Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 81 (2014) 2463 – 2468

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

Finite element method analysis of micro cross wedge rolling of metals

Zhengyi Jiang[a]*, Haina Lu[a], Dongbin Wei[a], K.Z. Linghu[b], Xianming Zhao[c], Xiaoming Zhang[c], Di Wu[c]

[a]*School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong, NSW 2522, Australia*
[b] *Shougang Research Institute of Technology, Shougang, Beijing 100043, China*
[c]*State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110004, China*

Abstract

A newly developed manufacturing technology - micro cross wedge rolling technology is an appropriate method to produce micro axisymmetric components such as micro stepped shafts. The development of this classic cold forming process is limited by a lack of sufficient understanding of geometric and material effects due to the size reduction of the components. In this study, a numerical model is proposed to simulate micro cross wedge rolling where the grain size effect is taken into account. Pure copper is chosen as the raw material. A finite element simulation is implemented where the diameter of the cylindrical workpiece is 0.8 mm and the polycrystalline aggregates are represented by Voronoi tessellation. The mean grain sizes of these workpiece range from 6 to 248 μm, in order to evaluate the grain size effect on the material flow. Meanwhile, a set of experiments are performed on the workpieces that have been heat treated. The experimental results show a good agreement with the simulation results by comparing the rolling forces and evolution of microstructures.

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

Keywords: Micro cross wedge rolling; Grain size effect; Finite element method; Cold forming

* Corresponding author. Tel.: +61 2 42214545; fax: +61 2 4221 5474.
E-mail address: jiang@uow.edu.au

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.10.351

1. Introduction

In last decades, microforming technology developed dramatically due to the increasing market demand for the micro components, specifically in the field of micro system technology and electro-mechanical systems. Microforming has been successfully developed as an appropriate technology to manufacture metallic micro components with at least two dimensions in the sub-millimeter range [1].

Lu et al. [2] proposed micro cross wedge rolling and produces micro components using micro cross wedge rolling technology as shown in Fig. 1. Besides the similar issues existing in cross wedge rolling, however, micro cross wedge rolling has to confront the common problems in microforming. The problems occurred during miniaturisation of metal forming process have been disclosed by Engel et al [3]. The challenges above are inevitable in micro cross wedge rolling technology. For example, the micro products are strongly compromised by the occurrence of defects such as the internal voids, surface asperity and excessive slip. Internal void is one of the main sources of the product mechanical failure, which determines the applicability and work life cycle of micro components. Therefore, the capability of predicting the material flow within deformed micro-metal parts as well as the generation of internal defects is significant for the further exploration of this novel technology.

There are only a few grains within the deformed region during microforming process, so the individual grain plays a significant role in microscale plastic deformation since each grain has unique property. Many explorations on the issue of grain size effect have been conducted and the corresponding constitutive models have been developed. Hall [4] and Petch [5] studied the effect of grain size on the yield stress and found a linear relationship between the yield stress and the reciprocal of the square root of grain size. Geiger and Engle [1] proposed the surface layer model, which divided the specimen into two portions, inner and surface layer portions, to explain the reduction of flow stress in metal microforming process. Lai et al [6] developed a mixed model by combining the modified Hall-Petch relationship and surface layer model. The grained heterogeneity was taken into account by Lu et al. [7] to investigate the decrease of flow stress and scatter of grained behaviour.

In this study, a mixed material model based on modified Hall-Peth relationship, surface layer model and grained heterogeneity is proposed, taking into account the size effect. The novel model was implemented with assistance of finite element simulation where the polycrystalline aggregate is represented by Voronoi tessellation. A set of micro cross wedge rolling tests have been carried out to observe and quantify the effect of grain size on flow stress. A micro cross wedge rolling machine was employed to roll several specimens with different grain sizes.

2. Numerical model considering grain size effect

The composite model developed by Meyers et al. [8] has been proven to be a valid and effective model to describe the relationship between the material yield stress and grain size. This composite model supposes that the deformation polycrystalline is composed of a hard grain boundary region and a soft grain interior region, as shown in Fig. 2.

