Influence of scale on hot rolling characteristics of Si-bearing steel sheets

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Abstract. In hot rolling processes, surface oxide layer, scale, may influence friction and affect rolling characteristics. Si-bearing steel was rolled between 1273 K and 1473 K after oxidation for 0 s to 40 s at a reduction of 30%. In Si-bearing steel, Fe$_2$SiO$_4$ is formed in the scale and causes eutectic transformation between FeO at 1450 K. The rolling force is affected by the eutectic transformation of the scale. If the rolling temperature is just below the eutectic temperature, roll force scatters and curling of the sheet occurs. This is due to inhomogeneous formation of the liquid phase because of the transformation.

1. Introduction
In hot rolling processes, an oxide layer called ‘scale’ is formed on steel surface by oxidation at high temperature. The scale influences the friction and heat transfer between rolls and workpiece and affects rolling characteristics significantly.

Scale microstructure formed on steel surface is affected by alloying elements and heating conditions. Scale growth and microstructure is rather affected by added Si [1]. Si is widely used to harden steels or to decrease hysteresis loss in electrical steel. On mild steel, the major component of the scale is FeO (wüstite). On Si-bearing steel, an Fe$_2$SiO$_4$ (fayalite) layer is also formed in the scale. At 1450 K, fayalite causes eutectic transformation between wüstite [2]. Liquid phase is formed in the scale above 1450 K. In low carbon steel, scale acts as a lubricant [3]. However, the scale on Si-bearing steel sometimes increases friction and causes surface defects and curling during rolling. Influence of scale on hot rolling characteristics is supposed to be affected by the alloying elements and the scale structure.

In this study, Si-bearing steel sheets were rolled after oxidation around the eutectic temperatures. The scale on the as-hot rolled sheet was preserved by sprinkling glass powder and observed by a scanning electron microscope (SEM) and energy dispersive X-ray analysis (EDX). Roll force, surface temperature and internal shear deformation were measured.

2. Experimental
3 mm thick Si-bearing steel (1% Si) sheets were received. After homogenization at 1473 K for 1200 s, the scale was removed by machining the surface. The cold sheet was inserted into an electric tube furnace at hot rolling temperatures (1273 K, 1373 K and 1473 K) filled with argon gas. After 900 s, the atmosphere was changed from argon to air to allow oxide scale to grow for 0 s, 10 s and 40 s. After
the oxidation, the sheets were immediately rolled on a two-high laboratory rolling mill of which roll diameter was 100 mm. The thickness was reduced by 30% without lubrication. Sheet surface temperature just after the hot rolling was measured by an infrared radiation thermometer. It is assumed that the emissivity is equal to unity. Roll force during rolling was also measured by the load cell. After passing the roll bite, glass powder was sprinkled over the sheet to preserve the scale as hot rolled [4]. Sectioned longitudinal plane (TD plane) at the center of the length was observed with a SEM. In order to investigate the frictional effect, internal shear deformation caused by the friction from the rolls was also assessed by a pin inserted into a sheet before the hot rolling. For this purpose, before the hot rolling, a hole was drilled through the thickness at the center of the sheet. The hole was filled with a steel pin 2 mm in diameter. After the hot rolling, the sheet was sectioned precisely at the center of the width and the longitudinal section was polished to observe the deflection of the interface between the pin and the sheet.

3. Results

3.1. Scale thickness before hot rolling
The thickness of the scale formed on the steel during oxidization is measured on SEM micrographs of the specimens glass-coated without hot rolling. Thickness increases with oxidation time as shown in Figure 1. Scale grew even in the case without oxidation time (t=0 s) because the sheet was oxidized slightly when the sheet was put into and taken out from the furnace. At 1273 K, the scale thickness was less than 5 μm after 40 s oxidation. At 1373 K, the scale was brittle and detached from the steel substrate during cooling before SEM observation. The thickness was 13 μm after 10 s oxidation. Scale grew much faster when heated at 1473 K. The scale thickness was 21 μm at 10 s oxidation. In this case, the scale is adhered to matrix steel.

