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Austenite stability and deformation behavior in a cold-rolled transformation-induced plasticity steel with medium manganese content

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Abstract—We elucidate here the impact of grain size and manganese concentration on the austenite stability and the deformation behavior of a cold-rolled transformation-induced plasticity (TRIP) steel with a nominal chemical composition of Fe–11Mn–4Al–0.2C (wt.%). Intercritical hardening at 770 °C led to a ferrite–austenite mixed microstructure, which was characterized by an excellent combination of ultimate tensile strength of 1007 MPa and total elongation of 65% and a three-stage work-hardening behavior. The grain size was a critical factor in governing the stability of austenite and the optimal grain size for maximum stability was observed to be ~0.6 μm. The superior mechanical properties are attributed to the discontinuous TRIP effect and the cooperative deformation of ferrite, where the discontinuous effect is a consequence of the non-uniform distribution of manganese, which is responsible for introducing varying degrees of stability in the austenite phase.

Keywords: Austenite stability; Discontinuous TRIP effect; Mechanical properties; Work hardening; Manganese distribution

1. Introduction

There is growing interesting in advanced lightweight automotive steels with excellent combinations of specific strength and ductility in order to meet the demand for energy conservation and environmental protection. There are primarily two kinds of lightweight steels, austenite-based and ferrite-based steels containing carbide particles. It has been reported that the mechanical properties of ferrite-based steels can be improved if the second phase is austenite in lieu of carbides and the concept of transformation-induced plasticity (TRIP) is exploited [1].

The TRIP effect derives from deformation-induced transformation of retained austenite to martensite [2]. This results in work hardening and hence delays the onset of necking, eventually leading to a higher total elongation [3]. TRIP steels are characterized by enhanced ductility at a very high strength level [4]. The TRIP effect enhances the mechanical properties via two mechanisms [5,6]: (i) composite strengthening via the formation of hard martensite particles and (ii) formation of dislocations around newly formed martensite regions as a result of the volume expansion during the austenite to martensite transformation. The TRIP effect depends on the amount and degree of stability of retained austenite

In 1972, Miller [7] established the possibility of medium-Mn TRIP alloys. The microstructural constituents of Fe–0.11C–5.7Mn consisted of ferrite and 29 vol.% austenite with a tensile strength of 878 MPa and a total elongation of 34%. Motivated by this success with medium-Mn alloy design in obtaining a combination high strength and high ductility, recent research [8–11] has focused on Fe–(5–10)Mn–(0.1–0.2)C TRIP steels with a large volume fraction (20–40%) of austenite, and has been suggested that the mechanical properties can be improved with an increase in Mn and C contents, which leads to an increase in the fraction of austenite. For example, Luo et al. [8] reported that Fe–5Mn–0.2C (wt.%) steel exhibited a tensile strength of 850–950 MPa combined with a ductility of 20–30%. Merwin [9] achieved a high tensile strength (1018 MPa) and a large total elongation (32%) with Fe–7Mn–0.1C (wt.%) steel. Shi et al. [10] reported a tensile strength of 1420 MPa with 31% total elongation on Fe–7Mn–0.2C (wt.%) steel.

Lightweight steels generally consist of substitutional elements, such as Al and Si, where the role of these elements is to optimize the austenite stability by suppressing cementite formation [12]. Furthermore, Al in TRIP steels encourages the growth of intercritical ferrite [13] and facilitates the presence of δ-ferrite during solidification, contributing to excellent tensile properties [14,15]. Ferrite is a soft phase with good ductility and helps to stabilize the austenite phase [16–18]. For the purpose of obtaining lightweight steels that combine high strength with high ductility, Al is added into medium-Mn containing TRIP steels. For

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instance, Suh et al. [19] reported that Fe–6Mn–0.1C–3Al (wt.%) steel demonstrated an excellent combination of high tensile strength (1000 MPa) and ductility (30%). Park et al. [20] achieved a tensile strength of 949 MPa and a total elongation of 54% with Fe–8Mn–0.2C–5Al (wt.%) steel.

The objective of the present study is to develop a scientific basis for obtaining excellent tensile strength and ductility in a low-density 4 wt.% Al-containing steel. The focus of the study is to optimize ferrite and austenite content together with the increase in the stability of austenite during the intercritical annealing step. In addition, the microstructural evolution and mechanical properties are described in order to demonstrate the potential of the proposed alloy design–processing relationship for obtaining desired mechanical properties.