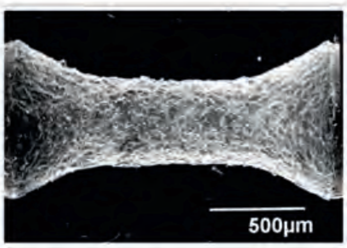

Fig.1. Workpiece of micro cross wedge rolling.

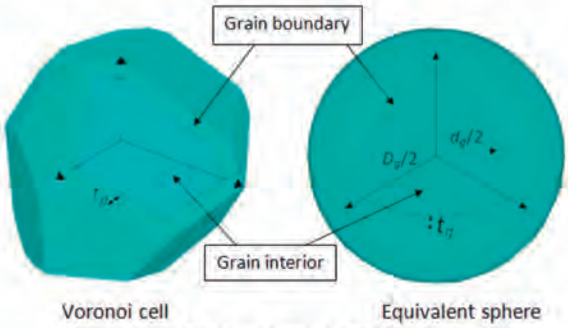

Fig.2. Grain interior and grain boundary model.

A composite model is thus proposed to calculate the flow stress of polycrystalline aggregate in the following:

$$\sigma_s = (1-f)\sigma_i + f\sigma_b, \tag{1}$$

where σ_s is the flow stress of polycrystalline aggregate. f is the volume fraction of grain boundary. σ_i and σ_b are the flow stress of grain interior and boundary respectively.

Assuming that the grain size is d_g and the thickness of grain boundary layer is t_g. The relationship between the thickness of grain boundary and the grain size is described as follows,

$$t_g = kd_g^n, \tag{2}$$

where k and n are regarded as constants for a specific material and $0 < n < 1$. According to the previous research report [9, 10], k and n are determined to be 0.133 and 0.7 respectively when the material is copper. The equivalent sphere is proposed to re place the Voronoi cell when the grain size is calculated. The volume of sphere is equal to the polyhedron volume and the grain size is equal to the diameter of the equivalent sphere. 3D simplex integration method is used to calculate the volume of each Voronoi cell. Assuming there are m grains involved in the inner portion of specimen, the volume faction of grain i (i=1, 2, … , m) in the inner portion of specimen can be calculated. Then, the total volume fraction of the grain boundaries is obtained,

$$f = \sum_{i=1}^{m} v_c(i) \times f_c(i) = \sum_{i=1}^{m} \frac{4\left[D_g(i)/2\right]^3\left[2kD_g^{n-1}(i)^3 + 1\right]}{3\left(r_s - D_{mg}\right)^2\left(h_s - 2D_{mg}\right)}, \tag{3}$$

where D_{mg} is the average grain size and $D_g(i)=[6v_{vc}(i)/\pi]^{1/3}$. r_s and h_s are the radius and height of the specimen respectively as shown in Fig. 3. The surface layer model is utilised to explain the geometry size effect on the decrease of flow stress during miniaturisation. The specimen is subdivided into two portions: surface layer and inner part.

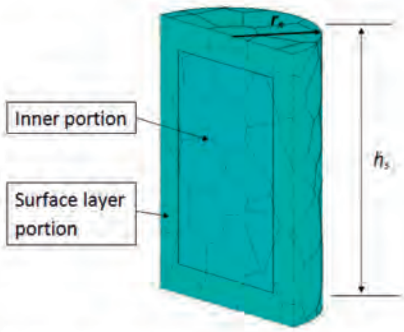

Fig. 3. Surface layer and inner portion of cylindrical specimen.

