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Effects of rolling temperature on the microstructure and mechanical properties of Ti–Mo microalloyed hot-rolled high strength steel

Yong Woo Kim [a], Jae Hyung Kim [b], Seong-Gu Hong [c,*], Chong Soo Lee [b,**]

[a] POSCO Technical Research Laboratories, Pohang 790-300, Republic of Korea
[b] Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
[c] Division of Industrial Metrology, Korea Research Institute of Standards and Science, Daejeon 305-340, Republic of Korea

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ABSTRACT

The effects of rolling condition on the microstructure and mechanical properties of Ti–Mo microalloyed hot-rolled high strength steel were investigated by varying rolling temperature from austenite recrystallization region to austenite+ferrite dual phase region. The results revealed that rolling temperature plays a decisive role in the mechanical properties by significantly affecting the characteristics of grain refinement and precipitation. Conducting the rolling in the regions through austenite recrystallization region to austenite non-recrystallization region was able to provide desirable microstructural features for impact properties as well as for strength by inducing a homogeneous and fine grain structure, well developed dislocation structures inside grain, and relatively high number density of fine carbides, although precipitation hardening effect was somewhat reduced by strain-induced precipitation.

1. Introduction

Hot-rolled high strength low alloy (HSLA) steels, widely being used as structural materials of bridges, building beams, industrial equipment, storage tanks, oil and gas pipe lines, etc., have been steadily demanded to have a higher strength together with an adequate toughness and weldability for high structural performance. To date, many efforts have been made to achieve this requirement by controlling thermomechanical controlled processing (TMCP) schedule and micro-alloy elements [1–7]. It is well recognized that the rolling in austenite non-recrystallization region is an effective means to improve the grain refinement because this makes austenite grain flat and induces the formation of deformation bands (i.e., dislocations) inside austenite grain, consequently leading to an increase of nucleation sites for austenite/ferrite phase transformation [8–13]; fine grain structure improves the strength through the Hall–Petch effect and is also beneficial to the toughness [6,7,14–16]. Addition of conventional alloy elements usually impairs the toughness and weldability as the strength increases [17]. Moreover, the precipitation of coarse carbides makes the precipitation hardening effect minor [18]. According to the recent study [14,15,19], however, the precipitation of nanometer-sized carbides becomes possible by microalloying with Ti and Mo, and this remarkably improves the precipitation hardening effect; the precipitation hardening stress of ~300 MPa is achieved. In this sense, it is now available to acquire excellent balance between strength and toughness by a combination of carefully controlled TMCP schedule and addition of microalloying elements, such as Ti, Nb, V, and Mo [1–7].

Recently, we developed a new hot-rolled HSLA steel with a yield strength of ~860 MPa and good impact properties by adding Ti and Mo in low carbon steel and by controlling the TMCP schedule (rolling temperature and coiling temperature) [19]. The results revealed that the rolling temperature plays a more critical role in the grain refinement and precipitation hardening, compared with the coiling temperature which influences just interphase precipitation characteristic (precipitation at austenite/ferrite interface during phase transformation), by affecting prior austenite grain structure, precipitation of coarse carbides (strain-induced precipitation), and dislocation structure. The rolling in austenite recrystallization region can maximize the precipitation hardening effect by preventing the precipitation of coarse carbides (the precipitation hardening stress of ~320 MPa is achieved) but the growth of prior austenite grain leads to a reduction of grain refinement, degrading the strength and impact properties. On the contrary, the rolling in austenite non-recrystallization region provides desirable features by introducing an accumulation of

* Corresponding author. Tel.: +82 42 868 5868; fax: +82 42 868 5032.
** Corresponding author. Tel.: +82 54 279 2141; fax: +82 54 279 2399.
E-mail addresses: sghong@kriss.re.kr (S.-G. Hong), cslee@postech.ac.kr (C.S. Lee).

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dislocations inside austenite grain and pancaked prior austenite grain structure, which can act as the nucleation sites for austenite/ferrite phase transformation and consequently enhances the grain refinement. The resulted fine ferrite grain and well developed dislocation structure improve the strength and impact properties simultaneously. However, it is noted that the precipitation hardening effect is somewhat reduced due to the precipitation of coarse carbides (i.e., strain-induced precipitation) during the rolling process, which consumes carbide formers, Ti, Mo, and C, and thus influences interphase precipitation during the coiling process; the precipitation hardening stress is reduced to ~276 MPa. The amount of coarse carbide precipitates is found to be in proportion to how long the rolling process proceeds in austenite non-recrystallization region. When considering that the rolling process proceeds through several passes where temperature continuously decreases to the finishing rolling temperature (FRT), it can be expected that by carefully selecting the rolling condition where the rolling process starts in austenite recrystallization region and finishes in austenite non-recrystallization region, both the grain refinement and precipitation hardening can be simultaneously enhanced and this will lead to a better strength and impact properties. In addition, the precipitation hardening effect can be expected to increase by conducting the rolling in austenite+ferrite dual phase region because austenite/ferrite phase transformation can take place during the rolling process, and thus most precipitates arise from interphase precipitation. These facts clearly suggest that there is a possibility to find out a more desirable rolling condition which can offer a better strength and impact properties, and furthermore a careful examination to understand the roles of rolling temperature in the grain refinement and precipitation hardening is essentially required for developing hot-rolled HSLA steel.

