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Sticking in Hot Rolled Sheet of Ferritic Stainless Steel

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Abstract:

In hot rolling of ferritic stainless steel, prevention of sticking is very important from the viewpoint of productivity. However, the formation mechanism of sticking has not been clarified sufficiently. Therefore, in this work, rolling experiments were carried out using a tribo-simulator. The results clarified the following points: Sticking occurs more easily on ferritic stainless steel than on high strength steel. On ferritic stainless steel, the work roll sticks with the hot-rolled sheet at the entrance of roll-bite, and the work roll then moves forward on the hot-rolled sheet. Therefore, it is thought that the surface layer of the hot-rolled sheet is fractured by large shear strain, and the work roll stuck to the fractured layer advances further on the sheet, forming a defect on an accumulated fractured surface layer of the hot-rolled sheet. Applying a lubricant oil is effective for prevention of sticking between the work roll and hot-rolled sheet.

1. Introduction

It is well known that sticking defects form easily on the strip surface in hot rolling of ferritic stainless steel containing a large amount of chromium (Cr)[1, 2]. When these defects occur on a strip, it is necessary to change the roll, which increases operational costs related to work rolls. Sticking defects also increase the process load for removing defects in the following descaling process, which reduces production efficiency and strip yield. For these reasons, there is great demand for clarification of the formation mechanism of surface defects during hot rolling of ferritic stainless steel and establishment of preventive techniques.

Kato et al.[3–5] studied the formation of surface defects on rolls during hot rolling of stainless steel using an Amsler type hot abrasion device, and reported that the surface of the stainless steel damages due to friction with the work roll, forming micron-order flaky particles which are transferred to the roll surface. This process is then repeated, and the particles accumulate in layers and grow into surface defects. It was also reported that work rolls containing a large amount of graphite are effective in preventing surface defects. On the other hand, Toriumi and Azushima[6] reported that lubrication oil containing a sulfur additive was effective for preventing surface defects based on experiments using a sliding type hot rolling lubrication simulator[7, 8].

As an alternative to austenitic stainless steels, which contain the scarce element nickel, demand for high Cr ferritic stainless steels has increased recently from the viewpoint of resource saving. For this reason as well, clarification of the formation mechanism and establishment of preventive methods are increasingly important for stable production and prevention of surface defects during hot rolling of ferritic stainless steel.

Although some reports have investigated the causes and mechanisms of surface defects on work rolls, no reports have examined surface defects on the strip surface. As the reason for this, as will be described later, sticking defects of work rolls are often formed in the first half of the finishing mill, while the strip surface can be observed only after the final stand. In other words, it is not possible to observe the strip surface immediately after rolling by a work roll with sticking defects in the first half of the finishing mill. As another problem, a rolling simulator that reproduces sticking defects in steel sheets has not been developed.

Since sticking defects in strips greatly affect production efficiency and manufacturing costs, it is very important to clarify the formation mechanism and pro-

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pose preventive methods. Therefore, in this study, the authors observed sticking defects on hot strips at an actual production line, and then attempted to reproduce the sticking defects that occurred in the actual strips by using a sliding type hot rolling lubrication simulator. Based on the results, we estimated the formation mechanism of sticking defects and proposed a preventive method.

2. Survey of Sticking Defects

First, the surface defects of work rolls and hot strips in the production line were investigated. In the hot rolling of ferritic stainless steels, the surface defect size and depth vary greatly. As an example of significant sticking defects, **Figure 1** shows a photograph of the work roll surface of the front-side stands of a finisher, and **Figure 2** shows the profile of the work roll surface. (The measurement result of the work roll replica is displayed inverted; that is, a positive value corresponds to a concavity of the work roll.) The concave part of the work roll is a stripe-like defect having a width of about 1 to 2 mm extending in the circumferential direction, and the roll base material drops off at a depth of about 20 to 30 μm. This is the same result as in the reports by Kato et al.[4, 5]. **Figure 3** shows the surface appearance of a ferritic stainless strip after rolling to the final stand and pickling. The defects in the strip are elongated streak-like defects corresponding to the work roll defects. **Figure 4** shows the results of cross-sectional observation, and **Figure 5** shows the results of an EPMA analysis of the surface defects on the strip. Since the indented material has the same composition as the steel sheet, it is judged that the oxide film (scale) on the strip surface and the steel itself were indented into the strip surface. Moreover, because sticking defects in a work roll are observed in the front half of the finishing mill, the defects in the strip are considered to be elongated five to ten times by subsequent rolling. Nevertheless, the sticking defect is a deep defect with a depth of over 30 μm.