3.2. Scale morphology before hot rolling
Longitudinal sections of the sheets before the hot rolling (r=0%) after 10 s oxidation are shown in Figure 2(a). At 1273 K, the scale formed on steel surface is very thin. The thickness was about 3 μm. At higher temperature, the scale consists of two layers which show different contrasts. At 1373 K, just below the eutectic temperature between FeO and Fe2SiO4, the lower scale (subscale) which is just above the metal surface contains many voids and has porous structure. If the temperature is above the eutectic temperature at 1473 K, the lower scale supposed to be liquid because the interface between the scale and the steel is irregular before rolling.

![Figure 1. Scale thickness before rolling measured on SEM micrographs as a function of oxidation time and temperature.](image_url)
EDX analysis was performed to analyse the subscale. Figure 3 shows the subscale at the interface with the steel substrate and distribution of Si. This subscale is supposed to contain fayalite because Si is detected in both cases. Si is also detected near the surface of steel substrate. SiO₂ is supposed to be formed due to intergranular oxidation and internal oxidation [5]. At 1373 K, Si is detected only in the subscale and near the surface of steel substrate. At 1473 K, liquid subscale penetrates deeply into the upper scale.

3.3. Scale observation after hot rolling
Longitudinal sections of the sheets after 10 s oxidation rolled by 30% reduction in thickness are shown in Figure 2(b). Rolling temperature is defined as heating temperature in the furnace. At 1373 K, the scale thickness was relatively uniform over the surface. The sheet surface was covered with thin scale layer. The interface between the scale and the steel sheet was smooth. At 1373 K, just below the eutectic temperature between FeO and Fe₂SiO₄, the scale after hot rolling was very thin. When the sheet was reduced by 30% in thickness, curling of the sheet occurred and the scale was detached from the sheet surface and adhered to a roll surface. The scale left on the sheet surface was very thin and the interface between the scale and the steel is relatively smooth. At 1473 K, above the eutectic temperature, when the sheet was reduced by 30% in thickness, the sheet does not curl up or down and the scale deformed into non-uniformly. The subscale is distributed intermittently to the rolling direction.

Figure 2. SEM micrograph on longitudinal section of the sheet oxidised for 10 s (a) before rolling and (b) after rolling at a reduction of 30% as a function of rolling temperature.

Figure 3. Longitudinal section of the sheet before rolling observed by SEM showing the morphology of the inner scale (subscale). Corresponding X-ray mappings show the distributions of Si.
3.4. Surface temperature

Surface temperature measured just after the hot rolling by a radiation thermometer is shown in Figure 4. The surface temperature decreases due to the heat transfer by touching the cold roll. For example, when a sheet was rolled at 1473 K after 0 s oxidation, the surface temperature decreased to 1230 K. Compared to the same reduction in thickness and rolling temperature, the surface temperature is higher when scale is thicker. The difference between 0 s and 40 s is about 30 K. The thermal conductivity of the scale, especially Fe$_2$SiO$_4$, is much lower than that of iron [6]. It is found that thick scale suppresses the heat transfer between roll and matrix steel.

3.5. Pressure multiplication factor

Pressure multiplication factor $Q$ is rolling load normalized by the ideal rolling force. The factor is calculated by measured roll force using the following equation (shown in Figure 5).

$$ P = Q k_m \sqrt{R' \Delta h w} \quad \text{Eqn. 1} $$

where $P$: roll force, $Q$: pressure multiplication factor, $k_m$: mean flow stress, $R'$: flattened roll radius, $\Delta h$: thickness draft, and $w$: width.

Theoretical pressure multiplication factor by Shida’s equation [7] assuming sticking friction is also shown. Below the eutectic temperature, the factor $Q$ is higher when the oxidation time is longer. The $Q$ value is close to the sticking condition. However, above the eutectic temperature, the factor $Q$ is lower when the oxidation time is longer. It is supposed that above the eutectic temperature, friction supposed to be in the slipping condition.

