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Coupled strengthening in a medium manganese lightweight steel with an inhomogeneously grained structure of austenite

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Abstract—The deformation mechanism of a medium-Mn lightweight steel with an inhomogeneously grained structure of austenite was investigated as a function of annealing temperature. All annealed specimens exhibited three different phases: γ-austenite, δ-ferrite and α′-martensite. Specimens annealed at temperatures below 1000 °C exhibited high strain-hardening rates (SHRs) and good combinations of ultimate tensile strength and ductility (~35,000–37,000 MPa%) due to the sequential occurrence of transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) during tensile deformation. The SHR–true strain curves of the annealed specimens are divided into four different stages: dynamic recovery of dislocations (stage I), active TRIP (stage II), slow TRIP (stage III) and mechanical twinning (stage IV). However, the specimen annealed at 1000 °C did not exhibit stage IV, most likely due to its coarse grain size. Whereas the TRIP occurred in coarse γ-austenite grains at small tensile strains, the TWIP took place in fine γ-austenite grains with a size of less than ~10 μm at large tensile strains. This result indicates that grain refinement induced the transition in deformation mechanism from the TRIP to the TWIP. The inhomogeneously grained structure of γ-austenite in the annealed specimens consists of coarse grains pre-existing in the hot-rolled state and fine grains newly formed during annealing.

Keywords: Grain size; Mechanical properties; Strain hardening rate; Twinning; TRIP-assisted steel

1. Introduction

Fe–high Mn–high Al lightweight steel has an outstanding specific strength (i.e. strength-to-density ratio), and has received much attention as the next-generation advanced high strength steel (AHSS) because the use of automotive steel with a lower density leads to both high fuel efficiency and the reduction of CO_2 exhaust. For example, Fe–(18–30)Mn–(4–14)Al–(0–1.8)C (wt.%) lightweight steels possesses a low material density of less than 7.5 g cm^{-3} due to the high Al concentration and a good combination of ultimate tensile strength (UTS) and ductility of over 35,000 MPa% [1–5]. The excellent tensile properties result from not only dislocation hardening, but also extra-strengthening mechanisms, such as transformation-induced plasticity (TRIP) [5], twinning-induced plasticity (TWIP) [6], shear band-induced plasticity (SBIP) [7] and microband-induced plasticity (MBIP) [8].

However, until now Fe–high Mn–high Al lightweight steels are not used as automotive steels due to their high material cost, poor weldability, and so on. Therefore, recently many studies have been performed to reduce the Mn concentration without a significant decrease in mechanical properties. Han et al. [9] investigated the microstructure and tensile properties of Fe–5Mn–6Al–0.3C (wt.%) steel, which was hot-rolled and annealed for 1 h at various temperatures ranging from 300 °C to 900 °C. The microstructures of all annealed specimens consisted of ferrite, κ-carbide and martensite. Specimens which were annealed at temperatures below 500 °C exhibited low combinations of UTS and ductility of less than 4000 MPa% because coarse κ-carbide particles formed at the grain boundaries of ferrite to cause cracks [10,11]. The annealed specimen at 700 °C had a better combination of UTS and ductility of ~25,000 MPa% due to fine κ-carbide particles homogeneously dispersed in the ferrite matrix. Heo et al. [12] examined the effects of Si on the microstructures and mechanical properties of Fe–8Mn–5Al–(0–2)Si–0.2C (wt.%) steels. Although Si suppressed the precipitation of κ-carbide, Si-added steels possessed low ductility due to the precipitation of $(Fe,Mn)_5(Si,Al)C$ carbide at the grain boundaries of ferrite.

Seo et al. [13] annealed cold-rolled Fe–3.5Mn–5.9Al–0.4C (wt.%) steel twice at 830 °C for 50 s and at 400 °C for 3 min to obtain a dual-phase microstructure of ferrite and austenite without κ-carbide. The double-annealed steel exhibited a combination of UTS and ductility of ~29,000 MPa% due to the TRIP effect. Park et al. [14]

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studied the microstructures and tensile properties of Fe–(8,12)Mn–5Al–0.2C (wt.%) lightweight steels, which were cold-rolled and annealed for 2 min at 800 °C. Both steels were composed of ferrite and fine metastable austenite without κ-carbide, and their combinations of UTS and ductility were between 29,000 and 31,000 MPa% due to the TRIP effect.

As mentioned above, although the combination of UTS and ductility of medium-Mn lightweight steels has been improved by using the TRIP effect, the combination value of medium-Mn lightweight steels is still lower than that of high-Mn lightweight steels. Therefore, in the present study, we attempted to endow medium-Mn lightweight steels with a higher strength and ductility by coupling the TRIP effect with the TWIP effect using retained austenite with an inhomogeneously grained structure.

