

Finite Element Modelling of Surface Roughness Transfer and Oxide Scale Micro Deformation in Metal Manufacturing Process

Zhengyi Jiang, Dongbin Wei and Heijie Li

School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia

Abstract. In the paper, the micro deformation of oxide scale in hot strip rolling has been investigated with considering the friction effect. The finite element simulation of the micro deformation of oxide scale has been successfully conducted, and the calculated surface roughness is compared with the measured value, which shows a good agreement. A crystal plasticity finite element method (CPFEM) model was also successfully developed to analyse the surface roughness transfer during metal manufacturing. The simulation results show a good agreement with the experimental results in the flattening of surface asperity, and the surface roughness decreases significantly with an increase of reduction. This study also indicates that the lubrication can delay surface asperity flattening.

Keywords: Surface roughness, Oxide scale, Micro deformation, Friction, Crystal plasticity finite element method.

INTRODUCTION

Rolling process including hot rolling and cold rolling of metals is widely used in metal manufacturing processes. Hot strip rolling is to make the strip thickness be reduced significantly in the hot strip mill [1] to the required dimensions. The strip is then passed onto the run-out table to obtain the product with the required mechanical properties and surface finish. In hot strip rolling, the temperature is from about 800 to 1050°C, depending on the rolled material [2]. Due to the high temperature of the strip and friction between the work roll and the strip, a coolant and/or lubricant is needed in each finishing rolling mill. When the hot strip is exposed to the atmosphere in the hot strip mill, the strip surface is continuously oxidised during rolling and forms a layer of oxide scale. The formed oxide scale affects the strip surface finish such as the surface roughness.

Surface roughness has a significant effect on the downstream metal forming, such as the cold strip rolling, sheet metal forming and strip coating. The micro deformation of the oxide scale in hot strip rolling has been topics of great interest in recent years, such as the researchers from Japan [3], Canada [4, 5], Italy [6], UK [7-10] and Australia [11-13] have carried out the research on oxidation of steels. Friction effect including the lubrication has been considered as a key issue in the analysis of the production line of hot strip mill [14]. Mellizzari et al. [15] and Vergne et al. [16] analysed the tribological behaviour of rolls in hot rolling. The interfacial heat transfer behaviour during hot rolling of steel with oxide scale formation was investigated [17]. For cold metal forming, there are many reasons may result in surface roughness change, such as the original surface roughness of the tools, and manufacturing parameters. Wilson et al. [18, 19] have investigated the effect of bulk plasticity on asperity flattening when the surface roughness lay is parallel to the bulk straining direction (longitudinal roughness), and found that the rate of asperity flattening with bulk straining was related to the spacing and pressure of asperities. Makinouchi et al. [20] have presented elastic-plastic finite element solutions for the case of transverse surface roughness. Sutcliffe [21] tested and developed Sheu and Wilson's theory, and pointed out that the high pressure between contact asperities and deformation of bulk material will affect the asperity deformation. Raabe et al. [22] studied the grain-scale micromechanics of the polycrystal surface. However, there are few reports studied on the interaction between the surface asperity flattening and friction. In order to figure out the relationship between the surface asperity flattening and friction, the commercial finite element software ABAQUS was employed to simulate the surface asperity flattening of workpiece along metal rolling direction, considering the effect of friction on surface asperity flattening.

In this study, the surface roughness micro deformation of the oxide scale and the strip considering the friction effect is analysed using the finite element method (FEM) simulation software, and the crystal plasticity finite element modelling of surface roughness transfer in cold metal forming is also carried out. Simulation results are compared with experimental values, which show that they are in good agreement.

OXIDE SCALE MICRO DEFORMATION IN HOT ROLLING

In order to be similar to the practical case, a model including oxide scale and steel surfaces was developed as shown in Figure 1, and V_0 is the initial velocity of the strip. The profile on the horizontal top of Figure 1 is a surface of the oxide scale that contacts with the work roll (inclined line with a surface roughness of $0.45 \mu\text{m}$), and the second profile (lower) is the interface of the oxide scale and the strip. In order to make the simulation conditions close to the practical ones, the surface asperities of the oxide scale and the strip are developed according to [23].

