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Effect of carbon content on formation of bimodal microstructure and mechanical properties of low-carbon steels subjected to heavy-reduction single-pass hot/warm deformation

Hyung-Won Park [a,*], Jun Yanagimoto [b]

[a] Graduate School of Engineering, The University of Tokyo, Komaba 4-6-1, Meguro-ku 153-8505, Tokyo, Japan
[b] Institute of Industrial Science, The University of Tokyo, Komaba 4-6-1, Meguro-ku 153-8505, Tokyo, Japan

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ABSTRACT

A compression test simulating heavy-reduction single-pass rolling was conducted to investigate the microstructural evolution based on the formation of a bimodal structure and the mechanical properties of 0.01% and 0.1% carbon steels and niobium steel. When thermomechanical processing was conducted near and above the critical transformation temperature (A_{c3}), microstructures of all steels were significantly refined and consisted of equiaxed grains without elongated grains. Nevertheless, these microstructures showed weak or no formation of the bimodal structure or coarse grains with decreasing carbon content, while they showed bimodal structure formation when 0.2% carbon steel was used in our previous research. The average grain size of Nb steel was about 2 μm and its microstructure was uniformly refined. These may be attributed to a decrease in the number of nucleation sites with decreasing carbon content in low-carbon steels and the occurrence of nucleation at grain boundaries as well as in grain interiors in Nb steel during processing. Mechanical properties of all steels deformed above the critical transformation temperature exhibited high performance characteristics with superior strength and marked elongation. Their fractographs indicated ductile fracture, which was revealed by SEM observation after a tensile test.

1. Introduction

Among the methods of microstructure control including precipitate control, dispersion strengthening, and solid-solution strengthening, grain refinement is the simplest means of controlling mechanical properties of metals by controlling the grain size, crystal morphology, and texture without any additive elements. Mainly focusing on the generation of ultrafine grains in a matrix, various studies have been conducted with the aim of achieving numerous high-strength metallic materials [1–10]. Such studies have intensified because of the strong demand for high-strength metals to realize new lightweight structural materials that can be applied to the components of vehicles. Grain refinement of steels to submicron size and nanosized has improved the strength of metals; however, for the nanostructured materials, it has been reported that fracture occurred immediately after yielding during plastic deformation at room temperature. This is considered to be due to the low strain capacity of nanostructured materials [11–13] with high dislocation density which was introduced as the severe plastic deformation (SPD) in the primary plastic deformation at the cold/warm state. The improvement of formability is suggested for ultrafine-grained materials [14]; however, in general, an ultrafine-grained material with high dislocation density cannot be applied to secondary plastic deformation processes in the cold state such as pressing, drawing, and forging.

Wang et al. [15] reported that a heterogeneous structure (the so-called bimodal structure) having dispersed micron-size grains (1–3 μm) in a matrix of nanosize grains (< 300 nm) in pure Cu produced by multipass equal-channel angular pressing (ECAP) and annealing showed a significantly improved ductility while maintaining its strength. Azizi-Alizamini et al. [16] revealed that ultrafine-grained steels with a bimodal structure produced by rolling and annealing exhibited excellent mechanical properties with an optimized balance between strength and uniform elongation. Several articles have also reported the achievement of metals with superior mechanical properties and a bimodal structure by forming in connection with an annealing process [17–20]. Nevertheless, these results showing the high performance of metals have seldom been applied to industry owing to the high energy consumption, high cost, and long manufacturing time required for processes such as multipass forming and further annealing. Moreover, we reported that a steel strip having a bimodal microstructure in 0.2% carbon steel could be manufactured through

* Corresponding author. Tel./fax: +81 3 5452 6204.
E-mail address: wonipark@iis.u-tokyo.ac.jp (H.-W. Park).

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heavy-reduction single-pass compression, which physically simulates hot strip rolling, around the critical transformation temperature (A_{c3}). This is a new technique used to produce a bimodal structure having fine grains (1–4 μm) distributed in a submicron-size matrix (< 1 μm) in 0.2% carbon steel with the combination of superior strength and marked elongation by inducing a phase transformation ($\gamma \rightarrow \alpha$) after SPD slightly above A_{c3}, and this should be a promising way of manufacturing steel strips with a bimodal structure [21]. However, the effects of the carbon and niobium contents on the formation of the bimodal structure have not yet been clarified. It is necessary to investigate whether the proposed process can be applied to low-carbon steels, which generally exhibit better formability, and niobium steels, which are used to manufacture fine-grained structures.

In this study, a heavy-reduction plane-strain compression (PSC) test, which simulates heavy-reduction hot rolling, is carried out. Also, a Vickers hardness test, a tensile test, and microstructure observation are carried out to reveal the effects of the carbon and niobium contents on the formation of a bimodal structure in steel strips.

