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Investigation of oxide scale on ferritic stainless steel B445J1M and its tribological effect in hot rolling

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Abstract

Severe sticking occurs in the hot rolling of ferritic stainless steel B445J1M. The characteristics of the oxide scale on the steel in hot rolling are associated with this phenomenon. The tensile failure of the oxide scale formed on the steel B445J1M was investigated by using a Gleeble 3500 thermo-mechanical simulator over temperature range from 1000 to 1150 °C in humid air. Two passes hot rolling were carried out on a 2-high Hille 100 experimental rolling mill. The results show that the temperature is a significant factor for the formed thickness of the oxide scale and its failure in tensile stress. On the specimen before hot rolling, irregular spinels are extruded from the surface of a thin oxide scale with Cr₂O₃ as its main component, which are hard and brittle at lower rolling temperature.

Keywords: steel; high temperature; sheet rolling; rolling friction; surface topography; surface analysis

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1. Introduction

Sticking often occurs in hot rolling of stainless steels. The sticking of bare metal to roll surfaces was strongly dependent on the high temperature tensile strength and the oxidation resistance of the stainless steel [1]. It is more difficult for oxide scale to be generated on the surface of stainless steels than that on the surface of carbon steels during high rolling temperature [2, 3]. Sticking refers to a phenomenon occurring in hot rolling process in which fragments of a rolled material are detached and get stuck onto a work roll surface, deteriorating not only the surface quality of the product, but also the rolls, which will result in shorter intervals of roll replacement or grinding [4, 5]. A sticking occurrence was more sensitive for the steels containing more chromium [6]. Fig. 1 shows the surface of high speed steel (HSS) roll after the sticking occurs during rolling stainless steel grade B445J1M. The B445J1M steel has high oxidation resistance in the reheating environment [2]. The HSS rolls shown in Fig. 1 were ground before hot rolling. The surface of the roll had circumferential scratch grooves after the sticking took place. These defects were appeared across the roll but more significant on where was close to the strip edges. This is caused by abrasion during the contact of the roll and the strip. Jin et al. [6, 7] and Ha et al. [1, 8, 9] have intensively investigated the sticking mechanism. For the rolled materials, the tensile strength and the oxidation behaviour of the materials affect the sticking in hot rolling.

In general, the water vapour contents between 7.0 and 19.5 vol. % in humid air are considered relevant to hot rolling [10]. In fact, the time intervals for oxidation of the hot steel strip are from half a second to about 30 s in the finishing stands of a hot strip mill [11, 12]. Because of high-temperature and high speed nature of hot working *in-situ* observation is extremely difficult. As the stock enters the roll gap, it is drawn in by frictional contact with

the roll, which is moving faster than the stock surface at entry. This produces a longitudinal tensile stress in the stock surface ahead of contact with the roll [13, 14]. The oxide scale can have transvers cracks or delamination by the tensile stress[14, 15]. The failure of the oxide scale on the steel stock in tensile stress displays the characteristics of the oxide scale before it enters the roll gap.

A novel design in Gleeble-3500 thermo-mechanical simulator chamber which can perform short time oxidation by controlling atmosphere and time was completed. Because of the capability of the Gleeble 3500, tensile tests can be carried out at different temperatures. In this paper, short time oxidation and tensile tests were carried out by the Gleeble-3500 thermo-mechanical simulator in a humid air that simulated the environment in the finishing mill during hot rolling of stainless steels. The effect of hot rolling temperatures and lubrication on the characteristics of the oxide scale of the steel B445J1M in hot rolling was investigated. The morphology of the oxide scale features of the strip before and after rolling was analysed. Deformation behaviour of the oxide scale and its effects on friction were also examined.

2. Experimental details

2.1. Material and specimen geometry

The chemical composition of the ferritic stainless steel B445J1M is shown in Table 1. The material used in the experiment was adopted from heat treated hot rolled strip. Fig. 2a shows the size of the specimen for the short time oxidation and tensile tests, and Fig. 2b shows the size of the specimen for the hot rolling test. In order to help bite the specimen, the sloping

front was machined. The surface of the specimens was ground and the measured surface roughness R_a is 0.25 μm . Each specimen was rinsed with acetone before testing.

