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Effects of high-temperature hardness and oxidation on sticking phenomena occurring during hot rolling of two 430J1L ferritic stainless steels

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ABSTRACT

Effects of high-temperature hardness and oxidation on sticking phenomena occurring during hot rolling of two STS 430J1L ferritic stainless steels were investigated in this study. Hot-rolling simulation test was conducted using a high-temperature wear tester. The sticking started from the initial nucleation stage in which the rolled materials were stuck onto the roll specimen surface, proceeded to the growth stage in which stuck fragments grew further, and reached the saturation stage. The modified 430J1L steel had a smaller number of sticking nucleation sites and slower growth rate than the conventional 430J1L steel because of higher high-temperature hardness, thereby leading to less serious sticking. When the simulation test was conducted at 1070 °C, Cr oxides were formed on the surface of the rolled materials, and thus the sticking was drastically reduced because of the increased surface hardness of the rolled materials. In order to prevent or minimize the sticking, thus, it was suggested to improve high-temperature properties of stainless steels in the case of hot rolling at 900–1000 °C, and to promote the formation of oxides in the case of hot rolling at temperatures higher than 1000 °C.

1. Introduction

Hot-rolling conditions have become gradually complicated and severe in many rolling plants because of the increasing amount of thin plates and high-strength steel plates [1–5]. The rolling process is a very complex one, and is integrally affected by various factors such as abrasive wear, oxidation, thermal fatigue cracking, heat impact, and sticking of rolled material onto the roll [6–12]. The sticking means a phenomenon in which fragments of a rolled material are detached and stuck to a roll surface. It involves microscopic and dynamic processes occurring at interfaces between the roll and rolled material, and is almost impossible to be directly observed. Interpretation is also difficult because kinetic, thermal, chemical, and material factors are intricately interacted. Since the rolled material is repeatedly under stress and heat conditions during hot rolling, its surface is often damaged. This poses serious problems in rolling performance, and considerably deteriorates the surface quality of rolled products.

Recently, it was reported that the sticking was serious in stainless steels, especially in ferritic stainless steels [13], and that it was less serious when a high speed steel roll (HSS roll) was used instead of a high-chromium cast iron roll [14,15]. This indicates that the sticking is affected by microstructures and high-temperature properties of the roll and rolled materials as well as rolling conditions such as rolling temperature, speed, and load. For instance, ferritic stainless steels have excellent hardness and strength at room-temperature, but their high-temperature hardness drastically decreases at about 900–1100 °C where actual hot rolling starts, resulting in easy separation of the rolled material due to the plastic deformation. In addition, oxidation which can harden the rolled material surface as oxide layers or oxide particles are formed in the surface region at high temperatures would favorably affect the sticking [11,12]. These findings mean that the sticking is determined by mutual interaction of the roll and the rolled material, in which the rolling temperature and the subsequent oxidation also play as important factors. Thus, studies on the sticking are essential for improving the rolling performance and surface quality of rolled products, but only limited information is available on the sticking of ferritic stainless steels. In particular, how the oxidation behavior occurring at high temperatures under stressed conditions influences the sticking has hardly been known.

In this study, mechanisms of the sticking occurring during hot rolling of ferritic stainless steels were investigated by analyzing microstructures, mechanical properties, and oxidation behavior of the rolled materials. STS 430J1L stainless steels which are representative ferritic stainless steels were used for the rolled materials,

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Table 1
Chemical composition of the two STS 430J1L stainless steels and the HSS roll used (wt.%)

Steel	C	Si	Mn	P	S	CE[a]	W_{eq}[b]	Cr	Ni	V	Cu	Nb + Ti + Co	N
A	≤0.02	≤0.5	≤0.3	≤0.04	≤0.03	–	–	16–20	0.1–0.2	–	0.3–0.8	0.4–0.6	≤0.02
B	≤0.02	≤0.5	≤0.3	≤0.04	≤0.03	–	–	19–21	0.2–0.3	–	0.3–0.8	0.4–0.6	≤0.02
HSS roll	–	–	0.2–0.5	≤0.05	≤0.05	2.0	10–12	4–6	0.5–1.0	5.9	–	–	–

[a] CE = C + 1/3Si; carbon equivalent.
[b] W_{eq} = W + 2Mo; tungsten equivalent.

while an HSS roll was used for the roll. Hot-rolling simulation tests were conducted using a high-temperature wear tester which can simulate actual hot rolling. Based on the simulation test results, sticking mechanisms were investigated by correlating high-temperature hardness and oxidation behavior.

2. Experimental

Two STS 430J1L stainless steels, one of which contained more Cr and Ni contents than the conventional STS 430J1L steel, were used in this study. They were obtained from hot-rolled slabs, and their chemical compositions are shown in Table 1. For convenience, the conventional 430J1L steel and the modified 430J1L steel are referred to as 'A' and 'B', respectively (Table 1). The chemical composition of the HSS roll is also included in Table 1. The HSS roll was manufactured by a laboratory-scale horizontal centrifugal caster. The melt was charged into a high-speed revolving mold to form a shell part. Prior to solidification, a core part of nodular graphite cast iron was introduced to produce the roll (diameter, 400 mm; shell thickness, 65 mm; length, 600 mm). Roll specimens were obtained from the shell part, and were austenitized at 900–1100 °C for 1 h, air cooled, and tempered at 450–600 °C.

