Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Simulation study on fluctuant flow stress scale effect

SHEN Yu†, YU Hu-ping, RUAN Xue-yu
([1]National Die and Mold CAD Engineering Research Center, Shanghai Jiao Tong University, Shanghai 200030, China)
†E-mail: shenyu@sjtu.edu.cn

Received Dec. 16, 2005; revision accepted Feb. 24, 2006

Abstract: Crystal plasticity theory was used to simulate upsetting tests of different dimensions and grain size micro copper cylinders in this study on the fluctuant flow stress scale effect. Results showed that with the decrease of billet grain quantity, flow stress fluctuation is not always increased, but there is a maximum. Through this study, the fluctuant flow stress scale effect can be understood deeper, and relevant necessary information was obtained for further prediction and control of this scale effect and to design the microforming process and die.

Key words: Microforming, Scale effect, Numerical simulation, Fluctuation
doi:10.1631/jzus.2006.A1343 **Document code:** A **CLC number:** TG301

INTRODUCTION

With the continuous development of science and technology, especially the rapid progress of electronic industry and micromachine, microparts are needed more and more, and their technical requirements are higher and higher (Geiger *et al*., 1994; 1996; Geiger and Engel, 2002). However, traditional processing technologies, like cutting, etc., do not meet these requirements. Traditional plastic forming technology has merits like high production rate, excellent mechanical properties of products, so it is suitable to produce mass micro parts. Under such circumstance, in the 1990's, microforming came into being, traditional plastic forming process is applied in micro scale to batch produce micro metal parts. As a completely new plastic processing technology, microforming is a technology that can be used to produce submillimetre parts in at least two dimensions by plastic deformation of materials (Geiger *et al*., 2001). Microforming inherits many merits which traditional plastic forming technology owns, and has good producing potentials, so its application range is broad. Typical processes of microforming can be classified into micro extrusion, micro sheet metal, micro die forging, etc. Up to now, this technology has been partially used in electronic industry for the production of microparts like micro screws, contact springs, IC socket, etc. With the continuous development of technologies, applications of microforming are rapidly extended to machinery, chemical industry, aerospace, biology, etc., and its status is more and more important in these fields.

However, existing studies show that in micro scale, with the downscaling of billet dimensions, grain size is increased relatively, so material is no more traditional isotropic continuum. Accordingly, material mechanical properties are explicitly different from that in traditional macro scale. With the downscaling of billet size, process parameters, flow stress, etc. are very sensitive to billet size, and a series of explicit scale effects emerged, which result in the failure of traditional (macro) forming process and theories. Of these scale effects, the fluctuant flow stress scale effect, defined as an increasing fluctuation of flow stress with the downscaling of billet size, further results in the non-uniform distribution of loads on billet and die, as well as a big fluctuation of forming force and formed part quality. Thus, the design of process and die in microforming is influenced, even its development and application are hindered.

