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# Analysis of micro flexible rolling with consideration of material heterogeneity

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## ABSTRACT

This paper establishes a finite element model to numerically study the springback in thickness direction during micro flexible rolling process, in which 3D Voronoi tessellation has been applied to describe grain boundary and generation process of grain in the workpiece. To reflect material heterogeneity, nine kinds of mechanical properties defined by nine types of heterogeneity coefficients are selected and assigned to Voronoi polyhedrons as per the statistical distribution of hardness of grains identified by micro hardness testing. Initial workpiece thicknesses of 100, 250 and 500 μm with reduction changing from 20% to 50% are respectively considered in the numerical simulation of micro flexible rolling process, and the effects of front and back tensions on the average springback have been discussed. With average grain sizes of 1, 10, 50, 100 and 250 μm respectively employed in the workpieces with the aforesaid initial thicknesses, the scatter of springback in thickness direction has been determined, and a model for springback has also been developed based on the simulation results.

## 1. Introduction

Flexible rolling is a novel forming method for the production of strips with longitudinal thickness variation. At present study on flexible rolling mainly targets at the macro world and plenty of technologies and theories have been set up and adopted for mass production of flexibly rolled strips in automotive, construction and energy industries.

Nevertheless it is promising to transfer the knowledge of flexible rolling from the macro to micro world due to the current trend towards miniaturisation of systems and devices, particularly in the field of electronics production. When the workpiece thickness is scaled down to the micrometre range with other two workpiece-dimensions decreased to the millimetre range in micro flexible rolling process, the so-called size effect that characterises the micro world has to be taken into account.

Many researchers have investigated the size effect numerically and experimentally in the forming process of minute sheet metal. Xu et al. [1,2] studied the effects of material thickness and grain size on deformation and fracture in micro blanking of brass foil, and they concluded that the ultimate shearing strength increased with the decrease of the foil thickness and the maximum blanking force showed a strong variation for the coarse-grained foil specimen. Wang et al. [3] did the experiments and finite element simulations to estimate the effects of sheet thickness and grain size on the springback in micro U-bending process of copper alloy sheets. It was drawn that the springback angle generally increased with the decrease of sheet thickness, which also increased with the average grain size in the cases with different thicknesses. Yeh et al. [4] adopted a new mathematical model that considers the thickness and grain size effects to analyse the cylindrical micro-cup deep drawing process. The simulated results showed the difference of maximum punch load was within 5% when the same relative punch stroke was achieved by using the material properties from conventional model and new constitutive equation. Shan et al. [5] performed experiments to observe the influence of thickness and grain size on the micro-bending process, and the bending force was found to become smaller as the grain size increased with the foil of same thickness. Fang et al. [6] evaluated the size effects on deformation behaviour and fracture of phosphor foil by the ratio of foil thickness $T$ to average grain size $D$. The results revealed the plastic deformation decreased with the decrease of the ratio of $T/D$, making materials more likely to conduct brittle fracture.

The size effect has also been revealed through the flow behaviour of the material obtained from the tensile test [7–9], in which a decrease in flow stress as well as integral flow curve was observed with a decrease in specimen thickness. This phenomenon can be explained as follows. With decreasing specimen thickness, the share of surface grains increases. As the surface grains are less constrained than grains inside the material, the increasing number of surface grains leads to less hardening and

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lower resistance against deformation of the whole specimen, which results in lower flow stress and flow curve [10–12].

On account of the dwindling specimen size, the influence of each grain on the micro-scaled deformation is enhanced. The grains with various sizes, orientations and shapes are distributed in the specimen non-uniformly, giving a rise to inhomogeneous material behaviour and the scatter of experiment results [13,14]. Consequently in the finite element simulation of microforming process, Voronoi tessellation has been widely applied to model the microstructure of grain aggregate, and then the material heterogeneity caused by different grain properties can be reflected via assigning a certain property to each Voronoi polyhedron [15–18].

This paper aims at investigating the springback in thickness direction which exerts a paramount impact on the profile of the product in micro flexible rolling process by use of finite element method. A mathematical model is set up to explicate the flexible rolling phases with thicker and thinner thicknesses respectively. According to the geometric parameters analysed in the mathematical model, the 3D micro flexible rolling finite element analysis (FEA) model is built, where initial workpiece thicknesses of 100, 250 and 500 μm with reduction changing from 20% to 50% are respectively taken into account. Voronoi polyhedrons with varying material properties classified by micro hardness testing are introduced to embody the material inhomogeneity of the workpiece. Five types of grain sizes are respectively employed in the workpiece to ascertain the scatter of the springback in thickness direction, and a model in accordance with the FEA results is deduced to quantitatively predict the springback.

