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Zhengyi Jiang
University of Wollongong, jiang@uow.edu.au

Weihua Sun

Jianning Tang

Dongbin Wei
University of Wollongong, dwei@uow.edu.au

A. K. Tieu
University of Wollongong, ktieu@uow.edu.au

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Micromechanics of Thin Oxide Scale and Surface Roughness Transfer in Hot Metal Rolling

Z.Y.Jiang, W.H. Sun, J.N. Tang, D.B. Wei, A.K. Tieu
(School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong
Wollongong NSW 2522, Australia)

Abstract: The deformation micromechanics of the thin oxide scale formed in hot metal rolling and surface roughness transfer characterization are very important for the quality of the finished product. Finite element simulation of the thin oxide scale deformation and surface roughness transfer is carried out. Surface asperity deformation of the thin oxide scale and strip is focused. Surface characterisation and micromechanics of the thin oxide scale deformation are obtained from the finite element simulation and experimental measurements. Simulation results are close to the measured values. The forming features of surface roughness transfer during hot metal rolling with lubrication are also discussed.

Key words: oxide scale, surface characterization, surface roughness transfer, finite element simulation

1 Introduction

In hot strip mill, the temperature range of hot rolling is 800-1000 °C where there is a significant oxidation process, which a thin oxide scale layer is inevitably formed on the steel surface. Oxide scale has a significant influence on mechanics of the deformation in the roll bite and strip surface finish. Previous research on morphology of the oxide scale layer shows that the oxide scale on the steel surface contains three layers [1-3], named hematite (Fe_2O_3), magnetite (Fe_3O_4) and wustite (FeO) and it is confirmed by experiment even when the oxidation duration is less than 0.6 s [4].

The surface of oxide scale is made up of asperities, and when two surfaces are placed in contact only the tips of 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. The scale particles are depressed deeper into the strip surface, and the hot metal is extruded outward to fill the void between the oxide scale particles, and thus generating a rougher surface. Surface roughness has a significant effect on the downstream metal forming and its surface quality, such as sheet metal forming and strip coating. The study on the mechanical and tribological characteristics of the oxide scale in hot strip rolling is of great interests in recent years [5-12]. Krzyzanowski and Beynon [8] conducted hot tension tests for producing oxide scales of 10-300 μm in thickness and found a noticeable fracture feature in the temperature range of 830-1150 °C. Lubrication has been introduced into the production line of hot strip mill [13] recently. The mixed circumstances in the roll bite [14] make the interface of roll/bulk materials rather complicated and will result in changes of the required rolling forces, torques and power consumption, as well as the overall roll wear and surface quality. Mellizzari et al.[15] and Vergne et al.[16] anlaysed the tribological behaviour of rolls including the friction and wear in hot rolling process. The interfacial heat transfer behaviour during hot rolling of steel with oxide scale formation was investigated [17], and the thermal and physical mechanisms governing interfacial heat transfer were analysed when the oxide scale deformation occurs. Zhao et al. [18] used a three-dimensional finite-element crystal-plasticity model to investigate the grain-scale surface roughing in FCC metals with plastic straining involved.

However, the analysis of the micromechanics of thin oxide scale and the micro-deformation of the surface roughness of oxide scale at the strip/roll interface and the effect of lubrication in the roll bite on the surface roughness transfer have not yet been revealed till now. In this paper, the thin oxide scale deformation and surface asperity deformation of the thin oxide scale formed in hot strip mill and the strip are analysed using finite element software MSC-MARC package. A model generating surface roughness profile [19] which remains well the random characteristics of surface roughness and asperity was applied in this study. The deformation features of the steel surface asperities and thin oxide scale with and without oil lubrication in the roll bite are analysed. Simulation results are compared with the experimental values. A developed finite element model for analysis of the micromechanics of thin oxide scale in hot strip rolling is obtained and the forming features of surface roughness transfer are discussed.

2 Surface roughness asperity and finite element model

Oxide scale layer has FeO, Fe_2O_3 and Fe_3O_4 layers, and FeO layer has most thickness of the whole scale layer [1]. For simplicity, the scale layer is considered that it is just formed by FeO. Because the scale layer is developed on the surface of fresh steel and the scale layer is thin, it is assumed that thickness of scale layer is uniform. Under this assumption, the surface profiles of the thin oxide scale and strip should be the same. The measured real strip surface roughness by Atomic Force Microscope (AFM) is a random pattern as shown in Fig. 1. In order to analyse the surface characteristics of oxide scale and strip, a profile of roughness asperity should be generated during the finite element modelling of oxide scale and surface roughness.