2.2. Short time oxidation and tensile tests

Fig. 3 shows the set-up of Gleeble-3500 thermo-mechanical simulator system for performing the oxidation and tensile tests. Each specimen was spot-welded with a thermo-couple on the middle of the surface. The Gleeble 3500 chamber was at first evacuated to 30 m Hg after the specimen was mounted into the system, and then argon was released into the chamber to 1 atm air pressure. The specimen was then heated to the setting temperature at a rate of 20 $^{\circ}\text{C}/\text{s}$ and held for 30 s to achieve a uniform temperature. Argon flow was switched off while water vapour and air were released and kept flowing into the Gleeble chamber in $2.5 \times 10^{-4} \text{ m}^3/\text{s}$ for 180 s. Tensile tests were carried out at the strain rate 0.2 or 4 at the elongation of 20 %. At the end of tensile test, argon flow was switched on to stop any further oxidation. The sample was cooled to room temperature at a rate of 10 $^{\circ}\text{C}/\text{s}$.

2.3. Hot rolling test

Hot rolling experiments were designed for two passes rolling, which carried out on a 2-high Hille 100 experimental rolling mill with rolls of 225 mm diameter and 254 mm roll barrel length. Rolling force can be measured by load cells equipped on the mill. Rolling speed can be set from 0.12 to 0.72 m/s. By considering the roll speed in the real industry is far faster than that in the laboratory, in this study, the rolling speed was kept as 0.72 m/s. The reduction of 30 % was selected. Reheating was carried out in a high temperature electric resistance furnace with a chamber size of 350(W) $\times$ 330(H) $\times$ 870 (D) mm^3 . The reheating temperature was 1100 $^{\circ}\text{C}$ and the reheating time was 120 min for the first pass rolling. The reheating

temperature was 1050 °C for the second pass rolling, and the furnace chamber was full of nitrogen, in this way, to prevent oxidation and to keep the oxide scale as it was after the first pass rolling. The reheating time was only 15 min for the second pass rolling.

The specimens were first dry rolled at 1050 and 950 °C respectively. The second pass rolling was carried out 50 °C lower than that of the first pass. This method was to obtain the same thickness of the oxide scale on the specimens, but was rolled at different temperatures. The lubrication of hot rolling was also employed in which the emulsion of 0.5 % hot rolling oil was applied to the rolls when the specimen was rolled at 1050 °C for the first pass and at 1000 °C for the second pass.

All the specimens were placed immediately in a cooling box with nitrogen after rolling to prevent further oxidation.

2.4. Analysis and observation

The surfaces of the small and the rolled samples were covered with the mixture of epoxy resin and catalyst to protect the oxide scale for the further process. After 24 hours the resin coagulated, and then the protected oxide scale part was sectioned along the rolling direction by Stuers Accutom50 Cutting Machine to obtain the cross section of the oxide scale. Finally, the oxide scale sample was cold mounted, ground and polished and then etched for metallographic examination. To analyse oxide scale cross-section, all oxidised samples were prepared using a technique reported by Chen and Yuen [16] to minimise preparation damage to the oxide scale.

The microstructures, composition and thickness of the oxide scale were examined by JEOL JSM 6490 scanning electron microscope (SEM) equipped with an Energy Dispersive Spectrometer (EDS). The surface profiles were examined by digital microscope VHX-1000 with 2D/3D imaging and measurement capability. Topographic features of the thin oxide scale surface were examined using atomic force microscope (AFM) before rolling. X-ray diffraction was used for the phase identification of the oxide scale.

