Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 81 (2014) 179 – 184

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Deformation characterization of micro rolling for stainless steel foil

Haibo Xie[a,b]*, Ken-ichi Manabe[a], Tsuyoshi Furushima[a], Kazuo Tada[a], Zhengyi Jiang[b]

[a] *Department of Mechanical Engineering, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan*
[b] *School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Northfield Ave, Wollongong, NSW 2500, Australia*

Abstract

Physical parameters such as microscopic roughness become very important in micro forming process due to increasing surface to volume ratio. As a very important phenomenon in metal forming process, friction size effects are becoming more attracting for researchers because traditional models are not reliable. In this study, the micro rolling deformation characterization has been investigated with SUS 304 stainless steel considering the effect of lubricant, and there exists a sticking area in the contact zone. The evolution of surface roughness and oil film thickness are analyzed. The foil thickness plays an important role in the tribological features of rolling. All the results have been verified experimentally via the desktop 2-Hi micro rolling mills.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Deformation characterization; Foil rolling; Oil film thickness; Surface roughness

---

1. Introduction

Due to the trend of miniaturization on electrical devices, medical devices, and energy, etc., the need for micro metallic foil has been extremely increasing, especially in stainless steel foils for their excellent corrosion resistances and high strengths. Metal foil is mostly obtained by multi-pass rolling process. However, the knowledge and technique developed in traditional metal rolling cannot be directly applied to the micro foil rolling process due to the so-called size effects which further affect the performance of microforming system and product quality in terms of deformation load, dimensional accuracy, surface finish and the mechanical properties.

---

* Corresponding author. Tel.: +61-426773015; fax: +61-426772701.
E-mail address: xie@tmu.ac.jp

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.09.147

Traditional cold rolling theories with an assumption that arc remains a circular with enlarged radius and one neutral point fail in foil rolling process due to significant elastic deformation of work roll. Fleck and Johnson (1987) suggests that the work rolls deform to a non-circular profile and a neutral region of no-slip exists in the roll bite for finite reductions of the strip. A new theory for cold foil rolling is presented by Fleck et al (1992) that plastic reduction takes place in two zones at entry and exit, which are separated by a neutral zone in which the rolls are compressed flat. Tribological analysis is very important in cold rolling process. Le and Sutcliffe (2003, 2006) applied a tribological model for mixed lubrication in rolling of thin strip and foil, and indicate the friction coefficient on the asperity contact is related to a theoretical oil film thickness and secondary-scale roll surface roughness. Sadowski and Stupkiewicz (2010) report the combined effect of friction and macroscopic deformation on asperity flattening. Roll roughness and lubricant viscosity influence the loads during cold rolling (Dick and Lenard 2005). Theories of hydrodynamic lubrication can be applied on smooth surfaces in cold rolling (Lugt et al, 1993; Wilson and Walwit, 1972). Batalha and Filho (2001) presented quantitative characterization of the surface topography of cold rolled sheets. For scale-down size effect, Vollertsen and Hu (2009) analyze tribological size effects in sheet metal forming measured by strip drawing test. Deng et al (2001) use an open and closed pockets theory analyze size effect on material surface deformation behaviour in micro forming process. Changing lubrication can alter the mode of deformation during forming processes and change the mechanical properties of the final product.

In this study, the micro rolling deformation characterization has been investigated in 2-Hi reversing micro rolling mill. The influences of the feature sizes on oil film thickness have been discussed in the high strength material of SUS 304 stainless steel with ranging thicknesses from 50 μm to 100 μm. The analysis of the evolution of surface roughness and oil film thickness has been conducted experimentally and analytically.

Nomenclature

H	initial foil thickness
h	foil thickness after rolling
$h_{oilfilm}$	oil film thickness in inlet zone
h_{out}	oil film thickness in outlet zone
L	contact zone length
R'	deformed roll radius
r	rolling reduction in thickness
v	rolling velocity
v_{entry}	roll surface velocity
v_r	entry velocity of the foil
σ_{fm}	average flow strength
σ_{entry}	tensile stress
γ	pressure-viscosity coefficient
η_0	dynamic viscosity

2. Experimental micro rolling mill and material used

The research on multi-pass rolling deformation behaviour of SUS 304 stainless steel is carried out on the 2-Hi reversing micro rolling mill. The new micro rolling mill shown in Fig. 1 includes gear system, paralleled motor, gap adjustment, micro rollers, shaft connection and control system. The rollers are driven by two separated motors featured by adjustable and flexible rolling speed ratio. The roll and rolled foil are degreased with acetone before each pass. The initial thickness of SUS 304 stainless steel foil is 100 μm and the foil width is 15 mm. The true stress-true strain curve of the foil obtained in tension test is 1250 MPa. Fig. 2 shows schematically the contact with areas of contact between the roll and strip and areas separated by an oil film.

