The Effect of Soluble Lubricant on Surface Imprinting in Temper Rolling by 4 Hi Rolling Mill

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1. Introduction

The purposes of using lubricants in temper rolling are as follows: washing of the roll, cooling of the roll, preventing the adhesion of wear powder on the steel sheet surface, and preventing corrosion of the steel sheet after rolling. Lubricants also affect the surface imprinting of the dull roll surface. Although various studies have been performed,1–6) the effects of lubricants have not yet been clarified. Mineral oil or emulsion lubricant has good lubricity, but inhibits surface imprinting due to the formation of an oil film, and therefore, there is less surface imprinting than under the dry condition. Meanwhile, the use of a water-soluble lubricant with very low high-pressure viscosity is expected to result in surface imprinting better than a mineral oil or the dry condition.

In this study, the effects of the lubrication state on surface imprinting have been evaluated in temper rolling.7–14) Temper rolling experiments were performed using a 4-high rolling mill under the following three lubrication states: (1) with a water-soluble lubricant with low high-pressure viscosity; (2) with a mineral oil with high high-pressure viscosity; and (3) under a dry condition (without using any lubricants). Surface microstructures as well as surface textures, of the temper rolled strips were observed directly in terms of the arithmetical mean deviation of the assessed profile ($Ra$), the material ratio ($Rmr$), the three-dimensional profile, the cross-sectional profile, and the probability density applied to evaluate the surface imprinting.

2. Experimental Procedure

2.1. Materials

Both as-annealed high-carbon steel and as-annealed low-carbon steel were employed as sheet materials. The characteristics of the high-carbon steel strip are as follows: carbon content, 0.65 wt%; thickness, 0.62 mm; width, 50 mm; length, 250 m; upper yield point, 454 MPa; lower yield point, 427 MPa; elongation at the yield point, 4%. The characteristics of the low-carbon steel strip are as follows: carbon content, 0.08 wt%; thickness, 0.61 mm; width, 50 mm; length, 250 m; upper yield point, 328 MPa; lower yield point, 320 MPa; elongation at the yield point, 8%. The hardness of the high-carbon steel is 158 Hv (10), which is equivalent to 24 Hs. The hardness of the low-carbon steel is 95 Hv (10). These strips were degreased using an alkaline agent before temper rolling.
2.2. Lubrication states

The experiments were performed under three lubrication states: dry condition, water-soluble lubricant, and mineral oil. As shown in Table 1, water-soluble lubricant with a kinematic viscosity of 0.690 mm²/s, and mineral oil with a kinematic viscosity of 4.208 mm²/s were applied.

2.3. Temper rolling conditions

Table 2 shows the specifications of the 4-high rolling mill and the rolling conditions. We evaluated surface imprinting of a dull roll after 80 m of rolling considering the initial roll microwear. The work roll surfaces were dull-finished by either electric-discharged machining or shot blasting. Hereafter, these work rolls are referred to as the electric-discharged dull roll (ED roll) and the shot-dull roll (SD roll), respectively. The diameters of the ED roll and SD roll were both 131–133 mm. The diameter of the backup roll was 200 mm, and its Ra was adjusted to 0.25 µm. The hardness of the ED roll (83 Hs) was lower than those of the SD roll (89 Hs) and the backup roll (85 Hs). The rolling speed was set at 50 m/min. The strain rate of this rolling speed was equivalent to that obtained under the actual rolling conditions with a work roll diameter of 550 mm at a rolling speed of 200 m/min. The inlet and outlet tensions were set at 32.4 MPa and 47.1 MPa, respectively, which are equivalent to those under the actual rolling conditions. In addition, to evaluate the influence of the tension on the roll microwear, both the inlet and outlet tensions were set at 9.8 MPa, which is the minimum tension necessary for stable rolling. Moreover, the inlet and outlet tensions were set as 47.1 MPa and 58.8 MPa, respectively, which are higher than those of the actual rolling conditions. The reduction ranges were set at 1% and 3%.

2.4. Measurement of Reduction

Before rolling, markers were engraved on the surface of the whole steel strips at an interval of 300 mm. After rolling, the distance of markers were measured by slide gauge. On the basis of the elongation of the intervals, the reduction in rolling was calculated using the assumption of plane-strain deformation.

2.5. Observation of Roll and Steel-sheet Surface

After rolling, roll surface imprinting on the same place on the steel strip surface and roll surface was directly observed using a laser microscope. In the microscope image (the range of which was 0.35/H₁₁₀₀₃–0.30 mm), the focused image was recorded by shifting the stage in the Z-axis direction (roughness direction), and the recorded image was converted into three-dimensional profile data. On the basis of the obtained data, the surface imprinting was evaluated. In particular, Ra, the three-dimensional profile, the cross-sectional profile, the material ratio curve, and the probability density were used for this evaluation.