3.6. Internal shear deformation

Figure 6 shows the longitudinal sections including pin/sheet interfaces in the 30% rolled sheets. The interface, which was vertical before rolling, deforms into a C-shape by the frictional shear stress acting on the surface. The slope of the pin/sheet interface decreases with increasing oxidation time when the rolling temperature is just below the eutectic temperature at 1373 K. The internal shear strain at the quarter plane in thickness increases from 0.60 to 0.76. If the sheet is rolled above the eutectic temperature at 1473 K, the slope increases with increasing oxidation time. The internal shear strain...
decreases from 0.91 to 0.74. It is found that the internal shear deformation showing the frictional effect in hot rolling is much affected by the eutectic transformation of the scale.

4. Discussions

4.1. Scale morphology and adhesiveness
When the scale was formed just below the eutectic temperature at 1373 K, the scale was detached from the steel substrate during cooling before SEM observation. When the sheet was reduced by 30% in thickness, the scale was separated from the sheet surface and adhered to a roll surface. In this case, the subscale contains a lot of voids and has porous structure. It is supposed that the interface between the steel substrate and the scale is brittle just below the eutectic temperature due to the porous solid subscale. When the scale was formed above the eutectic temperature, the scale adheres tightly to the matrix steel before and after rolling. At this temperature, liquid phase is formed in subscale. This liquid subscale penetrates deeply into the upper scale. This subscale is supposed to increase the adhesion between the upper scale and the steel substrate to prevent the scale from detaching.

4.2. Effects on eutectic transformation of the scale to rolling characteristics
Figure 7 shows the supposed model of scale deformation during hot rolling of Si bearing steel sheet. In hot rolling of Si-bearing steel, rolling characteristics are sensitive to the eutectic transformation of the scale between FeO and Fe$_2$SiO$_4$.

If the rolling temperature is much lower than the eutectic temperature between FeO and Fe$_2$SiO$_4$, the amount of Fe$_2$SiO$_4$ is supposed to be small and have negligible effect. In this case, roll force decreases with scale thickness due to the relative sliding between the scale and the matrix steel as in the case of low carbon steel [3].

If the rolling temperature is just below the eutectic temperature, the scale was detached from the sheet surface and adhered to the roll surface when the sheet was reduced by 30% in thickness. Internal shear deformation is higher when the scale is thicker. The solid inner scale is supposed to increase the friction between the scale and the matrix steel. In this case, curling of the sheet occurs. This is due to the inhomogeneous formation of liquid scale phase because of the eutectic transformation. As shown in Figure 7(a), the subscale is solid below the eutectic temperature. However, when the sheet is hot rolled, the lower scale is supposed to be partially liquid due to the temperature rise related to friction or plastic work in rolling or non-uniform temperature distribution in heating. In this case, the sheet curls up or down because rolling is not stable due to non-uniform distributions of liquid scale.
If the temperature is above the eutectic temperature at 1473 K, the lower scale is distributed intermittently in the rolling direction after hot rolling. As shown in Figure 7(b), if rolling temperature is high and the scale has liquid phase during rolling, liquid lower scale flows freely and is squeezed out to the outermost surface. This liquid lower scale is supposed to reduce the friction between outer scale and matrix steel and decrease the internal shear deformation of the sheet.

5. Conclusions
In hot rolling of Si-bearing steel, rolling characteristics are sensitive to the eutectic transformation of the scale between FeO and Fe₂SiO₄. At 1373 K, just below the eutectic temperature, lower scale (subscale) which is just above the matrix steel shows porous structure. When the sheet is rolled at 30%, internal shear deformation increases with scale thickness. The sheet curls up or down due to non-uniform distributions of temperature and scale. When the rolling temperature is above the eutectic temperature at 1473 K, liquid phase is formed in the scale. This liquid lower scale flows freely and is squeezed out to the outermost surface during rolling. The internal shear deformation decreases with the scale thickness.

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