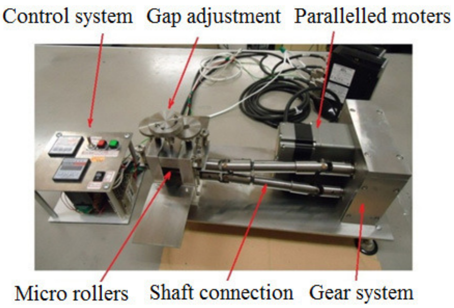


Fig. 1. Micro rolling mill with flexible speed ratio.

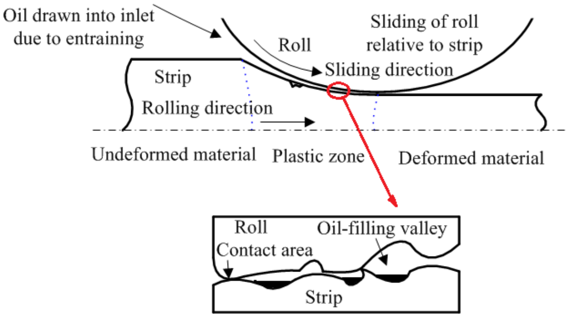


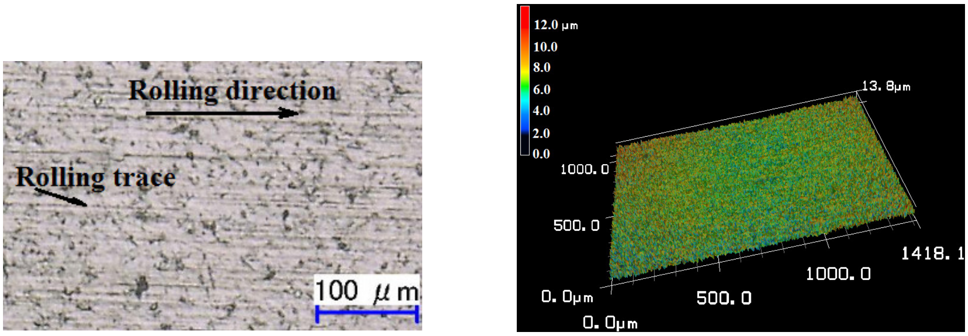
Fig. 2. Schematic of lubrication mechanisms in rolling.

Table 1 lists parameters used in experimental and analytical models. The annealed austenitic stainless steel of 100 μm thickness was prepared as rolled materials, and the 2-Hi desktop-scale reversing mill was used for multi-pass rolling. The rolled foil was collected, measured and compared after each pass. The pass reductions in foil thickness after each pass were in variation according to the rolling conditions.

Table 1. Parameter conditions in experimental and analysis.

	Work roll diameter(mm)	*Rolling velocity(rpm)*	*Roll Young's modulus(GPa)*	*Passion ratio*
Roll	27	0-100	580	0.30
	Entry foil thickness(μm)	*Reduction (%)*	*Young's modulus(GPa)*	*Poisson ratio*
Foil	100	3-50	180	0.30
Lubrication	Dry, O/W emulsion and oil lubricant (Niconic AWH) (viscosity: 44.13 mm^2/s in 40°C and 6.862 mm^2/s in 100°C)			

Surface topography display of the SUS 304 stainless steel foil is shown in Fig. 3. Rolling trace and surface valley are significantly indicated in the surface topography.



(a) SEM surface topography (b) Three dimensional surface roughness

Fig. 3. Topography display of the SUS 304 stainless foil.

3. Results and discussion

3.1. Micro rolling deformation characterization

In the case of foil rolling, deformation may be considered fairly homogeneous across the thickness of the rolled material. Note that in this model, the foil thickness is considered to be small compared to the length of the roll gap and its transverse width, and there is no stress variation in foil vertical direction. The stress only varies as the foil moves along the length of the roll gap. The contact pressure and roll shape for one pass with significant roll deformation are illustrated in Fig. 4 obtained from Fleck's model (Fleck et al, 1987 and 1992). The pressure was taken to be near Hertzian and the deviation of the roll profile from flat was incorporated by using a modified mattress model. The elastic and contained plastic compression of the foil can be ignored in the vertical direction because the foil is much thinner than the elastic deformation of the rolls. The sharp pressure peak is observed and the direction changes at the neutral section where the pressure peaks.

A characteristic feature of the pressure distribution for foil is the sharp pressure peak which occurs just beyond the end of the neutral zone (D position). The pressure peak causes the rolls to deform locally to a concave shape. The pressure increases steadily through the no-slip zone and the rolled material is in a state of contained plastic flow. The foil in the central flattened region (CD zone) goes from a contained plastic zone to an elastic no-slip zone characterized by maximum in the pressure in central flattened region and then to contained elastic slip zone. BC zone and DE zone are featured plastic deformation zones in the foil rolling.

