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Microstructure-Property Relationship of High Strength Low Alloy Steels During Tensile Testing at High Strain Rates

MOSS Matthew, TIMOKHINA Ilana, HODGSON Peter
(Institute for Technology Research and Innovation, Deakin University, Geelong, Victoria, 3217, Australia)

Abstract: The influence of strain-rate on the room temperature mechanical properties of Dual-Phase and Transformation Induced Plasticity (TRIP) steels was investigated. The results showed that both plastic strain, and strength properties increased with increasing strain rates at high strain rates. At strain rates ≤4s⁻¹ the properties no longer have an advantageous proportionality to strain rate and remain strain rate neutral. Possible explanations are offered for trends exhibited, in terms of thermal and athermal considerations, in relation to the respective microstructures of the two steels.

Key words: TRIP, Dual-Phase steel, high strain rate, microstructure, strain-rate sensitivity

Dual-Phase and TRIP steels are widely used for their high strength and high ductility properties. Automotive applications include areas of the car that require high energy absorption characteristics in order to improve the level of protection given to passengers in the event of an accident. Due to the very nature of the crumple zones of a car the strain rates involved can be comparatively high [¹] and could reach up to 1000s⁻¹. A better understanding of how these particular steels behave at high strain rates is required to improve the accuracy of crash test simulations that involve these steels.

Dual-Phase and TRIP steels exhibit a good combination of strength and plasticity through their respective microstructures. The microstructure of Dual-Phase steels generally consists of islands of martensite in a ferrite matrix [²]. The microstructure of TRIP steels have additional amounts of retained austenite that transforms to martensite during the course of deformation [³]. The high strength is derived from the hard particles within the matrix and the good plasticity obtained from additional strengthening mechanisms delaying the onset of necking. For instance the ferrite in Dual-Phase steels has an increased local dislocation density around the hard phases during the medium to high stage of straining.

The aim of the current study is to understand the behaviour of Dual-Phase and TRIP steels at high strain rate. It is necessary to obtain high strain rate mechanical properties and initiate a microstructural investigation to explain those results. Investigations have previously shown that the yield strength of Dual-Phase and TRIP steels increases from low to high strain rates [⁴, ⁵].

1. Experiment Method

Mechanical properties were obtained at strain rates from 0.002 to 560s⁻¹ via 2 tensile testing rigs. Strain rates of 0.002 to 2s⁻¹ were carried out on a traditional Instron tensile testing rig. Strain rates from 20 to 560s⁻¹ were carried out on an Instron High Strain Rate rig, capable of crosshead speeds up to 25ms⁻¹ through a high pressure pneumatic ram.

![Fig. 1 Schematic diagram of high strain test sample dimensions](image)

The microstructure of Dual-Phase steel is obtained by heating the steel to the ferrite + austenite region. Once the required amount of ferrite is formed the sample is quenched to form the ferrite + martensite microstructure. The heat treatment required to form the TRIP microstructure is initially the same as Dual-Phase, but instead of quenching the steel is rapidly cooled to the bainitic region, which results in the C enrichment of austenite and increase in ferrite, before finally quenching.

Microstructural investigations have been carried out by the optical microscopy of appropriately etched metallography samples and by a Philips CM20 Transmission Electron Microscope (TEM) operating at 200kV [⁶].

1.1 Experimental results

The chemical compositions of the two steels are given in Table 1. The Dual-Phase steel in this study consists of approximately 75% polygonal ferrite, and approximately 25% martensite. The TRIP steel used in this study consists of approximately 70% polygonal ferrite, 20% retained austenite and the remainder comprising bainite and martensite.
1.2 Tensile properties with respect to strain rate.

1.2.1 Tensile and yield strength

The change in the tensile strength, $R_m$, of the two steels with respect to strain rate can be seen in Fig. 2a). The change in yield strength, $R_{p10}$, with respect to strain rate is shown in Fig. 2b). Both show the same trends over the range of strain rates investigated. The respective strengths remain stable up until approximately $1s^{-1}$, a jump in strength is seen followed by increasing strain rate hardening at high strain rates. A difference in yield strength is seen between the two steels irrespective of strain rate. The accuracy of the results decreases as, in particular in the case of $R_{p10}$, at high strain rates due to shock waves that pass through the material at the onset of testing. $R_m$ has an improved accuracy as the amplitude of the oscillation decreases after the initial shockwave, and therefore has a greater effect on $R_{p10}$.

| Table 1 Chemical composition of Dual-Phase and TRIP steels |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|             | C     | Si    | Mn    | Al    | P     | Nb    | Ni    | Cr    | Ti    |
| DP800       | 0.112 | 0.445 | 1.520 | 0.045 | 0.012 | 0.017 | 0.039 | 0.027 | 0.002 |
| TRIP800     | 0.181 | 1.670 | 1.330 | 0.157 | 0.008 | 0.001 | 0.021 | 0.026 | 0.014 |

Fig. 2 a) Tensile strength ($R_m$) and b) yield strength ($R_{p10}$) of Dual-Phase and TRIP steels with respect to strain rate ($s^{-1}$)

1.2.2 Plasticity with respect to strain rate

The effect of strain rate on the plastic strain to failure, $\varepsilon_f$, of the two steels can be seen in Fig. 3. As the results show $\varepsilon_f$ changes with respect to strain rate and steel type. In the case of Dual-Phase steel $\varepsilon_f$ is stable up to approximately $1s^{-1}$ and then increases with increasing strain rate. The $\varepsilon_f$ of the TRIP steel decreases for rates up to $0.02s^{-1}$, remains relatively strain rate neutral until $220s^{-1}$, and increases with increasing strain rate thereafter.

