Deformation Behavior of Low Carbon TRIP Sheet Steels at High Strain Rates

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Two high strength transformation-induced plasticity (TRIP) sheet steels with 0.10 wt% and 0.14 wt% carbon were produced with retained austenite volume fractions varying from less than 3% up to 16%. These TRIP steels were tensile tested at strain rates ranging from \(10^{-3}\) to \(2.5 \times 10^{2}\) s\(^{-1}\) to determine the effects of strain rate and retained austenite volume fraction on tensile properties. Increasing the retained austenite volume fraction increases UTS, total elongation, uniform strain and total absorbed energy, but decreases yield strength and absorbed energy below 10% engineering strain. Increasing strain rate increases yield strength and UTS, and creates a better-defined yield point, but has little effect on strain hardening behavior for TRIP steels with 11% or less retained austenite. The TRIP steel with 16% retained austenite shows increasing strain hardening rate with strain rate at low strains.

KEY WORDS: high speed deformation; strain rate sensitivity; absorbed energy; strain hardening; TRIP steels; retained austenite.

**1. Introduction**

The demand for high strength steels with excellent ductility has increased in the automotive industry in order to improve manufacturing and safety and to reduce weight. High strength transformation-induced plasticity (TRIP) sheet steels have received increased attention, as they have both high strength and ductility due to the martensitic transformation of retained austenite during plastic deformation,\(^1\) making them excellent candidates for crash-sensitive components. In comparison to conventional HSLA steels with similar strength, the unique properties in TRIP steels are manifested as lower yield strength to ultimate tensile strength ratios and high strain hardening capacities. High strain hardening capacity enhances formability by resisting local necking during component manufacturing, and high UTS in the manufactured component enhances crash energy absorption and fatigue properties. With higher strain hardening, strain is more uniformly distributed and a greater volume of material is involved in the deformation event.

Several studies have evaluated processing histories to establish heat treat conditions to control retained austenite volume fractions, transformation products, ferrite grain size, and thus mechanical properties of low carbon TRIP steels\(^2\)–\(^7\). To date, most mechanical property studies on TRIP steels have concentrated on results obtained under quasi-static (i.e. low strain rate) deformation conditions. However, potential applications for TRIP steels in vehicle crash management require a better understanding of high strain rate properties. It is anticipated that these high strain rate properties will depend on the variations possible in the complex microstructures of TRIP steels. Several recent studies have evaluated the mechanical properties of selected TRIP steels with laboratory tensile tests or component crush tests\(^8\)–\(^10\). In this study two low carbon steels were chosen, based on previous results,\(^11\)–\(^14\) to allow systematic assessment of the effects of retained austenite and carbon content on the high strain rate behavior of TRIP steels.

**2. Experimental Procedures**

Two steel alloys, designated 0.10C and 0.14C, were fabricated by vacuum induction melting and aluminum killing. Steel ingots were hot-rolled to 25 mm thick slabs. The slabs were homogenized at 1250°C for 120 min, hot-rolled to 3 mm thick sheets at a finish rolling temperature of 900°C, and then air cooled. The hot-rolled steel sheets were pickled in a 10% HCl solution at 80°C and then cold-rolled to 0.8 mm in thickness.

The nominal compositions of silicon (1.5 wt%), manganese (1.5 wt%) and copper (0.5 wt%) were fixed, and the
carbon content was 0.10 or 0.14 wt%. Table 1 lists the chemical compositions together with the A1 and A3 temperatures measured using a dilatometer. The A1 and A3 temperatures were measured at a heating rate of 20°C/min up to 1 000°C.

The intercritical annealing and isothermal bainite transformation conditions significantly affect the retention of austenite and the subsequent mechanical properties in TRIP cold-rolled steels. In this study, to understand the effect of retained austenite on high-speed deformation behavior, different isothermal treatments were carried out to achieve high (>10%) and low (<3%) amounts of retained austenite in the materials. The heat treatment conditions are schematically illustrated in Fig. 1. Intercritical annealing for both materials was conducted for 5 min at a temperature for which the volume fraction ratio of ferrite to austenite was about 50:50. The isothermal treatments were carried out at different temperatures and times to vary the amount of retained austenite, followed by air cooling. Two separate salt baths were used for both the intercritical annealing and isothermal treatment. TRIP steels with high amounts of retained austenite are designated “H,” while the steels with low amounts of retained austenite are designated “L.” Heat treatment details for each of the four TRIP steels are contained in Table 2.

