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Deformation Behavior of Oxide Scale in Hot Strip Rolling

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Abstract

Oxide scale forming on steel surfaces during hot rolling significantly affects the surface quality of the products. In view of this, scale deformation during hot rolling has been examined using laboratory rolling mills of a 1/4 scale, and the following findings have been obtained. If the scale is thin before rolling, it will be smooth and have even thickness after rolling, but if it is thicker than 10 μ m before rolling, it will break during rolling and cracks visible with unaided eyes will form. The cracks form more easily as the scale thickness before rolling, and the rolling temperature increases. Strip surfaces turn red after rolling when the scale before rolling is 20 μ m or thicker and the rolling temperature is 900°C or lower; this is because the scale mainly comprising FeO is broken to powder during rolling and oxidized into red Fe₂O₂, during cooling.

1. Introduction

Steel strips are hot rolled in a temperature range from 800 to 1 200°C, and an oxide film called scale forms on the steel surfaces during heating and rolling. If steel is rolled with the scale on the surface, it leads to surface defects, and to prevent this, scale is usually removed with high-pressure water immediately before the steel goes into mill stands. At high temperatures, however, carbon steel is oxidized so quickly that, even when scale is removed, the steel is reoxidized immediately and rolling is always done on steel covered with scale. The existence of scale during hot rolling between steel and rolling rolls has significant effects on the tribology,¹⁻⁴) heat transfer,⁵ and steel surface properties.⁶⁻⁸ Various types of surface defects (scale defects) result especially from the deformation and breakage of scale.

This paper describes the formation behavior of scale on ordinary carbon steel and its mechanical properties and examines the scale forming conditions (scale thickness, rolling temperature, reduction ratio, etc.) and the mechanisms of its deformation during hot rolling, focusing on the cases where (1) it is stretched evenly,^{9–11} (2) it is cracked,^{12–22)} and (3) it is broken to powder.^{23–36)}

2. Test Method

Table 1 shows the chemical composition of the specimen plates used for the present test. Test pieces, 8-mm thick, 70-mm wide, and 300-mm long, were cut out by machining from slabs, 270-mm thick and 1 200-mm wide, continuously cast through a commercial caster, avoiding the portions up to 10 mm from the surface and 20 mm at

Table 1	Chemical	composition of s	pecimens	(mass%)
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0.15

		-	-	-	
С	Si	Mn	Р	S	Sol.Al

0.009

0.013

0.024

the thickness center.

0.005

(1) Test 1

0.05

Figure 1 schematically illustrates the equipment and method of the present test. Test pieces were encased in envelopes of stainless steel thin sheets (JIS SUS304, $0.3 \times 200 \times 300$ mm³ in size) and heated for 1800 s to 900 to 1200°C in a nitrogen atmosphere in an electric furnace. Rolling was conducted by exposing an end of a test piece out of the envelope, putting it into the roll bite of the No. 1 Mill, and then pulling it from out of the envelope. The rolling speed was set at 0.83 to 5.0 m/s, and the speed of the transfer table at 0.13 to 5.0 m/s so as to change the travelling time between the two mills and obtain the scale of different thicknesses. After rolling through the No. 2 Mill, the test pieces were water-cooled to room temperature in a nitrogen atmosphere, and the scale was observed through an electron microscope at the surface and a section. Note here that, of several test pieces tested under the same conditions (temperature, time between the mills), one went through the No. 2 Mill without reduction, and the thickness of its scale was defined as the scale thickness before rolling.

(2) Test 2

Two test pieces were stacked together and heated for 1800 s to 820–1280°C in a nitrogen atmosphere; this way, little scale formed

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Fig. 1 Test facilities

on the surfaces contacting each other. The stacked set was extracted from the furnace, held on a manipulator, unstacked, and air-cooled to oxidize. After the test pieces were cooled to predetermined temperatures (1000, 900, 850, 800, and 750°C) through 5 to 50 s of air cooling, one sheet of each set underwent three rolling passes and was then water cooled immediately, while the other was watercooled without rolling; the scale thickness of the latter was measured and defined as that before rolling. The reduction at each of the mills was set at roughly 20%, and the roll surface speed of each of them was set at 1.67 m/s. After the rolling, the test pieces were water-cooled to room temperature in the normal atmosphere. By measuring the L*a*b* index (under JIS 8729) of the water-cooled test piece surfaces using a colorimeter, their color was quantified in terms of psychometric chrome coordinates (a*), which agrees well with different degrees of redness by visual perception.

