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A strong and ductile 7Mn steel manufactured by warm rolling and exhibiting both transformation and twinning induced plasticity

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ABSTRACT

Using a new design strategy for the metastable phase in transformation induced plasticity (TRIP) steels, we have successfully manufactured a 7 wt.% Mn containing steel with an excellent combination of mechanical properties (950 MPa ultimate tensile strength and 63% total elongation) *via* warm rolling and intercritical annealing (IA) processes. Compared with the cold rolled microstructure that is usually completely recrystallized during annealing, the warm rolled microstructure is just partially recrystallized due to the lower driving force that is accumulated. This leads to about 50 vol.% of the retained austenite grains having both lamellar and equiaxed morphologies after IA, with the latter having a wide and almost evenly spaced size distribution. In-situ synchrotron X-ray examination revealed that about 40 vol.% of the retained austenite grains could transform to martensite in a sustainable way during deformation because they had a range of mechanical stability owing to their different morphologies and wide size distributions. Moreover, the partitioning of the solute elements during IA leads to some austenite grains having proper values of stacking fault energy using which they can twin during deformation. Finally, the retained austenite grains in the medium-Mn steel can either transform to martensite gradually or twin during deformation, and contribute to large elongation at high strengths *via* both TRIP-assisted and TWIP effects.

1. Introduction

Many advanced high strength steels (AHSS), such as transformation induced plasticity (TRIP) [1], quenching and partitioning (Q & P) [2,3], and austenitic twinning induced plasticity (TWIP) steels [4,5], have been recently developed to meet the weight and affordability requirements of automotive industries. Among them, high-Mn TWIP austenitic steels are particularly appealing due to their outstanding tensile properties. Bouaziz et al. [6] summarized that the typical tensile properties of TWIP steels, which contain 12–30% Mn and 0.6–1.2% C (all alloy compositions are in weight percentages unless otherwise mentioned), exhibit 300–450 MPa yield strength (YS), 1200–1800 MPa ultimate tensile strength (UTS), and 40–50% total elongation (TE). However, their high alloying cost, relatively low yield strength, difficulty in manufacturing, and susceptibility to delayed fracture after forming limit the immediate implementation of such TWIP steels.

Therefore, medium-Mn steels (5–12% Mn) have been proposed as third generation automotive steels. They are expected to lower the alloying cost and aid in more reliable and economical industrial production. Suh et al. [7] reviewed the extensive researches on medium-Mn TRIP steels that were manufactured by the hot/cold rolling and IA processes and summarized that their mechanic properties including UTS, TE and the product of UTS and TE (PSE) all greatly varied in the wide ranges of 0.8–1.6 GPa, 15–70% and 25–70 GPa·% (the combination of GPa and %), respectively. Such a variation is clearly due to different fractions of retained austenite (RA) with various stabilities after the employed many IA processes of studied steels with different compositions, which determine how the RA grains transform to martensite during deformation. In addition to TRIP, TWIP is also an important work hardening mechanism for the medium-Mn steels. For examples, Sohn et al. [8] developed a 0.3C–8.5Mn–5.6Al steel with a UTS of 734 MPa and a high TE of 77%, the latter was attributed to the occurrence of both TRIP and TWIP effects during deformation; Lee et al. [9] studied a 10Mn–0.3C–3Al–2Si steel, which exhibited surprisingly good UTS and TE values as 1200 MPa and 65%, respectively, also due to both TRIP and TWIP effects; Lee et al. [10], Wang et al. [11] and Yen et al. [12] have all found that both TRIP and TWIP effects can occur during the tensile deformation of steels with 10.1Mn–6.3Al–0.26C,

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9Mn–3Ni–1.4Al–0.01C, and 10.1Mn–0.07V–0.08C compositions but these values are lower than 40 GPa·%.

Besides the hot and cold rolling processes are popularly employed in the steel sheet researches, the warm rolling process can be also used to significantly refine the ferrite grain in the low alloyed steel [13,14]. There are very few researches on the warm rolled medium-Mn steels. One example is that Zhao et al. [15] have adopted the warm rolling to produce a 7.9Mn–0.14Si–0.05Al–0.07C steel, leading to the 1.6 GPa UTS and 29% TE. More examples are about hot-stamped steels. Li et al. [16] and Chang et al. [17] both made the comparison of microstructures and mechanic properties of the boron-alloyed 22MnB5 and 0.1C–5Mn steels after warm stamping. They found that the warm stamped medium-Mn steel indeed exhibited better mechanic response, such as more pronounced work hardening, higher ductility and better tear toughness.

The tensile properties of recently developed medium- Mn steels [6–29] are briefly summarized in Fig. 1 as a function of the Mn content; two conclusions can be drawn from this summary. One is that the TWIP effect is usually observed in steels with Mn content higher than 9% when the contents of other alloying elements such as C and Al are not high enough. This is because the high Mn content of austenite is necessary to tailor the stacking fault energy (SFE) to the optimum range of 12–35 mJ/m^2, which is necessary for the formation of mechanical twins [30,31]. De Cooman et al. discovered a boundary composition for a 6Mn–0.30C–1.5Si–3.0Al steel, which can exhibit 1.1 GPa UTS and 58% elongation due to both TRIP and TWIP effects [32]. This is clearly due to the unusually high contents of Al and Si in the steel that can make up for the decrease in the SFE resulting from the relatively low Mn content. However, the high Si content (>1%) often causes the problem of galvanizing, which is unsuitable for commercial production. The other is that the highest product of UTS and TE appear to increase with an increase in the Mn content (Fig. 1). Therefore, it seems that high tensile properties require heavy Mn alloying, particularly in the case of modest contents of Al and Si. This, however, results in difficulties in the commercial production of medium-Mn steels, which are similar to those experienced in TWIP steels since their compositions are almost similar. In this study, however, we report a new medium-Mn steel which contains just 7% Mn, no Si and a modest Al content of 2.6% but exhibits tensile properties similar to those of TWIP steels, as indicated in Fig. 1. Moreover, twinning induced plasticity was also found to occur during tensile deformation. Finally, the work hardening mechanism resulting in such high plasticity was analyzed with the aid of in-situ synchrotron X-ray measurements during deformation.

