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# Study on the influence of temperature on the surface asperity in micro cross wedge rolling

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## **Abstract**

When the common deformation processes are scaled down to micro/meso dimensions, size effect is the particular phenomena in microforming, which is related to the dominant influence of single grains inside the micropart. The conventional cross wedge rolling (CWR) is introduced into the micro scale in order to take the advantages of CWR. The micro cross wedge rolling (MCWR) has to confront with the phenomena of size effect that occurs in the common microforming processes inevitably. One of the approaches to compensate size effect is to increase the deforming temperature. An increased formability is achieved because more slip systems of polycrystal metal are activated at the elevated temperature. This reduces the anisotropic material behavior resulting in a more homogeneous forming with improved reproducibility. In this study, a YAG laser beam is applied to heat the workpiece. Finite element model (FEM) associated with a material constitutive formulation considering dislocation mechanics is set up to simulate the MCWR of pure copper utilizing the laser heating. The surface asperity as an indication of material heterogeneity in micro scale is quantitatively analysed. The simulation results show a good agreement with experimental results in terms of the surface asperity.

## **Keywords**

temperature, surface, study, asperity, influence, micro, cross, wedge, rolling

## **Disciplines**

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# Study on the Influence of Temperature on the Surface Asperity in Micro Cross Wedge Rolling

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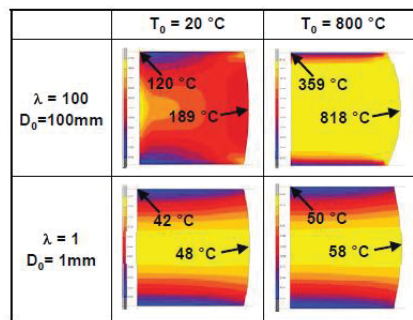
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**Abstract.** When the common deformation processes are scaled down to micro/meso dimensions, size effect is the particular phenomena in microforming, which is related to the dominant influence of single grains inside the micro part. The conventional cross wedge rolling (CWR) is introduced into the micro scale in order to take the advantages of CWR. The micro cross wedge rolling (MCWR) has to confront with the phenomena of size effect that occurs in the common microforming processes inevitably. One of the approaches to compensate size effect is to increase the deforming temperature. An increased formability is achieved because more slip systems of polycrystal metal are activated at the elevated temperature. This reduces the anisotropic material behavior resulting in a more homogeneous forming with improved reproducibility. In this study, a YAG laser beam is applied to heat the workpiece. Finite element model (FEM) associated with a material constitutive formulation considering dislocation mechanics is set up to simulate the MCWR of pure copper utilizing the laser heating. The surface asperity as an indication of material heterogeneity in micro scale is quantitatively analysed. The simulation results show a good agreement with experimental results in terms of the surface asperity.

**Keywords:** Microforming, Size Effect, Surface Asperity, Finite Element Method.

## INTRODUCTION

Microforming technology is one of the most promising technologies in modern industry due to the trend towards micro system technology and one of its increasingly important outcomes, micro electro-mechanical systems, microforming has been developed successfully as an appropriate technology to manufacture metallic micro components with at least two dimensions in the sub-millimeter range [1]. As the manufacturing processes are reduced from macro scale to micro scale, an inevitable phenomenon — size effect occurs which blocks the application of classical theories in microforming [1-3]. While the microstructure keeps a constant, only a few grains are involved within the micro scale components through the dimension of interest, and thus there are only a few grains located in the deformation zone. Size effects are caused by the orientation, size, and position of grains within the specimen, and simply the smaller size of the workpiece [4].



**FIGURE 1.** Workpiece Size Influence on Forming Temperature [8].

One of the approaches to compensate or reduce the influence of size effects is to increase the temperature during the forming process. This can be accomplished by heating the workpiece. An increased formability is achieved because more slip systems of polycrystal metal are activated at elevated temperature. This minimises the anisotropic material behaviour resulting in a more homogeneous forming with improved reproducibility. Echenhualler et al [5, 6] have validated it in the upsetting test at elevated temperature using micro specimen of CuZn15 and stainless steel.

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An alternative approach is to refine grain structure with the deformed part, which has been investigated by previous researchers [7].