3. Test Results

(1) Test 1

Figure 2 shows the relationship between the scale thickness and oxidation time under the following conditions: test pieces were heated to 1040°C in the wrappings of stainless steel sheets, rolled to 4.5 mm on the No. 1 Mill while being extracted from the wrappings, transferred to the No. 2 Mill at speeds of 0.13 to 5.0 m/s, and rolled on the No. 2 Mill at a reduction ratio of 1.5% or less. The longer the transfer time between the mills, the thicker the scale became: the relationship between the transfer time and the scale thickness roughly followed a parabolic curve. It is thus possible to obtain different scale thicknesses before rolling on the No. 2 Mill by changing the transfer time between the mills.

Figure 3 shows example photographs of scale surfaces. Here, test pieces (a) and (b) were heated to 1020 and 1080°C, respectively, rolled on the No. 1 Mill to 4.5 mm, transferred to the No. 2 Mill in 2.5 and 7.4 s at speeds of 1.17 or 0.35 m/s, the temperature at its entry being 945 and 954°C, respectively, and rolled to 2.9 mm. When the transfer time between the mills was shorter and the scale before the rolling was thinner (7.2 μ m), the surface was even and smooth. In contrast, when the transfer time was longer and the scale was thicker (14.5 μ m), there were surface cracks running in the width direction.

The former case was examined in more detail. **Figure 4** shows sectional photomicrographs in the rolling direction of the test pieces that were transferred and oxidized between the mills in 0.8 s at a



Oxidation period between mills X (s) Fig. 2 Relationship between oxidation period and scale thickness



Fig. 3 Appearances of specimen sheets oxidized for (a) 2.5s and (b) 7.4s between Nos. 1 and 2 Mills

temperature of 900 to 920°C and rolled at reduction ratios of 5%, 25%, and 55%. Scale was rolled thinner as the reduction ratio increased; after rolling at a reduction ratio as large as 55%, the scale thickness (roughly 2.5 μ m) was even, and there were few cracks and no partial flaking off the base metal surface. The relationship between reduction ratio and scale thickness is shown in **Fig. 5**. The results obtained at the inter-pass oxidizing times of 0.3 and 2.9 s are also plotted in the graph. In any of the cases, the scale thickness after rolling decreased in proportion to the reduction ratio, which indicates that the scale was elongated during hot rolling.

Sectional photomicrographs of the scale after hot rolling at 200 to 1000°C are given in **Fig. 6**; in this test, the heating temperature and the inter-pass oxidizing time were changed such that the scale

thickness at the entry to the No. 2 Mill was roughly $12 \mu m$, and the reduction of the mill was set at 35%. At 1000°C, the scale thickness was substantially even and there were no cracks. Cracks in the



Fig. 4 Effect of rolling reduction on scale thickness after rolling



Fig. 5 Effect of rolling reduction on scale thickness after rolling



Fig. 6 Cross section SEM micrographs of scales after rolling

thickness direction increased as the rolling temperature lowered; in particular, at 600°C or lower, cracks across the whole scale thickness increased, and at 200°C, the scale was fragmented by rolling.

As can be seen in Fig. 3, as the scale thickness increased, there were visually discernible cracks at the sheet surfaces after rolling. The authors investigated the effects of the thickness of scale on its cracking, changing the heating temperature and the inter-pass transfer speed so that the steel temperature was from 600 to 1080°C and the scale thickness was from 2 to 16 μ m at the entry to the No. 2 Mill; in this test, the sheet thickness was 4.5 mm before the No. 2 Mill, and 2.9 mm after it.

