Effect of Accumulative Bending Conditions on Grain Refinement on Hot-rolled Sheet

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As a technology to manufacture fine-grained steel, accumulative bending process after hot rolling was proposed, and multi-bending equipment of laboratory scale were established. The effects of accumulative bending on microstructure and ferrite grain size by changing the thermo-mechanical conditions were investigated. As the results, a microstructure with the grain size of 2.2 μm was obtained at specimen surface by accumulative bending after hot rolling in the optimized thermal condition. By the results of FE analysis, it was cleared that equivalent strain was accumulated on not only surface but also center of thickness.

KEY WORDS: grain refinement; fine grain; accumulative bending process; thermo-mechanical control process; hot rolled sheet; carbon steel.

1. Introduction

Recently, many studies on strengthening of steel sheets have been carried out with the aim of reducing the weight of automobile parts. Solid solution strengthening and precipitation strengthening are well known strengthening methods. Strengthening by grain refinement has also been studied energetically from the viewpoints of reducing consumption of microalloys and improving the recyclability of steel products.

To date, many studies1–6) on grain refinement by severe deformation have been reported, and practical steel rods and other products are now being produced using this method.7) On the other hand, the following have been reported as guidelines for obtaining ultra-fine grain hot-rolled steel strips.8–12)

(1) Low temperature deformation, e.g., in the supercooled austenite region
(2) Severe deformation
(3) Rapid cooling immediately after deformation

Hot strips with 5 μm ferrite(α) grains are already manufactured by controlled rolling and controlled cooling using the conventional hot strip mill, and hot strips with 2 μm ferrite grains have been manufactured by high-reduction rolling at low temperature with rapid cooling.13) However, severe deformation at low temperature causes deterioration of dimensional accuracy and surface defects such as heat scratches. For this reason, industrial production of hot strips with ultra-fine grains under 1 μm has not yet been realized.

As an industrial technology for manufacturing ultra-fine grained steel, this study proposes an accumulative bending process after hot rolling and investigates its grain refining effect. Although strip thickness is generally reduced by rolling, it is not reduced by accumulative bending, suggesting theoretically that infinite strain can be added using the proposed process. It is also thought that this process has a minimal influence on dimensional accuracy and surface quality. Because the accumulative bending process has two strain modes, i.e., the rolling mode and the bending mode, it is expected that α grains of various orientations will nucleate, grain growth can be suppressed, and grain refinement can be accomplished easily.

2. Experimental Procedure

2.1. Experimental Equipment

Figure 1 and Table 1 show a schematic illustration and the specifications of the laboratory equipment, respectively.

The multi-bending device comprises a total of 21 top and bottom driven work rolls with diameters of 50 mm, and segmented back-up rolls to reinforce each work roll. A pinch stand for stable bending is installed at the exit side. In the waiting condition, the top and bottom units are opened, and bending of the steel sheet is performed by allowing the top unit to drop after the tip of the sheet passes the bending equipment, triggered by bite at the pinch roll.

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2.2. Experimental Procedure

The specimens used in this study were commercial steel strip with a chemical composition of 0.15 mass% C, 0.01 mass% Si and 0.75 mass% Mn and thickness of 10 mm, width of 100 mm and length of 1 200 mm.

Figure 2 shows the experimental conditions. Specimens were reheated at 1 373 to 1 173 K for 30 minutes in a furnace, hot-rolled to 3 mm in thickness with 70% reduction at 1 323 to 1 073 K, water-cooled to the specified temperature, and then multi-bent at that temperature and air-cooled. The multi-bending temperature was in the range of 1 193 to 943 K, and the gap of the bending roll (δ) was from 3 to 7 mm.

For comparison, experiments were conducted by air-cooling after quenching without multi-bending (δ=0 mm). The rolling speed was 50 m/min. δ is the deformation index of multi-bending, and is defined as the distance which the top work roll presses into the steel sheet, as shown in Fig. 3.

