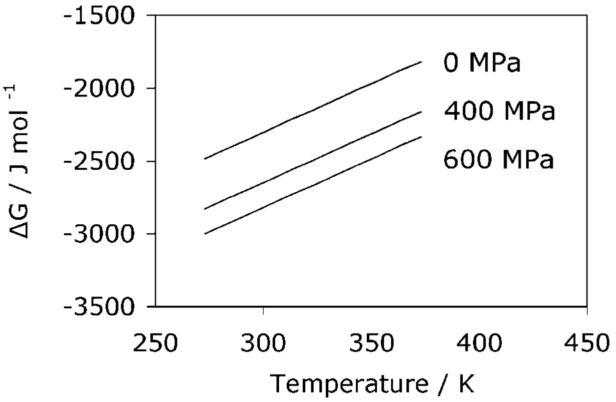
The effect of uniaxial stress is therefore to increase the martensite start temperature M_s. Stress induced martensite occurs when M_s exceeds the temperature at which deformation is carried out, usually the ambient temperature. The fraction $V_{\alpha'}$ of martensitic transformation can be estimated using[26]

$$1 - V_{\alpha'} = \exp[-\phi(M_s - T)] \tag{3}$$

where T is a temperature below M_s and ϕ=0·011 (Ref. 26). To utilise this equation, it is necessary to know the M_s. Table 3 lists data reported by Jacques *et al.*[24] Because the M_s of the retained austenite was not

Table 2 **Calculated composition of austenite at intercritical annealing temperatures and steel compositions reported in Refs. 18 and 19, wt-%**

Reference	Condition	C	Si	Mn	S	P	Al
18	Paraequilibrium	0·2	1·92	1·65	0·015	0·008	0·025
	Equilibrium	0·23	1·81	2·10	0·017	0·005	0·019
19	Paraequilibrium	0·44	1·5	1·4	0·009	0·013	0·027
	Equilibrium	0·42	1·3	2·5	0·013	0·005	0·016
19	Paraequilibrium	0·38	1·4	1·65	0·008	0·013	0·027
	Equilibrium	0·37	1·5	2·3	0·012	0·006	0·016
19	Paraequilibrium	0·5	0·53	1·8	0·017	0·018	0·04
	Equilibrium	0·5	0·32	2·5	0·018	0·005	0·02



2 Total driving force for austenite to martensite transformation for Fe–1C–2Mn–2Si austenite at different stress levels: note that 600 J mol^{-1} of strain energy is not deducted from data

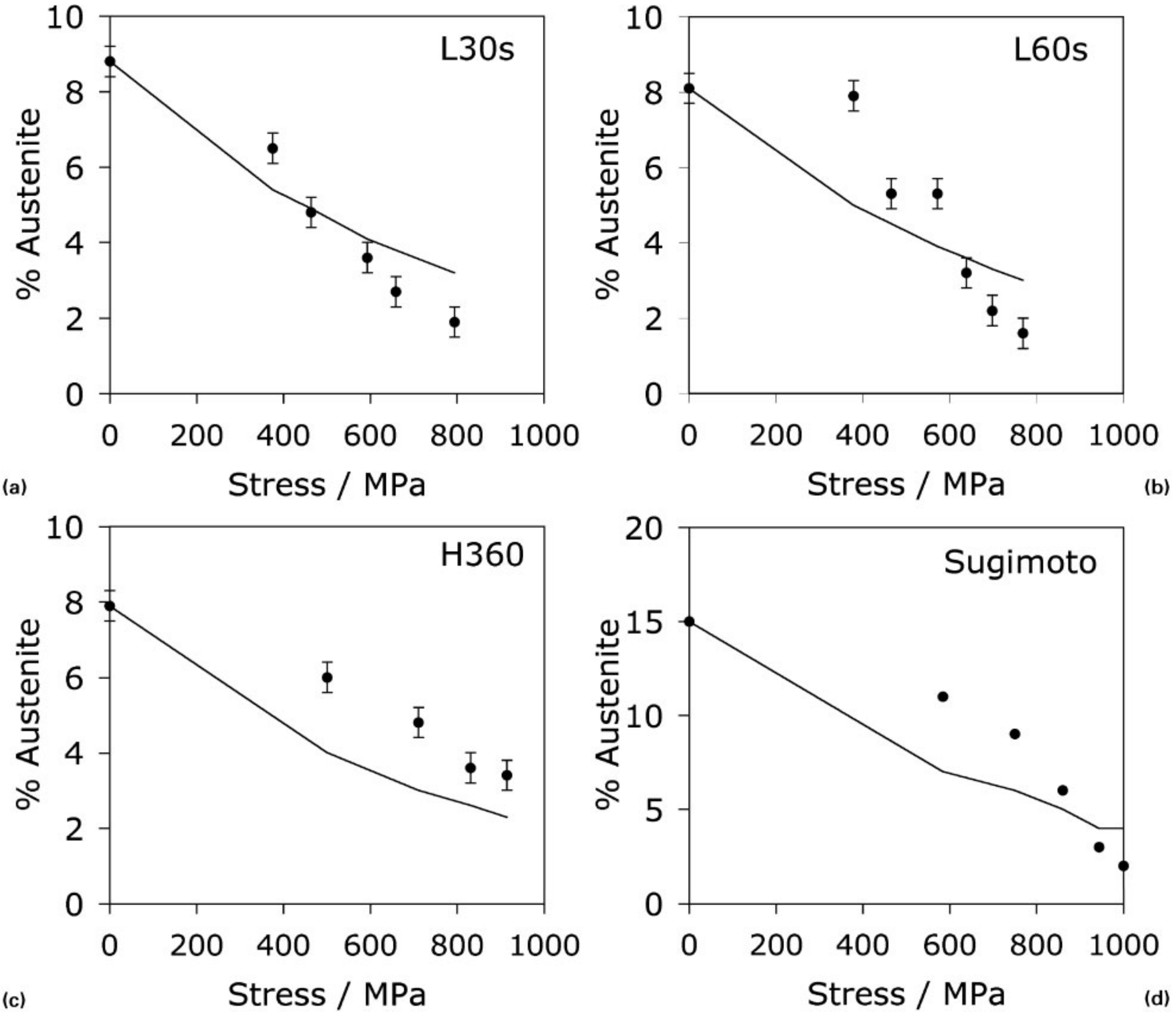
measured, it has been deduced using equation (3) and the reported values of $V_{\alpha'}$.