In the metal forming process, the mechanical properties of material are sensitive to temperature in certain temperature range. When heating assists in microforming, lower forming temperatures in smaller workpieces can be expected as the surface-volume-ratio increases, which can enhance the heat transfer to the environment with decreasing scale factor  $\lambda$  (Fig. 1) [8]. The heating temperature should be controlled in a certain range in case of the excessive grain growth and oxidation of metal workpieces. Warm forming ( $0.35T_m < T < 0.55T_m$ ) which allows crystal recovery without recrystallisation is considered as a sensible option to improve the deformability and avoid oxidation in microforming [9]. The warm forming capitalises on the advantages of cold forming (good surface quality and strain hardening) and the benefits of hot forming (lower forming force and better deformability). In conventional scale, the upper limit warm forming temperature is usually determined by the amount of oxidation which can be tolerated. Its lowest limit is determined by force which can be produced using the forming machines and the formability of the material [10]. Laser radiation may be the most appropriate method to heat the micro deformed part during microforming process because of its unique characteristics. Since the laser can be precisely controlled, dimensionally as well as directionally [11, 12]. One of the most common lasers used in metal processing is the Nd:YAG laser, operating in the near infrared just outside the visible wavelength region [13].

In this paper, the influences of temperature and grain size on the material forming behaviour in microforming are investigated. A series of micro compression tests with assistance of laser heating are conducted using cylindrical specimens made of pure copper. In addition, a constitutive model based on the dislocation mechanics theory, grain size effect and surface layer model is introduced. A finite element (FE) model is developed to simulate the micro cross wedge rolling (MCWR) with voronoi tessellation to describe the polycrystalline aggregates.

## EXPERIMENTAL SET-UP

The experimental investigations have been conducted using specimens made of 99.999% copper. The diameter of cylindrical specimen is 0.8mm. The mean grain size of specimen was enlarged by vacuum heat treatment. These specimens underwent heat treatment at 900K for 10 hours to increase grain size to approximately 235  $\mu\text{m}$  and the treated copper was carefully subdivided by wire cutting. The area reduction of 70% was achieved with the wedge plates moving at the speed of 0.1mm/s, which were conducted on the desk-top MCWR machine at 300K, 450K and 600 K. The deformed specimens (Fig. 2) were observed and measured by digital microscope VHX-1000E and the surface asperities of the samples processed at different temperatures revealed significant distinction.



FIGURE 2. Deformed Specimen by MCWR.

## FE MODEL OF MCWR

The numerical model was established with setting the diameter of the cylindrical sample as 0.8mm. The velocity of rigid tools movement was 0.1mm/s and the friction coefficient between tools and specimen was set 0.23. The algorithm of voronoi tessellation was used to generate ten models with mean grain size of 235  $\mu\text{m}$  while the specimen size keeps constant. Three groups of pure copper specimens with grain sizes 235  $\mu\text{m}$  were deformed at three different temperatures respectively.

In order to have a deep understanding on the deformation behaviour in MCWR, grains were meshed and 3D fully aggregates were computed. The workpiece was represented based on a space tessellation into 3D voronoi diagram which can describe grain boundary and generation process of grain vividly. After generating the appropriate topological structure of grains within the specimen, this geometrical feature was imported to FEM software ANSYS/LS-DYNA as shown in Fig. 3. The model was meshed into eight-noded structural solid164 elements with one point integration. Each node has six degrees of freedom, translation and rotation in  $x$ ,  $y$  and  $z$ .

In meshing process, space was discretised and described with a 3D digital image composed of voxels (pixels in 3D). According to the characteristics of voronoi diagram, a distance function was introduced and a segmentation algorithm associates each voxel to the nearest nucleus. According to the experimental conditions, the applied method of MCWR modeling has been developed on the grounds of the following assumptions:

- (i) grains involved in the workpiece can be approximately described by voronoi tessellation;
- (ii) the micro workpiece is heated up to the expected temperature within a negligible short time;
- (iii) the heat generated by plastic deformation is ignored within the workpiece;
- (iv) an even distribution of constant temperature within the workpiece during compression;
- (v) a constant friction coefficient on the material-tool contact surface.