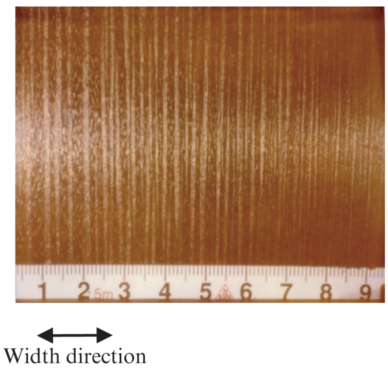

Fig. 1 Photograph of work roll surface after hot rolling of ferritic stainless steel strip[9)]

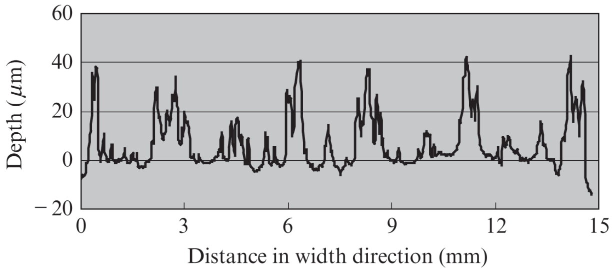

Fig. 2 Profile of work roll reprica[9)]

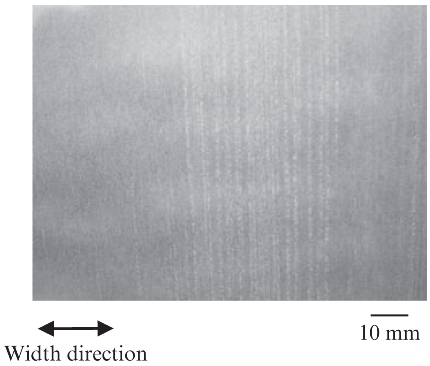

Fig. 3 Photograph of ferritic stainless steel strip surface after hot rolling and pickling[9)]

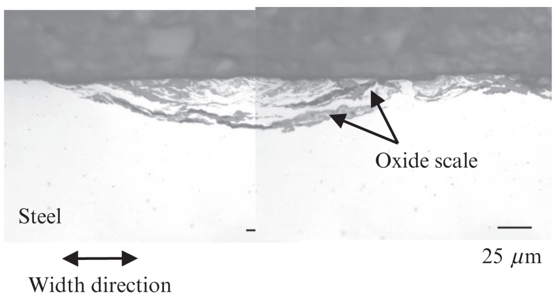

Fig. 4 Photograph of cross section of surface defect[9)]

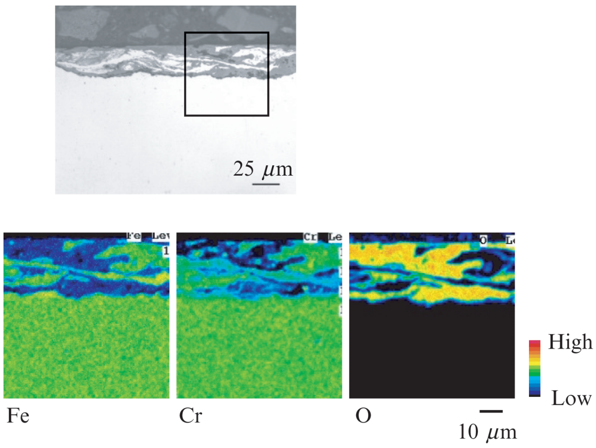

Fig. 5 Element mapping of surface defect by EPMA[9)]

As described above, this study clarified for the first time the fact that the linear defects formed in hot strips of ferritic stainless steel are defects in which material originating from the oxide film and the steel sheet itself are indented into the strip surface.