2.1 Profile of roughness asperity

Within a small rectangular area $x_1 \leq x \leq x_2$ and $y_1 \leq y \leq y_2$, it is assumed that the shape of surface roughness asperity can be described by a normal function:

$$z = A * e^{-[(x-\mu)^2/\sigma_x^2 + (y-\nu)^2/\sigma_y^2]/2} \tag{1}$$

For a section of the surface, the surface roughness can be expressed as

$$z = A * e^{-(x-\mu)^2/(2\sigma_x^2)} \qquad x_1 \leq x \leq x_2 \tag{2}$$

The profile of the roughness in the small area is then determined by the parameters A, μ, σ_x, ν, σ_y, where A is the height of the roughness asperity, μ and ν are the summit coordinate of the roughness asperity respectively, and σ_x, σ_y are the parameters that reflect the sharpness of the roughness asperity.

At the boundary x_1, x_2, y_1, y_2, the outline of a roughness asperity is joined with the outlines of other roughness asperity in adjacent area. To ensure the outlines of roughness asperities can be joined continuously to form a rough surface, let

$$\sigma_x = (x_2 - x_1)/6 = \lambda_x/6 \quad (3)$$

$$\sigma_y = (y_2 - y_1)/6 = \lambda_y/6 \quad (4)$$

where λ_x, λ_y are the wavelength of the roughness asperity in the x- and y-direction respectively. The height of every roughness asperity in the boundary of the rectangular area is close to 0. The summit of a roughness profile in the small rectangle is assumed to be in the centre of rectangle, so that μ and ν can be determined. For a rough surface, the height A and the wavelength λ_x, λ_y are random values. A, λ_x and λ_y, the parameters of a roughness asperity profile, are assumed to have a normal distribution in a specified rough surface.

2.2 Generation of rough surface

From a starting point at a corner of a specified rectangular area, random values A, λ_x and λ_y can be obtained from the normal functions respectively. A profile of roughness asperity can be constructed in the small rectangular area with the edge length λ_x, λ_y. Moving the starting point to a new position and obtaining new random values A, λ_x and λ_y from the normal functions, a new profile of roughness asperity can be generated in the new small rectangular area. According to the feature of normal function, the value z of each profile of roughness asperity is very close to 0 at the edge. To join the edges smoothly, all profile values of z at the edge are assigned to 0. As this procedure is repeated in the specified rectangular area, the roughness peak and valley can eventually cover all the area. The rough surface with specified roughness parameters is then generated.

As shown in Fig. 1, a scanned real surface, which is to simulate the oxide scale surface during hot strip rolling. The surface was obtained from the test sample that was heated to rolling temperature (900°C) in vacuum state then exposed to moist air for a certain time to be oxidized and then cooled down in vacuum to room temperature. Fig. 2 shows the rough surface generated by the above model in a rectangular area. The parameters used to generate the rough surface are $A_m = 1.3\ \mu$m, $\lambda_{xm} = 2.2\ \mu$m, $\lambda_{ym} = 2.1\ \mu$m, $\sigma_{xm} = 0.9$, $\sigma_{ym} = 0.8$.

Comparing Figs. 1 and 2, it can be seen that the peaks distribution and the profile of the two surfaces are qualitatively close. It can be concluded that the produced shape or profile of surface roughness can be similar with a real one if the parameters used for generating the surface roughness are suitable.

In order to be similar to the practical case, a two-layers model was developed as shown in Fig. 3. The profile on the top of Fig. 3 is a surface profile of the thin oxide scale that contacts with the work roll and the second profile (down) is the interface of the thin oxide scale and strip.

2.3 FE mesh

In hot strip rolling process, the strip width is much larger than its thickness. So the deformation along the width direction can be neglected, and the rolling is considered as a plane strain deformation process. As the work roll is harder than the hot strip, it is considered as a rigid body. The rolling process can be taken as a symmetrical system, only considering the upper half of the strip. The finite element model for general rolling process including the thin oxide scale layer and surface roughness with meshing is shown in Fig. 4.