Due to the problems mentioned above, fluctuant flow stress scale effect attracts the attention of many researchers. Up to now, there have been some studies on fluctuant flow stress scale effect. Geiger and Eckstein (2002) and Engel and Egerer (2003) conducted upsetting tests with different size small cylinder billets and found that under the condition of constant grain size, the fluctuation range of flow stress is gradually increased with the downscaling of billet size. Regarding this scale effect, Tiesler and Engel explained: with the downscaling of billet size, the quantity of grain in deforming area is decreased, and the flow stress of the whole billet is influenced more by the random variation of size, shape, orientation, position, etc. of each grain in the deforming area, so a big random fluctuation of flow stress emerged (Tiesler and Engel, 2000; Tiesler *et al*., 2002; Engel and Eckstein, 2002). Similarly, Raulea (1999) studied how microforming process is affected by the ratio of grain size to sheet thickness, and found that along the direction of sheet thickness, with the decrease of grain quantity (at least one grain), the fluctuation of forming force is increased remarkably. When grain size is larger than sheet thickness, the repeatability of experiments is decreased remarkably. Regarding these phenomena, they explained that the big fluctuation of forming force is influenced by the relative increase of grain size along the sheet thickness. When grain size is increased relatively, the influence of single grain on the whole deformation is increased, so the repeatability of experiments is decreased remarkably. Cao *et al*.(2004) did a series of tensile and upsetting tests with circular cross-section CuZn15 alloy specimens, with diameter of 0.2~2 mm. Similar fluctuant flow stress scale effect phenomena were also found. In order to decrease the fluctuation of flow stress and other data in microforming process, Engel and Egerer (2003) investigated the process of warm forming for the manufacture of microparts. Warm forming is defined as forming at a temperature above that of room temperature where hardening effects still occur and recrystallization does not take place during forming. The authors performed upsetting, backward can extrusion, and lateral extrusion on 0.5 mm diameter samples of CuZn15 brass and X4CrNi18-10 steel from temperatures of 20~300 °C. They were able to conclude that warm microforming gives improved material flow, a homogenized hardness distribution and a reduction of scatter in process parameters. Heating assisted micro stamping was also investigated by Balendra and Qin (2004) who studied the feasibility of using localized heating to achieve higher aspect ratios and improved micro stamping for high-strength materials.

It was found that up to now, there have been some relevant studies on the fluctuant flow stress scale effect. All these studies showed that with the downscaling of the billet size, the deformation and flow stress of single grain has more influence on the whole billet, so the fluctuant flow stress scale effect that comes into being can be studied through investigation of the deformation and flow stress of single grain. As a connection of micro grain deformation and macro billet deformation, the crystal plasticity theory has been widely used in texture simulation and prediction of traditional forming processes, and effects of grain deformation on macro deformation can be reflected objectively. However, few reports of crystal plasticity theory being used to simulate the fluctuant flow stress scale effect can be found. Thus, in this study, by using the rate dependent crystal plastic constitutive relation and the elasto-plastic large deformation incremental finite element method, upsetting tests of different grain size and diameter micro copper cylinders were simulated, and the simulation results were used to study the fluctuant flow stress scale effect. Effects of grain size and billet dimensions on fluctuation of flow stress are discussed. This paper provides deeper understanding of the fluctuant flow stress scale effect, and necessary relevant information for prediction and control of the fluctuant flow stress scale effect, as well as the design of process and die structure in microforming.

CRYSTAL PLASTICITY THEORY

Crystal elasto-plastic deformation (Wang and Duan, 1995)

Previous studies showed that the deformation of a grain is the integrative result of slipping which dislocates the slip along specific crystallographic planes and deformation (including rigid rotation) of a crystal lattice. The deformation of a crystal lattice can be regarded as the elastic deformation of continuum. As there are many dislocations in a grain, it is rational to suppose that the slipping is continuous in a grain, and that the total granular deformation gradient $\boldsymbol{F}$ can be expressed as:

$$\boldsymbol{F}=\boldsymbol{F}^{\mathrm{e}}\boldsymbol{F}^{\mathrm{p}}, \tag{1}$$

where $\boldsymbol{F}^{\mathrm{e}}$ is the deformation gradient of crystal lattice deformation and rigid rotation, $\boldsymbol{F}^{\mathrm{p}}$ is the deformation gradient of crystal homogeneous shear deformation along the slipping directions, as shown in Fig.1.

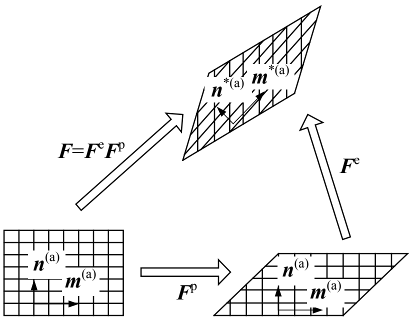

Fig.1 Elasto-plastic deformation of a crystal

Suppose the slipping direction of a slipping system α is $\boldsymbol{m}^{(\alpha)}$, and the normal direction of the slipping plane is $\boldsymbol{n}^{(\alpha)}$, according to the definition of $\boldsymbol{F}^{\mathrm{p}}$, the expression below can be obtained:

$$\boldsymbol{F}^{\mathrm{p}}=\boldsymbol{I}+\sum_{\alpha=1}^{n}\gamma^{(\alpha)}\boldsymbol{m}^{(\alpha)}\otimes\boldsymbol{n}^{(\alpha)}, \tag{2}$$

where $\gamma^{(\alpha)}$ is the slipping shear strain of the slipping system α, and n is the number of active slipping systems.

Thus, the current velocity gradient tensor $\boldsymbol{L}$ can be obtained from Eq.(1):

$$\boldsymbol{L}=\dot{\boldsymbol{F}}\boldsymbol{F}^{-1}=\boldsymbol{L}^{\mathrm{e}}+\boldsymbol{L}^{\mathrm{p}}, \tag{3}$$

where $\boldsymbol{L}^{\mathrm{e}}$ and $\boldsymbol{L}^{\mathrm{p}}$ are the elastic velocity gradient tensor and the plastic velocity gradient tensor respectively, as expressed below:

$$\boldsymbol{L}^{\mathrm{e}}=\dot{\boldsymbol{F}}^{\mathrm{e}}(\boldsymbol{F}^{\mathrm{e}})^{-1}, \tag{3.1}$$

$$\boldsymbol{L}^{\mathrm{p}}=\boldsymbol{F}^{\mathrm{e}}\dot{\boldsymbol{F}}^{\mathrm{p}}(\boldsymbol{F}^{\mathrm{p}})^{-1}(\boldsymbol{F}^{\mathrm{e}})^{-1}. \tag{3.2}$$

From Eq.(2), the expression below can be obtained:

$$\dot{\boldsymbol{F}}^{\mathrm{p}}(\boldsymbol{F}^{\mathrm{p}})^{-1}=\sum_{\alpha=1}^{n}\left(\boldsymbol{m}^{(\alpha)}\otimes\boldsymbol{n}^{(\alpha)}\right)\dot{\gamma}^{(\alpha)}. \tag{4}$$

So the plastic velocity gradient tensor $\boldsymbol{L}^{\mathrm{p}}$ can be obtained from Eq.(4) as

$$\boldsymbol{L}^{\mathrm{p}}=\sum_{\alpha=1}^{n}\left(\boldsymbol{m}^{*(\alpha)}\otimes\boldsymbol{n}^{*(\alpha)}\right)\dot{\gamma}^{(\alpha)}, \tag{5}$$

where $\boldsymbol{m}^{*(\alpha)}$ and $\boldsymbol{n}^{*(\alpha)}$ are the slipping direction and the slipping plane normal direction of the deformed grain respectively, and their expressions are shown below:

$$\boldsymbol{m}^{*(\alpha)}=\boldsymbol{F}^{\mathrm{e}}\boldsymbol{m}^{(\alpha)}, \tag{5.1}$$

$$\boldsymbol{n}^{*(\alpha)}=(\boldsymbol{F}^{\mathrm{e}})^{-\mathrm{T}}\boldsymbol{n}^{(\alpha)}. \tag{5.2}$$

Based on the above deduction, the strain rate tensor $\boldsymbol{D}$ at the current configuration can be expressed as

$$\boldsymbol{D}=\boldsymbol{D}^{\mathrm{e}}+\boldsymbol{D}^{\mathrm{p}}, \tag{6}$$

$$\boldsymbol{D}^{\mathrm{e}}=\frac{1}{2}[\dot{\boldsymbol{F}}^{\mathrm{e}}(\boldsymbol{F}^{\mathrm{e}})^{-1}+(\boldsymbol{F}^{\mathrm{e}})^{-\mathrm{T}}(\dot{\boldsymbol{F}}^{\mathrm{e}})^{\mathrm{T}}], \tag{6.1}$$

$$\boldsymbol{D}^{\mathrm{p}}=\sum_{\alpha=1}^{n}\boldsymbol{P}^{(\alpha)}\dot{\gamma}^{(\alpha)}, \tag{6.2}$$

$$\boldsymbol{P}^{(\alpha)}=\frac{1}{2}\left[\boldsymbol{m}^{*(\alpha)}\left(\boldsymbol{n}^{*(\alpha)}\right)^{\mathrm{T}}+\boldsymbol{n}^{*(\alpha)}\left(\boldsymbol{m}^{*(\alpha)}\right)^{\mathrm{T}}\right]. \tag{6.3}$$

The spin rate tensor $\boldsymbol{W}$ can be expressed as

$$\boldsymbol{W}=\boldsymbol{W}^{\mathrm{e}}+\boldsymbol{W}^{\mathrm{p}}, \tag{7}$$

$$\boldsymbol{W}^{\mathrm{e}}=\frac{1}{2}[\dot{\boldsymbol{F}}^{\mathrm{e}}(\boldsymbol{F}^{\mathrm{e}})^{-1}-(\boldsymbol{F}^{\mathrm{e}})^{-\mathrm{T}}(\dot{\boldsymbol{F}}^{\mathrm{e}})^{\mathrm{T}}], \tag{7.1}$$

$$\boldsymbol{W}^{\mathrm{p}}=\sum_{\alpha=1}^{n}\boldsymbol{W}^{(\alpha)}\dot{\gamma}^{(\alpha)}, \tag{7.2}$$

$$\boldsymbol{W}^{(\alpha)}=\frac{1}{2}\left[\boldsymbol{m}^{*(\alpha)}\left(\boldsymbol{n}^{*(\alpha)}\right)^{\mathrm{T}}-\boldsymbol{n}^{*(\alpha)}\left(\boldsymbol{m}^{*(\alpha)}\right)^{\mathrm{T}}\right]. \tag{7.3}$$

Rate dependent crystal elasto-plastic constitutive relation

Based on the above expressions, in the local crystal coordinate system, the crystal elasto-plastic constitutive equation can be built as shown below:

$$\overset{\triangledown}{\boldsymbol{\sigma}}=\boldsymbol{C}:\boldsymbol{D}-\sum_{\alpha=1}^{n}\left[\boldsymbol{C}:\boldsymbol{P}^{(\alpha)}+\boldsymbol{B}^{(\alpha)}\right]\dot{\gamma}^{(\alpha)}, \tag{8}$$

$$\boldsymbol{B}^{(\alpha)}=\boldsymbol{W}^{(\alpha)}\boldsymbol{\sigma}-\boldsymbol{\sigma}\boldsymbol{W}^{(\alpha)}, \tag{8.1}$$

where $\overset{\nabla}{\boldsymbol{\sigma}}$ is the Jaumann stress rate of the Cauchy stress tensor at the initial configuration, and $\boldsymbol{C}$ is the elastic modulus tensor.

The shear strain rate $\dot{\gamma}^{(\alpha)}$ is expressed with the rate dependent model:

$$\dot{\gamma}^{(\alpha)} = \dot{a}^{(\alpha)} \operatorname{sgn}\left(\tau^{(\alpha)}\right)\left|\frac{\tau^{(\alpha)}}{g^{(\alpha)}}\right|^{\frac{1}{m}}, \quad (9)$$

where $\tau^{(\alpha)}$ is the shear stress of the slipping system α; $\dot{a}^{(\alpha)}$ is the reference shear strain rate; sgn() is the symbolic function; $g^{(\alpha)}$ is the reference shear stress; m is the rate sensitive coefficient.

After substituting Eq.(9) into Eq.(8), the stress increment can be obtained from the strain increment. In the practical finite element (FE) simulation, in order to improve the precision and stability of calculation, the tangent coefficient method, proposed by Peirce *et al.*(1983), is used to calculate the shear strain increment $\Delta\gamma^{(\alpha)}$:

$$\Delta\gamma^{(\alpha)} = \left[(1-\theta)\dot{\gamma}^{(\alpha)}(t) + \theta\dot{\gamma}^{(\alpha)}(t+\Delta t)\right]\Delta t, \quad (10)$$

where θ is a parameter varying from 0 to 1. Expand Eq.(10) with the Taylor formula to obtain

$$\sum_{\beta} N_{\alpha\beta}\Delta\gamma^{(\beta)} = \left[\dot{\gamma}^{(\alpha)}(t) + \boldsymbol{Q}^{(\alpha)} : \boldsymbol{D}\right]\Delta t. \quad (11)$$

In addition, during the calculation of $\Delta\gamma^{(\alpha)}$ with Eq.(11), in order to improve the computational efficiency, when m is very small, if $|\tau^{(\alpha)}|/|g^{(\alpha)}|<0.9$, the effect of the slipping system α can be omitted.

The evolution of the reference shear stress $g^{(\alpha)}$ is calculated from the expression:

$$\dot{g}^{(\alpha)} = \sum_{\beta} h_{\beta}^{\alpha}\left|\dot{\gamma}^{(\beta)}\right|. \quad (12)$$

The hardening coefficient h_{β}^{α} is calculated with the two parameters model proposed by Peirce *et al.*(1983) and shown below:

$$h_{\beta}^{\alpha} = q\cdot h(\gamma) + (1-q)\cdot h(\gamma)\cdot\delta_{\beta}^{\alpha}, \quad (13)$$

$$h(\gamma) = h_0 \operatorname{sech}^2\left(\frac{h_0\gamma}{g_{\mathrm{s}} - g_0}\right), \quad (13.1)$$

$$\gamma = \sum_{\alpha=1}^{n}\left|\gamma^{(\alpha)}\right|, \quad (13.2)$$

where q is the ratio of the latent hardening to the self hardening in slipping systems, g_{s} is the saturated stress, h_0 is the initial yield hardening module. q, g_{s}, h_0 are material constants determined by experiments.

Polycrystal model

In order to obtain the stress and strain of a polycrystal from the single crystal constitutive relation, the Taylor polycrystal model is adopted. According to assumptions of the Taylor model, the strain rate tensor of each grain is equal to that of a polycrystal; when the stress and strain of each grain is obtained, corresponding values of a polycrystal can be obtained by the averaging below:

$$A = \frac{1}{V}\sum_{i=1}^{N} A_i V_i, \quad (14)$$

where N is the number of grains in a polycrystal; V and V_i are the volume of a polycrystal and the volume of the grain i, respectively.

UPSETTING SIMULATION

The billet material was typical FCC metal copper. Billets were cylinders with an aspect ratio of 1. In order to study effects of grain size and billet dimensions on the flow stress fluctuation, different grain size and billet diameter were chosen, and parameters are shown in Table 1. In order to reflect the strain and stress of each grain as accurately as possible, each grain was divided into several elements. The orientation of a grain was described with the Euler angle, as shown in Fig.2. The initial orientation of a grain was selected at random, and initial Euler angles of grains were determined by uniform distribution random numbers. Material parameters, obtained from the tests, are listed in Table 2, where μ and λ are the elastic shear module and the bulk module.

In addition, considering the symmetric condition is not rational any more when D/d is less, according to billets parameters used in this study, two kinds of FE models are chosen: when $D/d>7$, the 1/8 billet was chosen as FE model, otherwise the whole billet was chosen. The FE model of 1/8 billet is shown in Fig.3. During simulations, the loading speed was quasi-static, and the compressing strain rate was chosen as 0.001 s^{-1}. The aim of simulations in this study is to obtain stress-strain curves, so the effect of friction force was neglected to ensure that billets in the uniaxial stress state. In order to reflect as much as possible the influence of random grain orientation on flow stress fluctuation, each test of Table 1 was simulated several times with random grain orientations.