3. Experimental Procedure

In order to reproduce the sticking defects observed in actual strips and discuss the formation mechanism and preventive methods, it is important to observe the sheet surface immediately after formation of the sticking defect. Although sticking defects on the work roll can be reproduced with the Amsler type abrasion device used in Kato's research[3–5], this device cannot reproduce sticking defects in steel sheets, as hot-rolling of steel sheets is not possible. Therefore, in this study, we attempted to reproduce sticking defects in steel sheets by sliding rolling experiments using the hot rolling lubrication simulator developed by Azushima et al.[7, 8]. Since this tribo-simulator can increase the sliding speed difference between the work roll and the steel sheet to the same extent as that of the front stand of the finisher in the production line, it was considered possible to reproduce the severe deformation generated in an actual production line.

Figure 6 shows the appearance of the tribo-simulator. The Main stand (1) has a work roll diameter of 100 mm, a maximum speed of 207 m/min, a load capacity of 200 kN, and an allowable torque of 800 Nm, and only the upper work roll is driven. The Sub-stand (2) drives upper and lower work rolls and conveys the work piece at 8 to 32 m/min. The roll speeds of the Main stand and Sub-stand can be set to a speed ratio in the range of 6.3 to 24 by using the continuously variable transmission. The distance between the Main stand and the Sub-stand is 1 400 mm. The Furnace (3) is an infrared image type rated at 48 kW and can heat the workpiece up to 1 373 K. The Tensioning device (4) on the outlet side can be tensioned up to 3.5 kN by an air cylinder. It is possible to measure the torque and rolling load of the upper work roll on the Main stand.

High-Cr ferritic stainless steel (SUS444) and 590 MPa high strength steel (HSS) were prepared as workpieces. The high Cr ferritic stainless steel was Type 444 SUS containing 19.4 mass% Cr, 1.8 mass% Mo, and 0.4 mass% Nb. The HSS used for comparison was 590 MPa grade containing 0.2 mass% Si and 1.8 mass% Mn. The dimensions of the workpieces were 9 mm in thickness, 22 mm in width, and 3 000 mm in length. The materials for both workpieces were prepared by melting ingots to the specified composition by vacuum melting, followed by hot rolling to a thin thickness. The work pieces were then prepared by laser cutting and surface grinding. High-speed steel with a surface roughness of about 0.2 μmRa was used in the work roll.

Figure 7 shows the experimental procedure[7, 8]. As shown in Fig. 7 (a), the workpiece is first set on the table and a load is applied at the Sub-stand. Then, the workpiece end is clamped with the chuck part of the tension device, and a load is applied. The workpiece is heated at 1 073 K for 7 min using the infrared image furnace. Secondly, as shown in Fig. 7 (b), the workpiece with front tension is moved to the Main stand by being rolled in the Sub-stand (rolling velocity of Sub-stand: V). Next, as shown in Fig. 7 (c), as the heated zone of the workpiece reaches the Main stand, the heated workpiece is compressed by the upper roll, and the

①Main-stand, ②Sub-stand
③Furnace, ④Tension device

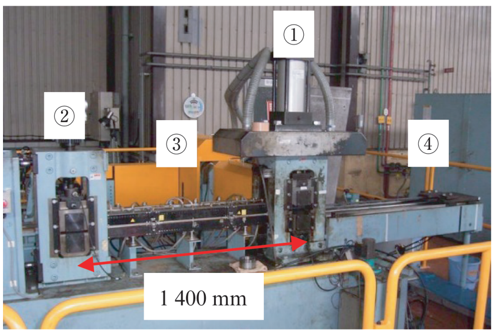

Fig. 6 Photograph of tribo-simulator[9]