The microstructure of the hot-rolled and multi-bent specimens was observed in the rolling direction section at the center of width. The grain size of each field of view was determined by the graft method. It should be noted that repeatability could not be evaluated, as the experiment was performed only one time.

3. Experimental Results and Discussion

3.1. Influence of Bending Temperature on Grain Refinement

In order to show the influence of bending temperature on grain refinement, the following experiments were carried out. Specimens were reheated at 1 373 K for 30 minutes in the furnace, hot-rolled to a thickness of 3 mm at 1 323 K, water-cooled to a temperature in the range of 1 193 to 943 K, and then multi-bent at that temperature and air-cooled. The multi-bending temperature was in the range of 1 193 to 943 K, and the gap of the bending roll (δ) was from 3 to 7 mm. For comparison, experiments were conducted by air-cooling after quenching without multi-bending (δ=0 mm). The rolling speed was 50 m/min. δ is the deformation index of multi-bending, and is defined as the distance which the top work roll presses into the steel sheet, as shown in Fig. 3.

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refinement by bending was observed at either 1 193 K or 943 K.

In order to measure the Ar3 transformation temperature
of this steel, the cooling curve was measured using a thermocouple during air-cooling after hot rolling under the same conditions as mentioned above. Figure 6 shows the cooling curve of the hot-rolled sheet, which revealed that the Ar3 transformation temperature was about 1023 K. As shown in Fig. 5, the most effective grain refinement was achieved at 1043 K, which is equivalent to supercooled austenite immediately before the ferrite transformation. Conversely, it is estimated that grain refinement was negligible at 1193 K because strain was not accumulated by recovery or recrystallization, and was also negligible at 943 K, as the ferrite transformation had already been completed before the sheet was deformed.

That is to say, fine-grained steel can be obtained effectively by raising the driving force of nucleation during the austenite-ferrite transformation by applying multi-bending to supercooled austenite.

3.2. Influence of Bending Strain on Grain Refinement

In order to show the influence of bending strain on grain refinement, the following experiments were performed. Specimens were reheated at 1373 K for 30 minutes in the furnace, hot-rolled to a thickness of 3 mm at 1323 K, water-cooled to 1043 K, and then multi-bent at that temperature and air-cooled. Bending was performed at $\delta=0, 3, 5$ and 7 mm. Bending at 1043 K was deformation in the supercooled austenite region, where the grain refinement effect was large.

Figure 7 shows the microstructures at the center of thickness, 1/4 thickness and surface of the sheet for $\delta=0$ mm and $\delta=5$ mm. Figure 8 shows the distribution of the ferrite grain size in the sheet thickness direction. The ferrite grain size is refined as $\delta$ increases, and is also refined approaching the surface from the center of thickness. However, a small amount of grain refinement was also observed in the center of thickness.

Although bending strain is not generally given in the center of thickness, in this experiment, refinement of ferrite grains was confirmed in the center. To explain this phenomenon, the authors performed FE analysis of bending deformation and evaluated the strain distribution in the thickness direction.

The FE analysis was a 2D dynamic positive analysis using ABAQUS/EXPLICIT(ver6.5). In this plane strain analysis, deformation in the width direction is ignored, and the relationship $d\varepsilon_x=-d\varepsilon_y$ is established. Figure 9 shows an outline of the FE analysis of bending deformation. The analytic conditions were the same as the experimental conditions. The distance between the work roll centers is 65 mm, the work roll diameter is 50 mm, the sheet thickness is 3 mm and the bending roll gap ($\delta$) is 5 mm. As one difference, the number of work rolls in the analysis was 7, compared with 21 in the experimental facility, as a semiquantitative evaluation was considered sufficient for the purposes of this study. As the analysis procedure, the strip was tensioned with a force of 2.0 kgf/mm², which is equivalent to the tension of the pinch stand in the experiment, the top work roll was dropped, and the work roll was rotated at a speed of 318.5 r/min. The work rolls were assumed to be rigid bodies. Although the dependence of the analytical results (strain distribution in the steel strip) could not be fully evaluated, the strip was divided into 6 elements in the thickness direction and 3190 elements in the rolling direction, for a total of 19140 elements. As the stress-strain curve of the strip, Eq. (1) was used so that the bending load in the analysis
coincided with that in the experiment. Similarly, as the coefficient of friction between the work roll and strip, 0.4 was used so that the bending torque in the analysis agreed with that in the experiment.

