**Significance of control of austenite stability and transformation
mechanisms in medium-manganese transformation-induced plasticity
steel**

Z.H. Cai¹, H. Ding^{1,*}, Z.Y. Tang¹, R.D.K. Misra^{2,*}

¹School of Materials and Metallurgy, Northeastern University, Shenyang, 110819,
China

²Laboratory for Excellence in Advanced Steel Research,
Department of Metallurgical, Materials and Biomedical Engineering, University of
Texas at El Paso, El Paso, TX 79968, USA

Abstract

In the context of obtaining high strength-high ductility combination in transformation induced plasticity (TRIP) steels, we underscore the practical significance of controlling the mechanical stability of austenite and transformation mechanisms during deformation. The steel subjected to tensile deformation near M_s^σ temperature exhibited excellent combination of tensile strength and ductility, which is attributed to the synergistic effect of stress-assisted transformation and strain-induced transformation. The calculated M_s^σ temperature was in good agreement with the experimental results.

Keywords: austenite stability; TRIP effect; work hardening behavior; tensile properties

*Corresponding authors: R.D.K. Misra (dmisra2@utep.edu), Tel: 1-915-747-8679,
Fax: 1-915-747-8036; H. Ding (dingneu@163.com);

1. Introduction

Medium-manganese transformation induced plasticity (TRIP) steels with superior strength and ductility combination have attracted a growing interest in recent years, and are considered to be developed for automotive applications. In TRIP steels, the amount and the stability of austenite are critical to obtaining excellent mechanical properties. Deformation-induced transformation from austenite to martensite increases the work hardening rate of TRIP steels, which delays the onset of necking and thereby increases ductility. Moreover, the austenite fraction increased with increase in Mn content, and contributed to enhanced mechanical properties [1-3].

We have recently proposed that a large amount of austenite was obtained in the experimental steel, furthermore, in order to obtain the maximum TRIP effect, good austenite stability is required[4]. The stability of austenite is governed by a number of factors, some of them include chemical composition [5], austenite grain size [6] and temperature [7], etc. In the present study, we underscore the effect of temperature on austenite stability.

The stability of retained austenite includes thermodynamic and mechanical stabilities. The thermodynamic stability of austenite against transformation during cooling is characterized by M_s temperature, while M_s^σ temperature is used to evaluate mechanical stability against stress/strain assisted transformation. M_s^σ temperature is defined as the temperature when austenite transforms to martensite under the assistance of stress which is equal to the yield stress of austenite [8].

It was reported that higher testing temperature can enhance the mechanical

stability of austenite, but resulted in lower ductility [9]. Moreover, it was suggested that M_s^σ temperatures should be below the service temperature (e.g. room temperature), which is favorable for the application of TRIP steels in the automobile industry [7, 10]. In the present study, M_s^σ temperature was measured through tensile tests at temperatures in the range of $-20 - 80^\circ\text{C}$. For comparison, M_s^σ was also estimated theoretically [10-12].

2. Materials and Experimental Procedure

The nominal chemical composition of the experimental TRIP steel was Fe-0.18C-10.62Mn-4.06Al-0.03Nb (wt.%) The selected composition is based on the role of alloying elements and an equilibrium thermodynamic analysis that is discussed elsewhere [4, 13]. A 40 kg experimental steel ingot was cast after melting the steel in a vacuum induction furnace. The ingot was heated at 1200°C for 2 h, hot forged into rods of section size $100\text{ mm} \times 30\text{ mm}$, and air cooled to room temperature (RT). Subsequently, the rods were soaked at 1200°C for 2 h, hot-rolled to 4 mm thick strip, and finally air cooled to RT. The as-hot-rolled strips were then cold-rolled to 1 mm in thickness. The cold rolled strips were annealed at 750°C for 5 min, followed by immediate quenching in water.

Specimens of 12.5 mm width and gage length of 25 mm were subjected to tensile tests using a universal testing machine (SANS CMT 5000) at a constant crosshead speed of $3\text{ mm} \cdot \text{min}^{-1}$ in the temperature range of -20 to 80°C . The samples were etched with 25% sodium bisulfite aqueous solution. The microstructures of the experimental steels prior to and after tensile deformation were examined by scanning

electron microscope (SEM). Austenite grain size was measured by EBSD. Austenite volume fraction was determined by X-ray diffraction (XRD) based on the integrated intensities of $(200)_\alpha$, $(211)_\alpha$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ diffraction peaks [14]. The volume fraction of austenite V_A was calculated using equation [15]:

$$V_A = 1.4I_\gamma / (I_\alpha + 1.4I_\gamma) \quad (1)$$

where I_γ is the integrated intensity of austenite and I_α is the integrated intensity of phases with body-centered cubic structure.