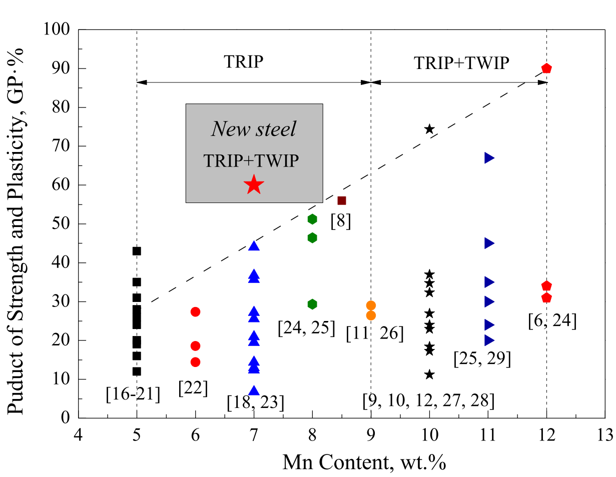

Fig. 1. A summary of the tensile properties of medium Mn steels reported in Refs. [6–29]; the properties are mapped as functions of the Mn content and can be categorized into two groups based on the work hardening mechanism - mere TRIP or TRIP + TWIP.

2. Materials and methods

The composition of the medium-Mn steel used in this study is 0.25C–7.17Mn–2.6Al (in weight percentage). Thermodynamic calculations using the ThermalCalc software and the TCFE8 database indicate that the temperatures for the ferrite and cementite phases to completely disappear are 863 °C and 665 °C, respectively (see Fig. S1(a) in the supplementary material). They also indicate that the equilibrium carbon content of austenite approaches the maximum value at 640–700 °C (Fig. S1(b)). These calculated results are important when designing the subsequent warm-rolling and annealing processes [33].

The medium-Mn steel was melted in a 50 kg vacuum induction furnace and cast into ingots, which were then hot-forged into 40 mm-thick billets. The billets were first homogenized at 1050 °C for 2.5 h, and then hot rolled to a thickness of 4 mm by 4 rolling passes in a pilot hot rolling mill with a finish temperature of 800 °C, followed by water cooling to room temperature. The hot rolled strips were further warm rolled to 2 mm thickness at 600 °C in a four-high cold rolling mill. During warm rolling, the hot rolled steel was first heated to 600 °C and isothermally held for 10 min in a box furnace (soaking treatment), then taken out and rolled to a thickness of 3 mm in three rolling passes, with about 0.33 mm thickness being reduced in each pass. During warm rolling, the temperature of the steel sheet decreased from about 550 °C to 250 °C due to the small thickness. Therefore, it was put back into the furnace again for the same period of isothermal holding at 600 °C and subjected to the same warm rolling process until the final thickness of 2 mm could be obtained. The warm rolled steel sheets were then intercritically annealed at temperatures of 640 °C, 660 °C, 680 °C, and 700 °C for 5 h, and finally air cooled to room temperature. For a more exhaustive description of the hot and warm rolling processes, please see the sketch maps in Fig. S2. The steel sheets annealed at 640 °C, 660 °C, 680 °C, and 700 °C are termed hereafter as W640, W660, W680, and W700 respectively, for easy discussion.

The tensile test samples were machined from the annealed sheets along the rolling direction with a gauge length and width of 50 mm and 12.5 mm, respectively. Uniaxial tensile tests were carried out at a strain rate of 2 mm/min on a WDW-200D tensile testing machine. The microstructures after annealing were firstly examined using a field emission scanning electron microscope (FE-SEM, JSM-6710F) after the samples were mechanically polished and etched with 4% nitric acid for 10 s. The microstructures after both IA and tensile fracture were further examined using a transmission electron microscope (TEM, FEI Tecnai G20) operating at an accelerating voltage of 200 kV and by electron backscattered diffraction (EBSD, FEI QUANTAFEG450) at an operating voltage of 25 kV. The EBSD data was processed by Oxford Instrument HKL Channel 5 software. Thin foils of the steel sheets were prepared for TEM by mechanically polishing them down to a thickness of 40 μm, followed by twin-jet polishing in a 92/8 (v/v) solution of ethanol and perchloric acid at around −20 °C. Samples for EBSD examination were electro polished in an 80/20 (v/v) solution of ethanol and perchloric acid at room temperature. X-ray diffraction (XRD) studies using Cu-Kα radiation were performed to measure the fraction of retained austenite (RA). In particular, in-situ synchrotron XRD experiments were performed at the BL14B beam line of the Shanghai Synchrotron Radiation Facility. The energy of the monochromatic X-ray beam was 18 keV, corresponding to a wavelength of 0.0688 nm. The diffraction patterns were recorded with a step