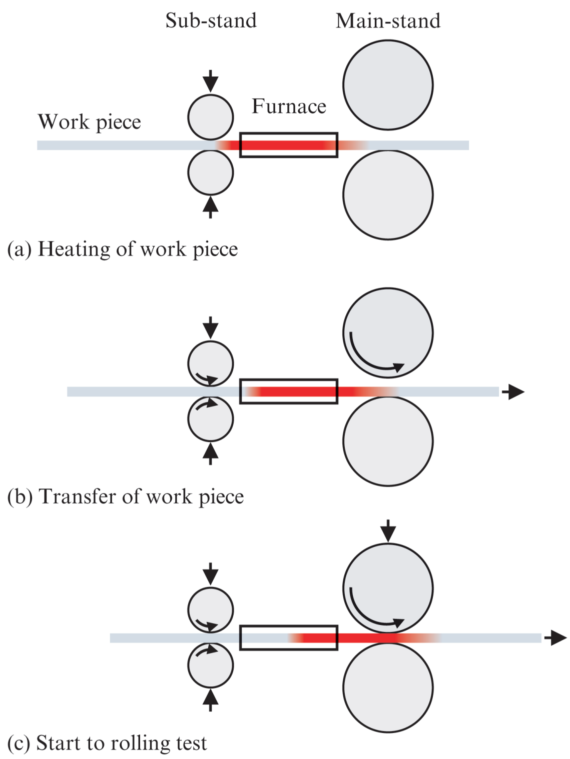

Fig. 7 Schematic illustration of experimental procedure[9]

workpiece is rolled at a constant sliding speed (rolling velocity of Main stand: U). The rolling force P and the upper roll torque G are measured under these conditions. The coefficient of friction μ can be calculated from P and G by using the following equation (1), where R is the roll radius.

$$\mu = G/PR \quad \cdots\cdots (1)$$

In this experiment, the Sub-stand speed V was set to 2 m/min, the Main stand speed U was set to 12 m/min or 24 m/min, and the sliding speed ratio γ was varied between 6 and 12. Reduction was 0.3 mm. Sliding rolling was performed by supplying cooling water between the work roll and the workpiece. The friction coefficient μ was calculated under each condition, and the longitudinal section of the workpiece after rolling was observed.

4. Experimental Results and Sticking Formation Mechanism

4.1 Experimental Results of Sliding Rolling

The formation of sticking defects with the SUS444 and HSS workpieces was compared. The rolling conditions were V=2 m/min and U=24 m/min (γ=12). **Figure 8** shows the experimental results. In the rolling test using SUS444, the test could not be completed normally because large noise occurred during hot rolling and the friction coefficient exceeded 1. **Figure 9** shows a comparison of the longitudinal sections of the workpieces after rolling, and **Figure 10** shows the appearance of the SUS444 after rolling. With the SUS444, significant sticking defects with large irregularities were formed. Thus, formation of sticking defects was much easier with SUS444 than with HSS.

The following three points were estimated as a possible explanation for the easy formation of sticking defects with ferritic stainless steel: (1) Ferritic stainless steel has a very thin oxide film, which has a lubricating effect. (2) The corundum-type Cr_2O_3 oxide film formed on ferritic stainless steel has poor plastic deformability. (3) Since the compositions of the work roll and the workpiece are similar, adhesion is likely to occur.

Figure 11 shows the longitudinal section of the SUS444, and **Figure 12** shows the results of element mapping of the sticking defect of the SUS444 by EPMA. It is observed that the steel sheet surface layer with a thickness of about 80 μm is peeled off from the base metal and folds down. This peeling of the surface layer seems to be broken not in the grain boundaries but in the grains. From the EPMA analysis, the composition of the folded part was the same as the composition of the rolled sheet, and not the work roll.

4.2 Discussion on Sticking Formation Mechanism

Based on the above observation results, the formation mechanism of the sticking defects in which the oxide film was pushed into the steel sheet was estimated. **Figure 13** shows a schematic illustration. Sticking occurs between the work roll and the workpiece