2. Experimental procedure

As-received hot-rolled steels with carbon of 0.01% and 0.1% (hereafter referred to as steels A and B, respectively), which had ferrite–pearlitic and ferrite–pearlite structures with elongated grains in the rolling direction with average ferrite grain sizes of approximately 111 and 13 μm, respectively, were used as shown in Fig. 1. They were machined into rectangular plates of 10 × 50 × 20 mm^3 for the PSC test. The chemical compositions of the steels used are shown in Table 1. The results for 0.2% carbon steel were used for comparison [21]. A niobium steel (steel C) was also subjected to the PSC test to determine the effect of niobium on the formation of the bimodal structure.

2.1. Plane-strain compression test

The PSC test that we adopted simulates the stress state in rolling [22]. Additionally, some articles indicating that rolling can be simulated by the PSC test have been reported [23,24]. In fact, the deformation and stress at every material point of the PSC test are not identical to those of rolling, but the PSC test is widely used to reproduce hot rolling because of its convenience on controlling the temperature history during hot deformation. The effects of deformation on the microstructure evolution are regarded to be represented only by the amount of height reduction for simplicity. According to Taylor et al. [25], they observed the microstructural evolution of Ni–30Fe austenitic alloy subjected to PSC test with different deformation temperatures and various strains of 0–1, and discussed a change in misorientation with subgrains and textures with various deformation parameters using TEM and EBSD. From this investigation, it has been concluded that the deformed matrix texture was similar to that expected for rolling/PSC deformation of FCC metals.

The PSC test was performed with a 150 kN compression testing machine [26]. The procedure used in the PSC test is shown in Fig. 2. The critical transformation temperatures A_{c1} and A_{c3} of the 0.01% (A) and 0.1% (B) carbon steels were estimated to be 722 and 892 °C, and 726 and 855 °C, respectively, using the empirical equations of Andrews [27]. Mica was placed between each

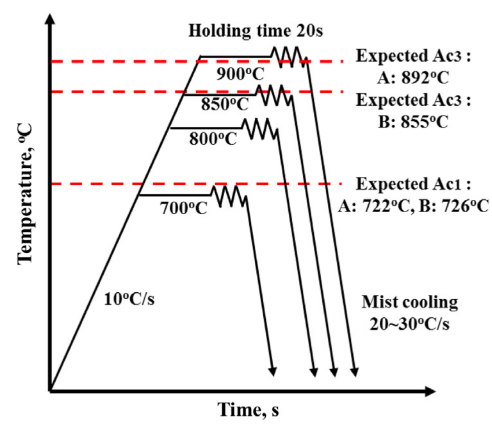

Fig. 2. Schematic diagram of experimental procedures in compression test.

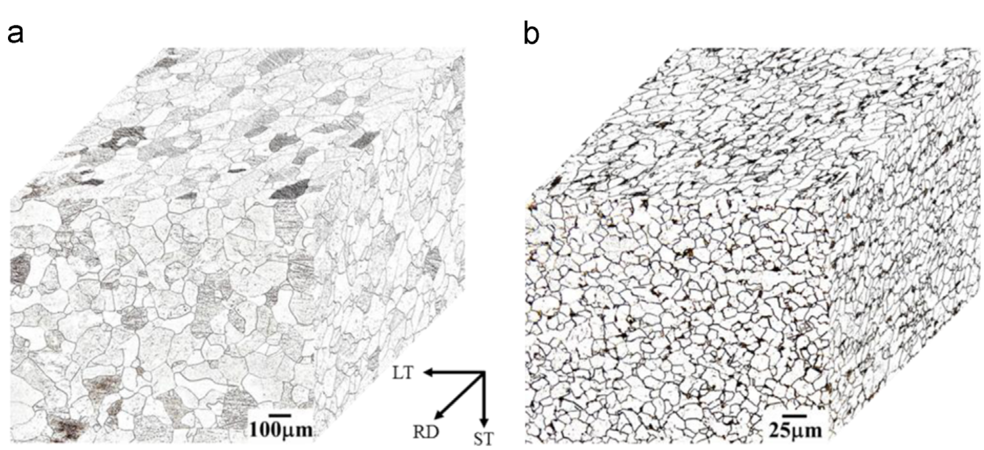

Fig. 1. Orthogonal views of as-received low-carbon steels; rolling (RD), long transverse (LT) and short transverse (ST) directions indicated; (a) steel A: C.E. = 0.05%, (b) steel B: C.E. = 0.19%.

Table 1
Chemical compositions of low-carbon steels and niobium steel (mass%).

	C	Si	Mn	P	S	Cr	Ni	Cu	N	Nb	Fe
A	0.01	0.05	0.20	0.015	0.015	–	–	–	–	–	Bal.
B	0.10	0.21	0.41	0.016	0.014	0.02	0.02	0.02	–	–	Bal.
C	0.16	0.2	1.41	< 0.005	< 0.0005	–	–	–	0.0006	0.03	Bal.