The flow stress of the material is composited by that of inner portion and surface layer of specimen as follows:

$$\sigma = \gamma\sigma_{inner} + (1-\gamma)\sigma_{surf}, \tag{4}$$

where σ is the flow stress of material. σ_{inner} and σ_{surf} are the flow stress of the grain located at inner and surface region, respectively. γ is the fraction of inner portion and it can be expressed as follows:

$$\gamma = \left(r_s - D_{gm}\right)^2\left(h_s - 2D_{mg}\right)/ r_s^2 h_s. \tag{5}$$

The flow stress of inner portion can be described by that of polycrystalline aggregate, $\sigma_{inner} = \sigma_s$, the grains located at the free surface have less hardening effect than those of inner grains. Therefore, the grain boundary strengthening effect in surface layer is ignored. The flow stress of surface layer portion is equal to that of grain interior, $\sigma_{surf} = \sigma_i$. As a result, the geometry size effect is taken into account in the composite model. The flow stress in microfoming can be expressed:

$$\sigma = (1 - f\times\gamma)\sigma_i + f\times\gamma\times\sigma_b. \tag{6}$$

A parameter F is introduced to replace $f\times\gamma$.

$$F = \gamma \times f = \frac{4}{3r_s^2 h_s} \sum_{i=1}^{m} \left[D_g(i)/2\right]^3 \left\{\left[2kD_g^{n-1}(i)-1\right]^3+1\right\}, \tag{7}$$

where F is defined as a size-effect factor and can be figured out when the dimension of micro part and its grain size are specified. Therefore, in the developed constitutive model, the flow stress of grain interior and grain boundary are unknowns. No less than two strain-stress curves of deformed material with different grain sizes are required to determine σ_i and σ_b. The values of σ_i and σ_b at a certain strain can be obtained. The flow stress curves of grain interior and boundary are finally determined. When the dimension of cylindrical sample is Φ 0.8×1.2 mm^2, a series of flow stress curves with different grain sizes are obtained based on Equation (4).

At micro scale, the deformation behaviour is characterised by the deformability of individual grain, so nano-indentation was adopted to identify the grained heterogeneity. Hardness is the ability of a material to resist plastic deformation via scratch or indentation. The hardness of grains obtained from the nano-indentation test is an effective parameter to estimate the deformability of individual grain, so grained heterogeneity can be figured out. Statistical distribution of hardness is divided into 7 classes (Fig. 4a). The ratio of the hardness at each class divided by the average hardness was defined as an inhomogeneity coefficient to make the strain-stress curves vary following the statistical distribution. As shown in Fig. 4b, α_h is the inhomogeneity coefficient.

For the sake of better understanding of the deformation in micro-compression, grains were meshed and 3D fully aggregates were computed with finite element simulation. The material constitutive model as illustrated by Eq. (6) is to attribute to the corresponding regions, viz., individual grains randomly.

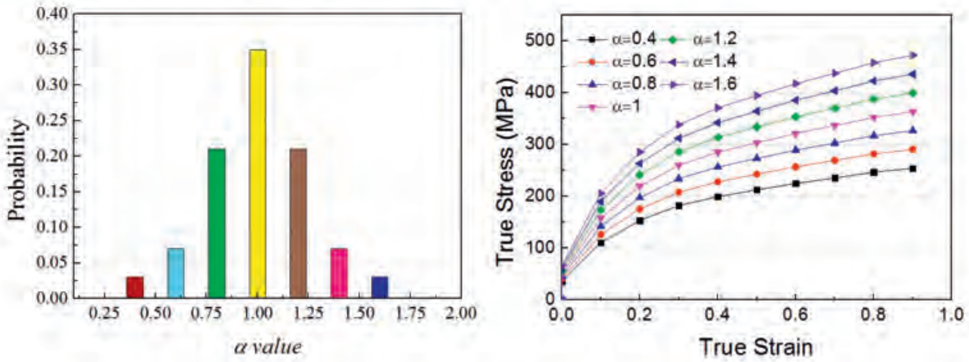

Fig.4. Strain-stress curves based on scatter of grained deformation behaviour. (a) Statistical distribution of αh-value and (b) flow stress of inhomogeneous material.

3. Finite element simulation

After generating the appropriate topological structure of grains within the specimen using Voronoi tessellation, this geometrical feature was imported into finite element analysis software ANSYS/LS-DYNA and meshed into elements. During meshing process, space is discretised and described with a 3D digital image composed of voxels (pixels in 3D) that can be labelled with the number of grains that they belong to. According to the characteristics of Voronoi diagram, a distance function is introduced and a segmentation algorithm associates each voxel to the nearest nucleus. This image can be discretised into finite elements using a regular mesh. These cylindrical workpieces with grain size 6, 120 and 248 μm were discretised into eight-noded structural solid164 elements with one point integration. Each node has six degrees of freedom, translation and rotation in x, y and z directions.