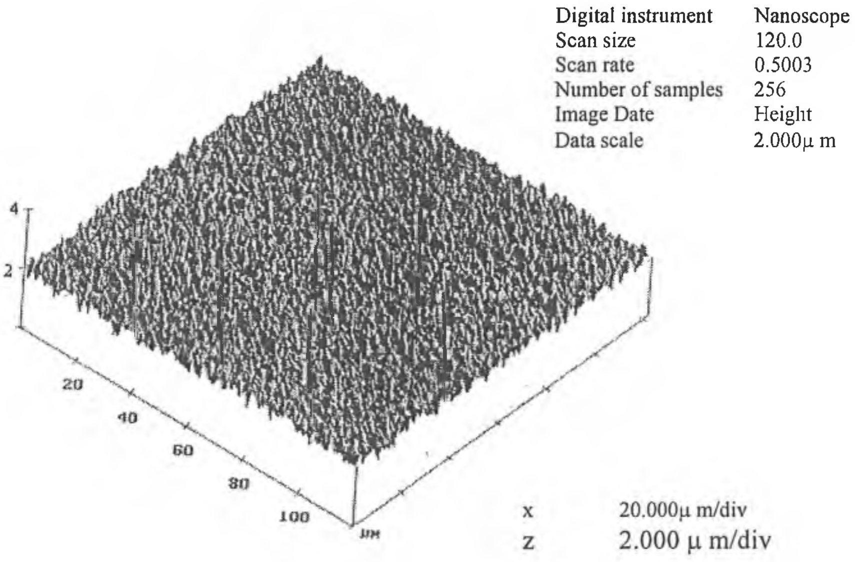

Fig. 1 3D surface image of oxide scale scanned by atomic force microscope

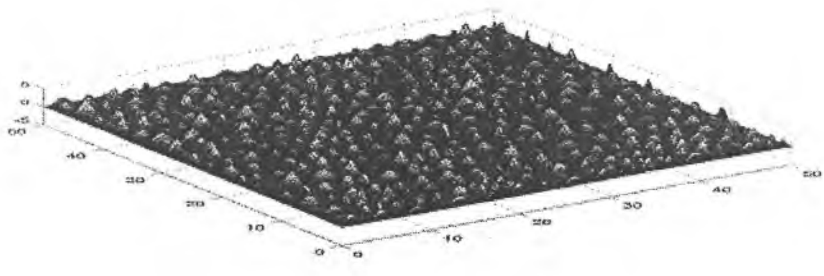

Fig. 2 A generated random surface roughness

To explore the effect of the work roll surface roughness on the final surface roughness of the oxide scale and strip, a random surface roughness is applied to the work roll surface. Therefore, the FE model in Fig. 4 has a random roll surface roughness. Starting roughly from the same initial strip surface roughness, the rolling process can be simulated with different work roll roughness.

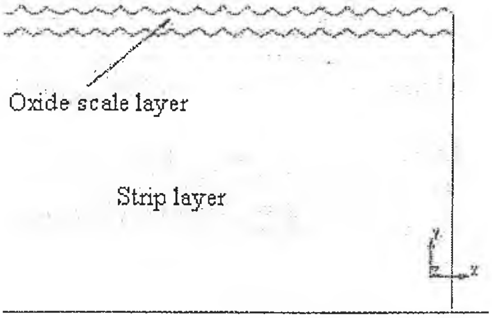

Fig. 3 Two-layer surface roughness

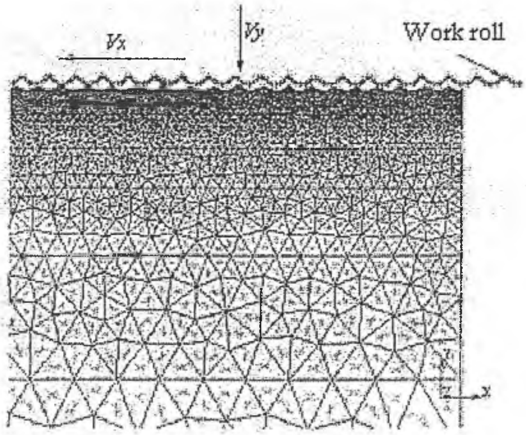

Fig. 4 FE mesh with rough roll surface

3 Results

Based on the analysis of the developed finite element model, a simulation was carried out on a PC using software MSC-MARC package. The calculated surface roughness transfers of the thin oxide scale and strip, the micro-deformation features of the oxide scale are obtained, which are compared with the measured values. Surface roughness of the thin oxide scale and strip was measured by a Surtronic surface profilometer.

3.1 Oxide scale deformation

Simulation conditions are rolling temperature 1025 °C, rolling speed 0.12 m/s, oxide scale thickness 25.5 μm and work roll surface roughness 0.45 μm. Comparison of the calculated oxide scale deformation with measured values is shown in Fig. 5. It can be seen that the calculated oxide scale thickness decreases with an increase of reduction. As the plastic deformation of oxide scale occurs [20, 21] at high temperature, so the thickness of oxide scale reduces when the reduction increases. The experimental result at reduction 16 % is close to the result of 7.5 %, maybe the effect of experimental temperature error. It can also be seen that the calculated results are fairly close to the measured values.