Longitudinal tensile specimens with a gage length of 50 mm and width of 12.7 mm were prepared from the cold-rolled steel sheets. All tensile specimens were machined according to ASTM E-8 specification, with one grip section elongated to accommodate a strain gage. The specimens were tested at room temperature over the strain rate range of 10⁻³ to 2.5×10⁴ s⁻¹ on a commercial servohydraulic high-rate tensile testing machine. On each sample, load data were obtained from a strain gage mounted directly to the center of the reduced gage section. Details of the test procedures are summarized elsewhere.¹⁵)

Since C–Mn–Si TRIP steels have complex microstructures composed of ferrite, bainite (or martensite), and retained austenite, identification of each phase was unclear when the sample was etched in a nital solution. Thus, a sodium metabisulfite solution (10 g Na₂S₂O₃·H₂O+100 ml H₂O) was used in conjunction with nital etching. When the specimens etched by the sodium metabisulfite solution are observed in a light optical microscope, ferrite appears gray, bainite or martensite appears black, and retained austenite is white.

The retained austenite volume fractions were measured using X-ray diffraction techniques. Specimens were prepared by mechanically and chemically polishing the sheets to half of their original thickness. MoKα characteristic X-rays were used, and the retained austenite volume fractions (V_r) were calculated from the integrated intensities of ferrite and austenite peaks using the equation V_r=1.4I_a/(I_a+1.4I_f). Here, I_a is the average integrated intensity obtained from the {220} and {311} peaks, and I_f is that obtained from the {211} peak.

3. Results and Discussion

3.1. Microstructure

Figure 2 shows light micrographs of the 0.10C-H, 0.10C-L, 0.14C-H, and 0.14C-L steels. All steels show homogeneous microstructures with uniform distributions of second phases such as bainite and retained austenite. In Figs. 2(a) and 2(c), the bright white phases at the ferrite grain boundaries are retained austenite. Figure 2 shows that “H” steels have more retained austenite than “L” steels. According to X-ray diffraction analysis, the amounts of retained austenite for 0.10C-H and 0.14C-H are 11% and 16%, respectively, and the amount of retained austenite for both “L” steels is less than 3%. Comparing Figs. 2(a) and 2(b) to Figs. 2(c) and 2(d) also indicates that the 0.14C steels have finer microstructures than 0.10C steels.

3.2. Tensile Testing

Quasi-static engineering stress–strain curves are shown in Fig. 3 for each of the four TRIP steels studied and the corresponding standard tensile properties are summarized in Table 3. As expected, “H” steels exhibit greater total elongation and lower yield strengths than “L” steels due to the greater amounts of retained austenite in “H” steels. The 0.14C steels have higher strengths than 0.10C steels due to the greater carbon content and refined microstructure.

Representative true stress–strain curves, for two strain rates which differ by a factor of 10⁴, are shown in Fig. 4 for each TRIP steel. These stress–strain curves are plotted for true strains up to plastic instability. In all cases, with increasing strain rate, yield strength increases, the load drop at yielding becomes more pronounced, and strain hardening remains essentially constant or increases slightly. For both 0.10C and 0.14C steels, the “H” heat treatment results in greater uniform strain than the “L” heat treatment. Also, 0.14C-H exhibits higher uniform strain than 0.10C-H. These results are expected since transformation of retained austenite to martensite during tensile deformation suppresses necking when the transformation occurs at strain levels near uniform strain.¹⁶) “H” steels have much higher retained
austenite content than “L” steels and 0.14C-H has more retained austenite than 0.10C-H.

After tensile testing, X-ray diffraction was used to determine the amount of retained austenite remaining in the broken samples for each TRIP steel tested at all strain rates (10⁻³ up to 2.5×10⁻¹ s⁻¹). There was no detectable retained austenite in any of the samples, which implies that all retained austenite transformed to martensite during tensile deformation in these steels.