2.6. Measurement of Surface Imprinting

The surface imprinting was evaluated on the basis of various experimental results. The imprinting ratio is defined by

\[
\text{Imprinting ratio (\%)} = \frac{(R_a \text{ of steel sheet after rolling} - R_a \text{ of steel sheet before rolling})}{(R_a \text{ of roll after 80 m rolling} - R_a \text{ of steel sheet before rolling})} \times 100.
\]

3. Experimental Results

3.1. Surface Imprinting on High-carbon Steel

3.1.1. Surface Imprinting of ED Roll

High-carbon steel strips were rolled using the ED roll under the three lubrication states. Figure 1 shows the relationship between the reduction and rolling force. Under any...
lubrication state, no differences are observed in the rolling force among the lubrication states. Figure 2 shows the relationship between the reduction and imprinting ratio. At the reduction of 1%, no differences are observed in the imprinting ratio among the lubrication states. At the reduction of 3%, the lubrication states have a significant effect on the imprinting ratio. Namely, the imprinting ratio is the highest with the water-soluble lubricant, followed by dry rolling, and is the lowest when mineral oil is used. Figure 3 shows the laser microscope images of the roll surface and the steel-sheet surface after rolling. At the reduction of 1%, part of the roll surface texture is imprinted onto the steel-sheet surface. At the reduction of 3%, the detailed texture of the roll surface is imprinted on the steel-sheet surface. This tendency can be confirmed from the SEM images shown in Fig. 4. Figure 5 shows the cross-sectional profiles of rolls and rolled steel sheets. At the reductions of both 1% and 3%, peaks of the roll surface texture are imprinted onto the steel-sheet surface. Under the dry condition or when using the water-soluble lubricant, peaks of the roll surface are directly imprinted onto the steel-sheet surface and form valleys on the steel-sheet surface. On the other hand, when using mineral oil, the shape of valleys on the steel-sheet surface differs from that of peaks of the roll surface. Figure 6 shows the material ratio curves obtained using the three-dimensional profile data. In the figure, positive and negative sides of the vertical axis express peaks and valleys on the steel-sheet surface, respectively. For easy comparison with the steel sheet, positive and negative sides of the vertical axis are reversed for the roll surface; namely, the negative side expresses peaks of the roll surface. At the reduction of 1%, under all lubrication states, the shape of valleys on the steel-sheet surface approaches to that of the peaks of the roll surface. At the reduction of 3%, the shape of valleys on the steel-sheet surface is similar to that of the peaks of the roll surface with the dry rolling. With an increase of reduction from 1 to 3%, the shape of peaks on the steel-sheet surface approaches to that of the peaks of the roll surface with the water-soluble lubricant. However, this tendency is slight with the dry rolling and with the mineral oil. Figure 7 shows the probability densities obtained from the material ratio curves. In the figure, positive and negative sides of the vertical axis correspond to peaks and valleys on the steel-sheet surface, respectively. Under all lubrication states, the probability densities of the steel-sheet after rolling are slightly biased toward both peaks and valleys of the steel sheet at the reduction of 1%; namely, the difference in the probability density between the lubrication states is unclear. At the reduction of 3%, the probability densities of the steel sheets after rolling are greatly biased toward valleys on the steel sheet and the probability densities become close to the shape of the roll under all lubrication states. The probability densities of the steel sheets after rolling become closer to the shape of the roll under the conditions with the water-soluble lubricant and with the mineral oil than under the dry condition.

3.1.2. Surface Imprinting of SD Roll

High-carbon steel strips were rolled using the SD roll under the three lubrication states. Figure 8 shows the relationship between the reduction and the rolling force. At the reductions of 1% and 3%, no differences are observed in the rolling force among the lubrication states. Figure 9 shows the relationship between the reduction and the im-
printing ratio. At the reduction of 1%, no differences are observed between the lubrication states. At the reduction of 3%, the imprinting ratio is the highest with the water-soluble lubricant, followed by that under the dry condition. The imprinting ratio is the lowest when mineral oil is used as the lubricant. Figure 10 shows the material ratio curves. At the reduction of 1%, the shape of valleys on the sheet surface rolled under the dry condition is the closest to that of the peaks on the roll surface. With an increase of reduction from 1 to 3%, the shape of valleys on the sheet surface approaches to that of peaks of the roll surface with the water-soluble lubricant and with the mineral oil. However, this tendency is slight with the dry rolling. On the other hand, the shape of peaks on the sheet surface is closer to that of the valleys of the roll surface with the water-soluble lubricant and with the mineral oil than with the dry rolling at the both reductions of 1% and 3%. Figure 11 shows the probability densities. At the reduction of 3%, the probability densities of the steel sheets after rolling become closer to the shape of the roll when using the water-soluble lubricant than under the dry condition and when using the mineral oil. Moreover, the probability densities of the steel sheets after rolling become closer to the shape of the roll when using the water-soluble lubricant and mineral oil than under the dry condition.

3.2. Effects of Lubricants on Low-carbon Steel Strips

Low-carbon steel strips were rolled using the ED roll under the three lubrication states. Figure 12 shows the rela-

![Table 1](image1)

<table>
<thead>
<tr>
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<th>Reduction 1%</th>
<th>Reduction 3%</th>
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<td><img src="image3" alt="Image" /></td>
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<tr>
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<tr>
<td>Mineral</td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
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Fig. 4. SEM images of high carbon steel sheet surfaces after temper rolling with ED roll.