Fig. 3 Plastic strain to failure ($\varepsilon_f$) of Dual-Phase and TRIP steels with respect to strain rate ($s^{-1}$)
1.2.3. Explanation of strength behaviour in relation to strain rate

It is important to understand that the amount of adiabatic heating increases with strain rate so long as the material exhibits a positive strain rate sensitivity. If the material is absorbing higher amounts of energy at higher strain rates the temperature rise is given by Eqn. 1.

\[ \Delta T = \frac{\dot{\varepsilon}}{\rho C_p} E_{vol}(\varepsilon) \]  

(Eqn. 1)

where \( \Delta T \) is the change in temperature experienced by the sample, \( \dot{\varepsilon} \) is the amount of mechanical energy transformed into heat (\( \dot{\varepsilon} = 0.9 \) in adiabatic conditions and 0 in isothermal conditions), \( \rho \) is the material density and \( C_v \) the specific heat capacity of the material, which is assumed to be independent of strain rate. \( E_{vol}(\varepsilon) \) is the amount of mechanical volume energy absorbed in the test. Temperature increases of up to 100K have been measured for room temperature tested samples at high strain rates.

The response in material strength in relation to strain rate can be explained by separating the strength vs. strain rate graph into 3 sections when testing is carried out at room temperature. These are displayed in Fig. 4. Different mechanisms have been found to be operating in low strain rate, intermediate strain rate, and very high strain rate conditions [6,7].

2 Discussion

The strain rate sensitivity curves exhibit trends that coincide with the trends and mechanisms suggested in the previous section. Low strain rate testing produces a neutral strain rate sensitivity. A distinct second section appears in the curves at intermediate strain rates. This suggests that the relationship between thermal and athermal stress component has changed due to a change in a thermal or athermal strengthening mechanism.

The \( \dot{\varepsilon} \) over this strain rate range is different for both steels. In the case of Dual-Phase steel the shape of the curve is almost identical to the \( R_m \) and \( R_p/\dot{\varepsilon} \). This suggests that the affected stress component is mutually beneficial to both strengthening and improved plasticity. Increased amounts of adiabatic heating would improve the mobility of dislocations which would lead to improved strength and \( \dot{\varepsilon} \) properties.

The TRIP steel displays a different relationship to strain rate. The curves of \( R_p/\dot{\varepsilon} \) and \( \dot{\varepsilon} \) do not coincide with each other in any respect up until the very high strain rates. The strengthening mechanism of TRIP steel is more complex than Dual-Phase steel. The retained austenite is transforming to martensite during straining and the transformation rate of retained austenite is known to be strain and temperature dependent. Quasi-static testing of TRIP steel has shown \( R_p \) and \( \dot{\varepsilon} \) to peak just above room temperature [4]. Below this temperature the strength and strain to failure decreased as the transformation to martensite is completely more rapidly. This information suggests that the rate of change of retained austenite is most temperature sensitive in this temperature range and is one of the reasons for the different straining behaviour.

The strengthening seen in the cases of Dual-Phase and TRIP steels with respect to strain rate can relate well to the known example of mild steel [7] and the proposed mechanisms seem reasonable. TEM investigations will be carried out in order to detail the apparent mechanisms further.

With the advanced strengthening mechanisms of the two steels, it will be necessary to link the behaviour to the microstructures shown at respective strain rates. This will include trying to quantify the dislocation concentrations and mobility at different strain rates. In
particular it will be important to understand how the dislocations interact with the soft/hard phase interface. Fig. 5 shows an example of these interactions, with the arrows highlighting increased dislocation activity in this region.

In order to provide a more inclusive prediction model for high strength/high plasticity steels other steels will need to be investigated, and the strengthening mechanisms present in those steels will need to be understood to relate their mechanical behaviour to produced tensile data. For example Twinning Induced Plasticity (TWIP) steels have high strength/high plasticity properties via twinning. In the example of mild steel, used to derive the different mechanisms for the Dual-Phase and TRIP steels behaviour, the type III twinning mechanism is found at low temperatures, overlapping with type II mechanisms at higher temperatures [6].

3 Conclusions

The mechanical data produced for the Dual-Phase and TRIP steels has been analysed with respect to the strain rate range found in automotive crash testing. Good similarities have been drawn to the strengthening behaviour of mild steel over a similar strain rate range, and the same thermal and athermal stress components can be used to offer an initial understanding of the strengthening mechanisms of the two steels in the present investigation. The straining behaviour of the two steels is predominantly dissimilar, and it is likely that the transformation rate of retained austenite needs to be thoroughly investigated in relation to the determining factors.

The use of TEM will be incorporated to understand changing dislocation motion behaviour as strain rates increase. TEM investigations will also attempt to better understand the transformation behaviour of retained austenite over intermediate strain rates.

References: