Computational Materials Science 110 (2015) 134–143

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Numerical simulation of flexible micro-bending processes with consideration of grain structure

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 11 August 2015
Accepted 14 August 2015
Available online 27 August 2015

Keywords:
Micro-bending
Size effects
FE-simulation
Constitutive model
Voronoi tessellation

ABSTRACT

A finite element model of the flexible micro-bending process based on various grain sizes of pure copper is developed. The geometrical model of grain structure is established with Voronoi tessellation, which is employed to describe the polycrystalline aggregation. A model based on dislocation density is adopted to describe the flow stress of grain interior (GI) and grain boundary (GB) quantitatively. In this paper, silicon rubber is used as the flexible punch and four annealing conditions of pure copper as the workpieces, respectively. The influence of grain structure and grain size is discussed. It is observed that as the ratio of workpiece thickness (t) to grain size (d) decreases, the forming depth increases. The inhomogeneous deformation occurs in the coarse-grained micro-parts. Furthermore, the results indicate that the surface asperity increases with grain size. The numerical simulation results agree well with the tendency of experimental results. During the micro-bending process, the phenomenon of stress concentration occurs at the grain boundary of the micro-parts. The maximum von mises stress appears at the grain boundary located at the fillet position. The maximum von mises plastic strain primarily concentrates on the junction of the grain interior and grain boundary in the fine-grained parts, while it concentrates at the surface of the grain interior in the coarse-grained parts.

1. Introduction

In recent years, with the development of the electronic industry, micro–electro–mechanical systems and medical devices, the demand for micro-parts has increased. Micro-forming is one of the most promising manufacturing processes for fabricating micro-parts with high productivity, low cost and good mechanical properties [1]. With the geometrical dimension of micro-parts decreasing to the microscale, affected by the micro-structure and feature size of the micro-parts, the deformation mechanism, the material behaviour and the friction condition are different from those of the macro-parts [2]. These properties are the so-called size effects.

Many experimental studies have been conducted to explore the impact of size effects on the material mechanical properties of micro-parts. A variety of mathematical models have been proposed. One of the most classic models is the Hall–Petch model, which was proposed by Hall and Petch [3]. The Hall–Petch model assumes that the material yield stress has a linear relation with the reciprocal of the square root of the grain size. Shan [4] explained that the yield stress decreased with the increase of the grain size during the micro-bending forming process of the Hall–Petch model.

However, upon further study, it was discovered that the material yield strength no longer followed the Hall–Petch relationship [5] when the workpiece thickness was reduced to a constant grain size. The influence of the ratio of the workpiece thickness (t) to grain size (d), i.e., the N value, became the primary impact factor in material flow stress [6,7]. Leu [8] focused on the flow stress affected by the ratio of workpiece thickness to grain size via sheet material tensile tests.

Therefore, the surface layer model, which divides a specimen into two portions, the inner layer portion and the surface layer portion, was proposed [9]. Flow stress in the surface layer is smaller than that in the inner layer because fewer grain boundaries and dislocation can slip to the surface of the specimen freely in the surface layer. The volume fraction of the surface layer increases as the N value decreases. Therefore, the flow stress decreases as the N value decreases. Based on this model, many phenomena can be well explained. Chan [10] studied the flow stress and spring back angle affected by size effects based on the surface layer model. Lin [11] used the surface layer model to explain the reduction of flow stress with the decrease of workpiece thickness when the grain size was a constant. Wang [12] investigated the size effects

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http://dx.doi.org/10.1016/j.commatsci.2015.08.030
0927-0256/

on deformation behaviour in the laser dynamic microforming of copper foil based on the surface layer model.

A methodology based on the composite model to study the effects of grain size on material behaviour was developed [13,14]. In the composite model, a grain was considered as being composed of both a grain boundary and grain interior. The flow stress of workpieces was determined by the volume fraction and the flow stress of each grain portion. By using the composite model, Liu [15] successfully predicted flow stress affected by grain size and workpiece thickness and studied the springback angle of the micro-bending process. Fu [16] investigated the micro blanking and deep drawing compound process to study the effects of grain size, the thickness of workpiece and the radius of punch on the deformation mechanism.

To reveal the variation of the micro structure during the micro forming process, the constitutive model based on the mechanism of plastic deformation has been rapidly developed. Dislocation slip is the main mechanism of plastic deformation. Some researchers have established the flow stress model based on the evolution equations of dislocation density [17]. Therefore, the plastic deformation behaviour of polycrystalline materials is described by the microscopic mechanism. Fu [18] explained the grain boundary strengthening mechanism with the model based on the dislocation density during the micro-forming process.

Based on the above models, several numerical simulations to study the influence of size effects on deformation behaviour have been conducted. Geißdörfer [19] simulated the size effects on the forming force during the micro-upsetting process by using the Hall–Petch model and the surface layer model. Wang [20] divided a workpiece into three portions, namely, the free surface portion, transition portion and internal portion, and used a numerical simulation method to study the change of flow stress with the workpiece thickness. Based on the dislocation density model and the surface layer model, Molotnikov [21] calculated the flow stress with different grain sizes and workpiece thicknesses, and the limited drawing ratio, influenced by grain size, was studied using the finite element (FE) simulation. A FE model based on the surface layer model was established by Lu [22] to study the effect of grained heterogeneity on the microcross wedge rolling process.