Using the M_s data in Table 3, corresponding stress–strain curves,[24] MT-DATA calculations of the elevation of M_s as a function of stress and equation (3), it was possible to calculate the stress induced transformation of retained austenite (Fig. 3*a–c*). It is evident that although there are discrepancies with the measured data, the majority of the variation in the retained austenite content can be explained purely on the basis of stress induced transformation.

Table 3 Data for TRIP assisted steels with sample designations as in original paper by Jacques *et al.*[24]; carbon concentration in wt-%

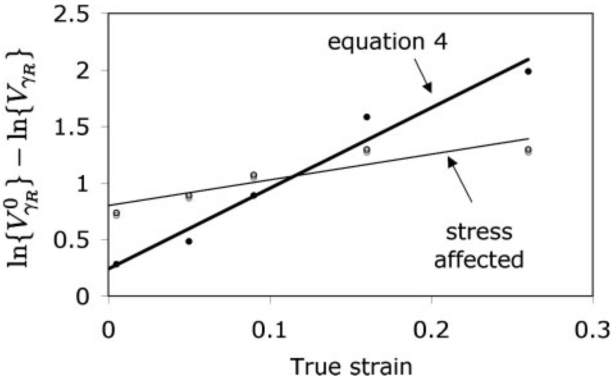
Sample	Martensite, %	γ_r, %	Carbon in γ_r	M_s, K
L30s	7	8·8	0·61	351
L60s	5	8·1	0·68	341
H360	~0	7·9	0·85	298

Figure 3*d* shows similar calculations for retained austenite containing 1·473 wt-% carbon.[21] The M_s required for the calculations was estimated to be 285 K by the method recently published by Sourmail and Garcia-Mateo.[27] Figure 1 shows that it should be impossible to induce strain induced transformation because the slightest plastic strain should lead to



a–c data due to Jacques *et al.*;[24] *d* data due to Sugimoto *et al.*[21]

3 Calculated changes in γ_r due to stress induced martensitic transformation: points are actual experimental data (errors not reported)



4 Variation in retained austenite content as function of plastic strain: data due to Sugimoto *et al.*[21]

mechanical stabilisation. Furthermore, the yield strength of this very high carbon austenite is expected to be >1000 MPa.[14,16] Figure 3*d* therefore confirms that the changes in retained austenite content can mostly be explained in terms of stress induced martensitic transformation.

A common equation used to interpret the evolution of martensite as a function of plastic strain in TRIP assisted steels is as follows[21,28]

$$\ln V^0_{\gamma_r} - \ln V_{\gamma r} = k_\gamma \varepsilon \qquad (4)$$

where $V^0_{\gamma_r}$ is the fraction of austenite at zero strain, $V_{\gamma r}$ the corresponding fraction at strain ε and k_γ is an alloy dependent empirical constant. The equation is popular because a plot of $\ln V^0_{\gamma_r} - \ln V_{\gamma_r}$ versus ε gives a straight line, as illustrated in Fig. 4. However, it can also be seen that the observed straight line behaviour using equation (4) may be fortuitous because such a line is also obtained using the theory described above for stress affected transformation, but with the data plotted against strain using the stress–strain relationship.

Summary

It is known that retained austenite in TRIP assisted steels is very hard by virtue of its high carbon concentration. This means that it does not begin ordinary plastic deformation until large stresses are reached. Furthermore, the theory for mechanical stabilisation indicates that plastic strain in such austenite should actually retard or suppress its transformation.

In contrast, it appears that much of the variation in the retained austenite content can in fact be explained by stress induced transformation due to the interaction of the applied stress with the shape deformation of the martensite. In these circumstances, any early deformation exhibited by the austenite should be due to phase transformation rather than ordinary plasticity.

The procedure for calculating the stress induced decomposition of austenite requires a knowledge of its martensite start temperature, the chemical free energy change and the applied stress. This information is then used to calculate the elevation of the martensite start temperature due to stress. The induced martensite fraction can then be calculated using equation (3). The greatest uncertainty in so doing lies in the assumption that the constant ϕ (=0·011) in equation (3) is generally applicable.[29]

Acknowledgements

The authors are grateful to Tata Steel (India) for financial support and to Professor A. L. Greer for the provision of laboratory facilities at the University of Cambridge.

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