The Geometrical model of wedge too was generated in the Computer Added Design software and then import into ANSYS/LS-DYNA. As described in Fig. 5, the two wedge tools were constrained in y and z directions but have manually opposite velocities of 0.1m/s in x direction.

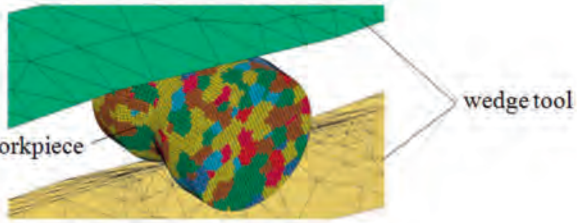

Fig.5. FEM simulation models.

4. Results and discussion

The variation of the workpiece shape during the rolling process can be observed and analysed using finite element model. Fig. 6 illustrates the progressive rolling of a step shaft, showing how the wedges cut into the middle of the workpiece in the knifing zone (I) to generate v-shaped groove over the entire periphery after the guiding zone (II), and then the cross section is reduced in the stretching zone (III) to the required width. The geometrical dimensions are then refined in the sizing zone (IV). At last, the workpiece separates from the unloading zone (V) which prevents the surface fracture due to the sudden unloading of rolling force. It is also available to detect how the stress and strain states developed from finite element simulation results.

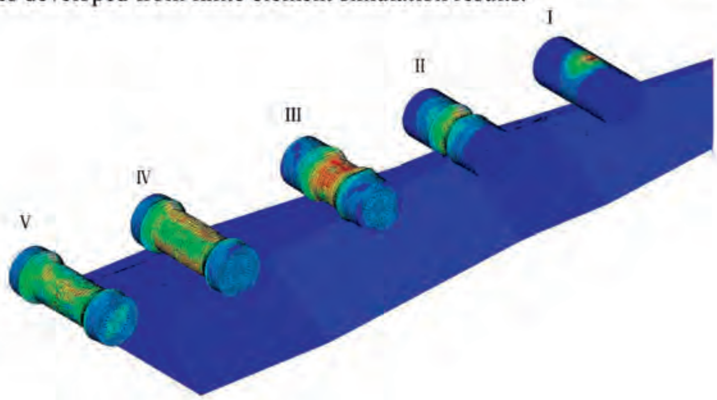

Fig.6. Process of forging shape during rolling.

In the macro cross wedge rolling, there is a probability of internal defect - a type of void pattern as a result of hydrostatic tension within the central regions of workpieces, and the generation of internal void can be easily detected due to the typical laminar cricoid distribution of strain. However, the grain size effects make the strain and stress distribution become more complicated. At micro scale, the influence of grained heterogeneity on the metal deformability and strain distribution cannot be ignored. The cross sections shown in Fig. 7 locate in the middle of the cylindrical billets when the deformation of billets is in the guiding stage. As shown in Fig. 7, with an increase of grain size, the continuous laminar distribution of strain in the workpiece has been more significantly disturbed due to inhomogeneous mechanical properties. Because the material at macro scale is regarded as homogeneous, the location of maximum strain and stress cannot be determined easily as that in the conventional cross wedge rolling process.

When the grain size is 40 μm, the disturbance of stress distribution is much smaller than that of the workpiece with grain size 248 μm. Moreover, the workpiece with grain size 6 μm shows a similar distribution of stress. Fig. 8 illustrates the stress distribution evolution of the workpiece with grain size 40 μm in each rolling stage. It can be seen that the effects of grain size on the stress in radial direction are more obvious than that in axial direction because the geometry dimension in axis direction is larger than that at radial direction.