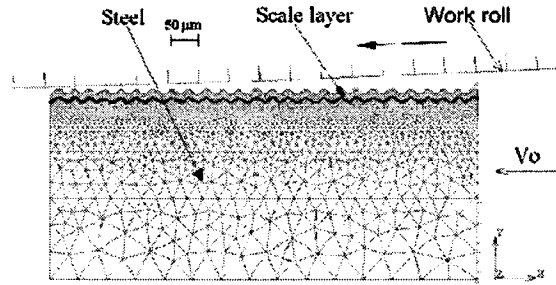


FIGURE 1. Finite Element Model with Oxide Scale Layer and Surface Roughness.

In strip rolling practice, the strip width is much larger than its thickness. So the deformation along the width direction can be neglected, and the rolling can be considered as a plane strain deformation process. The work roll is considered as a rigid body as it is harder than the hot strip. The rolling process can be taken as a symmetrical system, only considering a half of the strip. The finite element model for rolling process including the oxide scale layer and surface roughness with meshing is also shown in Figure 1.

Simulation Conditions and Results of Hot Strip Rolling

Friction exists at the roll-scale and scale-steel interfaces. Coulomb's friction model is used in this study. As the direction of friction is always opposite to relative velocity, and the direction of friction can be determined by the unit vector of relative velocity \vec{r} . The friction model is as follows:

$$\vec{\tau}_f = -\mu\sigma_n\vec{r} \quad (1)$$

Equation (1) has a jump point at zero relative velocity. This discontinuity in the value of τ_f may result in numerical difficulties in finite element method (FEM) analysis. A modified Coulomb model is implemented in FEM package as shown in Equation (2).

$$\vec{\tau}_f = -\mu\sigma_n \frac{2}{\pi} \arctan\left(\frac{V_r}{k_l}\right)\vec{r} \quad (2)$$

where V_r is the relative velocity and k_l is a small positive number ranged from 0.01 to 0.1. In most calculations, k_l is 0.1. The friction becomes a continuous function of relative velocity with Equation (2).

Figures 2 and 3 show a comparison between the simulation and experiment of the oxide scale surface roughness transformation with rolling speed during lubricated hot rolling. The flat roll FEM model with a roll-oxide scale friction coefficient 0.2 was used in the simulation [24]. The reduction is 15.8% for all cases. The results indicate that the oxide scale roughness changes less than 11% with an increase of rolling speed from 0.12 to 0.72 m/s, and the values of surface roughness change irregularly. The irregular values may be due to a hot strip rolling process with different initial surface roughness. This is consistent with the experimental results that the effect of the rolling speed on the final roughness is insignificant [25].

After deformation when the oxide scale surface roughness shown in Figures 2 and 3, and are drawn together, as shown in Figure 4, this can evaluate the effect of the rolling temperature on the surface roughness. It can be seen that

the values of the oxide scale surface roughness change in the same trend with roll speed, and it increases with the temperature. However, the maximum difference is about 14.6% when the temperature changes from 850 to 950°C for the rolling speed from 0.12 to 0.72 m/s.

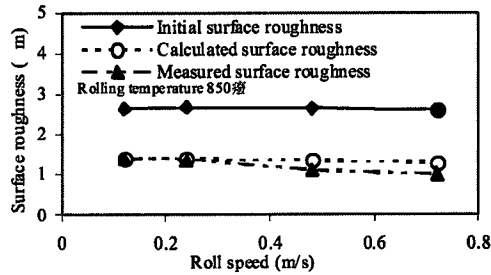


FIGURE 2. Effect of Work Roll Speed on Surface Roughness at Rolling Temperature 850°C.

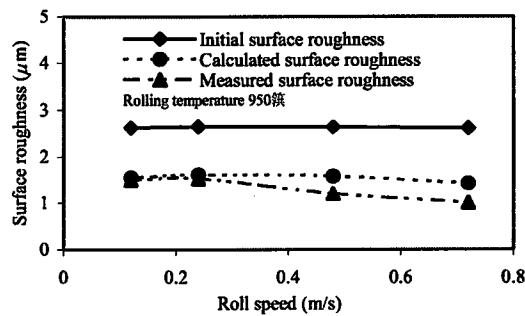


FIGURE 3. Effect of Work Roll Speed on Surface Roughness at Rolling Temperature 950°C.