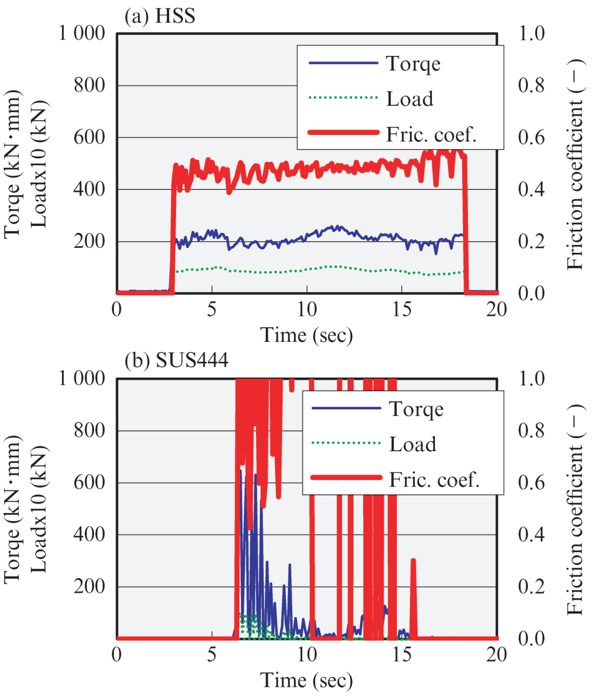

Fig. 8 Comparison of experimental results[9)]
(a) HSS, (b) SUS444

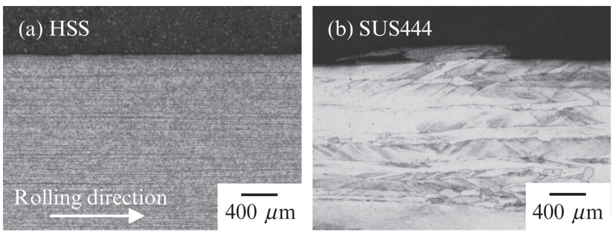

Fig. 9 Comparison of cross section of work piece[9)]
(a) HSS, (b) SUS444

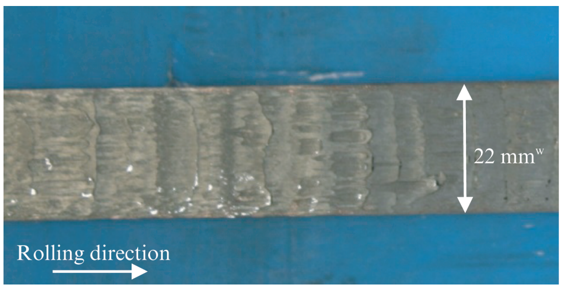

Fig. 10 Photograph of SUS444 surface after hot rolling[9)]

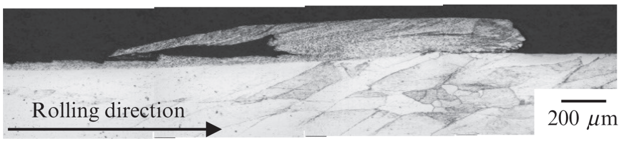

Fig. 11 Photograph of cross section of SUS444[9)]

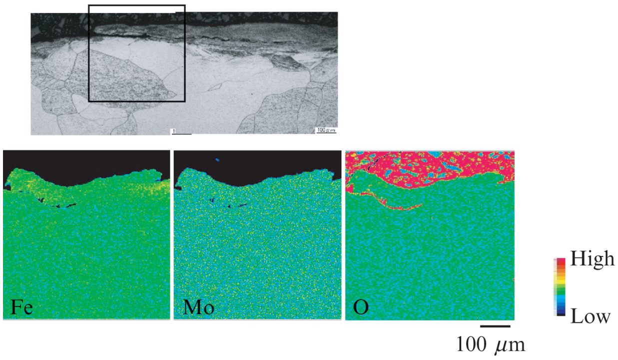

Fig. 12 Element mapping of SUS444 by EPMA[9)]

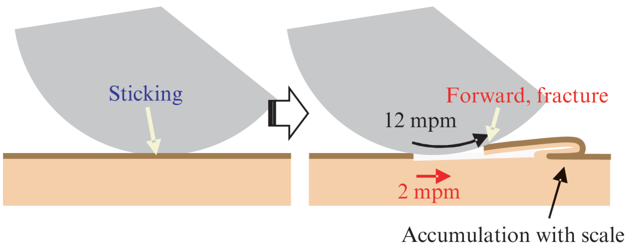

Fig. 13 Schematic illustration of sticking formation mechanism[9)]

due to the high pressure at roll-bite. After sticking occurs, the sticking part tries to advance further on the sheet because the work roll moves forward against the steel sheet. Very large shear stress exceeding the fracture stress is generated in the steel sheet surface layer, and the surface layer peels off from the base material. As a result, the peeled layer becomes a defect that is folded in the front part of the steel sheet. At this time, the oxide film (scale) on the sheet surface is also entangled with the peeled layer, forming a defect that consists of the accumulated fractured surface layer and scale. The defect is then elongated by subsequent rolling, and defects like those shown in Fig. 4 are formed. Here, it should be noted that the slip speed difference of 10 m/min in this experiment can easily occur in actual production lines.