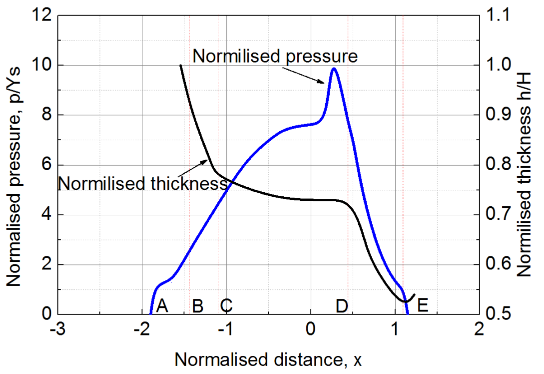


Fig. 4. Normalised thickness and pressure distribution for H=50μm, D=27 mm, μ=0.15, E$_R$=580GPa.

3.2. Oil film thickness

In order to investigate the oil film thickness in lubricant rolling, the oil drop method was applied. The test involved dropping a known quality of oil on the foil surface at the beginning of rolling, rolling the strip in the rolling mill, taking a digital photograph of mark left on the foil after rolling. The drop volume divided by the surface area of the mark gives the finial thickness of the oil film between the roll and the foil in the bite. The lubricant film thickness at the end of the inlet is determined by the lubricant rheological properties, the rolling speed and the roll geometry (Lenard, 2007). Wilson and Walowit (1972) derive an expression for the oil film thickness $h_{oilfilm}$ as below. Contact zone length L can be obtained from the Fleck model and the ratio $\Lambda_s = h_{oilfilm}/\varphi_c$ of the smooth film thickness $h_{oilfilm}$ to the combined roll and initial strip roughness $\varphi_c = \sqrt{\varphi_r + \varphi_s}$ is used to characterize the lubrication regime.

$$h_{oilfilm} = \frac{3\eta_0\gamma(v_{entry}+v_r)R'}{L\{1-\exp[-\gamma(\sigma_{fm}-\sigma_{entry})]\}} \quad (1)$$

A film thickness at the outlet of the contact zone of

$$h_{out} = h_{oilfilm}\frac{v_{entry}+v_r}{v_{out}+v_r} \quad (2)$$

The calculated film thickness from mixed film model was compared with the measured film thickness shown in Fig. 5. Both of the oil film thicknesses in experiment and calculation decrease with increasing pass reduction in thickness. The calculated value is always smaller than the experiment measured value. The main reason is the film formation by the entraining action has not yet been considered in the calculation model. The oil thickness in 50 µm thick foil is lower than that in thickness of 100 µm. This is because with increasing miniaturization, more open lubricant pockets appear and less lubricant is kept in the micro tribological contact zone. This also increases real contact area between the roll and foil.

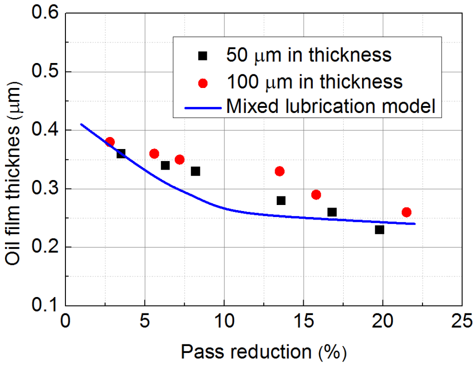


Fig. 5. Measured film thickness for emulsion and film thickness based on the Wilson model (H=100 µm and 50 µm; *v*=25 rpm).

Fig. 6 shows the oil film thickness versus the rolling velocity in experiment. It can be seen that both data increase with increasing rolling velocity slightly. As viscosity decreases, the film thickness decreases and the asperity contact area increases. As the asperity contact area rises, the pressure in asperity contact area increases too, so the film pressure drops. The oil thickness in neat oil lubricant is higher than that in emulsion lubricant.

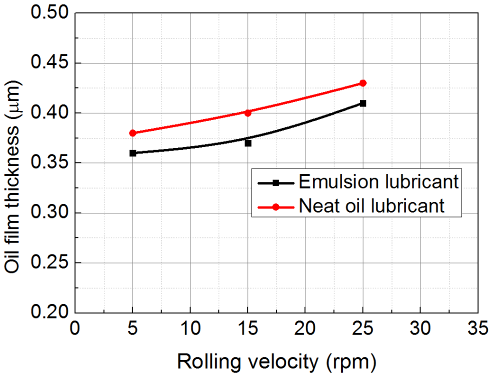
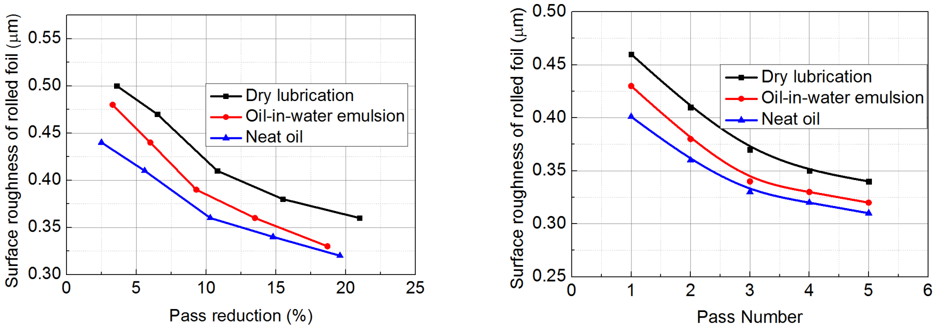