Figure 7 shows the effects of the rolling temperature and scale thickness over scale cracking; the scale cracks when the rolling temperature is high and its thickness is large. Figure 8 shows surface and sectional photomicrographs through a scanning electron microscope (SEM) of scale after rolling at a reduction ratio of 33% at 950°C from an initial thickness of 14 μ m. The gray areas in the surface photo are scale, and the white areas the base metal substantially without scale. From the sectional photo, it is clear that the thickness of the scale in the gray areas is mostly the same as it was before rolling, which seems to indicate that, while the base metal is elon-



Fig. 7 Effect of scale thickness before rolling and rolling temperature on surface appearance



Fig. 8 Surface and cross section SEM micrographs of scale after 1st rolling



Fig. 9 Surface appearance of steel rolled at 900 °C and air cooled (Test 2) (a) Air cooled from 1 040 °C for 11 s (before rolling) (b) Air cooled from 1 240 °C for 29 s (before rolling)



Fig. 10 Effect of scale thickness before rolling on value of chromaticity (a*)

gated by rolling, the scale is divided rather than elongated. Where the scale was thick, whereas the front end of scale in the rolling direction (part A) was truncated nearly in right angles, the thickness gradually decreased towards the tail end (part B).

(2) Test 2

Different scale thicknesses were obtained by stacking two specimen sheets together, heating the stacks to different temperatures, separating the sheets from each other, and air-cooling them to predetermined rolling temperatures. As a result, the scale thickness ranged from 10 to $60 \ \mu m$ in Test 2, while the same in Test 1 was 20 μm at the largest.

As examples of steel sheet surfaces after rolling, Fig. 9 shows the surfaces of two sheets (a and b) that were heated, respectively, to 1040 and 1240°C, then air-cooled to 900°C for 11 and 29 s, respectively, rolled through three passes, and water-cooled. The one that was air-cooled for the shorter period and had the thinner scale (12 μ m) before the rolling had black surfaces, and the other that was cooled for longer and covered with thicker scale (30 μ m) was red. Figure 10 shows the relationship between the scale thickness before rolling and the chromaticity value (a*) of the sheet surfaces after rolling at 900°C. The thicker the scale before rolling, the larger the value of a*, that is, the redder the surfaces. The effect of rolling temperature over a* is shown in Fig. 11. When the rolling temperature was 900°C or lower and the scale thickness before rolling was 20 μ m or more, the a^{*} value was 0.5 or higher, meaning red scale, but when the rolling temperature was 1000°C, the a* value did not exceed 0.5, that is, there was no red scale, even when the scale before rolling was as thick as 50 μ m.



Fig. 11 Effect of scale thickness before rolling and rolling temperature on value of chromaticity (a^{*})

4. Discussion

4.1 Mechanical properties and deformation behavior of scale

With respect to the mechanical properties of scale at high temperatures,^{37–40} Matsuno et al.³⁸ conducted three-point bending tests and measured the hardness at high temperatures, and Hidaka et al.⁴⁰ carried out tensile tests and demonstrated that FeO was capable of plastic deformation at 700°C or above. Matsuno et al.³⁸ also conducted high-temperature tensile test of steel sheets with scale on the surfaces and exhibited that while scale was capable of elongating together with base metal maintaining adhesion, cracks formed at its grain boundaries.

When scale forming during hot rolling is thin, the surfaces are smooth after rolling, appearing as if scale is also elongated. As seen in Fig. 5, the thickness of the scale is reduced after rolling in proportion to the reduction of the base metal, and roughly speaking, the scale can be assumed to elongate at the same ratio as the base metal.

When scale apparently looks to do so, however, many small cracks are observed at the surface at close examination. Cracks are clearly discernible especially when rolling lubrication conditions are good, such as when roll surfaces are smooth and lubricant oil is applied. **Figures 12** and **13** show SEM photomicrographs of surfaces and sections, respectively, of scale after rolling at 920°C and at reduction ratios of 0, 3, 15 and 43% from an original thickness of 12 μ m.