## 2. Mathematical modelling of deformation zone in micro flexible rolling

### 2.1. Angle of bite

During the micro flexible rolling process, the exit position of the workpiece is not at the central line of the rolls because of the existence of tilt angle of the workpiece.

Fig. 1 shows the rolling phase with thicker thickness, in which the exit point *A* lies to the right of the central line of the rolls. Roll radius *OA* is perpendicular to the incline plane *AC* while the central line of the rolls is perpendicular to line *CD*. Hence angle *AOB* is equal to the tilt angle *ACD* denoted by $\theta$. On the basis of angle of bite defined as the central angle of the arc of contact between the rolls and the rolled material [19], the angle of bite in the rolling phase with thicker thickness is expressed by

$$\alpha' = \alpha - \theta \tag{1}$$

where $\alpha$ is the angle of bite in the initial bite phase of the whole rolling process.

Similarly in the rolling phase with thinner thickness, the exit point *A* is located to the left of the central line of the rolls, as shown in Fig. 2. Both angles *AOB* and *ACD* equal $\theta$ by right of line *OA* perpendicular to line *AC* and line *OB* perpendicular to line *BD* separately. Thus, the angle of bite in the rolling phase with thinner thickness is written as

$$\alpha' = \alpha + \theta \tag{2}$$

In the light of bite condition for stable rolling process [20]

$$\mu = \tan\beta > \tan\frac{\alpha_y}{K_x} \tag{3}$$

where $\mu$ is the friction coefficient between rolls and workpiece, $\beta$ is the angle of friction, $\alpha_y$ is the angle of bite in the stable rolling stage, and $K_x$ is the coefficient of acting point of resultant force, which is approximately equal to 2, the bite condition for a steady process of micro flexible rolling can be written as

in the rolling phase with thicker thickness

$$\beta > \frac{\alpha - \theta}{2} \tag{4}$$

and in the rolling phase with thinner thickness

$$\beta > \frac{\alpha + \theta}{2} \tag{5}$$

### 2.2. Reduction

The reduction in micro flexible rolling process continues to vary as the rolling process proceeds in order to obtain the predefined thickness profile. As can be seen in Fig. 3, for the rolling phase with thicker thickness the workpiece thickness at arbitrary location *x* is given by

$$\delta_x = \delta_0 - 2v\cdot t\cdot \tan\theta \tag{6}$$

where $\delta_0$ is the thickness of the head of the workpiece, $v$ is the rolling speed and *t* is the time that the workpiece spends moving from the head to the location *x*. Accordingly, the reduction at arbitrary location *x* in the rolling phase with thicker thickness is expressed in terms of the following form

$$r_x = \Delta - \delta_x = (\Delta - \delta_0) + 2v\cdot t\cdot \tan\theta \tag{7}$$

where $\Delta$ is the initial workpiece thickness, and likewise (Fig. 4), the reduction at arbitrary location *x* in the rolling phase with thinner thickness can be expressed as

$$r_x = \Delta - \delta_x = (\Delta - \delta_0) - 2v\cdot t\cdot \tan\theta \tag{8}$$

It can be seen from Eqs. (7) and (8) that the reduction $r_x$ is a function of speed $v$, time *t* and tilt angle $\theta$, and it only changes in view of whatever *t* takes on when the other two variables remain a constant during micro flexible rolling process.

### 2.3. Length of arc of contact

The length of arc of contact is defined to be the horizontal projection length of the arc of contact between the rolls and the rolled workpiece [21]. In conformity with this definition, the length of arc of contact in the rolling phase with thicker thickness is indicated by line *DE*, as shown in Fig. 5. Using geometric relationship

$$CE = \sqrt{OE^2 - OC^2} = \sqrt{OE^2 - (OB - BC)^2}$$

$$= \sqrt{R^2 - \left(R\cos\theta - \frac{r}{2}\right)^2} = \sqrt{(R\sin\theta)^2 + R\cdot r\cdot\cos\theta - \frac{r^2}{4}} \tag{9}$$

where *R* is the roll radius and *r* is the reduction. Then

$$DE = CE - CD = \sqrt{(R\sin\theta)^2 + R\cdot r\cdot\cos\theta - \frac{r^2}{4}} - R\sin\theta \tag{10}$$

As is shown in Fig. 6, the length of arc of contact in the rolling phase with thinner thickness can be calculated in the same way

$$DE = CE + CD = \sqrt{(R\sin\theta)^2 + R\cdot r\cdot\cos\theta - \frac{r^2}{4}} + R\sin\theta \tag{11}$$

From Figs. 5 and 6 it can be seen that with respect to an equal reduction the length of arc of contact gets shorter in the rolling phase with thicker thickness while it becomes longer in the rolling phase with thinner thickness compared with that in the rolling phase for an invariable thickness, which thereby brings about the change of corresponding deformation area in micro flexible rolling process.