3. Results and discussion

3.1. The morphology of the oxide scale in the short time oxidation and tensile tests

The surface morphology of the oxide scale after short time oxidation and tensile tests were examined using digital microscope VHX-1000. Fig. 4 shows the crack patterns of the oxide scale. The horizontal direction is the elongation direction. Fig. 4a1 and a2 show the surface morphologies at 1000 °C at a strain rate of 0.2 and 4 s⁻¹ respectively. No oxide scale spallation was observed. There are very dense cracks on the surface, and bright yellow steel substrate can be seen in the cracks, indicating a very thin oxide scale. Fig. 4b1 and b2 show the surface morphologies at 1050 °C at different strain rates. No oxide scale spallation was observed. Dense oxide scale cracks (lighter colour) were observed. The oxide cracks appear narrower at the high strain rate than that at the low strain rate. Fig. 4c1 and c2 show the surface morphologies at 1100 °C at different strain rates. No oxide scale spallation was observed. The oxide scale cracks (lighter colour) are obviously less than those at 1000 and 1050 °C, especially at the strain rate of 4 s⁻¹. Fig. 4d1 and d2 show the surface morphologies at 1150 °C at two different strain rates. No oxide scale spallation was observed. The oxide

scale cracks can be seen but the colour is darker, and oxide scale cracks display less dense than those at lower temperatures. The oxide scale cracks appear narrower at the high strain rate.

The tensile failure of tertiary oxide scale is similar at different temperatures. There is no delamination or draft of the oxide scale showing that the oxide scale adheres to steel substrate during tensile loading, even after larger strain. The thin scales are compact without pores in the oxides at different temperatures. The through-thickness cracks of the oxide scale in tensile stress between 1000 and 1150 °C indicate that the Cr_2O_3 scale is more brittle than the steel substrate. However, the decrease in crack density shows less fracture of the oxide scale and the improvement of the scale ductility with increasing temperature. The difference of the oxide scale crack in higher strain rate indicates that the mechanical property of the Cr_2O_3 scale is strain rate dependent, which is like some ceramics, for instance, Al_2O_3 , Fe_2O_3 , FeO , at high temperatures [17, 18].

Fig. 5 shows the oxide scale thickness of the specimen oxidised for 180 s at different oxidation temperatures in air containing 18% water vapour. The oxide scale thickness increases with increasing temperature. At 1000 °C, the oxide scale thickness is less than 0.5 μm . At 1050 °C, the oxide scale thickness is about 1 μm , which is twice the thickness of the oxide scale at 1000 °C. At 1150 °C, the oxide scale thickness is nearly twice than that at 1050 °C.

Fig. 6a-d show the cross section of the specimens oxidised for 180 s at different oxidation temperatures in air containing 18% water vapour. The specimens were sectioned along the elongation direction. It can be seen that the oxide scale adheres to the steel substrate at different oxidation temperatures under the tensile stress. The oxide scale is compact and it is constituted of Cr_2O_3 . The black islands underneath the Cr_2O_3 scale are enriched in Si. Some researchers have concluded that SiO_2 formed at the metal-scale interface acts as a diffusion barrier which can reduce the rate of penetration of oxygen and also pegs the chromia scale onto the substrate [19, 20]. Fig. 6d shows a very thin oxide scale formed in the oxide scale cracks even with the protection of argon when the specimen was cooled down, indicating that there is an air residue and the exposed steel substrate can quickly form a thin Cr_2O_3 scale at 1150 °C.

The sticking phenomenon of the ferritic stainless steel is significantly affected by the distribution and volume fraction of oxides present on the steel surface [8]. Ha et al. [9] investigated the temperature effect on the sticking behaviour. The sticking is more likely to occur at the temperature range in which the rolled steel is soft with low tensile strength, and also little amount of oxide scale is on the surface. The work of Jin et al. [6] indicated that there was a critical oxide scale thickness (about 3.0 μm) in the suppression of the sticking phenomenon. The thicker oxide scale is desirable. This steel grade B445J1M displays very strong oxidation resistance more than other ferritic stainless steels, like SUS 430 [21, 22]. The thickness of the oxide scale is less than 2 μm at 1150 °C for 180 s in a humid air. Chen et al. [12] has studied the short time oxidation behaviour of low carbon and low silicon steels. The oxide scale thickness already reaches 75 μm on the sample oxidised at 1100 °C for 42 s.