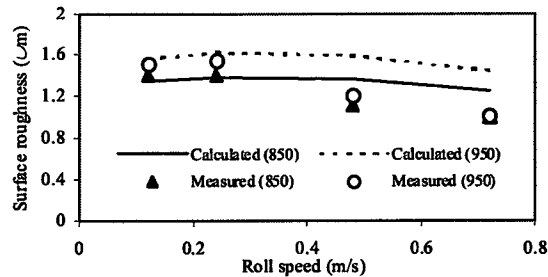


FIGURE 4. Effect of Roll Speed on Oxide Scale Surface Roughness.

CRYSTAL PLASTICITY FINITE ELEMENT SIMULATION OF SURFACE ROUGHNESS TRANSFER

The crystal plasticity constitutive model and the associated numerical procedures are applied to the commercial finite element code ABAQUS. Due to the simple relationship between the single crystal plasticity and the polycrystal plasticity models, the single crystal model is selected as a model to describe the stress response of polycrystal plasticity deformation. The single crystal plasticity model that is utilised in this research is as follows.

Crystal Plasticity Model

Following Kalidindi and Anand's work [26], the total deformation gradient (F) can be decomposed into elastic and plastic deformation as

$$F = F^* \cdot F^p \quad (\det F > 0) \quad (3)$$

The constitutive equation for stress in the crystal can be expressed as

$$T^{(1)} = L : E^{(1)} = F^{*-1} \{(\det F^*)T\} F^{*-T}, \quad E^{(1)} = \frac{1}{2}(F^{*T} \cdot F^* - I) \quad (4)$$

where $T^{(1)}$, $E^{(1)}$ are a pair of work conjugate stress and strain measures, respectively. The velocity gradient of plastic deformation can be expressed as

$$\dot{F}^p \cdot F^{p-1} = \sum_{\alpha=1}^n \dot{\gamma}^{\alpha} u_0^{\alpha} \otimes v_0^{\alpha}, \quad S_0^{\alpha} = u_0^{\alpha} \otimes v_0^{\alpha} \quad (5)$$

where u_0^{α} indicates the slip direction of the slip system α , v_0^{α} is the slip plane normal of the slip system α , $\dot{\gamma}^{\alpha}$ is the shearing rate of the slip system α . The shearing rate on each slip system depends on the resolved shear stress (τ^{α}) and the slip resistance (s^{α}) of that slip system. From reference [27], it can be expressed in a power-law relationship as

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \operatorname{sgn}(\tau^{\alpha}) \left| \frac{\tau^{\alpha}}{s^{\alpha}} \right|^{1/l}, \quad \tau^{\alpha} \approx T^* \cdot S_0^{\alpha} \quad (6)$$

In the simulation, $\dot{\gamma}_0$ is taken as 0.001 s^{-1} and the time t is 0.001 s . The slip system resistance rate can be expressed in the following general form

$$\dot{s}^{\alpha} = \sum_{\beta=1}^n h_{\alpha\beta} |\dot{\gamma}^{\beta}| \quad (7)$$

The rate of strain hardening $h_{\alpha\beta}$ can be expressed as

$$h_{\alpha\beta} = q_{\alpha\beta} h^{\beta} \quad (8)$$

where h^{β} is the single slip hardening rate, and $q_{\alpha\beta}$ is a matrix describing the latent hardening behaviour of a crystallite. The single slip hardening rate can be obtained as

$$h^{\beta} = h_0 \left\{ 1 - \frac{s^{\beta}}{s_s} \right\}^l \quad (9)$$

where h_0 , l and s_s are the hardening parameters of the slip system, respectively.