3. Results and Discussion

The SEM micrograph of as-coldrolled steel quenched from 750°C is presented in Figure 1a. The microstructural constituents consisted of austenite and ferrite. Figure 1b through 1f describes the microstructure in the vicinity of the fracture surface of sample tensile tested at -20, 0, 20, 30 and 50°C, respectively. The microstructural constituents comprised of austenite, ferrite and martensite. It is clear from the micrographs that the fraction of austenite increased with increase in test temperature, which was confirmed by XRD.

The variation in the volume fraction of austenite of fractured samples as a function of test temperature is presented in Figure 2a. The undeformed sample had an initial austenite fraction of 57.3%. The austenite fraction of samples tensile tested in the range of -20 – 10°C was reduced to a small extent (~4%), whereas a large amount of austenite (>40%) was retained in samples tensile tested at temperature higher than 50°C. Thus, it is inferred that austenite stability increased with increase in test temperature. In the attempt to further quantify this behavior, equation (2) was used

[16, 17]:

$$f_{\gamma} = f_{\gamma 0} \exp(-k\varepsilon) \quad (2)$$

In equation (2), $f_{\gamma 0}$ and f_{γ} are initial austenite fraction, austenite fraction at strain ε , and k is a constant related to the mechanical stability of austenite. A high value of k corresponds to lower austenite stability.

Figure 2b shows that the estimated value of k decreases with increase in test temperature. On the basis of k values, the samples tensile deformed at different temperatures can be divided into three classes. The samples tested in the range of -20 – 10°C with high k values, can be referred as class 1 and represent stress-assisted transformation. In contrast, the samples tensile tested at temperature higher than 50°C with low k values represent strain-induced transformation, referred as class 2. The samples tested in the range of 20–40°C with medium stability of austenite, can be classified as class 3.

Figure 3 summarizes the effect of test temperature on yield and ultimate tensile strength (YS and UTS, respectively) and total elongation (TE) for the as-coldrolled sample quenched from 750°C. It is important to note that the YS increased with decrease in temperature up to 20°C, followed by a sudden decrease at 10°C, and then increased with decrease in temperature. The abnormal point at 20°C is referred as the transition temperature (M_s^{σ}) between stress-induced martensitic transformation and strain-induced martensitic transformation [7]. According to the previous studies, stress assisted nucleation occurs in the temperature range of $M_s - M_s^{\sigma}$, and above M_s^{σ} new nucleation sites are introduced by the plastic strain. Near M_s^{σ} both mechanisms

operate [11]. Moreover, it was suggested that M_s^σ temperature should be below the service temperature in order to in the strain induced region of the TRIP effect, thus enhancing the elongation [18], however, the relationship between M_s^σ temperature and ductility in our case turn out to be different.

It is clear that UTS decreased continuously with increase in test temperature, whereas TE varied significantly with test temperature. A maximum value of 56.8% was measured at 20°C. TE decreased rapidly when the test temperature was higher than 40°C. As presented in Figure 3d, the value of PSE, i.e., the product of UTS and TE ($PSE = UTS \times TE$) attained a maximum of 55 GPa% at 20°C (M_s^σ temperature). It is interesting that the samples tensile tested in the range of 0–20°C had similar values of PSE to those tested in the range of 20–40°C. Based on the aforementioned discussion, it is inferred that the two mechanisms coexisted in samples tensile tested in the range of 0–40°C leading to excellent combination of UTS and TE. It can be further deduced that the mechanism of stress-induced martensite transformation played a dominant role in samples tensile deformed in the range of 0–20°C, which contributed to higher UTS and lower TE than the samples tested in the range of 20–40°C where the mechanism of strain-induced martensite transformation played a determining role.

Based on the discussion above, the transformation mechanisms were influenced by test temperature, which significantly impacted the mechanical properties. To establish the relationship between the mechanical properties and the mechanical stability of austenite, the work hardening behavior of the samples tensile tested at -20, 0, 20 (M_s^σ temperature), 40 and 80°C, representing different classes of austenite

stability were studied.

The work hardening rate (WH) is presented in [Figure 4](#). There were four stages of WH evolution. In all the samples, the WH decreased rapidly in stage 1 and increased quickly in stage 2, whereas the variation in WH in stage 3 and 4 was different. The first stage is mainly associated with the deformation of ferrite, the variation of WH in stages 2 and 3 is attributed to TRIP effect [13, 16, 17, 19]. The decrease in WH in stage 4 is primarily resulted from the weak TRIP effect.