Overall, many experiments have been performed to study the influence of size effects on material behaviour, but the number of numerical simulation studies is relatively fewer. Moreover, those numerical simulations mainly focused on the tensile tests and compression processes. However, little work has been performed with respect to the micro-bending process. Conversely, many reports have ignored the influences of grain boundary strengthening and the grain structure. In this paper, Voronoi tessellation is introduced to generate the polycrystalline structure. The grain structure is divided into two portions: the grain boundary (GB) portion and the grain interior (GI) portion. Based on the dislocation density model, the flow stress of grain boundary and grain interior is established. The deformation behaviour of micro-bending influenced by grain size and grain structure is discussed.

2. FE simulation

2.1. Dislocation density-based model for pure copper

In the process of grain plastic deformation, dislocation slip is the main plastic deformation mechanism. Due to the proliferation of dislocation sources, the number of dislocations in crystal will increase during the plastic deformation process. The flow stress model, using dislocation density as the internal variable, can really describe the deformation behaviour of polycrystalline material [23]. Pure copper is chosen as the workpiece in this paper. The dislocation density is affected by the equivalent plastic strain and plastic strain rate. The dislocation accumulation in the grain boundary and grain interior can be expressed as [24]

$$\frac{d\rho_{GI}}{d\varepsilon_{GI}} = k_{GI}\sqrt{\rho_{GI}} - k\rho_{GI} \quad (1)$$

$$\frac{d\rho_{GB}}{d\varepsilon_{GB}} = k_{GB}\sqrt{\rho_{GB}} - k\rho_{GB} - \frac{A}{\dot{\varepsilon}_{GB}}\rho_{GB}^2 \quad (2)$$

where ρ_{GI} is the dislocation density in GI, ρ_{GB} is the dislocation density in GB, $k_{GI} = \alpha_{GI}/b$, $k_{GB} = \alpha_{GB}/b$, α_{GI} and α_{GB} are the numerical constants ($\alpha_{GI} = 0.1$, $\alpha_{GB} = 0.4$ [25]), and $b = 0.3$ nm is the Burgers vector [26]. ε_{GI} and ε_{GB} are equivalent plastic strain in GI and GB, respectively, $\dot{\varepsilon}_{GB}$ is the equivalent plastic strain rate in GB, $k = k_0(\dot{\varepsilon}/\dot{\varepsilon}_{ref})^{1/n}$ is a factor with $k_0 = 4.6$ [27], and $\dot{\varepsilon}$ is the plastic strain rate. $\dot{\varepsilon}_{ref} = 100^{-1}$ s is the reference plastic strain rate [28], the exponent $n = 100$ [29], and the diffusion coefficient [30] is

$$A = \frac{4c}{\pi(1-\upsilon)}(c_j b)D_c\left(\frac{\mu\Omega}{kT}\right)\left(\frac{\chi}{\mu b}\right)^2 \quad (3)$$

where $c = 10^3$ is a constant, $\upsilon = 0.34$ is Poisson's ratio, $b = 0.3$ nm is the Burgers vector, c_j is the extended jog density along the dislocation line, with $c_j b \approx 10^{-2}$ [30], $D_c = 2.2 \times 10^{-19}$ m² s^{-1} is the grain boundary diffusion coefficient [31], $\Omega = 1.27 \times 10^{-29}$ m³ is the atomic volume for copper, $T = 276$ K is room temperature, $\chi = 78$ mJ m^{-2} is the stacking fault energy [32], and $\mu = 42$ GPa is the shear modulus [26].

The initial dislocation densities in GB and GI are considered to have values of $\rho_{GB} = 10^{14}$ m^{-2} and $\rho_{GI} = 10^{13}$ m^{-2} [21]. The plastic strain rate of the workpiece is assumed as 0.02 s^{-1}. Based on Eqs. (1) and (2), the evolution of dislocation density with the strain in GB and GI is shown in Fig. 1. With the increase of strain, more dislocation accumulates in the grain boundary. The dislocation density in GB increases much faster than that in GI.

The flow stress of GB and GI are determined by the local dislocation density from Taylor's relational expression:

$$\sigma_f = M\alpha b\mu\sqrt{\rho} \quad (4)$$

where $M = 3.06$ is the Taylor factor [26], $\alpha = 0.3$ is a constant [26], $b = 0.3$ nm is the Burgers vector [26], $\mu = 42$ GPa is the shear modulus [26], ρ is the dislocation density. Fig. 2 shows the true strain–stress curves of GB and GI from Eq. (4). The true stress in GB is larger than that in GI due to the higher dislocation density.

In the finite element model, the material model of multilinear isotropic hardening, which is suitable for simulating the lager deformation of metal materials, is used to describe the material

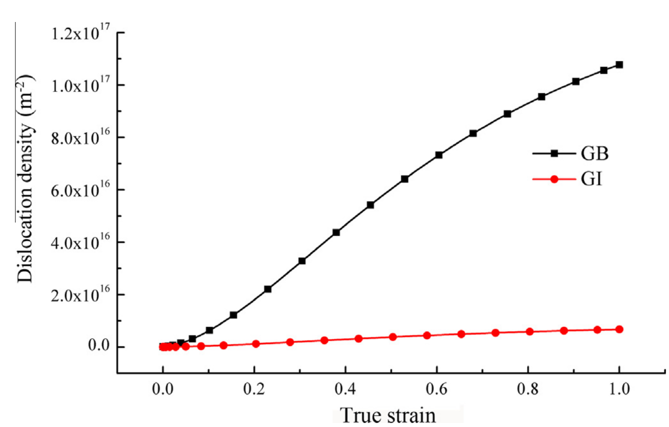

Fig. 1. Dislocation density evolution with increasing strain for pure copper.