Experimental, Simulation Results and Discussion

The workpiece was polished by the auto polishing machine along the transverse direction, as well as that along the rolling direction. All workpieces have a surface roughness of about $0.7 \mu\text{m}$. When the compression is carried out, the workpiece is constrained along the transverse direction, and its deformation develops along the rolling direction. The compression test was carried out in the INSTRON Materials Testing System. The size of workpiece is $10\text{mm} \times 10\text{mm} \times 6\text{mm}$. The original surface roughness of workpiece is measured by Atomic Force Microscope (AFM) as shown in Figure 5a. The compressed workpieces (40 % reduction) with and without lubrications are shown in Figure 5b and 5c. The scan size and scan rate shown in Figure 5 are $60.00 \mu\text{m}$ and 1.001 Hz , respectively. It can be seen that with an increase of reduction, the surface asperity of workpiece tends to be flattened. Under the condition of without lubrication, if the reduction increases, the surface roughness of workpiece decreases from 0.7 to $0.1 \mu\text{m}$ quickly (Figure 5c). However, the surface asperity flattening takes place slowly under lubrication, and the surface roughness decreases from 0.7 to $0.2 \mu\text{m}$ (Figure 5b). After deformation, the surface qualities of workpiece are also different. Under the same reduction, the workpiece compressed under lubrication has a much smoother surface, and no obvious surface scratches are generated. While the workpiece is compressed without lubrication, it has flat surface with surface scratches. Lubrication can constrain the surface asperity flattening effectively, and reduce the friction between the workpiece and the tool. During the compression, if the workpiece contacts with tool directly, its surface will be dependent upon the tool surface. In this study, the tool surface roughness is about 10 nm . After compression, the surface roughness of workpiece is also about 10 nm .

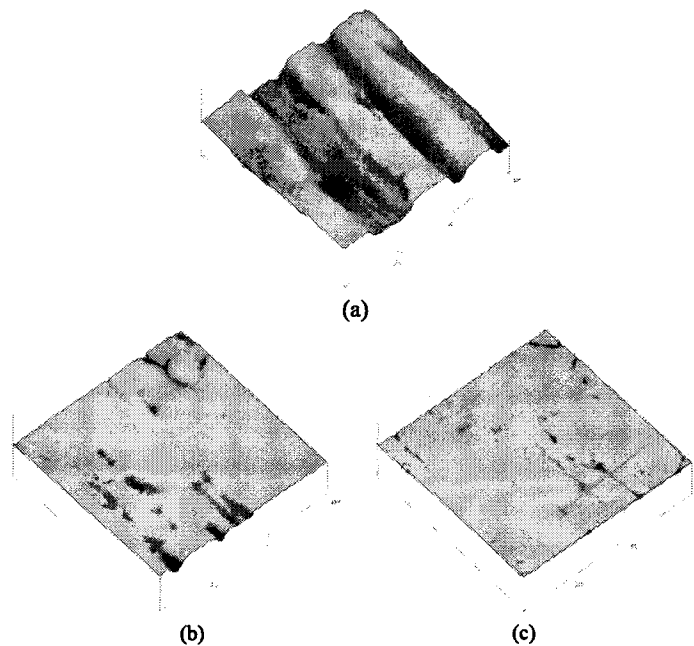


FIGURE 5. 3Dimensional Surface Roughness under Different Conditions: (a) Original Surface, (b) Surface after 40% Reduction with Lubrication, (c) Surface after 40% Reduction without Lubrication.

An FE simulation was conducted for the workpiece of aluminium alloy 6061T5. The size of the two-dimensional model is $500 \mu\text{m} \times 500 \mu\text{m}$, the original surface roughness of the three workpieces is $0.72 \mu\text{m}$ which is the same as the original surface of the workpieces, the reduction of workpiece is 40 %, and the contact friction coefficient between the workpiece and rigid compressing tool and mould is $0.001 - 0.35$. Due to symmetry, all the nodes on edge ab (Figure 6) have no displacement in direction 1. A crystal plasticity finite element polycrystal model is employed in this study. The two dimensional model has 902 CPE4R reduced integration elements, and one grain set with one element. The rigid tool and mould both have 20 discrete rigid elements. Kalidindi's method [26, 27] was

used to incorporate the crystal plasticity model into FEM simulation. The constitutive model and time-integration procedures were implemented into the ABAQUS by employing the user material subroutine UMAT. The other material parameters were according to [28].

The comparison of the calculated surface roughness with the measured values under dry and lubrication conditions is shown in Figure 7. It can be seen that the experimental results are close to the simulated results. Both results show that, with an increase of reduction, the surface roughness of workpiece decreases significantly, and lubrication can delay the process of surface asperity flattening. This verifies the developed crystal plasticity FEM model is applicable for the analysis of the surface roughness transfer during metal manufacturing.