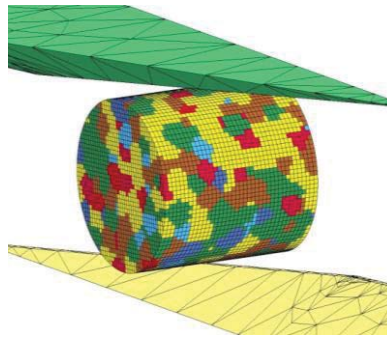


FIGURE 4. FE Model of MCWR of Polycrystal Copper

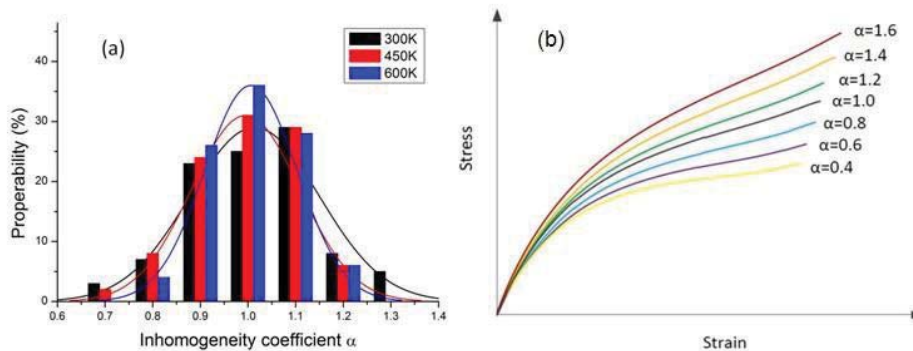


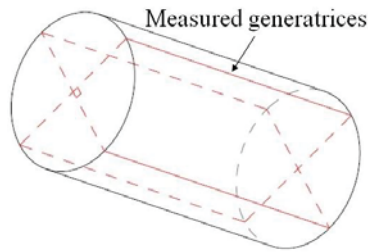
FIGURE 5. (a) Statistic Distribution of Inhomogeneity Coefficient Influenced by Temperature, (b) Strain-stress Curve Varies along with Inhomogeneity Coefficients

A previous material model of pure copper developed by the authors was used in this FEM simulation. It is based on dislocation mechanics theory and Hall – Petch relation. It is expressed as:

$$\sigma_u = \sigma_0 + 0.478\varepsilon^{-0.1}d^{-1/2} + 808 \cdot \sqrt{1 - \exp(-10\varepsilon)} \left[ 1 + 10^{-4}T \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \right]^{0.45} \quad (1)$$

where  $\sigma_u$  is stress,  $\varepsilon$  and  $\dot{\varepsilon}$  are strain and strain rate respectively,  $T$  is deforming temperature and  $d$  is grain size. In this study,  $\sigma_0=15$  Mpa,  $\dot{\varepsilon}_0=1.76 \times 10^8$  s<sup>-1</sup>,  $\dot{\varepsilon}=0.065$  s<sup>-1</sup>. A series of flow stress curves can be obtained at different temperatures.

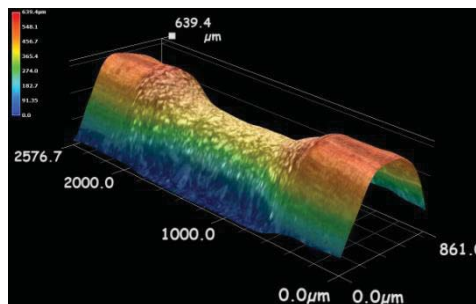
When the compression tests were repeated under the same experimental conditions (e.g. grain size and temperature), a discrete distribution instead of a superposition of flow stress curves was observed due to the grain heterogeneity in micro scale. The scatter of flow stresses obtained from experiments reflects the inhomogeneous material behaviour in microforming. Therefore, the scatter of flow stresses was used to represent grained heterogeneity in this study. Statistical distribution of flow stresses is divided into 7 classes. The ratio of the flow stress at each class divided to the average flow stress is defined as an inhomogeneity coefficient  $\alpha$  which is relevant to the grain size of workpiece and temperature of compression process. Fig. 4a illustrates the statistical distribution of inhomogeneity coefficient at different temperatures. Multiplication of the strain-stress curve obtained from Equation 1 by the inhomogeneity coefficients can make strain-stress curves of the inhomogeneous grains following this statistical distribution (Fig. 4b). This introduces grained heterogeneity into the constitutive relation. These inhomogeneous material models will be applied in FE simulation. The material constitutive model illustrated above is to attribute to the specific region, viz. individual grain randomly.