Finite element simulation found that the calculation of the micro-deformation of the thin oxide scale is stable. Therefore, the developed finite element model is applicable for determining the thin oxide scale deformation in hot strip rolling.

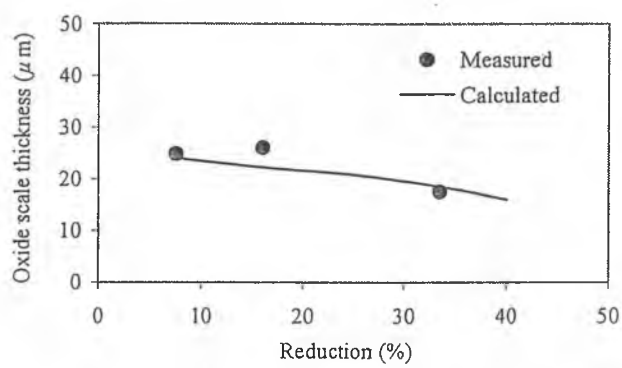

Fig. 5 Effect of reduction on oxide scale thickness

3.2 Oxide scale surface roughness transfer

For random roughness applied to the work roll surface, strip reduction 20 %, starting from roughly the same initial strip surface roughness, the effect of work roll surface roughness on surface roughness of thin oxide scale and strip is shown in Fig. 6. It can be seen that the final surface roughness of the thin oxide scale reduces significantly, but it decreases a little for strip and their surface roughness almost does not change when the work roll roughness changes within a range of 1 μm. After the roll surface roughness is larger than 1 μm, the decrease of the final surface roughness of the strip becomes small and its surface roughness may be larger than its initial value when the work roll surface roughness increases. However, for thin oxide scale, the decrease of surface roughness becomes small significantly with an increase of the work roll surface roughness. These results indicate that the surface roughness of work roll affects the surface roughness transfer significantly. When the work roll surface is smooth (very low surface roughness value), the surface roughness of the thin oxide scale and strip reduces significantly during hot strip rolling, but rougher work roll surface will leave the deformed oxide scale and strip to be rougher.

There are two cases they are with or without lubrication in hot strip rolling. For without lubrication, rolling temperature 1025 °C and rolling speed 0.12 m/s, work roll surface roughness is 0.3-0.65 μm, the effect of the reduction on the surface roughness of the oxide scale is shown in Fig. 7. It can be seen that the oxide scale surface roughness decreases with an increase of the bulk material reduction, and the calculated surface roughness is close to the measured values.

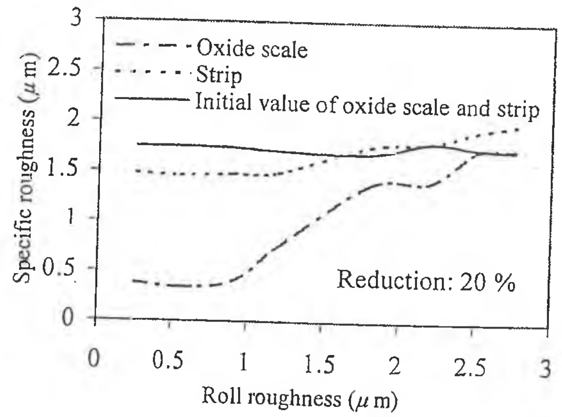

Fig. 6 Effect of the work roll surface roughness on the specific surface roughness