As mentioned above, we succeeded for the first time in reproducing the formation of the linear defects of steel sheets observed in hot strips of ferritic stainless steel manufactured on actual production lines. Furthermore, we also estimated the formation mechanism based on those results.

5. Investigation of Sticking Defect Prevention in Steel Sheets

Considering the defect formation mechanism proposed above, reducing the speed difference between the work roll and the steel sheet and reducing the contact pressure between the roll and the sheet are considered effective measures for preventing these defects, but adoption of these measures may be difficult from the viewpoint of productivity. Therefore, prevention of sticking defects in steel sheets by supplying a lubricant oil was verified.

The same type of lubricant oil containing a sulfur additive as in Toriumi and Azushima[6)] was used, and a 10% emulsion was supplied between the work roll and the workpiece. The emulsion supply rate was 800 mL/min. The effectiveness of lubrication using this emulsion and water lubrication in preventing sticking defects during hot sliding rolling of SUS444 was compared under rolling conditions of V=2 m/min and U=12 m/min (γ=6). **Figure 14** shows the experimental results. In the case of water lubrication, large sticking defects that caused abnormal noise occurred. However, when the emulsion containing 10% lubricant oil was supplied, the rolling state became stable, μ was 0.39, and sticking defects did not form in the steel sheet. Thus, it became clear that supplying lubricant oil is very important for reducing the friction coefficient and preventing sticking defects in hot rolling of ferritic stainless steel.

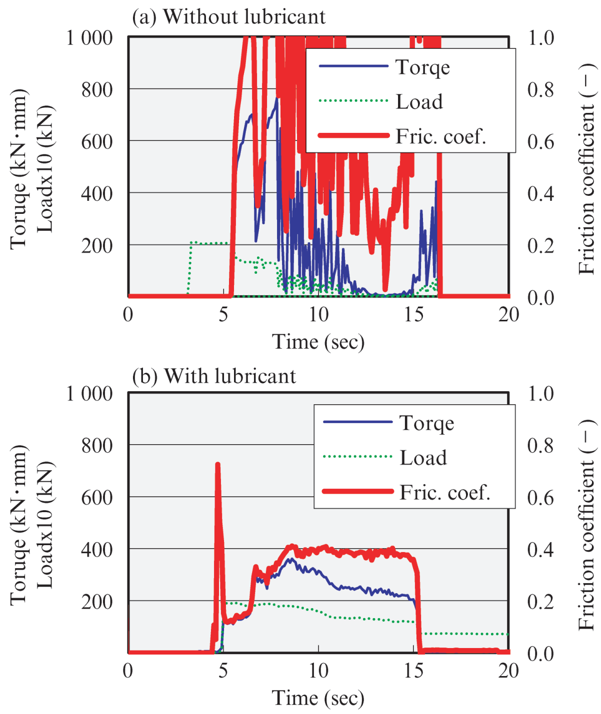

Fig. 14 Comparison of experimental results[9)]
(a) Without lubricant, (b) With lubricant

6. Conclusions

The authors investigated the sticking defects that occur in steel sheets during hot rolling of ferritic stainless steel, clarified the following points, and obtained useful knowledge for improving the production efficiency and yield of ferritic stainless steel.

(1) In hot strips manufactured on actual production lines, longitudinal linear defects in which a portion of the surface layer of the steel itself and the oxide film (scale) are indented into the strip surface were observed.

(2) Hot-rolling experiments with a tribo-simulator successfully reproduced defects like those that formed on actual hot strips. On ferritic stainless steel, the work roll sticks with the hot-rolled sheet at the entrance of roll-bite, and the work roll then moves forward on the hot-rolled sheet. Therefore, it is thought that the surface layer of the hot-rolled sheet is fractured by large shear strain, and the work roll with the adhering fractured layer advances further on the sheet, forming a defect consisting of the accumulated fractured surface layer and scale.

(3) The formation of sticking defects in steel sheets could be reduced by supplying a lubricant oil containing a sulfur additive.

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