The chemical composition of the experimental TRIP steel had a nominal composition (wt.%) of Fe–0.18C–11Mn–3.8Al. The selected composition is based on the role of alloying elements and an equilibrium thermodynamic analysis that was discussed in our recent research [21]. 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, then 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. Given that the melting was carried out in vacuum and high-purity raw material with an extremely low sulfur content was used to make this steel, the inclusion content of the processed steel is expected to be insignificant. This aspect was confirmed through optical microscopy and scanning electron microscopy (SEM) observations.

Given that in the recent studies [16–18], we demonstrated that the “austenite reverted transformation” (ART) heat treatment used for medium Mn-content steels is not applicable to the experimental steel studied here, we therefore adopted the approach of intercritical hardening of the cold-rolled strips. Intercritical annealing was carried out at temperatures in the range of 730–850°C for 3 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} at room temperature. Prior to the tensile tests, the uneven surface of the samples was polished. 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 SEM. The chemical compositions of austenite and ferrite phases were determined by energy-dispersive spectroscopy (EDS) in the scanning electron microscope. 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 [22]. Austenite grain size was measured by electron backscatter diffraction (EBSD).

2. Results and discussion

2.1. Microstructure and mechanical properties

The SEM micrographs of the as-cold-rolled samples intercritically hardened in the temperature range of 730–800 °C are presented in Fig. 1. The microstructural constituents comprised of austenite, intercritical ferrite (IF) that formed during intercritical annealing, and layered δ ferrite (δ-F). Generally, the medium-Mn-containing TRIP steels contain 20–40 vol.% austenite [23]. In contrast, XRD indicated that the austenite content in samples increased from 59 to 69 vol.% with an increase in the intercritical hardening temperature from 730 to 800 °C, followed by a decrease to 59 vol.%, when intercritical hardening was carried out at 850 °C because of martensitic transformation (Fig. 2).

The mechanical properties are summarized in Fig. 3. The ultimate tensile strength (UTS) increases continuously with the increase in intercritical temperature primarily because of the enhanced TRIP effect induced during tensile deformation (consistent with Fig. 2(d)). However, the total elongation (TE) attained a maximum value of 70% at 750 °C, and then decreased with an increase in temperature. On the other hand, the near-linear decrease in yield strength (YS) occurred because of the increase in grain size (as shown in Fig. 1) with increasing temperature, consistent with the well-known grain size–yield strength relationship (i.e. the Hall–Petch equation).

The sample intercritically hardened at 770 °C exhibited the best mechanical properties of all the samples, and was characterized by an excellent combination of TE of 65%, UTS of 1007 MPa, and UTS × TE of 66 GPa%, which are significantly superior to the values reported for the medium-Mn TRIP steels at a similar tensile strength level. The reason underlying the superior mechanical properties of the sample quenched at 770 °C can be further elucidated by studying its work-hardening behavior.

2.2. Deformation behavior and austenite stability

Considering the significant difference in ductility and tensile strength among the samples intercritically hardened at 730, 770 and 800 °C (henceforth referred as the 730 °C, 770 °C and 800 °C samples), it is proposed from Fig. 2 that the austenite stability plays a dominant role in governing the ultimate mechanical properties. The 770 °C sample was comprised of 67 vol.% austenite, and after tensile deformation to fracture, 64% of the austenite was transformed to martensite. In contrast, the 730 °C and 800 °C samples comprised 59 and 76 vol.% austenite, respectively. The austenite transformation ratios of these two samples were 35% and 76%, respectively, during tensile deformation. This implies that a higher transformation ratio of austenite-to-martensite led to higher strength (UTS: 1087 MPa) for the 800 °C sample, whereas in the 730 °C sample austenite was relatively more stable, resulting in lower strength (UTS: 875 MPa). Interestingly, the corresponding TE for the two samples were similar (730 °C sample: 45%; 800 °C sample: 43%), but were well below the value of 65% obtained for the 770 °C sample.

As discussed above, it is inferred that the stability of austenite decreases with increase in intercritical hardening temperature. In an attempt to quantify this behavior, the following equation was used [24]:

$$f_\gamma = f_{\gamma 0} \exp(-k\varepsilon) \quad (1)$$

In Eq. (1), $f_{\gamma 0}$, f_γ and k are the initial austenite fraction, the austenite fraction at strain ε, and the mechanical stability of austenite, respectively. A higher value of k corresponds to a higher driving force for transformation and lower austenite stability. Fig. 4 is a plot of parameter k