博士論文（要約）

大圧下制御圧延法による易成形高強度バイモーダル薄鋼板の製造

朴　亨原

論 文 の 要 約

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The aim of this investigation is to establish a manufacturing process for formable high-strength steel strip sheets with a bimodal microstructure by a heavy-reduction controlled rolling process. 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 ECAP and annealing showed a significantly improved ductility while maintaining its strength; however, most of the investigations on a bimodal structure in metals showing superior performance have been carried out by multipass forming in combined with annealing process, being seldom applied to industry owing to the high energy consumption, high cost, and long manufacturing time. Therefore, the heavy-reduction controlled rolling process, which is single-pass processing, is proposed to produce steel strips with the bimodal structure in combination with a phase transformation, the SPD, and accelerated cooling process. This should be a promising way of manufacturing steel strips with the bimodal structure.

As the first step in this research, a single-pass heavy-reduction PSC test was conducted for several kinds of carbon steels (carbon contents of 0.01%, 0.1%, and 0.2%) and a Nb steel (0.16%C-1.41%Mn-0.03%Nb), which was used as a precipitation steel, to collect basic data on the resistance to deformation, the formation process of the bimodal structure, in which fine grains (1-4 μm) are dispersed in a matrix of submicron-size grains (<1 μm), and the mechanical properties of the bimodal structure. When thermo-mechanical processing was conducted near and above the critical transformation temperature (A_{c3}), the microstructures of all steels were significantly refined and consisted of equiaxed grains without elongated grains. Nevertheless, the microstructure showed weak or no formation of the bimodal structure or coarse grains with decreasing carbon content, while only 0.2% carbon steel with the average grain size of 1.4 μm showed the formation of the bimodal structure. The average grain size of

Nb steel compressed at 850 ^{o}C 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 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 showed ductile fracture. Particularly for the 0.2% carbon steel specimen deformed at 850 ^{o}C, the bimodal microstructure was formed with a mixed structure of fine grains (1-4 μm) and a matrix of submicron-size grains (<1 μm). The specimen deformed at 850 ^{o}C exhibited the average uniform elongation (7-8%) was about twice that of the other specimens deformed at from 700 to 800 ^{o}C, while holding high strength (677 MPa). Furthermore, bimodal dimples consisting of submicron-size (<1 μm) and fine (2-4 μm) dimples were observed on the fracture surface in the specimen deformed at 850 ^{o}C. From this step, an applied strain of about 1.2, a deformation temperature of 850 ^{o}C, right above A_{c3}, and mist cooling after the SPD are required as optimal conditions for producing the bimodal structure in 0.2% carbon steel with the carbon equivalent of about 0.3%.

As the second step, on the basis of the previous results for each steel obtained from the PSC test, the heavy-reduction single-pass controlled rolling process was carried out to investigate optimal conditions of the formation of the bimodal structure in 0.2% carbon steel strips and to examine the microstructural evolution including texture development, mechanical properties, and fracture behavior. Upon increasing the heating temperature from 700 to 900 ^{o}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 ^{o}C, the bimodal structure could be observed by SEM, which was very similar to the result of a PSC test. Moreover, the 900- and 1000 ^{o}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 ($\gamma \rightarrow \alpha$), and the 1000 ^{o}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, resulting in relatively homogeneous anisotropies. The uniform and total elongations of the 900- and 1000 ^{o}C-heated specimens were higher at roughly 12-14% and 23-28% than those of the 700- and 800 ^{o}C-heated specimens, respectively, as clarified from the nominal stress-strain curves. Additionally, the bimodal structure on the fracture surface consisting of submicron-size (<1 μm) and fine (2-5 μm) dimples led to higher ductility while retaining outstanding strength. This is attributed to the submicron-size grains having excessive strength and the micron-size grains having high ductility.

Finally, Erichsen and deep drawing tests were performed to examine the formability of 0.2% carbon steel sheets with the bimodal microstructure fabricated by the heavy-reduction single-pass controlled rolling process. The formability of steel strips having the bimodal structure was analyzed and discussed in terms of the microstructure, the crystallographic texture, the strain-hardening exponent, and the anisotropy coefficient, which were obtained from OM, SEM, EBSD, and the tensile test. In the Erichsen test, poor formability in 700- and 800 ^{o}C-heated specimens was represented owing to the subgrains consisting of LAGBs, while 900- and 1000 ^{o}C-heated specimens showed remarkable stretchability. In particular, the formability of the 1000 ^{o}C-heated specimen was almost same with that of as-received specimen. In the deep drawing test, 900- and 1000 ^{o}C-heated specimens were uniformly deformed without ears, whereas strong 45^{o} ears occurred in the 800 ^{o}C-heated specimen with a drawing ratio of 2.0. From the results of formability tests for 0.2% carbon steel sheets control-rolled with different heating temperatures, 900- and 1000 ^{o}C-heated specimens with the bimodal structure not only showed marked formability but also had superior balance with the strength and elongation, although they consisted of ultrafine grains, which are considered to have low formability, with average grain sizes of 1.34 and 1.63 μm diameter, respectively.