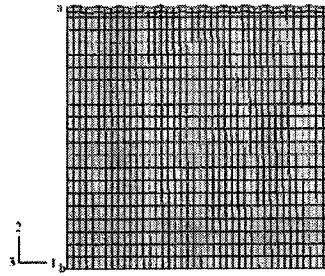


FIGURE 6. Two Dimensional Model and Mesh.

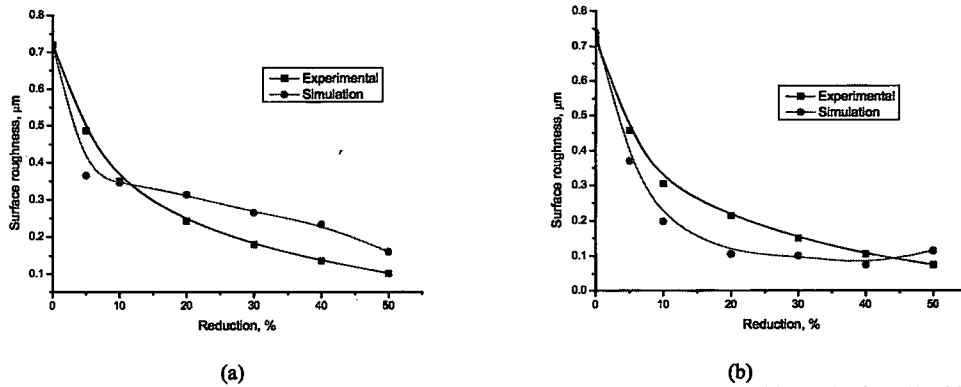


FIGURE 7. Relationship Between the Surface Roughness and Friction and Reduction (a) with Lubrication, (b) without Lubrication.

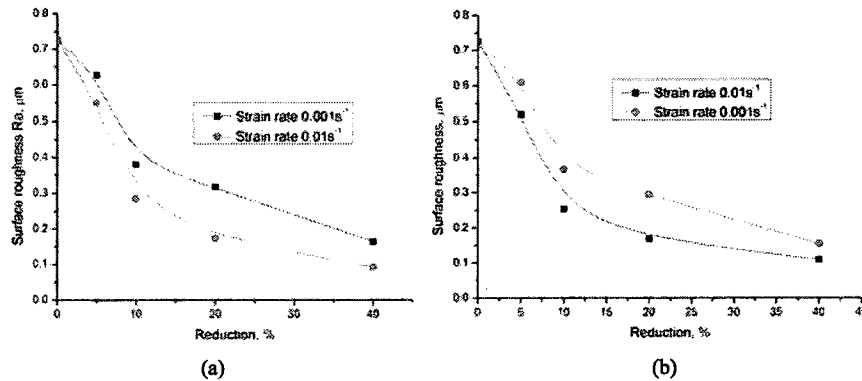


FIGURE 8. Effect of strain rate on surface roughness R_a (a) Experimental, (b) Simulation.

Figure 8 shows the effect of strain rate on surface roughness. It can be seen that both experimental and simulated results show: increasing strain rate can lead to a decrease of surface roughness under the same reduction. Furthermore, with an increase of reduction (between 5-20 %), influence of strain rate on surface roughness tends to be more obvious. When the reduction is less than 10 %, the elastic deformation plays an important role in the surface asperity flattening process. Because the strain rate has no obvious effect on the elastic deformation, increasing strain rate shows no significant influence on the surface roughness. If the gauged reduction exceeds 10 %, influence of the plastic deformation of surface area increases. Assumed slip is the only deformation mode, and increasing strain rate can lead to the increase of activated slip system by increasing slip shear rate. As a result, the surface deformation increases even under the same reduction. The increase of slip shear rate can lead to more slip system reaches the critic slip shear stress, and then more slip systems can be activated. Therefore, surface roughness will decrease greatly with an increase of strain rate. Due to the simplification of model and calculation, the simulated results are lower than those from the experiments.

CONCLUSIONS

In hot strip rolling, the surface roughness of both oxide scale and steel surface increases with an increase of the coefficient of friction on the roll-scale interface. However, the increment of the roughness is limited. The values of the oxide scale surface roughness change in the same trend with the roll speed, and it increases with the temperature. But the maximum difference is about 14.6% when the temperature changes from 850 to 950°C for the rolling speed from 0.12 to 0.72 m/s.

