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Microstructural evolution and formation mechanism of bimodal structure of 0.2% carbon steel subjected to the heavy-reduction controlled rolling process

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ABSTRACT

A heavy-reduction controlled rolling process with approximately 75% thickness reduction was carried out to investigate the microstructural evolution including texture development, focusing on the formation of a bimodal structure of 0.2% carbon steel with heating temperatures of 700, 800, 900, and 1000 °C. Upon increasing the heating temperature from 700 to 900 °C, the microstructure was refined and precipitates such as Fe_3C were uniformly distributed throughout the microstructure. For the microstructures control-rolled at heating temperatures of 900 and 1000 °C with average ferrite grain sizes of 1.34 and 1.63 μm, respectively, a bimodal structure could be observed by scanning electron microscopy (SEM), which was very similar to the result of a plane-strain compression (PSC) test. Moreover, the 900 and 1000 °C-heated specimens had less well developed textures primarily consisting of {113}–{4 4 11}⟨110⟩ and {332}⟨113⟩ components, which usually developed by the transformation (γ→α), and the 1000 °C-heated specimen exhibited various textures and a low intensity of the {100}⟨011⟩ component, which was generally transformed from the {100}⟨001⟩ component of the recrystallized austenite.

1. Introduction

To satisfy the social demand for lightweight construction, over the past few decades, a number of investigations on enhancing the strength and performance of metals have been carried out involving various methods of microstructure control such as solid-solution strengthening [1,2], precipitation hardening [3,4], cold work hardening [5,6], and dispersion strengthening [7,8]. Among these methods, grain refinement is suitable for producing high-strength materials without any additive elements, showing that a reduction in elongation is less significant than an increase in strength with superior cost performance. Thus, various studies concerning the grain refinement of metals including those by severe plastic deformation (SPD) have also been steadily carried out [9–22]. The variation of the strength of the metallic materials as a result of such grain refinement has been well established by Hall [23] and Petch [24] and many investigations are still based on the Hall–Petch equation ($\sigma_y = \sigma_0 + kd^{-1/2}$) [25–28]. In the grain refinement of steel and aluminum, high strength and good ductility are maintained when the grain size is between 1 and 10 μm. However, fracture soon begins to occur after yielding takes place during plastic deformation at ambient temperatures when the grain size is reduced to less than 1 μm. The uniform elongation will become almost zero when the grain size is reduced to nanometer scale, even though the strength is significantly enhanced [29,30], leading to the reduced formability of metals [31]. This indicates that it is difficult to manufacture products such as vehicle and aircraft components made of ultrafine-grained metals, particularly nanocrystalline metals, through secondary plastic deformation methods such as forging, pressing, drawing, and extrusion.

Wang et al. [32] proposed an innovative method for the intended fabrication of heterogeneous microstructures (so-called bimodal structures) to enhance ductility while retaining strength. They reported that micron-sized grains (1–3 μm) were dispersed in a matrix of nanosized grains (< 300 nm) in pure Cu produced by multipass equal-channel angular pressing (ECAP) in conjunction with a further annealing process. The resulting microstructure exhibited significantly improved ductility while maintaining superior strength. Most recent studies on the formation of heterogeneous structures such as a bimodal structure have been performed to improve the mechanical properties of metals by SPD

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with multiple passes in conjunction with an annealing process [33–41]. However, these results exhibiting the high performance of metals have hardly been applied to industry or to mass production including that of metal strip sheets because of the high production cost, high energy consumption, and long manufacturing time required for such processes.