3.3. Strain Hardening

Strain hardening exponents were calculated according to a simple power law (Eq. (1)) for strain rates below 10 s⁻¹ for each of the four TRIP steels. In Eq. (1), \( \sigma \) is true stress, \( \varepsilon \) is true strain, \( K \) is a constant, and \( n \) is the strain hardening exponent.

\[
\sigma = Ke^{n} \tag{1}
\]

To calculate \( n \), true stress–strain data beyond the yield point elongation were plotted on logarithmic scales and the slope of a straight line fitted through the data was taken as the strain hardening exponent. The logarithmic plots showed that the materials exhibited two distinct linear regions, one for true strain values below 0.05 and one for strain values of 0.05 to instability. Therefore, strain hardening exponents

| Material | Lower Yield Strength (MPa) | Yield Point Elongation | Ultimate Tensile Strength (MPa) | % Elongation in 5mm gauge section |
|----------|---------------------------|------------------------|-------------------------------|---------------------------------|
| 0.10C-H  | 410                       | 1.3%                   | 685                           | 32%                             |
| 0.10C-L  | 455                       | 1.8%                   | 640                           | 25%                             |
| 0.14C-H  | 470                       | 1.3%                   | 750                           | 33%                             |
| 0.14C-L  | 480                       | 1.5%                   | 680                           | 22%                             |
Fig. 4. True stress–strain curves at two strain rates for each of the four TRIP steels studied.

Fig. 5. Strain hardening exponents versus true strain rate for low and high values of true strain for all four TRIP steels. (a) TRIP 0.10C steel for true strain values less than 0.05. (b) TRIP 0.10C steel for true strain values greater than 0.05. (c) TRIP 0.14C steel for true strain values less than 0.05. (d) TRIP 0.14C steel for true strain values greater than 0.05.
were calculated separately for these two regions to determine differences in early and late strain hardening behavior. The results of these calculations are shown in Fig. 5.

For the 0.10C TRIP steels, the strain hardening exponent for “H” steels is higher than that of “L” steels for both low and high strains at all strain rates, with the difference becoming greater at high strains. For the 0.10C-L and 0.14C-L TRIP steels, the strain hardening exponents at both low and high strain values are similar. Both of these steels have <3% retained austenite. Also, for the 0.10C-H and 0.14C-H TRIP steels at high strains (Figs. 5(b) and 5(d)), the strain hardening exponents are similar. However, the strain hardening exponents for 0.14C-H steel at low strain values are significantly lower than those of the other materials at low strain values. This suggests that the retained austenite in the 0.14C-H steel is more stable than the retained austenite in the 0.10C-H steel. If the retained austenite is more stable, it would take a greater amount of plastic deformation to transform it to martensite and therefore the initial strain hardening would be lower. The greater stability of the retained austenite in the 0.14C-H steel compared to the 0.10C-H steel may be due to higher carbon content or a finer austenite particle size.17 As shown in Fig. 5(c), the strain hardening exponent for 0.14C-H at low strains appears to increase with increasing strain rate, which might suggest that increasing strain rate allows the retained austenite to transform to martensite with less plastic deformation, perhaps as a consequence of the higher stresses encountered during deformation at high rates.

3.4. Tensile Strength

Figure 6 shows ultimate tensile strength (UTS) versus true strain rate for 0.10C-H, 0.10C-L, 0.14C-H and 0.14C-L TRIP steels. In general, UTS increases with increasing strain rate and the UTS values for 0.14C are higher than those for 0.10C. Also, heat treatment “H” produced higher UTS values than heat treatment “L.” This behavior was expected since the higher retained austenite content creates more martensite transformation with strain, which increases both uniform strain and UTS. Figure 6 also displays increasing strain rate sensitivity of UTS with increasing strain rate.

3.5. Flow Stress at 0.05 True Strain

Flow stress values at 0.05 true strain were calculated for all tensile samples. The flow stress at 0.05 true strain was chosen instead of yield strength to evaluate strength after transients on yielding.