It is obvious that WH decreased with increase in test temperature, which is related to the enhanced mechanical stability of austenite (as evidenced in [Figure 2b](#)). The WH of -20°C sample, which had low mechanical stability of austenite ($k=8.3$) and involved stress-assisted transformation increased quickly both in stages 2 and 3 and decreased slowly in stage 4. In contrast, the WH of 80°C sample which had high mechanical stability of austenite ($k=0.3$), involving strain-induced transformation decreased slowly in stage 3 and then rapidly in stage 4. It is interesting that the two samples had similar total elongation. However, -20°C sample had significantly higher WH and UTS (1173MPa) than 80°C sample (773MPa). Considering that more austenite transformed into martensite in -20°C sample than 80°C sample (as evidenced in [Figure 2a](#)), it is inferred that the mechanism of strain-induced transformation apparently contributed more to ductility than the mechanism of stress-assisted transformation, which had greater effect in improving the WH and UTS. Thus, the variation in stages 2 and 3 mainly resulted from the competition between the mechanisms of stress-assisted transformation and strain-induced

transformation. When the mechanisms operated independently, good combination of UTS and TE was not obtained. The underlying reason for 20 °C sample tensile deformed at M_s^σ temperature and exhibited the best combination of UTS and TE is the synergistic result of two mechanisms. M_s^σ temperature is an important factor in tensile property determination, but its measurement is not simple. Thus, it is important that if it is estimated theoretically, as described below.

M_s^σ temperature can be obtained by equation (3), which is appropriate for TRIP steels [10-12]:

$$M_s^\sigma = (6.7891 - 33.45 X_C)^{-1} \cdot \left(A + 5712.6 - 78224 \cdot X_C - 21542 \cdot X_{Mn} + 18876 \cdot X_C \cdot X_{Mn} + \sigma_y \cdot 0.715 + 0.3206 \cdot (\sigma_h / \sigma) \right) \quad (3)$$

$$\text{where } A = \frac{2\alpha\gamma_s/\rho}{\ln\{-[\ln(1-f)]/N_v^0 \cdot V_P\}} \quad (4)$$

where X_C , X_{Mn} , and X_{Al} are concentration of carbon, manganese, and aluminum in austenite, respectively, in wt.%, α is a constant, γ_s is martensite nucleus specific interfacial energy, ρ is density of atoms in closed-packed plane, f is fraction of particles transformed, N_v^0 is total number of nucleation sites of all potencies, and (σ_h/σ) is ratio of hydrostatic to equivalent stress. The values of the various parameters in the expression for A are the following: $\alpha=0.866$, $\gamma_s=0.15\text{J/m}^2$, $\rho=3 \times 10^{-5}\text{mol/m}^2$, $f=0.01$, $N_v^0=2 \times 10^{17}$, $(\sigma_h/\sigma)=1/3$ for uniaxial tension. The austenite grains are assumed spherical, thus, volume $V_P = \frac{4}{3}\pi r^3$ can be obtained by using austenite particle radius. More than 400 austenite grains were measured by EBSD, and the average grain size of austenite was $0.55\mu\text{m}$.

The Mn and Al-content of austenite was measured by SEM/EDS from more than

20 randomly selected austenite grains and average values were calculated as 12.2 wt.% and 3.43 wt.%. The C-content in austenite was calculated from the following equation[20]:

$$\alpha_\gamma = 0.3556 + 0.00453X_C + 0.000095X_{Mn} + 0.00056X_{Al} \quad (5)$$

where α_γ is the lattice parameter of the austenite, in nm, which can be determined by XRD using Cohen's approach [21]. Thus, the C-content in austenite was calculated as 0.34 wt.%. Inserting the values of different parameters and the yield strength, σ_y , obtained in the temperature range of 0–40 °C in equation (3), the calculated M_s^σ temperature was in the range of 17.2–20.9 °C, and is in good agreement with the experimental value.

4. Conclusions

The study of M_s^σ temperature underscored the significance of controlling the mechanisms of stress-assisted transformation and strain-induced transformation. The mechanism of strain-induced transformation contributed more to ductility than the mechanism of stress-assisted transformation which had greater effect in improving WH and UTS. Thus, the samples tensile tested near M_s^σ temperature exhibited excellent combination of UTS and TE, and was a consequence of synergistic effect of two mechanisms. The calculated M_s^σ temperature (17.2 – 20.9 °C) is in good agreement with the experimental value (20 °C), which provides a basis for better controlling mechanical properties of TRIP steels in particular.

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Figure captions

Figure 1. SEM micrographs of (a) as-coldrolled steel quenched from 750°C and tensile deformed microstructure near the tip of the fractured surface of samples tensile tested at (b) -20°C, (c) 0°C, (d) 20°C, (e) 30°C, (f) 50°C, respectively. (A: austenite, F: ferrite, M: martensite)

Figure 2. (a) Measured austenite fraction of samples tensile fractured at various temperatures and (b) corresponding k values as a function of test temperature.

Figure 3. Tensile properties of the samples tensile tested in the range of -20 – 80°C. (a) yield strength, (b) UTS, (c) TE, (d) UTS×TE (UTS: ultimate tensile strength, TE: total elongation).

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