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The effect of warm deforming and reversal austenization on the microstructure and mechanical properties of a microalloyed steel

X.J. Shen [a], S. Tang [a,*], J. Chen [a], Z.Y. Liu [a], R.D.K. Misra [b], G.D. Wang [a]

[a] State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China
[b] Laboratory for Excellence in Advanced Steel Research, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, 500 W. University Avenue, El Paso TX 79968, USA

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ABSTRACT

The influence of warm deforming and reversal austenization on the microstructure and mechanical properties of a microalloyed steel was elucidated. Grain refinement induced by warm deforming and reversal austenization was studied by thermal simulation experiments, and its effect on properties was assessed by thin-plate hot rolling experiments. The study suggested that austenite was refined to ~10 μm after reversal austenization, which was further refined to ~5 μm after reversal austenization and application of warm deforming. Warm deforming recrystallized the microstructure during the reheating process, when the reheating rate was less than 2 °C/s. While recrystallization was inhibited at reheating rates greater than 5 °C/s. The ultimate microstructure obtained from the refined austenite via combination of warm deforming and reversal austenization, comprised of fine-grained (4.7 ± 3.2 μm) ferrite and pearlite with small colony size (1.3 ± 0.6 μm). On the other hand, the fine-grained microstructure was characterized by reduced extent of coarse precipitation (9.3 ± 3.4 nm), compared to the coarse-grained thermo-mechanical controlled processing (TMCP) plate with dispersed and fine precipitation (4.0 ± 1.3 nm), which was responsible for lower strength (~70 MPa) of the fine-grained plate than the coarse-grained TMCP plate. However, the fine-grained plate had an excellent low temperature toughness resulting from fine grain size, coarse precipitation, and small pearlite colony size.

1. Introduction

There is increased demand for high strength steels to reduce weight and fabrication cost of large steel structures. However, increased strength is generally accompanied by decrease of low-temperature toughness. It has been previously reported that SUF (surface layers with ultrafine grains) steels provide excellent resistance to crack growth because large amount of energy is absorbed during plastic deformation by the surface layers during crack propagation [1–3]. The SUF steels are water-cooled prior to the completion of the rolling process (i.e., during middle of the rolling process). The formation of SUF is attributed to recovery and recrystallization of ferrite, ferrite precipitation from undercooled austenite, and strain-induced ferrite transformation or increased nucleation rate due to deformation of undercooled austenite in the controlled rolling process after water-cooling. However, it is difficult for recrystallization of ferrite to occur during the hot rolling process when the strain rate is relatively high, because of its high stacking fault energy [4–6]. Hence, the above mentioned SUF steels may exhibit obvious anisotropy.

It is well known that reversal austenization is a powerful method to refine the austenite grains [7–9]. Refined ferrite grains with isotropic behavior can be obtained by controlled transformation of fine austenite. Thus, reversal austenization can be introduced during the hot rolling process to obtain fine-grained steel plates that involve water-cooling during the middle of the rolling process to transform the plate microstructure, followed by reheating to realize inverse transformation. Meanwhile, warm deforming can be also introduced to this process to further refine the microstructure. Thus, in this study, the effect of warm deforming and reversal austenization on the microstructure and properties of a microalloyed steel was studied using thermal simulation experiments and thin-plate hot rolling experiments.

2. Experimental procedure

2.1. Thermal simulation experiments

The chemical composition and key parameters of the experimental steel are listed in Table 1. Steel of initial thickness of

* Corresponding author.
E-mail address: tangshuai@ral.neu.edu.cn (S. Tang).

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Table 1
Chemical composition and key parameters of the experimental steel (wt%).

C	Si	Mn	P	S	Nb	V	Ti	*Ms*	Ac_1	Ac_3
0.10	0.32	1.5	0.015	0.003	0.04	0.06	0.015	410 °C	732 °C	854 °C

$$M_S(K) = 764.2 – 302.6\omega_C – 30.6\omega_{Mn} – 16.6\omega_{Ni} – 8.9\omega_{Cr} + 2.4\omega_{Mo} – 11.3\omega_{Cu} + 8.58\omega_{Co} + 7.4\omega_W – 14.5\omega_{Si}$$ [10]

$$Ac_1(^oC) = 739 – 22.8\omega_C – 6.8\omega_{Mn} + 18.2\omega_{Si} + 11.7\omega_{Cr} – 15\omega_{Ni} – 6.4\omega_{Mo} – 5\omega_V – 28\omega_{Cu}$$ [11]

$$Ac_3(^oC) = 937.3 – 224.5\sqrt{\omega_C} – 17\omega_{Mn} + 34\omega_{Si} – 14\omega_{Ni} + 21.6\omega_{Mo} + 41.8\omega_V – 20\omega_{Cu}$$ [11]

140 mm was hot rolled to 15 mm using a two-hi 450 mm hot rolling mill. Two plates of dimensions 15 mm × 55 mm × 300 mm were cut from the plate and soaked at 1200 °C for 2 h, hot rolled to 12 mm at 1100 °C to refine the austenite grains, and then water-cooled to ~400 °C at a cooling rate of ~60 °C/s followed by hold time of 60 s. Subsequently, one sample was immediately water-quenched to room temperature, and is referred as B1 in Fig. 1(a) and the other sample was subjected to warm deforming with a final thickness of ~6.7 mm, followed by water-quenching to room temperature and is referred as B2 in Fig. 1(a).