We have attempted to resolve these issues through a heavy-reduction single-pass controlled rolling process, which can be used to mass-produce steel strip sheets. As the first step, a heavy-reduction single-pass plane-strain compression (PSC) test, which simulates the hot-rolling process, was performed to investigate the formation mechanism of the bimodal structure and its mechanical properties using a variety of steels such as 0.01, 0.1, and 0.2% carbon steel as well as niobium steel (0.16%C–1.41%Mn–0.03%Nb) with different deformation temperatures [42,43]. It was found that high-performance steels composed of equiaxed fine or ultrafine grains with uniformly dispersed cementite or fine pearlite grains were produced in all the steels. However, a bimodal structure containing a mixture of micron-sized grains (1–4 μm) and submicron-sized grains (< 1 μm) could only be observed in 0.2% carbon steel; this steel exhibited an excellent balance between superior strength and marked elongation. This process is a promising means of manufacturing steel strips having a bimodal structure with industrially acceptable productivity by inducing a strain-induced transformation ($\gamma \rightarrow \alpha$) after SPD slightly above the critical transformation temperature (A_{c3}). Moreover, in the conventional controlled rolling process (Fig. 1) [44], 6 rolling stands (F1 to F6) are required to produce a steel sheet strip, which consists of fine ferrite grains (about 4–8 μm), with a thickness reduction from 35 to 2.3 mm. In the heavy-reduction controlled rolling process, a thickness reduction from 35 to 2.3 mm could be achieved by 3 rolling stands (F1 to F3): in the first rolling stand (F1), the crown and shape of a steel plate during the controlled rolling process are controlled with a thickness reduction from 35 to 14.2 mm; in the second rolling stand (F2), a bimodal structure in steel is formed with a thickness reduction from 14.2 to 2.78 mm (80% thickness reduction); finally, flatness and roughness of a steel strip are controlled with a thickness reduction from 2.78 to 2.3 mm. This is our concept of the heavy-reduction controlled rolling process and it is expected to not only reduce the production cost but also produce a high-performance steel strip with a bimodal structure in comparison with the conventional controlled rolling process. In this study, as the second step, on the basis of the previous results for each steel obtained from the PSC test, heavy-reduction single-pass controlled rolling with approximately 75% thickness reduction was conducted to investigate the optimal conditions for producing the bimodal structure in 0.2% carbon steel strips and to explore the microstructural evolution including the crystallographic texture via optical microscopy (OM), scanning electron microscopy (SEM), field-emission scanning electron microscopy (FE-SEM), and electron backscattering diffraction (EBSD).

2. Experimental procedure

2.1. Material

0.2% carbon steel (C.E. = 0.3%) was used in the present investigation for the heavy-reduction single-pass controlled rolling process. The chemical composition of low-carbon steel is shown in Table 1. The as-received 0.2% carbon steel had ferrite–pearlite structures with an average ferrite grain size of approximately 41 μm, as shown in Fig. 2. The as-received steel was machined into a plate of w50 or 80 mm × t10 mm × l300 mm for the controlled rolling process.

2.2. Heavy-reduction single-pass controlled rolling process

Schematic diagrams of the width-restricted heavy-reduction controlled rolling machine and the experimental procedures in the heavy-reduction controlled rolling process are presented in Figs. 3 and 4, respectively. Experimental details of the controlled rolling process are listed in Table 2. A glass lubricant was applied around the surface of the specimen, after the specimen was heated in an electric resistance furnace and held at 700, 800, 900, or 1000 °C,

Table 1
The chemical composition of 0.2% carbon steel used in the controlled rolling process (mass%).

C	Si	Mn	P	S	Cr	Ni	V	Mo	Fe
0.213	0.25	0.47	< 0.005	0.0012	0.01	0.02	0.01	0.01	Bal.

	Bar thickness	Thickness of rolled strip and reduction in each stand					
		F1	F2	F3	F4	F5	F6
Conventional process	35 mm	16 mm	9.5 mm	5.58 mm	3.8 mm	2.78 mm	2.3 mm
		54%	41%	38%	35%	27%	17%
Novel process (shorter)	35 mm	14.2 mm	2.78 mm				2.3 mm
		59%	80%				17%

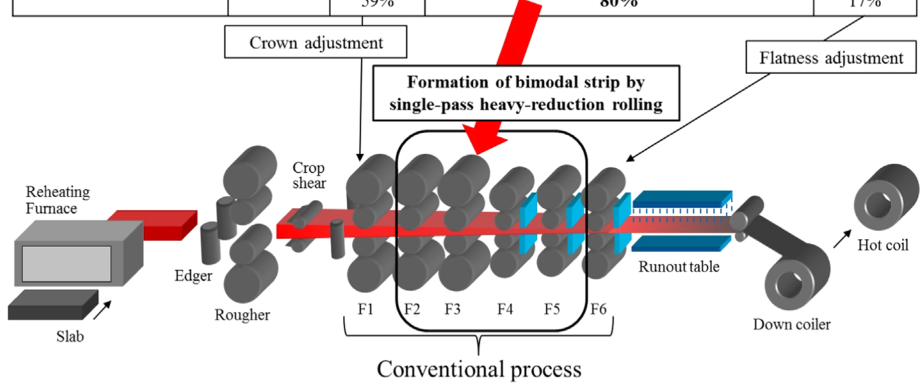

Fig. 1. Schematic diagram of a novel process: single stand to form the bimodal strip undertakes a role of four stands (F2–F5) in conventional tandem hot strip mill, and realizes the manufacturing of steel coil with bimodal microstructure within a shorter process.