For cold strip rolling, with an increase of reduction, the surface roughness of workpiece decreases significantly, and lubrication can delay the process of surface asperity flattening. Increasing strain rate can lead to a decrease of surface roughness under the same reduction. The calculated surface roughness is in good agreement with the measured results. This demonstrated that the developed CPFEM models are applicable for metal manufacturing.

ACKNOWLEDGMENTS

The authors would like to thank the Australian Research Council (ARC) for funding support for the research.

REFERENCES

1. M. Torresa and R. Colas, *J. Mater. Proc. Technol.* **105**, 258-263 (2000).
2. G. Wood, "Introduction of hot strip mill in BlueScope Steel", BlueScope Steel, Presentation in University of Wollongong (2003).
3. T. Fukagawa, H. Okada and Y. Maehara, *ISIJ Int.* **34**, 906-911 (1994).
4. Y. Yu and J.G. Lenard, *J. Mater. Proc. Technol.* **121**, 60-68 (2002).
5. P.A. Munther and J.G. Lenard, *J. Mater. Proc. Technol.* **88**(1999) 105-113.
6. I. Iordanova, M. Surtchev, K.S. Forcey and V. Krastev, *Surf. Interface Anal.* **30**, 158-160 (2000).
7. D.P. Burke and R.L. Higginson, *Scripta Mater.* **42**, 277-281 (2000).
8. M. Krzyzanowski and J.H. Beynon, *Steel Research* **70**, 22-27 (1999).
9. M. Krzyzanowski, J.H. Beynon and C.M. Sellars, *Metallurgical & Mater. Transactions B* **31**, 1483-1490 (2000).
10. M. Krzyzanowski and J.H. Beynon, *J. Mater. Proc. Technol.* **125-126**, 398-404 (2002).
11. W.H. Sun, A.K. Tieu, Z.Y. Jiang, H.T. Zhu and C. Lu, *J. Mater. Proc. Technol.* **155-156**, 1300-1306 (2004).
12. W.H. Sun, A.K. Tieu and Z.Y. Jiang, *J. Mater. Proc. Technol.* **140**, 77-84 (2003).
13. W.H. Sun, A.K. Tieu and Z.Y. Jiang, *Steel GRIPS Journal of Steel and Related Materials* **2**, 579-583 (2004).
14. A.K. Tieu, Z.Y. Jiang and C. Lu, *J. Mater. Proc. Technol.* **125-126**, 638-644 (2002).
15. M. Pellizzari, A. Molinari and G. Straffelini, *Wear* **259**, 1281-1289 (2005).
16. C. Vergne, C. Boher, C. Levaillant and G. Gras, *Wear* **250**, 322-333 (2001).
17. Y.H. Li and C.M. Sellars, *J. Mater. Proc. Technol.* **80-81**, 282-286 (1998).
18. S. Sheu and W.R.D. Wilson, in: Proc. NAMRC XI (SME), 1983, p.172.
19. W.R.D. Wilson and W.M. Lee, *J. Manufacturing Science and Engineering* **123**, 279-283 (2001).
20. A. Makinouchi, H. Ike, M. Murakawa and N. Koga, *Wear* **128**, 109-122 (1988).
21. M.P.F. Sutcliffe, *Int. J. Mech. Sci.* **30**, 847-868 (1988).
22. D. Raabe, M. Sachtleber, H. Weiland, G. Scheele and Z.S. Zhao, *Acta Materialia* **51**, 1539-1560 (2003).

23. Z.Y. Jiang, J. Tang, W.H. Sun, A.K. Tieu and D.B. Wei, *Tribology Int.* **43**, 1339-1345 (2010).
24. J. Tang, "A study of oxide scale deformation and surface roughness transformation in hot strip rolling", PhD Thesis, University of Wollongong, 2006.
25. W.H. Sun, "A study on the characteristics of oxide scale in hot rolling of steel", PhD Thesis, University of Wollongong, 2005.
26. S.R. Kalidindi and L. Anand, *Int. J. Mech. Sci.* **34**, 309-329 (1992).
27. S.R. Kalidindi, C.A. Bronkhorst and L. Anand, *J. Mech. and Physics of Solids* **40**, 537-569 (1992).
28. D. Raabe, Y. Wang and F. Roters, *Computational Materials Science* **34**, 221-234 (2005).