It can be concluded that the oxide scale is barely generated on B445J1M in a short time oxidation when the temperature is below 1000 °C. The oxide crack patterns at different temperatures illustrate that more steel substrate will be exposed at lower temperatures under tensile stress. This indicates the sticking is more likely to occur at 1000 °C than that at or above 1050 °C. On the other hand, the oxide scale formed on B445J1M is not thick enough to prevent the sticking, therefore, the descaling process before the finishing rolling is not necessary.

3.2. Morphology of oxide scale before hot rolling

Fig. 7a-d shows the micrograph, the XRD patterns and topography of the oxide scale formed on the surface of the B445J1M steel oxidised at 1100 °C for 120 min before hot rolling. Fig. 7a shows the surface morphology of the oxide scale. Some coarse hexagonal spinel crystallites are embedded in the fine chromia scale matrix. A conventional diffraction meter operating with Cu-K α radiation was used for X-ray analysis by applying the step method with a constant counting time per step. The step method involves 0.02° steps and a counting time of 4 s at each step. Fig. 7b shows that the oxide scale is composed of Cr₂O₃, spinel M₃O₄, and little amount of TiO₂. M might be Cr, Mn, and/or Fe because of the similar ionic radii of Cr, Mn, and Fe [23]. The spinel is identified as (Mn, Cr)₃O₄ by EDS analysis. Fig. 7c shows the topographic 3D image of the oxide scale surface. Tetrahedral spinel oxide crystals were observed on the external surface. The spinels are with general formulation AB₂O₄ which crystallise in the cubic crystal system, with the oxide anions arranged in a cubic close-packed lattice and the cations A and B occupying some or all of the octahedral and tetrahedral sites in the lattice. The charges of A and B in the prototypical spinel structure are +2 and +3, respectively. Cr₂O₃ has a corundum structure. The corundum structure consists of an hcp

array of oxygen with two-thirds of the octahedral sites occupied by the metal [26-28]. The size of some spinels can reach 5 μm and some spinels are extruded from the surface, displaying the sharp edges. Fig. 7d shows the location A in Fig. 7c.

Fig. 8 shows the EDS element maps of B445J1M oxidised for 120 min at 1100 °C. The oxide scale is made up primarily of Cr, indicating that the main composition is Cr_2O_3 . Mn distributes across the oxide scale, showing high intensity at the interface of gas-scale. This indicates the spinel $(\text{Mn,Cr})_3\text{O}_4$. Si segregates at the interface of metal-oxide scale where the black islands underneath the Cr_2O_3 are.

3.3. Morphology and surface roughness of oxide scale after hot rolling

Fig. 9 shows surface morphology of the deformed oxide scale under two passes rolling. Fig. 9a and b show the same specimen rolled at 1050 and 1000 °C. There are transverse oxide scale cracks on the rolled surface, some of the oxide scale is fragmented and some tetrahedral spinel crystallites can be seen, but less in amount at the second pass. These SEM micrographs reveal that the surface with spinel crystallites is hard and lacks of plasticity. The exposed substrate between the oxide cracks is oxidised, but the thickness of the oxide scale will be significantly dependent on the temperature (Fig. 5). At the second pass, the spinel becomes brittle at a lower temperature and is broken by the rolls under the load. Fig. 9c and d show the same specimen rolled at 950 and 900 °C. In Fig. 9c, there are transverse oxide scale cracks, and the surface is similar to that in Fig. 9b. The spinel is more likely to be broken at the lower temperature under the high load. At the second pass, Fig. 9d shows that no spinel crystallite is observed.