The stainless steels were sectioned, polished, electrochemically etched in a Viellela's etchant (picric acid 1 g + HCl 10 ml + C_2H_5OH 100 ml) at 2.5 V for 90 s, and observed by an optical microscope. Grain sizes were quantitatively measured by an image analyzer. The HSS roll specimen was etched by a Murakami etchant [16] (3 g $K_3Fe(CN)_6$ + 10 g NaOH + 100 ml H_2O), in which MC, M_7C_3, M_6C, and M_2C carbides are selectively etched but not the matrix, and were observed by an optical microscope. Tensile and hardness tests were performed for the HSS roll and the stainless steels since strength and hardness are closely related to sticking mechanisms [3,10,17–19]. Tensile specimens with a gauge length of 25.4 mm and a gage diameter of 6.3 mm were machined, and were tested at room-temperature and at a cross-head speed of 0.5 mm/min by a universal testing machine. Hardness was measured by a Vickers hardness tester under a 300 g load. High-temperature hardness also was measured under a 500 g load by a high-temperature Vickers hardness tester in the temperature range from room-temperature to 800 °C. 800 °C is the maximum temperature, up to which the high-temperature Vickers hardness tester allows, because the indenter might be ruined over this temperature.

Disc specimens were used for the simulation test of the hot-rolling process as shown in Fig. 1(a). Shape and dimensions of the roll and rolled disc specimens are shown in Fig. 1(b), and the initial surface roughness of the HSS roll specimen was 0.1 μm. The rolled specimen was heated by a high-frequency heating coil, and the roll specimen was cooled by water, like in the actual rolling process. Temperature of the rolled specimen was ranged from 900 °C to 1070 °C, revolution speed was 0.3 m/s, backward rear slip rate was 34%, and maximum contact stress was 565 MPa as determined by the Hertz formula [20]. The sticking amount was evaluated by measuring the weight of the roll specimen. Friction coefficient (μ) was calculated from the formula, $\mu = T/PR$ [21], where T, P, and R are torque applied on the revolving axis, vertical load on the roll specimen, and radius of the roll specimen, respectively. After the test, the surface and cross-section of the roll specimen were observed by a scanning electron microscope (SEM), and average surface roughness was measured by a roughness gage.

3. Results

3.1. Microstructure and mechanical properties of rolled and roll materials

Optical micrographs of the two STS 430J1L stainless steels and HSS roll are shown in Fig. 2(a) through (c). The grain sizes of the A and B steels are similar (132–133 μm). The microstructure of the two stainless steels is composed of ferrite, and contains a small amount of etch pits (Fig. 2(a) and (b)). In the HSS roll, M_7C_3 and M_2C carbides are formed along solidification cell boundaries, and MC carbides are formed inside cells (Fig. 2(c)). The matrix is mainly composed of lath-type tempered martensite [8,22].

Table 2 shows the room-temperature hardness and tensile test results of the A and B steels. The hardness of the A steel is 180 VHN,

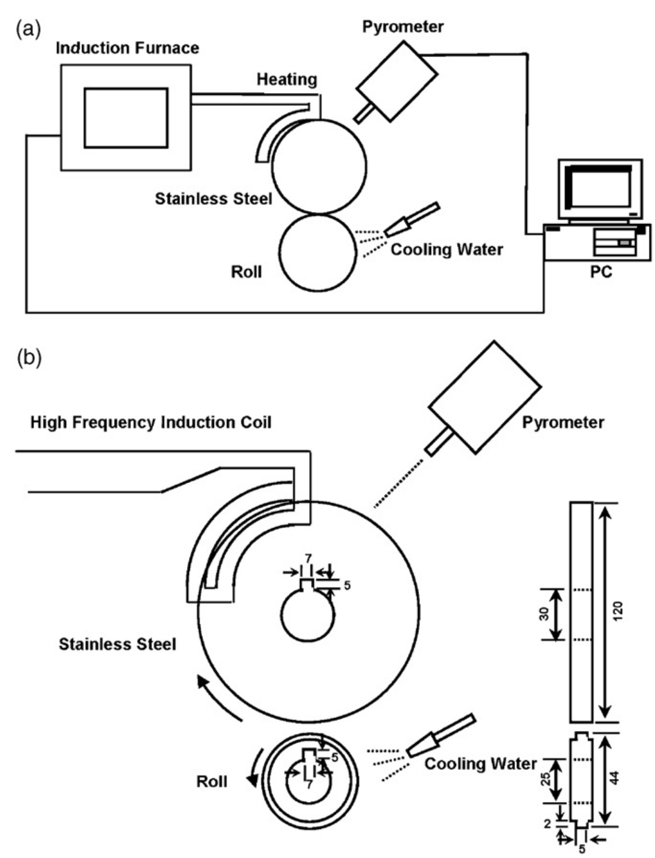

Fig. 1. (a) Schematic diagram of the high-temperature wear tester used for hot-rolling simulation. (b) Shape and dimensions of the disc specimens used for the hot-rolling simulation test (mm).