Flow stress at 0.05 true strain versus true strain rate for 0.10C-H, 0.10C-L, 0.14C-H and 0.14C-L TRIP steels are plotted in Fig. 7. In general, flow stress increases with increasing strain rate, although there is a slight decrease for some steels in the strain rate range from 1 to 20 s⁻¹. Figure 7 also displays increasing strain rate sensitivity of flow stress at 0.05 true strain. This effect is similar to that found in conventional low carbon and alloy steels.18,19

Similar to the UTS values presented earlier, flow stress values at 0.05 true strain for 0.14C are higher than those for
0.10C since 0.14C has higher carbon content. However, heat treatment “H” produced lower flow stress values at 0.05 true strain than heat treatment “L.” This behavior can be explained by the fact that “L” samples contain more bainite (as opposed to retained austenite) in the microstructure prior to deformation, and the yield strength of bainite is expected to be higher than that of retained austenite.

3.6. Total Absorbed Energy

Calculations were made to estimate the total absorbed energy of the TRIP steels over a wide range of strain rates. Absorbed energies were calculated by estimating the areas under the entire engineering stress–strain curves with a very simple method as shown in Eq. (2). The results of calculations based on Eq. (2) are shown in Fig. 8.

\[ U_T = s_u e_f \]  

\( U_T \) = work per unit volume (area under stress–strain curve)  
\( s_u \) = ultimate tensile strength (UTS)  
\( e_f \) = strain at failure

Strain at failure values were calculated by measurement of gage marks on the samples before and after tensile testing. The data show considerable scatter with fairly constant values of strain energy at lower strain rates and slightly increasing values at higher rates. As expected, the “H” steels with more retained austenite display higher values of total absorbed energy because they exhibit greater total elongation and higher UTS values.

3.7. Energy Absorbed up to 10% Engineering Strain

For some crash-worthiness models, stress–strain data up to 10% strain are the most important. Therefore, the actual areas under the engineering stress-strain curves up to 10% engineering strain were calculated and the results are shown as a function of imposed strain rate in Fig. 9.

Figure 9 shows increasing absorbed energy with increasing strain rate for all TRIP steels tested. The “L” heat treatment (with 3% retained austenite) steels have higher absorbed energy up to 10% engineering strain than the “H” heat treatment steels, which is opposite the case for total absorbed energy. As a result of differences in strain hardening behavior at low strains, Fig. 3 shows that the areas under the “L” engineering stress-strain curves are greater than those of the “H” conditions below 10% engineering strain. As seen in Fig. 3, the quasi-static engineering stress-strain curves for “H” steels cross those of “L” steels because the “H” steels have lower yield strengths but higher UTS values. This behavior persists as strain rate increases.

4. Summary

This study investigated the effects of retained austenite volume fraction and strain rate on tensile properties of four TRIP steels. For all four steels, an increase in the retained austenite volume fraction increased UTS, total elongation, uniform strain and total absorbed energy, but decreased yield strength and absorbed energy below 10% engineering

Fig. 8. Estimated total energy absorbed (estimated area under entire stress–strain curve) versus true strain rate for four different TRIP steels.

Fig. 9. Energy absorbed up to 10% engineering strain versus true strain rate for four different TRIP steels.
strain. For all four TRIP steels, increasing strain rate increased yield strength and UTS, and created a better-defined yield point. For 0.10C-H, 0.10C-L and 0.14C-L TRIP steels, increasing strain rate had little effect on strain hardening behavior. However, for 0.14C-H steel in the low strain (less than 0.05 true strain) region, increasing strain rate increased the strain hardening exponent, which suggests that increasing strain rate might aid transformation of retained austenite to martensite.

Potentially different conclusions with respect to the effect of microstructure variations on absorbed energy may result if different methods are used to calculate absorbed energy. In this paper, comparison of energy calculations based on tensile data in Figs. 8 and 9 illustrates the importance of stress–strain curve shape (i.e. strain hardening behavior) on measured absorbed energies. Specifically, conclusions based on the total absorbed energy indicate that TRIP steels with high amounts of retained austenite absorb more energy up to the point of fracture. However, the opposite conclusion is true for absorbed energies calculated to a fixed low strain (10% in this study). Due to the effects of austenite on the shapes of stress–strain curves, it should be noted that comparison between materials will depend on the specific strain limit chosen. Furthermore, all of the conclusions presented in this paper have been determined based upon tensile test results. More work needs to be done to evaluate properties such as absorbed energy based on more complex loading scenarios, such as in crush tests.

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