Fig. 10 illustrates the longitudinal cross section of the oxide scale before and after the deformation. The thickness of the oxide scale before rolling is approximate 6.3 μm . Fig. 10a and c show that the thickness of the oxide scale decrease more at 1050 $^{\circ}\text{C}$, and more oxide fragments are observed at 950 $^{\circ}\text{C}$, indicating that the oxide scale exhibits the better ductility at higher temperature and the brittleness at a lower temperature. Fig. 10b and d show specimen at the second pass that were rolled at 1000 and 900 $^{\circ}\text{C}$ respectively. The interface of steel/oxide is rougher at the lower rolling temperature.

Fig. 11 shows the surface morphology and longitudinal cross sections of the specimen that were rolled at 1050 $^{\circ}\text{C}$ for the first pass and at 1000 $^{\circ}\text{C}$ for the second pass with emulsion. There are transverse oxide scale cracks but the crack gap is smaller than that without emulsion. Similar to dry hot rolling, the oxide scale is fragmented, but the uniformity of the oxide scale and steel/oxide interface are better than that in the dry hot rolling.

Fig. 12 shows oxide scale thickness after hot rolling. The steel/oxide interfaces are rough in all rolling conditions, and causing big standard deviation of the oxide scale thickness for the measurement. The oxide scale was fragmented and was indented to the matrix steel. This characterisation of the oxide scale is attributed to its hard and brittle properties [24].

Surface roughness of the stainless steel sample after hot rolling test was measured using Hommel Tester T1000 wave. The vertical resolution is 0.01 μm . The sampling length is 0.8 mm and the evaluation length is 5 sampling length. The roughness was measured along the rolling direction on the surface without oxide scale cracks and at least repeated 5 times. Fig. 13 shows the relationship between the surface roughness and the rolling temperature and passes. R_a is the arithmetic average of the absolute values of the roughness profile ordinates. R_y is a maximum height of the profile. R_{Pc} is the peak Count, which is always used in sheet metal industry to measure quality of surfaces subjected to bending, forming and painting, and where appearance is critical.

When the specimen is firstly rolled at 1050 $^{\circ}\text{C}$, the surface roughness R_a is lower than that at 950 $^{\circ}\text{C}$. At the second pass, the surface roughness R_a declines and lowest surface roughness is achieved with lubrication. The surface roughness R_a increases at the second pass when the specimen was firstly rolled at 950 $^{\circ}\text{C}$ in dry condition. R_y increases when the specimens were rolled at the second pass in dry rolling condition, but R_y decreases at the second pass when the specimen was first rolled at 1050 $^{\circ}\text{C}$ in lubrication condition. R_{Pc} decreases at the second pass in all cases. The sample that was rolled at 1050 $^{\circ}\text{C}$ in lubrication condition exhibits the lower surface roughness at the first and second pass.

The surface of an oxidised hot steel strip is reported to be rough [25]. The oxide scale may be depressed deeper into the strip surface and the hot metal is extruded outward to fill the void between the oxide scale cracks, thus a rougher surface is generated [26]. The roughness

values of the steel surface increase with an increasing coefficient of friction at the roll–scale interface. However, the increment of the roughness is limited. Higher rolling speed corresponding to higher strain rate of the steel has complex effect on the surface roughness [27], but with the descaled thin oxide scale on, the surface roughness decreases with increasing rolling speed [28]. The temperature also affects the scale roughness transfer [27]. Chang et al. [29] found that the rolling temperature is an important factor affecting the surface roughness R_a of low carbon strip. When the amount of the outer brittle $\alpha\text{-Fe}_2\text{O}_3$ formed above 927 °C increases, the roughness of the product will increase.

3.4. Inverse calculation of coefficient of friction

The coefficient of friction is calculated by a formula developed by Alexander [30] on the basis of Oroman's model. This model is described in [31-33].

$$\frac{d(\sigma_x h)}{dx} + p \frac{dh}{dx} \mp 2\mu p = 0 \quad (1)$$

where p is the roll pressure, h is the strip thickness, σ_x is the stress in the rolling direction and x is the distance in the direction of rolling. The sign of the frictional traction in Eq. (1) changes from being negative to positive at the neutral point[34].