The effect of warm deforming and reversal austenization on austenite grain size was studied using MMS-200 thermo-mechanical simulator, and the simulation process is shown in Fig. 1(b). Cylindrical samples of 6 mm diameter and 12 mm length ware prepared from B1 and B2 plates. The samples were rapidly reheated to 410 °C at a rate of 20 °C/s, further reheated to 880 °C to realize reversal austenization at different rates in the range of 0.5–50 °C/s. After holding for 10 s, all samples were water-quenched to room temperature to observe the original austenite grain boundaries (OAGBs). On the other hand, some samples were water-quenched to room temperature in the dual phase region to observe the microstructural evolution during the reheating process.

The samples were mechanically polished and etched with picric containing hydrofluoric acid to reveal the OAGBs. On the other hand, samples for studying the austenization process were etched with 4% nital. All samples were observed using a LEICA optical microscope.

2.2. Thin-plate hot rolling experiments

On the basis of thermal simulation experiments results, the thin-plate hot rolling tests were carried out to assess the effect of warm deforming and reversal austenization on mechanical properties and the hot rolling process is presented in Fig. 2(a). After warm deforming, the steel was reheated to 880 °C and air-cooled to room temperature at a cooling rate of ~1.3 °C/s to obtain ferrite plus pearlite microstructure, and this steel is referred as B3 plate. The reheating was carried out by a furnace set at 880 °C, and the average reheating rate was ~1 °C/s. Conventional TMCP process illustrated in Fig. 2(b) was also carried out to compare with this process. After deformation at 1100 °C, the steel was air-cooled to 880 °C, hot rolled using single pass deformation with the same reduction as the second pass of B3 plate, followed by air-cooling to room temperature at a cooling rate of ~1.3 °C/s to obtain ferrite plus pearlite microstructure. This steel is referred as B4 plate. The temperature was measured by thermocouple inserted in all the plates.

The microstructures were observed along the rolling direction (RD) using a field emission scanning electron microscope (FE-SEM, ZEISS ULTRA 55) operated at 15 kV. The specimens were mechanically polished and etched with 4% nital. Electron backscattered diffraction (EBSD) studies were carried out to characterize the grain boundaries. The specimens for EBSD studies were electrochemically polished at 25 V using a solution containing perchloric acid and alcohol with a volume ratio of 1:7. These measurements were performed on the ZEISS ULTRA 55 equipped with an electron backscattered diffractometer (Oxford Instruments, INCA Crystal) and operated at 20 kV. The scanned areas were 567 μm × 200 μm and the step size was 0.3 μm. In the present study, high angle grain boundaries were defined with a misorientation angle of $\theta \geq 15°$, and low angle grain boundaries were defined as $2° \leq \theta < 15°$. Transmission electron microscopy (TEM) was used to study precipitation. Thin slices were cut from the plates and ground to 50 μm thickness. Disks of diameter 3 mm were punched from the foils and twin-jet electropolished with a solution of 10% perchloric acid in ethanol. TEM studies were carried out using a field emission Tecnai G2 F20 operated at 200 kV.

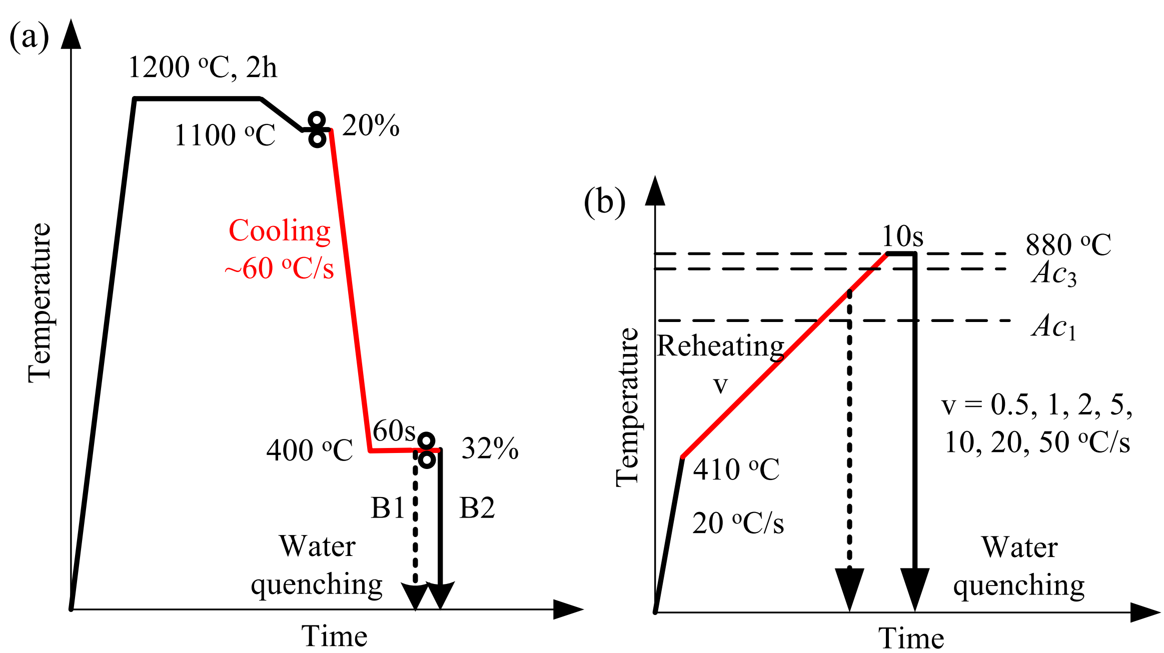

Fig. 1. Hot rolling tests to prepare samples for thermal simulation experiments (a) and thermal simulation experiments to study the effect of austenite refinement after reversal austenization (b).