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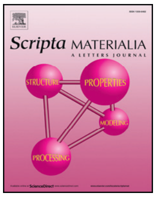

Reverse transformation from martensite into austenite in a medium-Mn steel

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ABSTRACT

The mechanism of austenite reversion from martensite in a cold rolled medium manganese steel has been clarified. Both displacive and reconstructive transformation happens but at a specific temperature ranges. Mechanical stabilisation of martensite into austenite were observed to take place between 300 °C and 500 °C proving the transformation at this temperature range is displacive. The time-dependent characteristic and the plastic deformation stimulating austenite transformation reveal that the transformation occurs above 500 °C is reconstructive. A thermodynamic theory was developed to express the mechanical stabilisation phenomenon of martensite.

The displacive martensitic transformation from austenite happens in a manner of coordinated movements of atoms in which diffusion is not needed [1]. The dislocation strengthening of austenite can resist interface movements and hence the displacive transformation, a phenomenon that is called “mechanical stabilisation” [2]. It is a unique feature of the displacive transformation and an essential indicator in distinguishing the displacive and reconstructive transformation [3]. It has been proven that the formation of martensite [4], bainite [5] and Widmanstätten ferrite [6] can all be mechanically stabilized by deformation of austenite before transformation.

The reverted transformation from martensite into austenite could occur by both displacive or reconstructive transformation. The latter takes place, relying on the atom diffusion and rearrangement. The reverse displacive transformation from martensite into austenite has been studied in some highly-alloyed steels such as Fe-Ni, Fe-Cr-Ni alloys [7,8]. The mechanical stabilisation of martensite to austenite displacive transformation has been reported in Fe-Ni [9] and Ni-Ti [10] alloys.

Medium Mn-TRIP steels containing 5–12 wt% of manganese have received a lot of attention due to their excellent combination of strength and ductility [11–15]. Austenite reverted transformation intercritical annealing from fresh martensite, or severely deformed martensite was adopted to obtain a duplex microstructure of austenite and ferrite. However, only one study [16] focused on the phase transformation mechanism of martensite to austenite, and there is no report on the mechanical stabilisation phenomenon of martensite in these steel types. There is also lack of a quantitative theory to express the mechanical stabilisation phenomenon of martensite in steels or other alloys.

In the present work, the displacive and reconstructive transformation of martensite to austenite in a medium-Mn steel was investigated. The chemical composition of the experimental alloys is Fe-0.28C-6.22Mn-1.57Si (wt%), which was cast as a 50 kg ingot in a vacuum induction furnace. The casting was hot forged into a slab with a cross-section dimension of 60 × 100 mm after reheating to 1200 °C. The slabs were reheated to 1200 °C for 2 h and hot-rolled into 2.7 mm in thickness between 1100 and 800 °C, followed by air cooling. The hot rolled plates were then received a soft-annealing at 620 °C for 10 h in a box furnace. The annealed plates (620A) were surface ground to 2.5 mm and cold-rolled with a thickness reduction of 12% and 36% to a final thickness of 2.2 mm and 1.6 mm, named 12CR and 36CR, respectively. The cold-rolled specimens with 10 mm in length and 4 mm width were heat-treated using a quench dilatometer (TA, DIL 805A), in which the heating rates were between 1 and 50 $^\circ\mathrm{C s^{-1}}$ and the cooling rate of $-50\ ^\circ\mathrm{C s^{-1}}$ were used.

The microstructures of the specimens were observed by a field-emission transmission electron microscope (FE-TEM; FEI, Tecnai G^2 F20) operated at 200 kV, was equipped with energy-dispersive X-ray spectroscopy (EDXS). Specimens for TEM were cut from the surface and mechanically ground to 50 μm and twin-jet-polished in a solution of 92% ethanol and 8% perchloric acid. The austenite volume fraction was determined by X-ray diffraction (XRD) based on the integrated intensities of α(200), α(211), γ(200), γ(220) and γ(311) diffraction peaks [17]. The surface of XRD specimens was electropolished using

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the same solution as in TEM sample preparation. The carbon concentration of the austenite was estimated from the lattice parameter determined by the position of the diffraction peak obtained from the XRD data [18]. Austenite grain orientation was detected by electron backscattering diffraction (EBSD) with a step size of 50 nm.

The martensitic hot-rolled specimen exhibits a dual-phase microstructure of lath-shaped ferrite and austenite after intercritical annealing at 620 °C for 10 h, as shown in Fig. 1a. The EDXS results showed Mn and Si partition between ferrite and austenite. Mn and Si content in austenite were about 11.0 wt% and 1.1 wt%, compared to 4.2 wt% and 1.8 wt% in ferrite, respectively. The C content in austenite was calculated to be about 0.6 wt% from the XRD data. The enrichment of C and Mn prevent the austenite transform to martensite during cooling to ambient temperature. The ferrite and austenite laths show a Kurdjumov-Sachs (K-S) orientation relationship (Fig. 1a). The reverted austenite within each prior austenite grain has the same crystal orientation (Fig. 1b). This phenomenon is so-called as “austenite memory” previously observed in Fe-Ni and Fe-Cr-Ni alloys [19–21].

The thickness reduction of 12% by cold rolling lead to the transformation of austenite to martensite, by which the austenite reduces from 31.1 vol% to 4.1 vol% as shown in Fig. 1c. The 12CR specimen mainly contains lath-shaped ferrite and Mn-rich martensite (Fig. 1d), as the martensite inherits the composition of austenite in the 620A specimen. The austenite in the 12CR specimen is little, with further cold-rolling deformation, it is a process of coordinative deformation of ferrite and martensite. Therefore, the martensite in 36CR have received more plastic deformation compared to that in 12CR. This Mn-rich martensite in the 12CR and 36CR specimens would preferentially revert to austenite during the following reheating process.