According to [35], the yield stress of the steel can be described as

$$\sigma = \sigma_0 \cdot e^{-aT} \cdot k_1 \varepsilon^{m_1} \cdot k_2 \dot{\varepsilon}^{m_2} \quad (2)$$

where σ is the yield stress, σ_0 the base yield stress, ε and $\dot{\varepsilon}$ the true strain and strain rate (s^{-1}) respectively, T the temperature in K , and a, k_1, k_2, m_1 and m_2 are constants.

In Alexander's program, the flow stress is modified in the following form [30].

$$\sigma = A \cdot (1 + B\varepsilon)^{n_1} \cdot (1 + D\dot{\varepsilon})^{n_2} \quad (3)$$

In which $A = \sigma_0 \cdot e^{-aT}$, where B, D, n_1 and n_2 are constants. Assuming $D = B = 1000 \gg 1$, Eq. (2) still complies with Eq. (2). Sufficiently, A, n_1 and n_2 in Eq. (3) are determined by multiple-regression.

The hot rolling tests were carried out in the temperature range from 950-1050 °C. Because the rolling speed is unchanged, the strain rate is in the range 7 - 18 s^{-1} that depends on rolling reduction. In order to determine the flow stress model adapted by Alexander's program, compression tests were carried out for the steel B445J1M on Gleeble-3500 Hydro Wedge testing system at the strain rate of 10 s^{-1} . Fig. 14 shows the compressive true stress-strain curves for the B445J1M ferritic stainless steel between 900 and 1150 °C. Decreasing the deformation temperature leads to an increase of the flow stress of the steel. The stress-strain curves which were for fits of Eq. (3) at different temperatures were used to calculate the coefficient of friction in hot rolling.

A programme was developed according to Eq. (1) by software FORTRAN. The coefficient of friction was adjusted to a number until the output separating rolling force is less than 1% error with measured value. The output parameters are total rolling force, roll pressure, roll torque per width, angle in the roll bite, nominal pressure, neutral angle in radians, and the forward slip, defined as the relative difference in roll surface/strip exit velocity. Fig. 15 (a) shows the relationship between the coefficient of friction and the rolling temperatures. With same thickness and composition of the oxide scale on the steel substrate, the two pass hot rolling which was carried out at the higher temperature exhibits lower coefficient of friction, and with the applied emulsion, the coefficient of friction is lower than that in the dry rolling.

Many researchers presented formulas to calculate friction coefficient for hot rolling of flat steel [36, 37]. Usually the ductility of the steel and the oxide scale increases if the temperature is high enough, and then frictional resistance decreases. Lenard et al. [35], by quoting Geleji's work, described friction coefficient as linear functions of work-piece temperature and rolling speed depending on different roll materials. The friction coefficients are given by:

$$\mu=1.05-0.0005T-0.056v \quad \text{for steel rolls} \quad (4)$$

$$\mu=0.94-0.0005T-0.056v \quad \text{for double poured and cast roll} \quad (5)$$

$$\mu=0.82-0.0005T-0.056v \quad \text{for ground roll} \quad (6)$$

where T is the work-piece temperature in $^{\circ}\text{C}$ and v is the rolling velocity in m/s .

Emulsion possesses many favourable properties such as good lubricating ability, excellent cooling efficiency, non-flammability, low environmental effect and low cost, therefore, it has been widely used in hot rolling mills [38-40]. During hot rolling, the surface of the oxide scale is made up of asperities and when two surfaces are placed in contact only the tips of the asperities touch. Forces normal to the surface deform the asperities and they weld together at points of contact. Forces parallel with the surfaces are resisted by the shearing strength of these junctions. By applying oil in water emulsion on the rolls, full film or boundary lubrication can be achieved [41-43], therefore the direct contact of metal to metal or metal to oxides can be eliminated, and this results in reducing friction and the roll wear, which would lead to a smaller surface roughness [26].