Table 1 Billet parameters

Number	Billet diameter D (mm)	Grain diameter d (μm)
1	0.49	45
2	0.49	90
3	0.49	135
4	0.98	45
5	0.98	90
6	0.98	135
7	1.47	45
8	1.47	90
9	1.47	135

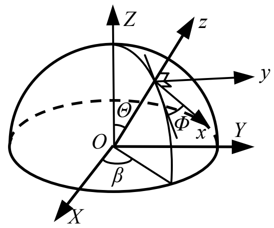

Fig.2 Definition of Euler angle

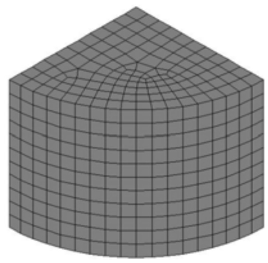

Fig.3 1/8 billet model

SIMULATION RESULTS

Simulated flow stresses under different conditions are shown in Fig.4.

Fig.4 shows that for different grain size billets, with the decrease of billet dimensions, standard deviations of flow stresses are increased gradually, namely the explicit random fluctuation of flow stress emerged, and the fluctuation is increased with the increase of strain. The so-called fluctuant flow stress scale effect emerged. This scale effect can be explained with the crystal plasticity theory below: in

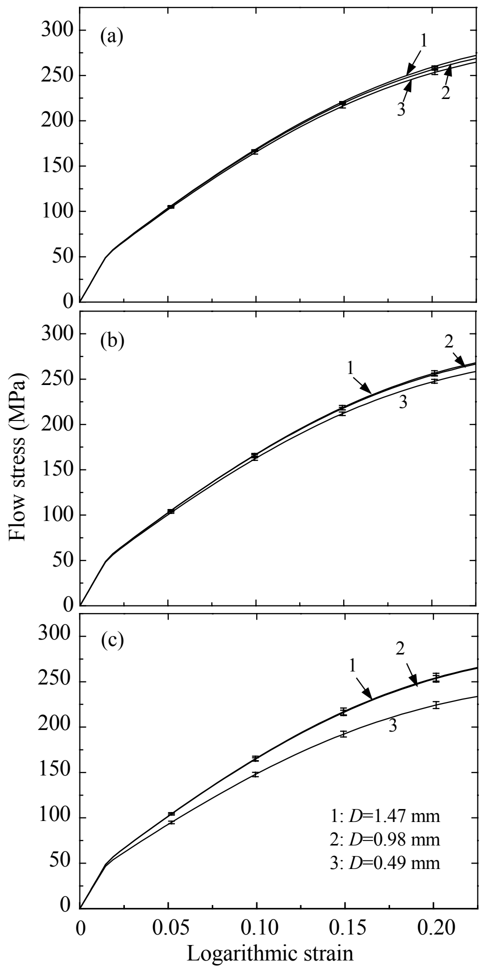

Fig.4 Relation of flow stress standard deviation to billet dimension for I: standard deviation. (a) d=45 μm; (b) d=90 μm; (c) d=135 μm

Table 2 Material parameters

$\dot{a}$ (s^{-1})	m	q	h_0 (MPa)	g_0 (MPa)	g_s (MPa)	μ (MPa)	λ (MPa)
0.001	0.01	1.4	182.0	23.8	109.83	1282.7	2261.3

essence, a metallic polycrystal is an aggregate composed of many single crystals (grains) bounded at grain boundaries. As grains of a polycrystal are stochastically different from each other in orientation, dimensions, shape, position even component, when a polycrystal is deformed under external forces, the flow stress of each grain is different stochastically. Therefore, influenced by the random variation of a single grain, the flow stress of a polycrystal, the resultant effect of single grain flow stresses, are also varied stochastically at a certain extent. When the grain size is far less than billet dimensions, that is, the billet is in macro scale, as grain quantity is very large, the fluctuation of flow stress is tiny; with the decrease of billet dimensions, grain quantity is decreased accordingly, so the contribution of single grain flow stress to the whole billet flow stress is increased, and the fluctuation of the whole billet flow stress is increased, the fluctuant flow stress scale effect emerged. In addition, with the increase of strain, the rigid rotation of grains is increased, and the diversity of grain orientations is increased, so the difference of flow stress between grains is further increased, and the fluctuation of flow stress is increased.