![Figure 5](image8)

Fig. 5. Cross section profiles of high carbon steel sheet surfaces after temper rolling with ED roll.

![Figure 6](image9)

Fig. 6. Material ratio curves of high carbon steel sheet surfaces with ED roll.
Fig. 7. Probability densities of high carbon steel sheet surfaces with ED roll.

Fig. 8. Comparison of rolling force/width between several rolling conditions (SD roll, high carbon steel sheet).

Fig. 9. Comparison of imprinting ratio between several rolling conditions (SD roll, high carbon steel sheet).
Fig. 10. Material ratio curves of high carbon steel sheet surfaces with SD roll.

Fig. 11. Probability densities of high carbon steel sheet surfaces with SD roll.
tionship between the reduction and the rolling force. The rolling force is the same for the three lubrication states. Figure 13 shows the relationship between the reduction and the imprinting ratio. At the reduction of 3%, the imprinting ratio is higher under the condition with the water-soluble lubricant and under the dry condition than under the condition with the mineral oil.

Figure 14 shows the material ratio curves. At the reductions of 1% and 3%, the shape of the valleys on the steel-sheet approaches to that of the roll curve and no differences are observed in the shape of valleys on the steel-sheet between the lubrication states. With an increase of reduction from 1 to 3%, the shape of valleys on the steel-sheet approaches to that of the peaks of the roll surface with the water-soluble lubricant. However, this tendency is slight with the dry rolling. Figure 15 shows the probability densities. The probability densities become closer to those of the roll when using the water-soluble lubricant than those under the dry condition and when using the mineral oil.

3.3. Effect of Lubrication States at Different Tensions

Low-carbon steel strips were rolled using the SD roll under three tension conditions. Figure 16 shows the influence of tension on the reduction and rolling force. When the tension decreases, the rolling force of the water-soluble lubricant does not exceed that under the dry condition. Figure 17 shows the relationship between the reduction and the imprinting ratio. Compared with that after rolling under the dry condition, the imprinting ratio does not increase when the tension decreases under the condition with the water-soluble lubricant. Thus, the imprinting ratio is high when using the water-soluble lubricant with high tension, and under the dry condition with low tension.

4. Discussion

The degree of surface imprinting is greater under the condition with the water-soluble lubricant than those under the dry condition and under the condition with the mineral oil. The reason is considered using the imprinting model shown in Fig. 18. Under the dry condition, metallic contact occurs between the roll surface and the rolled steel-sheet surface. Consequently, the roll surface is not deeply pressed into the rolled steel surface, and the degree of surface imprinting becomes low. In the case of rolling with mineral oil, an excellent lubricating ability could be achieved at the contact point between the roll surface and the rolled steel sheet surface as a result of the formation of an oil film. However, because of the pressure of the film of oil with high-pressure viscosity, the roll surface is not pressed deeply into the rolled steel-sheet surface, and the degree of surface imprinting is also low. In the case of the water-soluble lubricant, since the high-pressure viscosity of the water-soluble lubricant is very low, the influence of its oil-film pressure is small. Moreover, although the film is thin, it has a lubricating effect as an absorption film. For the above reasons, a good lubricating ability can be achieved at the contact point between the roll surface and the rolled steel surface. Consequently, the roll surface is pressed deeply into the rolled steel sheet surface, and the surface imprinting rate becomes high.

Thus, the state with a water-soluble lubricant having low high-pressure viscosity is superior to other lubrication states in terms of surface imprinting because of the good
Fig. 15. Probability densities of low carbon steel sheet surfaces with ED roll.

Fig. 16. Effect of tension on rolling force/width (SD roll, low carbon steel sheet).

Fig. 17. Effect of tension on imprinting ratio (SD roll, low carbon steel sheet).
lubricating ability. The surface imprinting is expected to be improved by using an appropriate water-soluble lubricant.

5. Conclusions

The effects of the lubrication states on surface imprinting by temper rolling have been evaluated. Temper rolling experiments were performed using a 4-high rolling mill under the following three lubrication states: (1) with water-soluble lubricant with low high-pressure viscosity; (2) with mineral oil with high-pressure viscosity; and (3) under a dry condition. The following results were obtained:

1. On the high-carbon steel strips, the water-soluble lubricant caused surface imprinting better than the dry rolling and than the mineral oil.
2. On the low-carbon steel strips, the water-soluble lubricant caused surface imprinting better than the mineral oil and almost equivalent to the dry rolling did. It was demonstrated that the effect of the water-soluble lubricant is greater on the high-carbon steel strip than on the low-carbon steel strip.
3. The effects of tension on surface imprinting were less with the water-soluble lubricant than under the dry condition.
4. Surface roughness imprinting is expected to be improved by using a water-soluble lubricant with minimum high-pressure viscosity and fairly good lubricating ability.

REFERENCES


Fig. 18. Models of imprinting of dull roll surface on mild steel sheet.