The oxide scale formed on B445J1M is primarily made of Cr_2O_3 , and some spinel $(\text{Mn,Cr})_3\text{O}_4$ is on the top of Cr_2O_3 . The reported hardness values of the bulk Cr_2O_3 were from 918 to 3008 HV [44], and the hardness of the chromite spinel is above 669 HV (Mohs 5.5). In our study, the measured vicker hardness of the oxide scale on B445J1M is between 947 and 989 HV at room temperature. When the oxide scale is formed on carbon steel at high temperature, the relative thickness of FeO : Fe_3O_4 : Fe_2O_3 are in the ratio of roughly 95:4:1 at 1000°C [45]. The hardness of FeO , Fe_3O_4 , and Fe_2O_3 are 460, 540 and 1050 HV, respectively at room temperature [46]. Although Fe_2O_3 is very hard it is only a small fraction of the whole oxide scale. Plastic deformation occurred for FeO tested above 700°C [47]. FeO was also found to reduce sticking in hot rolling stainless steel [48]. On B445J1M, the hard oxide is the only composition of the oxide scale, exhibiting little plasticity at the lower

temperature, and is easily fragmented (Figs. 9c and 10c). Some big and extruding spinel crystallites, as shown in Fig. 15b, will increase the possibility of scratching the roll surface, and the lower the temperature the harder the oxide scale. Once there are more scratches on the roll surface, the sticking will become significant because these scratches might provide the nucleation site for the sticking particles, and the sticking particle grows more and more on the site as the rolling processes [6]. At a higher temperature, the thicker oxide scale (Fig. 5) and less dense of the oxide scale cracks (Fig. 4) will be beneficial to decrease the sticking.

In the study of Jin et al. [6], five different stainless steel grades were heated at 1050 °C and the heating time is between 0 and 550 sec. The thicknesses of the oxide scale were presented but no information about the compositions. In the case of the steel grades 445 and 446, because of their high amount of Cr, the main composition of the oxide scale is supposed to be Cr_2O_3 at 1050 °C in 550 sec. The sticking is more likely to occur when the oxide scale is thin and hard. The less sticking behaviour of the steel 409L and 430 should be attributed to their softer and thicker oxide scales with iron oxides as their compositions.

Spinel crystallite structure oxide always exists in the hot working of stainless steels. For instance, ferritic stainless steel SUS 430, the Fe-Cr spinel is located upon the steel substrate [21]. Ferritic stainless steel B445J1M, the Mn-Cr spinel is on top of the Cr_2O_3 scale [2]. The hardness of the spinel oxides was found harder than Fe_3O_4 [49]. Cr_2O_3 is even harder than Fe_2O_3 [50, 51]. Lundberg et al. [52] reported that the composition of the oxide is important since the oxides have different properties. Abrasive wear may become severe when a significant amount of Fe_3O_4 and Fe_2O_3 exist [36]. The abrasive wear rate is also dependent on the hardness of the abrading oxide particles over the area of contact between the rolls and the

stock, and on the load level. In our study, on the steel B445J1M, the very hard oxide scale, consisted of Cr_2O_3 and Mn-Cr spinel oxide, will cause severe abrasive wear. However, if the composition of the oxide scale change to softer iron oxides, for instance, by raising reheating temperature and rolling at higher temperature, this sticking behaviour will be reduced.

4. Conclusions

Short time oxidation and tensile tests of the ferritic stainless steel B445J1M were carried out in a humid air by a Gleeble-3500 Thermo-mechanical Simulator. Hot rolling tests were carried out on a 2-high Hille 100 experimental mill.

1. In the temperature range of 1000-1150 °C, the formation of the oxide scale on the steel during short time oxidation is less than 2 μm , and only Cr_2O_3 is its composition. Temperature has a significant influence on the thickness of the oxide scale of the steel.
2. On the steel the oxide scale has transverse cracks in the tensile stress at high or low strain rate, but it adheres strongly to the steel substrate. The oxide scale formed at high temperature exhibits less dense oxide scale cracks, and a very thin oxide scale reappears on the exposed steel substrate.
3. Before hot rolling, the oxide scale formed for 120 min at 1100 °C is primarily constituted of Cr_2O_3 , and some irregular spinels are extruded from the surface with a crystallite structure. The main composition of the spinel is $(\text{Mn,Cr})_3\text{O}_4$.
4. The steel exhibits lower coefficient of friction at the higher rolling temperature. The oxide scale is thinner, harder and more brittle at or below 1000 °C than that at 1050

°C. The roll wear is mainly abrasive wear, which is caused by the hard oxide scale with some coarse spinels on the top.

