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Study of micro flexible rolling based on grained inhomogeneity

Feijun Qu[a], Zhengyi Jiang[a,b,*], Dongbin Wei[a,c], Qingqiang Chen[d], Haina Lu[a]

[a] School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong. Northfields Avenue, Wollongong 2522, Australia
[b] School of Materials and Metallurgy, University of Science and Technology Liaoning, Anshan Liaoning 114051, P. R. China
[c] School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney. 15 Broadway, Ultimo 2007, Australia
[d] Key Laboratory of Electromagnetic Processing of Materials, Ministry of Education, Northeastern University. 3-11 Wenhua Road, Shenyang 110819, P. R. China

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ABSTRACT

This paper shows an analytical, numerical and experimental investigation to comprehend the role of grained inhomogeneity which plays in micro flexible rolling in terms of the average rolling force and the thickness directional springback of the workpiece after it exits the roll bite zone. Miniature tensile tests and micro hardness tests are accomplished to identify the scattered stress-strain curves for 500 µm thick aluminium alloy 1060 samples with grain size of approximately 23-71 µm and to determine the weighted heterogeneity coefficient for each sample separately, according to which the theoretical calculations and numerical simulations based upon 3D Voronoi tessellation technique have been performed under actual experimental conditions where reductions of 25 to 50 % are selected. The scattering effect associated with the anisotropic nature of single grains has been perceived in the micro flexible rolling process and both the analytical and finite element models developed have been validated via experimental data to hold promise for predicting the rolling force and the thickness directional springback of the workpiece, as well as boosting the thickness profile control performance of the micro flexible rolling mill.

1. Introduction

Rolling process, which reduces the thickness as well as enhances material properties of the metal by passing it between rolls, has been developed worldwide over the past decades mostly by means of analytical and numerical methods [1,2]. One relatively common approach to describe the stress state in the roll bite is to deploy the two-dimensional differential equation derived by von Karman under condition of equilibrium [3], for which a bundle of solutions exist, depending upon the assumptions adopted by the individuals, and whereof Tselikov [4] proposed a typical one with Coulomb's law of friction employed and the arc of contact substituted for its chord. Orowan [5] presented a graphic-analytical model to calculate the rolling pressure taking into account the variation of friction coefficient along the arc of contact, in the light of which Bland and Ford [6] and Sims [7] obtained their respective models via various simplifications. Stone [8] established a mathematical model for cold rolling of thin strip, including the effects of friction, strip tension and roll flattening. Several semi-empirical formulas were constructed by Ekelund [9] and Misaka and Shida [10] to compute the rolling force in hot rolling mills in terms of material and geometrical parameters. More recently Johnson and Smelser [11] applied the asymptotic method to incorporate shear effects in plane-strain rolling into earlier models to improve the forecast accuracy of rolling force, whose work had been extended by Domanti and McElwain [12] through scalings to a special case of the friction causing the roll pressure to seriously exceed the flow stress in the roll gap. Fleck et al. [13] treated the rolls as elastic half-spaces in their modelling of cold rolling of thin strip and related the distribution of roll pressure in the no-slip zone to the elastic roll deformation by a conversion equation. Le and Sutcliffe [14] later added a new element to the modelling of the neutral zone involved in the work by Fleck et al. [13], and wherein they combined the flow continuity for the strip with the change in roll shape to link the pressure gradient and shear stress with the roll slope. Larkiola et al. [15] integrated the neural network theory into a physical model to obtain better agreement between predicted and measured rolling force so as to indirectly optimise the capacity and efficiency of a tandem cold rolling mill.

Nowadays, finite element method, a power numerical technique to provide more intuitive and precise solutions to complex scientific and engineering problems, is increasingly being used to simulate and investigate the rolling process. Jiang et al. [16,17] employed this approach to describe the strip rolling process considering the friction variation in the roll bite, during which the numerical calculations, such as rolling force and rolling torque, showed a good agreement with the

* Corresponding author at: School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong. Northfields Avenue, Wollongong 2522, Australia.
E-mail address: jiang@uow.edu.au (Z. Jiang).

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experimental results. A rigid-plastic finite element code combined with a realistic friction model was developed by Hsu et al. [18] for analysis of lubricant flow and determination of hydrodynamic friction stress within the billet-roll interface, which had given accurate estimates of the rolling force, rolling torque as well as the outlet velocity ratio during lubricated cold rolling process. Shahani et al. [19] evaluated the influence of process parameters inclusive of initial slab thickness, rolling speed, thickness reduction and friction coefficient on the rolling force, temperature history, strain history and contact pressure distribution in hot rolling of aluminium slab by coupled thermo-viscoplastic finite element analysis. Devarajan et al. [20] similarly described a 2D elastic-plastic finite element model to investigate the effect of roll speed and roll diameter on the contact pressure and residual stress in cold rolling of steel plate. Liu et al. [21] focused their analysis on the metal flow in slab rolling based upon a three-dimensional elastic-plastic finite element method and the comparison of forecasted metal flow with experimental data, including the profile evolution of the workpiece, grid distortion and velocity fields, exhibited a very good agreement over a wide range of workpiece width/thickness ratios and reductions.

