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

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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.

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 temperature 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 to −80 °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 mm × 30 mm, and air cooled to room temperature (RT).

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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 (SANSCMT 5000) at a constant crosshead speed of 3 mm 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-cold rolled steel quenched from 750 °C is presented in Fig. 1a. The microstructural constituents consisted of austenite and ferrite. Fig. 1b through f describes the microstructure in the vicinity of the fracture surface of samples 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 Fig. 2a. The undeformed sample had an initial austenite fraction of 57.3%. The austenite fraction of samples tensile tested in the range of −20 to − 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, Eq. (2) was used [16,17]:

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

In Eq. (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 higher value of k corresponds to lower austenite stability.

Fig. 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 to − 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.

Fig. 3 summarizes the effect of test temperature on yield and ultimate tensile strength (YS and UTS, respectively) and total elongation (TE) for the as-cold rolled 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^σ, 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

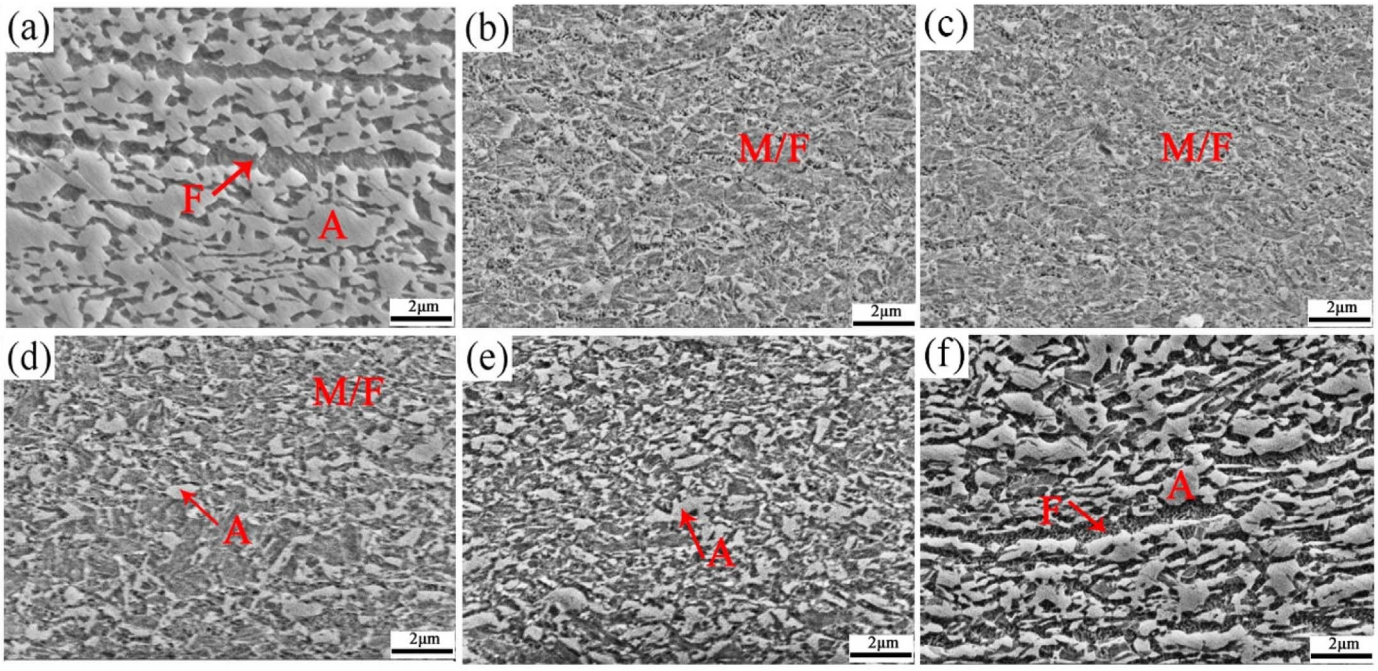

Fig. 1. SEM micrographs of (a) as-cold rolled steel quenched from 750 °C and tensile deformed microstructure near the tip of the fractured surface of samples tensile tested at (b) −20 °C, (c) 0 °C, (d) 20 °C, (e) 30 °C, (f) 50 °C, respectively. (A: austenite, F: ferrite, M: martensite).