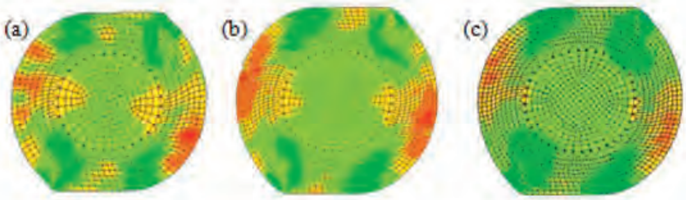

Fig.7. Von Miss Stress distribution on middle cross section of workpieces with different grain sizes: (a) 248, (b) 40 and (c) 6 μm.

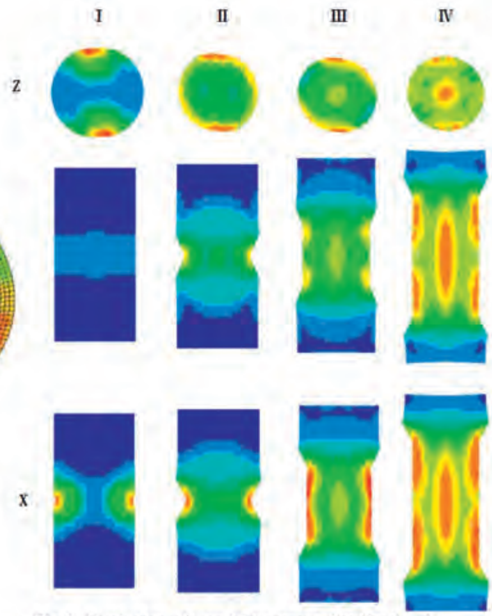

Fig.8. Evolution of von Miss stress distribution in longitudinal and cross sections of cylindrical workpiece.

5. Conclusions

Using an experimentally verified finite element analysis, the grain size effect on the material flow within workpieces were captured and figured out initial region where the material failure may occur. Such a finding was accordant with the prior work done by the authors, who developed a numerical model for metal microforming. Based on the finite element simulation results, it was determined that the critical grain size of workpieces should be around 40 μm in order to obtain more uniform stress distribution. The evolution of stress in three directions were analysed and the simulation results showed the material heterogeneity had a more significant influence on the flow stress in radial direction.

Acknowledgements

The authors would like to thank the Australia Research council (ARC) for its financial support.

References

[1] Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N., Engel, U., 2001. Microforming, Annals of the CIRP. 50, 445-462.
[2] Lu, H.N., Wei, D.B., Jiang, Z.Y., Manabe, Furushima, K.T., 2011. Study on size effect in micro cross wedge rolling, International Journal of Steel Research, 962-967.
[3] Engel, U., Eckstein, R., 2002. Microforming – from basic research to its realization, J. Mater. Proc. Technol. 125-126, 35-44.
[4] Hall, E.O., 1951. The Deformation and Ageing of Mild Steel: III Discussion of Results, Physical Society Proceeding. 64, 747-753.
[5] Petch, N.J., 1953. The cleavage strength of polycrystals, Iron and Steel Institute. 174, 25-28.
[6] Lai, X.M., Peng, L.F., Hu, P., Lan, S.H., Ni, J., 2008. Material behavior modelling in micro/meso scale forming process with considering size/scale effects, Comput. Mterial. Sci. 43, 1003-1009.
[7] Lu, H.N., Wei, D.B., Jiang, Z.Y., Liu, X.H., Manabe, K.. 2013, Modeling of size effects in microforming process with consideration of grain heterogeneity, Comput. Mterial. Sci. 77, 44-52.
[8] Meyers, M.A., Ashworth,1982. A model for the effect of grain size on the yield stress of metals, E., Philos. Mag. A. 46, 737-759.
[9] Fu, H.H., Benson, D.J., Meyers, M.A., 2001. Analytical and Computational Description of Effect of Grain Size on Yield Stress of Metals, Acta Mater. 49, 2567-2582.
[10] Geiger, M., Geibdorfer, S., Engle, U., 2007. Mesoscopic model: Advanced simulation of micro-forming process, Production Engineering. 1, 79-84.