In this study, we explored how the rolling temperature influences the microstructure and mechanical properties of a Ti–Mo microalloyed hot-rolled HSLA steel by controlling the rolling condition in the temperature range from austenite recrystallization region to austenite+ferrite dual phase region. Microstructural analyses were made particularly focusing on the grain refinement and precipitation hardening, and their contributions to the strength and impact properties were estimated. The optimum rolling conditions were also discussed in terms of strength and impact properties.

2. Experimental details

The chemical composition of the investigated steel was C—0.075, Si—0.2, Mn—1.7, Al—0.035, Ni—0.175, Cr—0.16, Mo—0.275, Ti—0.17, N—0.005, P—0.015 and Fe—balance (wt%). Five different TMCP schedules were designed by varying the rolling condition in the temperature range from austenite recrystallization region (T_{nr}=970 °C) to austenite+ferrite dual phase region (Ar_3=840 °C and Ar_1=720 °C); the coiling temperature was fixed as 620 °C at which the most effective precipitation of interphase precipitates can be obtained [19]. Fig. 1 shows the schematic illustration of the used TMCP schedules. The sample was first solution-treated at 1300 °C for 1 h and air-cooled to the starting rolling temperature (SRT). The rolling process was composed of 7 passes with a total thickness reduction of ~90% (a thickness reduction of ~13% per each pass); the initial slab of 50 mm thickness was rolled to the final plate of 6 mm thickness. After completing the rolling process, the sample was water-quenched to the coiling temperature (620 °C) with a cooling rate of 20 °C/s and held for 1 h. Then, it was finally furnace-cooled to room temperature. Five different rolling conditions were carefully selected by considering the recrystallization of austenite and austenite/ferrite phase transformation during the rolling process: (1) the rolling in austenite recrystallization region ([SRT, FRT]=[1150 °C, 1050 °C]); (2) the rolling in the regions through austenite recrystallization region to austenite non-recrystallization region ([SRT, FRT]=[1060 °C, 960 °C] and [980 °C, 880 °C]), which simulates the industrial hot rolling process; and (3) the rolling in the regions through austenite non-recrystallization region to austenite+ferrite dual phase region ([SRT, FRT]=[900 °C, 800 °C] and [850 °C, 750 °C]). For convenience, the samples made by individual TMCP schedules were designated as 105-62, 96-62, 88-62, 80-62, and 75-62 by reflecting the FRT and coiling temperature in the remainder of the paper (Table 1).

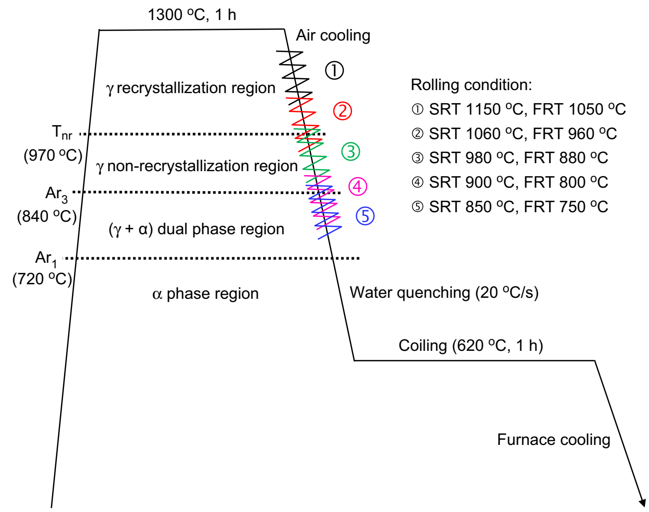

Fig. 1. Schematic illustration describing the used TMCP schedules.

Table 1
Microstructural characteristics.

Sample	TMCP schedule (°C)			Microstructure	
	SRT	FRT	CT	Grain size (μm)	LAB fraction[a]
105-62	1150	1050	620	6.8 (2.3)[b]	0.02
96-62	1060	960	620	1.9 (0.6)	0.19
88-62	980	880	620	3.0 (0.9)	0.11
80-62	900	800	620	3.1 (0.9)	0.06
75-62	850	750	620	2.4 (0.8)	0.09

[a] LAB ($2° \leq \theta < 15°$).
[b] The number in parenthesis indicates the standard deviation of ferrite grain size.

The characteristic temperatures, Ar_3 and Ar_1, were evaluated by conducting dilatation tests. The samples were heated to 1250 °C at a heating rate of 10 °C/s and held for 3 min. Then, they were cooled to 900 °C at a cooling rate of 10 °C/s and compressed by 30%. The compressed samples were finally cooled to room temperature at various cooling rates of 1, 2, 5, 10, 20 and 50 °C/s. Multistage torsion tests were used to determine the T_{nr}, where total 20 passes were applied to the sample with a torsion strain of 20% per each pass and a time interval of 10 s between two consecutive passes, and temperature decreased from 1200 °C to 700 °C. The related experimental details can be found elsewhere [20].

The size and size distribution of ferrite grain, and volume fraction of low angle boundary, which is composed of dislocations, were measured by the electron backscatter diffraction (EBSD) technique (resolution of 0.1 μm). For the EBSD measurement, the surface of test sample was ground on conventional grinding papers and electro-polished using 95% acetic acid+5% perchloric acid at 60 V at room temperature for 25 s. Orientation imaging