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Table Captions:

Table 1 Chemical composition (wt. %) of the ferritic stainless steel B445J1M.

Figure Captions:

Fig. 1 The surface feature of HSS roll after the sticking occurs

Fig. 2(a) Specimen for short time oxidation and tensile test (b) specimen for hot rolling test

Fig. 3 The set-up of Gleeble-3500 thermo-mechanical simulator system and the thermo-cycle diagram for oxidation and tensile tests

Fig. 4 Micrographs showing micro-cracks on the specimen surface (a1) 1000 °C, $\dot{\epsilon}=0.2 \text{ s}^{-1}$, (a2) 1000 °C, $\dot{\epsilon}=4 \text{ s}^{-1}$, (b1) 1050 °C, $\dot{\epsilon}=0.2 \text{ s}^{-1}$, (b2) 1050 °C, $\dot{\epsilon}=4 \text{ s}^{-1}$, (c1) 1100 °C, $\dot{\epsilon}=0.2 \text{ s}^{-1}$, (c2) 1100 °C, $\dot{\epsilon}=4 \text{ s}^{-1}$. (d1) 1150 °C, $\dot{\epsilon}=0.2 \text{ s}^{-1}$, (d2) 1150 °C, $\dot{\epsilon}=4 \text{ s}^{-1}$

Fig. 5 The oxide scale thickness after short time isothermal oxidation at 1000 -1150 °C, in air with 18% water vapour

Fig. 6 Micrographs of the cross section of the oxide scale, after the oxidation and tensile tests at $\dot{\epsilon}=4 \text{ s}^{-1}$. (a) 1000 °C (b) 1050 °C (c) 1100 °C and (d) 1150 °C

Fig. 7 Surface features of the B445J1M steel oxidised for 120 min at 1100 °C: (a) micrograph of the surface of the oxide scale, (b) XRD pattern of the oxide scale, (c) 3D topographic image of the oxide scale, and (d) the enlarged micrograph in (c)

Fig. 8 EDS element maps of the cross section of the B445J1M steel oxidised for 120 min at 1100 °C.

Fig. 9 Deformed oxide scale surface micrographs: (a) first pass; rolled at 1050 °C (b) second pass; rolled at 1000 °C (c) first pass; rolled at 950 °C (d) second pass; rolled at 900 °C

Fig. 10 Cross section of the oxide scale. Left: SEM micrograph of the fractured oxide scales before rolling (a) first pass; rolled at 1050 °C (b) second pass; rolled at 1000 °C (c) first pass; rolled at 950 °C (d) second pass; rolled at 900 °C

Fig. 11 Deformed oxide scale micrographs after the emulsion was applied to the rolls: (a) and (c) first pass; rolled at 1050 °C (b) and (d) second pass; rolled at 1000 °C

Fig. 12 Oxide scale thicknesses before and after hot rolling

Fig. 13 The relationship between surface roughness and rolling temperature and rolling pass. (a) Ra (b) Ry and (c) Rpc

Fig. 14 True σ - ϵ curve of the steel at the strain rate of 10 s^{-1}

Fig. 15(a) Coefficient of friction at different rolling conditions, and (b) schematic plot of hot rolling the steel B445J1M

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Table 1 Chemical composition (wt. %) of the ferritic stainless steel B445J1M.

	C	Si	Mn	P	Cr	Cu	Mo	Ti	Nb
B445J1M	≤0.01	0.30	0.15	0.03	21.50	0.10	0.60	≤0.20	0.12