**FIGURE 6.** Generatrices for Measuring

## RESULTS AND DISCUSSIONS

The influences of temperature on flow behaviour are even more pronounced in micro metal forming, because so-called ‘size effects’ cause inhomogeneity in terms of the material flow behaviour and inaccuracy in the shape of the items produced. The latter was focused in this paper. The MCWR tests as well as FE simulations were implemented at the temperatures of 300, 450 and 600K. The experimental and simulation results obtained were analysed in terms of the surface quality.



**FIGURE 7.** Micro Product Profile Observed by 3D Digital Microscope VHX-1000E

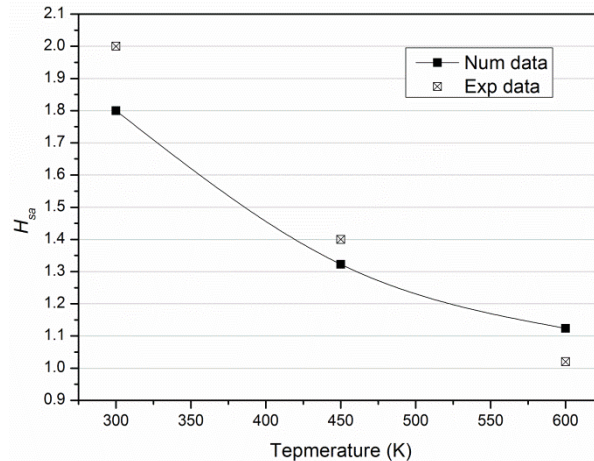
In order to measure the surface asperity quantitatively, twelve generatrices uniformly spreading on the side surface of cylindrical specimen were determined as illustrated in Fig. 5. After deformation, surface becomes roughed comparing with the original sample surface, which can be measured by the distance between the nodes at the generatrice and the original centre, and the average values of the distance obtained from the four generatrices were calculated. Assuming the deformation behaviours of grains inside the sample are homogeneous, side surface of the compressed sample is perfectly smooth. One generatrice of this assumed compressed sample is used as a reference. The results by adopting the homogeneous model and inhomogeneous model are compared. The side surface asperity was measured by 3D digital microscope VHX-1000E as show is Fig. 6.

The absolute value of the difference between the values by adopting conventional model with homogeneous material property and the model considering grained heterogeneity is defined as  $H_{sa}$ . The meaning value of the



absolute differences obtained from all of the twelve generatrices is defined as  $H_{sa}$  and has been used to assess the surface roughening quantitatively. The experimental and numerical results were calculated and analysed to obtain  $H_{sa}$ .

Fig. 7 demonstrates the influences of temperature on the side surface asperity between the copper samples. It is noticed that there was a significant decrease of  $H_{sa}$  with increasing temperature for copper specimen with grain size of 235  $\mu\text{m}$ .  $H_{sa}$  declined linearly from 1.8 to 1.1 when temperature increased from room temperature to 600K as illustrated in numerical results and the experimental data show the same tendency. During the plastic deformation of metals, dislocations move and accumulate, which has to overcome the obstacles spreading among the crystal structure. For the typical FCC metal, copper, the primary short-range barriers are other dislocations which intersect the slip plane and impede the motion of gliding dislocation. The increasing temperature of deformed part can activate the constrained slip system resisted by short-range obstacles, which homogenize grained deformability of the metal polycrystalline.



**FIGURE 8.** Influence of Temperature on  $H_{sa}$

## CONCLUSIONS

The influence of deforming temperature on the surface quality of MCWR product was experimentally and numerically investigated using pure copper with grain size of 235  $\mu\text{m}$ . A constitutive model based on dislocation mechanics developed by the authors was attributed to the FE model. This constitutive model was capable of modelling the FCC material responses in micro scale at certain range of temperature. Meanwhile, a FE model was set up with voronoi tessellation to describe metal polycrystalline and grained heterogeneity was considered as well.

The experimental and numerical results illustrate a homogeneous phenomenon of deformability due to elevated temperature, which was analysed based on surface asperity. With the thermal activation, more slip systems were activated, leading to improvements in the edge quality of the deformed workpieces in MCWR.

## ACKNOWLEDGMENTS

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