Fig. 6. Oil film thickness versus rolling velocity in experiment (H=100 µm; r=20%).

3.3. Surface roughness evolution

Since the roll is very much harder than the foil, the foil's asperities are expected to change shortly after entry. As a laboratory rolling mill, where the volume of the rolled metal is much less, the roll's surface roughness is not expected to change significantly. There are solid contact, the static and the dynamic lubricant pockets in the contact of the roll and the foil where the solid contact corresponds to the real contact area.

Fig. 7 shows the surface roughness evolution in rolling process. The roughness of the rolled foil depends on the reduction and pass number chosen, which is directly related to the roll separating force. It can be seen that the surface roughness decrease with increasing pass reduction and pass number. The foil in dry lubrication remains the roughest. The surface roughness decreases dramatically in the first several passes.



(a) Pass reduction (H=100 μm; *v*=20 rpm) (b) Pass number (*v*=15 rpm; r=15%)

Fig. 7. Surface roughness evolution in micro foil under various rolling experimental conditions.

4. Conclusions

The micro rolling deformation characterization has been investigated successfully in micro rolling mill. Tribological size effect is also observed for different foil thickness of 100 μm and 50 μm. The oil film thickness decreases with increasing pass reduction and decreasing rolling velocity. Surface roughness decrease with increasing pass reduction and pass number. The lubricant conditions influence the surface roughness evolution during rolling. The theory analysis will be conducted in near future.

Acknowledgements

The authors would like to give thanks to Prof. Yoshino of Tokyo Institute of Technology and Prof. Koyama of Chiba University in rebuilding of micro rolling mill. The first author is grateful to the Japan Society for Promotion of Science (JSPS), Japan for awarding of JSPS fellowship (FY 2012-2013) to carry out research in Japan. This research was supported by the Grant-in-Aid for JSPS Fellows (Grant No. 24.02770).

References

Batalha, G., Filho, M., 2001. Quantitative characterization of the surface topography of cold rolled sheets- new approaches and possibilities, Journal of Materials Processing Technology, 113 (5), 732-738.

Deng, J., Fu M., Chan, W., 2001. Size effect on material surface deformation behaviour in micro-forming process, 528 (13), 4799-4806.

Dick, K., Lenard, J., 2005. The effect of roll roughness and lubricant viscosity on the loads on the mill during cold rolling of steel strips, Journal of Materials Processing Technology, 168 (1), 16-24.

Fleek, N., Johnson, K., 1987. Towards a new theory of cold rolling thin foil, International Journal of Mechanical Science, 29 (7), 507-524.

Fleek, N., Johnson, K., Mear, M., Zhang, L., 1992. Cold rolling of foil, Journal of Engineering Manufactur, 206 (6), 119-131.

Le, H., Sutcliffe, M., 2006. A multi-scale model for friction in cold rolling of aluminium alloy, Tribology Letters, 22 (1), 95-104.

Le, H., Sutcliffe, M., 2003. A friction model for cold strip rolling with two-wavelength surface roughness in the “mixed” lubrication regime, Transactions of the ASME, 125 (7), 670-677.

Lenard, J., editor, 2007. Primer on flat rolling, A monograph for those who need to understand the basic of the flat rolling process, Elsevier, 84 Theobald’s Road, London WC1X8RR, UK.

Lugt, P., Wemekamp, A., Napel, W., Liempt, P., Otten, J., 1993. Lubrication in cold rolling: elasto-plasto-hydrodynamic lubrication of smooth surfaces, Wear, 166 (3), 203-214.

Sadowski, P., Stupkiewicz, S., 2010. Combined effect of friction and macroscopic deformation on asperity flattening, Tribology International, 43 (9), 1735-1741.

Wilson, W., Walowit, J., 1971. An isothermal hydrodynamic lubrication theory for strip rolling with front and back tension, in: Proceedings of the Tribology Convention, I. Mech. E. London, 169-172.

Vollertsen, F., Hu, Z., 2009. Tribological size effects in sheet metal forming measured by strip drawing test, Ann. CIRP 55, 291-294.