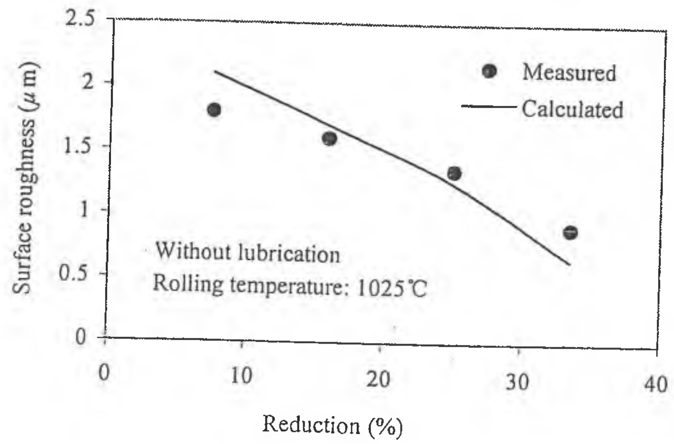

Fig. 7 Effect of reduction on surface roughness

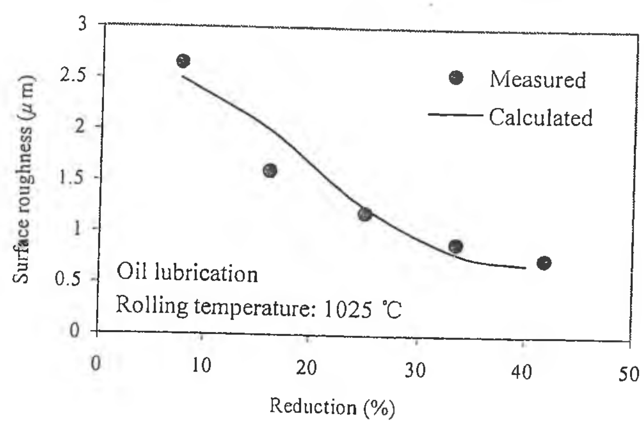

Fig. 8 Effect of reduction on surface roughness with oil lubrication

Fig. 8 shows the effect of reduction on surface roughness of the thin oxide scale with oil lubrication. It can be seen that the oxide scale surface roughness decreases with an increase of the bulk material reduction. It can also be seen that the calculated oxide scale surface roughness is in good agreement with the measured value. Therefore, the developed model can predict the surface roughness transfer of oxide scale during hot strip rolling.

3.3 Rolling temperature effect

Rolling temperature has an effect on the oxide scale surface roughness as shown in Fig. 9 when the rolling speed is 0.12 m/s, work roll surface roughness is 0.3-0.65 μm and oil lubricant is applied in the rolling experiment. It can be seen that the value of oxide scale surface roughness at higher temperature is larger than that at lower rolling temperature, which implies that the mechanical properties of the thin oxide scales will be changed in hot rolling process. When the rolling temperature reduces, the feature of plastic deformation of oxide scale varies, which will affect the feature of surface roughness of oxide scale. It can also be seen that the calculated surface roughness of oxide scale is close to the measured value. Therefore, the developed prediction model of surface roughness transfer for the thin oxide scale and strip in hot strip rolling, considering the effect of rolling temperature, is applicable.

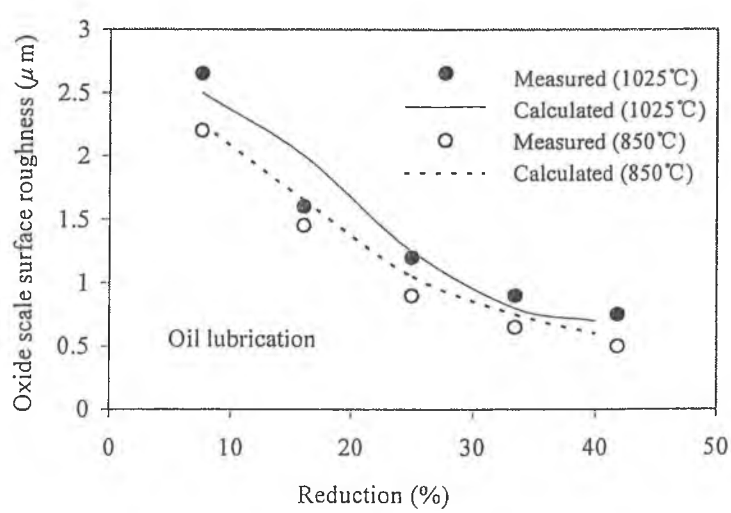

Fig. 9 Effect of rolling temperature on oxide scale surface roughness

4 Conclusions

The mechanics of surface roughness transfer and the micro-deformation of the thin oxide scale formed in hot strip rolling have been analysed using finite element method. The surface roughness of work roll affects the surface roughness transfer significantly. The decrease of the final surface roughness of the strip becomes small and its surface roughness may be larger than its initial value when the work roll surface roughness increases for a larger work roll surface roughness (>1 μm). If the work roll surface is smooth (very low surface roughness value), the surface roughness of the thin oxide scale and strip reduces significantly during hot strip rolling, but rougher work roll surface will leave the deformed oxide scale to be rougher. With or without lubrication in roll bite, the surface roughness of the thin oxide scale decreases with bulk material reduction, and the oxide scale surface roughness reduces with a decrease of rolling temperature, which implies that the mechanical properties of the oxide scales change in hot strip rolling.

The thickness of the thin oxide scale decreases with an increase of bulk material reduction. Simulation results show that the strip surface roughness can be reduced through rolling process and the strip surface roughness is larger than that of the thin oxide scale, and the calculated results are close to the measured values. Therefore, the developed finite element model is applicable for determining the thin oxide scale deformation and for predicting the mechanics of the surface roughness transfer of the thin oxide scale during hot strip rolling.

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