When the reduction ratio is 0, the scale surface is rough, and grain boundaries are seen along the contours of unevenness. The grains are FeO crystals; there is only one grain in the thickness direction and the surface is covered with a thin film of Fe_3O_4 . Under 3% reduction, the crystal grains are flattened and the surface becomes smooth. In the 3% photo, cracks are seen to run along the grain boundaries. Under 15% reduction, the grain-boundary cracks are wider, and the scale crystals become separated from each other in the rolling direction. Under 43% reduction, each scale crystal is deformed and pressed into the base metal. Even when the scale is thin and is apparently elongated by rolling, close observation reveals that the boundaries between the FeO crystal grains are broken, and they are not elongated evenly. This agrees with the finding of Matsuno, Hidaka et al. that FeO is capable of plastic deformation at high temperatures, but its grain boundaries are easily broken.



Fig. 12 Surface SEM micrographs of scale after 2nd rolling



Fig. 13 Cross section SEM micrographs of scale after 2nd rolling

4.2 Relation between scale breakage and blistering

As seen in Fig. 3, when steel sheets have thick scale, cracks easily discernible with unaided eyes form at the scale surface after rolling; the distance between the cracks is sometimes as large as 10



Fig. 14 Mechanism of scale breakage during hot rolling

mm. It is difficult to consider that such cracks should form during the deformation in the roll bite. In fact the contact arc in the present test was as short as 13 mm, approximately, and it is hard to imagine that scale should be divided there at intervals of 10 mm.

As schematically illustrated in **Fig. 14**, scale is considered to break not in the roll bite but by cracking and flaking off the base metal at the entry to it. Thus, it is inferred that parts of scale that flaked off at the entry get into the roll bite at the roll circumference speed, and those that remain on the sheet surface proceed at the speed of the base metal. The gaps between the flaked pieces and the remaining ones appear as the cracks after rolling. The reason why the leading end of scale (part A) in Fig. 8 was roughly in right angles while the trailing end (part B) became gradually thinner is presumably that, at a leading end, the piece of scale that remained on the base metal is pressed into the metal keeping the thickness unchanged, while at the trailing end, the piece is not restricted and is pressed into the metal while being broken.

When steel is oxidized at high temperatures, scale gets off the metal surface to form blisters. Matsuno,⁴¹ Kizu,⁴² and Kondoh⁴³ et al. examined the forming of scale blisters, and reported that steel oxidation for only several seconds was enough for blister formation. The background of scale cracks, easily recognizable by unaided eyes, after rolling is probably that there are blisters before rolling, and scale undergoes rolling while being flaked off the metal at many positions. The scale scarcely cracks when the rolling temperature is low presumably because blisters do not form readily at low temperatures.

4.3 Red scale forming and scale breakage into powder

Asai et al. investigated the relationship between the color of scale and scale powder, and reported that steel sheet surfaces appeared red when there was hematite (α Fe₂O₃) in the powder, 2 μ m or less in particle size. This was also the case in the present study; there was hematite powder on the red sheet surfaces. Hematite powder forms when the scale is partially broken during hot rolling, and the FeO powder thus formed is oxidized further during cooling in the atmosphere to turn into α Fe₂O₃. As seen in Fig. 10, the surfaces of rolled sheets appear increasingly redder as the scale before rolling becomes thicker. This is presumably because the thicker the scale, the more scale powder is generated. On the other hand, Fig. 11 shows that scale does not appear red after rolling at 1000°C even when it is thick; this is probably because scale is deformable at high temperatures and is not easily pulverized.

5. Closing

The study results on the behavior of iron oxide scale during hot rolling of ordinary carbon steel sheets using laboratory rolling facilities have been summarized in this paper. The scale deforms during hot rolling depending on conditions such as steel temperature, roll properties, use or otherwise of lubricant, and scale thickness. While

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scale is rolled reasonably evenly with the base metal when it is thin, it tends to be cracked or broken into powder, easily leading to scale defects of the steel product, when it is thick. To understand the behavior of the scale in more detail and depth, it is necessary to examine its mechanical and thermo-physical properties at high temperatures and other basic physicality as well as the dynamics of stress inside scale layers during rolling.

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