\[
\sigma = 35(e_p + 0.002)^{0.2} \quad \ldots (1)
\]

Figure 10 shows the change of strain by bending at the surface and center of thickness. \(\varepsilon_x\) is plastic strain in the rolling direction, \(\varepsilon_y\) is plastic strain in the thickness direction, \(\gamma_{xy}\) is plastic strain in the shear direction \((\gamma_{xy} = 2\varepsilon_{xy})\) and \(\varepsilon_{eq}\) is equivalent plastic strain. \(\varepsilon_x, \varepsilon_y\) and \(\gamma_{xy}\) show change over time, and \(\varepsilon_{eq}\) shows the accumulation of the increment of plastic strain for micro-time, as expressed by Eqs. (2) and (3). It was found that bending with 7 work rolls gave equivalent plastic strain of 0.34 at the surface and equivalent plastic strain of 0.06 at the center. As the reason why bending introduced equivalent plastic strain in the center of thickness, it is thought that the center of thickness did not coincide with the neutrality line of bending, and as a result, shear strain was applied at the center of thickness.

\[
\varepsilon_{eq} = \int_0^\infty \frac{d\varepsilon_{eq}}{dt} \quad \ldots (2)
\]

\[
d\varepsilon_{eq} = \frac{2}{3}(d\varepsilon_x^2 + d\varepsilon_y^2 + \frac{1}{2}d\gamma_{xy}^2) \quad \ldots (3)
\]

From the results of the FE analysis with 7 work rolls in Fig. 10, equivalent plastic strain is increased 6 times. In this examination, equivalent plastic strain with 21 work rolls is converted to \((\text{mean of 4 repetitions of equivalent plastic strain except at the 2 ends}) \times 18\) \(\pm\) (equivalent plastic strain at 2 ends). Here, 18 is the incremental number of repetitions except at the 2 ends in bending with 21 work rolls. Figure 11 shows the distribution of equivalent strain in the sheet thickness direction by bending with 21 work rolls, as given by FE analysis. Figure 12 shows the relationship between the equivalent strain calculated by FE analysis and the ferrite grain size observed in the experimental results. Because the ferrite grain size displays a substantially linear relationship with equivalent strain, it is estimated that the grains at the center of thickness were refined mainly by shear strain.

### 3.3. Influence of Rolling Temperature on Grain Refinement

Ferrite grains around 5 \(\mu m\) in size could obtained by bending when ferrite grains of around 10 \(\mu m\) were obtained in the as-hot-rolled condition, i.e., without bending. In order to evaluate the grain refinement effect of bending when the grain size after hot rolling is smaller, hot rolling experiments were performed at a lower temperature. Specimens were reheated in the range of 1 373 to 1 173 K for 30 minutes in the furnace, hot rolled to 3 mm at 1 323 to 1 123 K, water-cooled to 1 043 K, and then multi-bent at that temperature and air-cooled. Bending was performed at \(\delta=0\) mm and 5 mm. The Ar3 point changes to some extent depending on the reheating temperature and rolling temperature, but in this experiment, the bending temperature was fixed to 1 043 K in reference to the Ar3 point of 1 023 K under conditions of reheating at 1 373 K and rolling at 1 323 K.

Figure 13 shows the effect of the rolling temperature on the microstructure of the sheet surface. Figure 14 shows the relationship between the rolling temperature and ferrite grain size. At \(\delta=0\) mm, the ferrite grain size is refined as the rolling temperature decreases, and additional refinement of
the ferrite grain size is achieved by bending. A ferrite grain size of 2.2 μm at the sheet surface was obtained by lower temperature hot rolling and bending.

4. Conclusions

An accumulative bending process after hot rolling was proposed for the purpose of grain refinement of steel sheets.