Fig. 2 shows the austenite volume fraction, measured by XRD on the final microstructure changes in the 12CR and 36CR specimens after undergoing continuous heating to the specified temperatures followed by cooling to room temperature. No martensitic transformation was detected during cooling in the dilatometric curves. At the heating rate of 10 °Cs^{-1}, shown in Fig. 2a, the austenite in the 12CR specimen starts to form when the temperature is over than 300 °C. Approximately, 6 vol% of austenite forms from 300 to 500 °C, such austenite transformation stops between 500 and 550 °C, and re-starts again after 550 °C. So, the transformation of martensite into austenite during continuous heating can be divided into two stages. The first stage (stage I) is approximately from 300 to 500 °C and the second stage (stage II) starts at above 500 °C. The different shapes of the volume fraction of austenite vs the peak temperature curve obtained between the two stages suggest that the austenite transformation mechanism change from displacive to reconstructive [7].

The displacive transformation exhibits the athermal characteristic and is not heating rate dependence. The transformation takes place in the way of coordinate movements of atoms in the interface and does not rely on the time-dependent process such as atom diffusion. In order to confirm the transformation mechanism of displacive or reconstructive, both specimens of 12CR and 36CR are heated to 300, 500 and 670 °C peak temperature with a heating rate of 1, 10 and 50 °Cs^{-1}, respectively, followed by direct cooling. The austenite content did not change, at 4.1 vol% and 0.9 vol% in 12CR and 36CR, respectively (Fig. 2b and c) when the peak temperature is at 300 °C. The austenite formation between 300 and 500 °C are calculated by subtracting the volume fraction of austenite at 300 °C from the volume fraction of austenite obtained at 500 °C. The same method is used to determine the

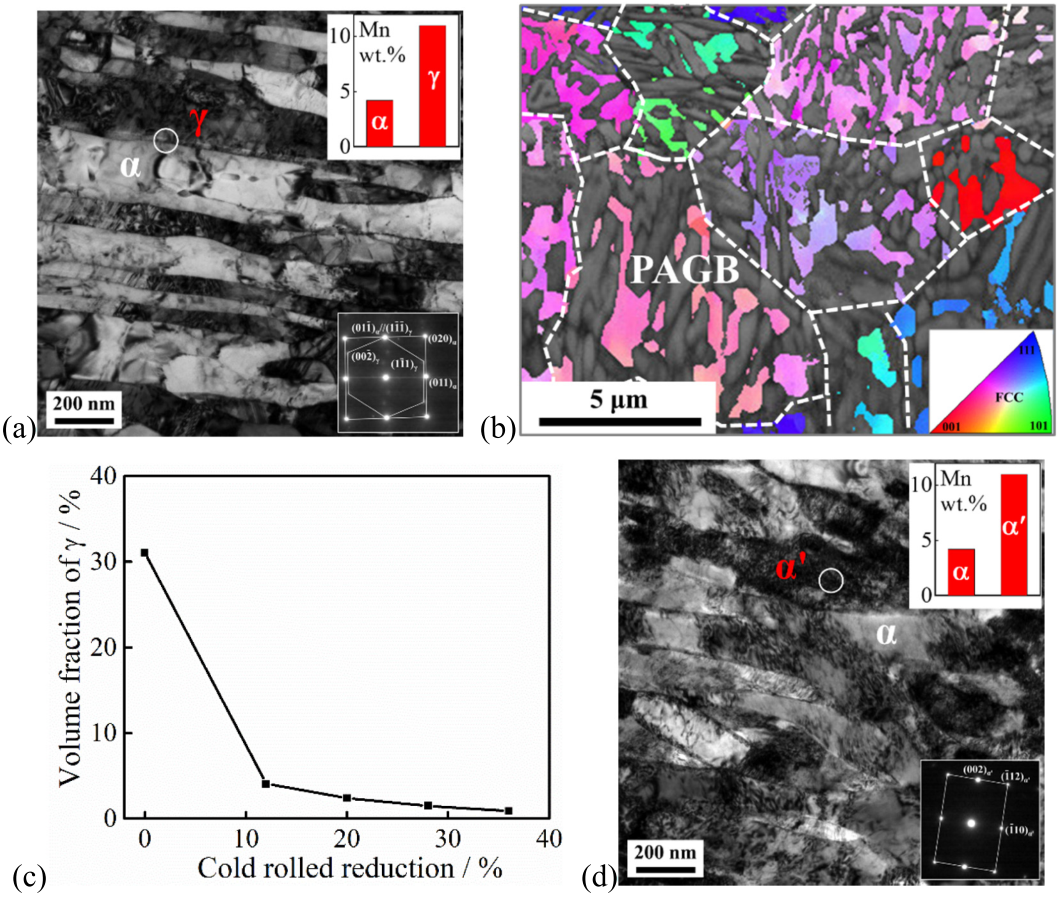

Fig. 1. Microstructure evolution during soft annealing and cold rolling. (a) TEM micrograph and (b) austenite orientation map of the 620A specimen. (c) Austenite volume fraction changes of the 620A specimen as a function of cold rolled reduction. (d) TEM micrograph of the 12CR specimen. γ: austenite, α: ferrite, α′: martensite, PAGB: prior austenite grain boundary. The inserted images in (a) and (d) showed Mn contents in different phases and diffraction patterns of the selected areas as circled in white.