Over recent years, an innovative technique named flexible rolling has been devised by Kopp et al. [22,23] to keep pace with the increasing demand for lightweight construction, of particular significance to the automotive industry. In this process, the roll gap is selectively altered during the pass to produce a workpiece with variable thickness along its length to allow an exact adaptation to the respective loads under which it is to be placed [24]. Liu et al. [25,26] performed parametric studies of the influences of reduction, friction coefficient and blank horizontal velocity on the rolling force, forward slip and final thickness profile utilising the nonlinear transient dynamic explicit type of finite element analysis in order to manipulate process parameters in actual flexible rolling. Current research in flexible rolling technology deals predominantly with thick metals; nonetheless, these laws may differ when the thickness of the material reaches from the millimeter down to the micrometer range, the other two dimensions whereof are to be reduced accordingly, because the effect of each grain rises to prominence and plays a more critical role in the overall material deformation behaviour.

This phenomenon, known as size effect, is being investigated for various metal forming processes at micro scale. Joo et al. [27] designed and assembled a micro punching press to make micro-holes on brass and stainless steel foils during which shear-dominated hole wall and relatively large burr were formed as the grain number got decreased along the foil thickness. Lee et al. [28] conducted micro deep drawing experiments with 304 stainless steel foils and the results revealed that both the blank holder force and the limit drawing ratio increased with the increasing ratio of foil thickness to the average grain size (T/D ratio). Chen and Jiang [29] discussed the material behaviour of thin iron sheets in micro V-bending; they concluded that the maximum punch force decreased with the decrease in the T/D ratio whereas the springback amount decreased with the increase of T/D ratio, and the spring-forward was detected when the T/D ratio fell below 2. Rosochowski et al. [30] executed a set of backward cup extrusion experiments using both the coarse-grained and the ultrafine-grained aluminium billets, in which more uniform material flow, better shape capability and smaller surface discontinuities on the edge of the cup were observed for the ultrafine-grained materials. Shimizu et al. [31] carried out the micro coining tests on the pure copper sheets with different average grain sizes, the results whereof provided evidence that the coarse-grained material helped increase the maximum transfer height, suggested a smaller coining load for the same transfer height and received higher assistance from the ultrasonic vibration on this forming process to create a smoother surface.

With respect to the finite element modelling for materials with size effect, Voronoi tessellation is a prevailing technique exploited to construct a polycrystalline microstructure comprising grains that have different properties equipped with them. Cao et al. [32,33], Jiang et al. [34] and Luo et al. [35,36] produced numerical studies on the micro extrusion, micro hydroforming, micro cross wedge rolling, micro deep drawing and micro hydro deep drawing processes of polycrystalline materials generated by the Voronoi algorithm, respectively; all these results showcased that the mechanical properties and formability of the materials as well as the final product quality had strong affiliations with the properties of individual grains such as its size, morphology and orientation. In the wake of the uneven distribution of heterogeneous grains within these materials, the scatter effect of their general flow curves has been recognised and modelled with a normal bell-shaped distribution [37]. A scattering effect of this kind was also examined and found to be greater at larger grain size and smaller workpiece dimension by Miyazaki et al. [38,39], Gau et al. [40] and Diehl et al. [41].

Additionally, in most cases of metal forming, the products are unlikely to be manufactured exactly to the specifications like size, shape, etc., as the deformed regions are prone to a certain amount of elastic recovery after release of the loading. Material behaviour of this type is termed springback, e.g., a slight decrease in the bending angle after the V-bending process, a slight increase in the flange angle after the deep drawing process, etc., which are affected by the factors such as process parameters, material properties and tooling geometries and have a chance of being compensated by overbending the material [29,35,42–45]. Whilst for the strip rolling process springback may refer to the elastic recovery in the thickness after the strip exits the roll bite, and it is likely to be rectified by dint of increasing the rolling speed, adding tensions to the strip, decreasing the roll gap for a supplementary amount of reduction, and so forth [46–50]. In this context, analytical techniques are introduced firstly to construct mathematical models respecting the rolling force and the thickness directional springback of the workpiece in micro flexible rolling, integrating the influential role played by inhomogeneous grains; micro hardness tests are conducted to determine the weighted heterogeneity coefficients for the 500 μm thick aluminium alloy 1060 strips with various average grain sizes, which reflect the inhomogeneous nature of the grains in each specimen separately. Secondly, laboratory-scale micro flexible rolling experiments are implemented with reductions of 25 to 50 %; quantitative analysis is performed in regard to the variation of average rolling force and thickness directional springback in relation to the average grain size, and whereof the scatter effect is qualitatively evaluated in respect of average grain size. Finally, miniature tensile tests are executed to achieve the scattering stress-strain curves for samples of grain size of approximately 23-71 μm, which are subsequently assigned to the workpiece created on the basis of 3D Voronoi tessellation technique so as to carry out the finite element analysis of micro flexible rolling with consideration of grained heterogeneity; both analytical and numerical approaches developed to model the micro flexible rolling process are validated via quantitative comparison with experimental results, which in turn help enhance the thickness profile control performance of the micro flexible rolling mill.

2. Mathematical models of rolling force and thickness directional springback in micro flexible rolling

2.1. Von Karman unit pressure differential equation with consideration of grained inhomogeneity

In the development of mathematical models of rolling force for micro flexible rolling process, von Karman unit pressure differential equation has been used to first establish the pressure distribution along the arc of contact based on the assumptions that (1) stress is uniformly distributed over the height of the cross section of the rolled workpiece with a sufficiently small discarded lateral spreading in the deformation zone, (2) friction coefficient along the arc of contact remains constant, (3) a uniform constrained yield stress of the material occurs along the arc of contact and (4) the work rolls do not sustain any elastic

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