2. Experimental procedure

An ingot of Fe–10.1Mn–6.3Al–0.26C (wt.%) steel was prepared using a vacuum induction furnace. The ingot was reheated at 1200 °C for 1 h under an argon atmosphere, hot-rolled at temperatures between 900 °C and 1000 °C to a 3 mm thick plate and then air-cooled to room temperature. The plate was ground by ~1 mm to remove the decarburized surface layer. Three small samples of ~1.2 g per each were fabricated from the ground plate for the measurement of material density. The density of the steel was measured by the Archimedes method using a pycnometer [15]. The average density was 7.23 g cm^{-3}. Specimens for microstructural observation and tensile tests were also taken from the plate, annealed at various temperatures ranging from 700 °C to 1000 °C for 10 min and then air-cooled.

The microstructures of annealed specimens were observed using a scanning electron microscope (SEM; JEOL, JSM6700F) attached with an electron backscatter diffractometer (EBSD; Oxford instruments, INCA Crystal). SEM specimens were polished mechanically and electrochemically in a mixed solution of 90% acetic acid and 10% perchloric acid, and then etched by a mixed solution of 4 g picric acid, 100 ml ethanol, and 1.5 ml hydrochloric acid. EBSD specimens were mechanically ground with emery papers, diamond suspensions and colloidal silica particles of 0.04 μm, and then finally electrochemically polished using the same acidic solution employed for SEM specimens. The EBSD analysis was operated at 15 kV and the step size was 0.06 μm. The average size of austenite grains was measured using an image analyzer (MediaCybermetics, image-pro) with highly magnified SEM images [16]. In the present study, fine grains were defined as grains with sizes of less than 10 μm. The microstructures of the specimens, deformed with various strains, were observed using a field emission transmission electron microscope (FE-TEM; JEOL, JEM-2100F) operated at 200 kV. Thin foils for TEM observation were prepared by twin-jet electro-polishing in a mixed solution of 10% perchloric acid and 90% acetic acid at 15 °C. The concentrations of Mn and Al in retained austenite were measured using an energy dispersive X-ray spectrometer (EDXS).

X-ray diffraction tests were performed to examine phase constituents in annealed specimens and to measure the volume fraction of retained austenite using an X-ray diffractometer (XRD; Rigaku Corporation, D/MAX-2500H) with Cu-Kα radiation ($\lambda = 1.542$ Å). The scanning speed and range (2θ) were 2° min^{-1} and between 40° and 100°, respectively. The applied voltage and current were 40 kV and 30 mA, respectively. The volume fraction of ferrite was measured using an image analyzer (Olympus, TS Material) and SEM images. The volume fraction of martensite was obtained by subtracting the measured volume fractions of both retained austenite and ferrite from the total volume fraction.

The hardness values of both retained austenite and ferrite phases in annealed specimens were measured eight times for each phase with a load of 98.07 mN using a micro-Vickers hardness tester (Mitutoyo, 810–129 K) and then averaged. Uniaxial tensile tests of annealed specimens were conducted using an Instron 3382 machine at room temperature with a constant strain rate of 1×10^{-4} s^{-1}. The size of the gauge portion was 6 mm in width and 25 mm in length according to the relationship $L_o = 5.65 \times A^{1/2}$, where L_o and A are the length and cross-sectional area of the gauge portion, respectively [17].

To investigate the formation of fine γ-austenite grains during annealing, in situ surface observation of the hot-rolled specimen was performed using a high-temperature confocal laser scanning microscope (CLSM; Laser-tec Inc., VL2000). An R-type thermocouple was attached to the surface of the specimen to measure its surface temperature. A heating chamber was filled with Ar gas to prevent oxidation and then evacuated at least five times at room temperature. The specimen was continuously heated up to 800 °C with a rate of 10 °C s^{-1}.

3. Results and discussion

Fig. 1 shows microstructures of the specimens annealed for 10 min at various temperatures ranging from 700 °C to 1000 °C. All annealed specimens exhibit banded microstructures, which are elongated along the rolling direction. To identify phase constituents in detail, EBSD mapping was performed using the specimen annealed at 700 °C, as shown in Fig. 1e. The microstructure is composed of three different phases such as coarse δ-ferrite (white), fine γ-austenite (red) and α′-martensite (yellow). This EBSD result is different from the thermodynamic calculation result (Fig. 2), obtained using Thermo-Calc (ver. S) with the TCFE7 database, showing a dual-phase microstructure of ferrite and austenite at the annealing temperatures adopted for the present study. Accordingly, it is thought that α′-martensite formed from some grains of γ-austenite with relatively low phase stability during cooling after annealing [14].

Both measured (Fig. 3a) and calculated (Fig. 3b) volume fractions of the three phases in the annealed specimens are plotted as a function of annealing temperature. The measured volume fraction of δ-ferrite gradually decreases with increasing annealing temperature, showing a good agreement with the calculated volume fraction of δ-ferrite. While the measured volume fraction of γ-austenite is nearly unchanged, the calculated one increases with increasing annealing temperature. The difference between calculated and measured volume fractions of γ-austenite results from the formation of α′-martensite. As shown in Fig. 3a, for the specimen annealed at 700 °C the volume fraction of