DISCUSSION ON FLUCTUANT FLOW STRESS SCALE EFFECT

In order to discuss the relation of flow stress fluctuation to billet dimensions and grain size further, in this study, the standard deviation of flow stress was chosen to characterize the flow stress fluctuation, and its expression is shown below:

$$S(\sigma)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\sigma_i-\sigma)^2}\ , \qquad (15)$$

where σ_i is the flow stress of each test, and σ is the average flow stress of several tests, which is equivalent to the traditional flow stress. n, the test times, was chosen 4 here. Dispose simulation results with Eq.(15), to obtain flow stress fluctuations of different conditions as shown in Fig.5 and Fig.6.

Fig.5 shows that when grain size is less (here it is 45 μm), with the decrease of billet dimensions, the fluctuation of flow stress is increased gradually; when grain size is larger (90 μm and 135 μm here), with the decrease of billet dimensions, the fluctuation of flow stress is increased first, then decreased.

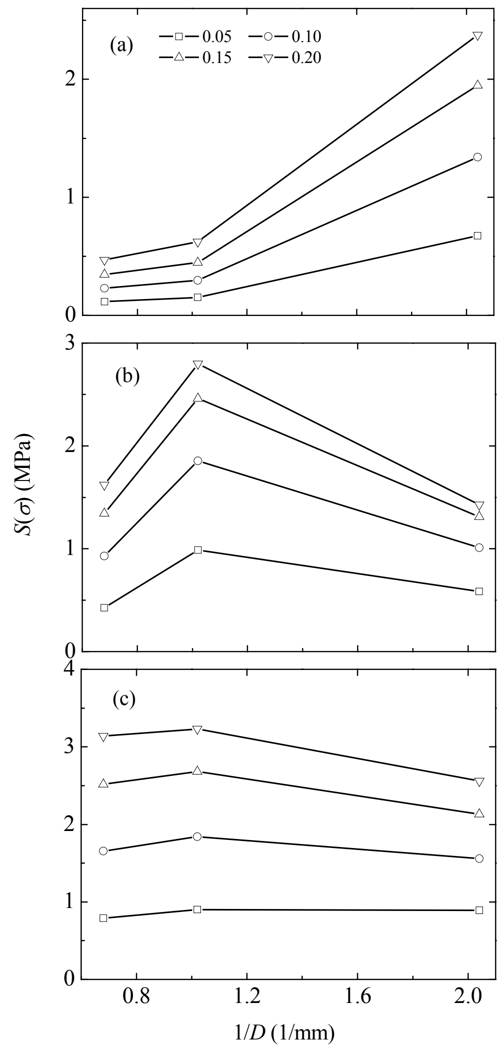

Fig.5 Relation of flow stress standard deviation to billet dimension. (a) *d*=45 μm; (b) *d*=90 μm; (c) *d*=135 μm

Fig.6 shows that when billet dimensions are less (here it is 0.49 mm), with the increase of grain size, the fluctuation of flow stress is decreased first and then increased gradually; when billet dimensions are larger (here they are 0.98 mm and 1.47 mm), with the increase of grain size, the fluctuation of flow stress is increased gradually.

In addition, study of the relation of flow stress fluctuation to grain size and billet dimensions showed that even if there is a maximum of flow stress fluctuation, on the whole, with the increase of billet grain quantity, the fluctuation of flow stress is gradually increased, as shown in Fig.7.

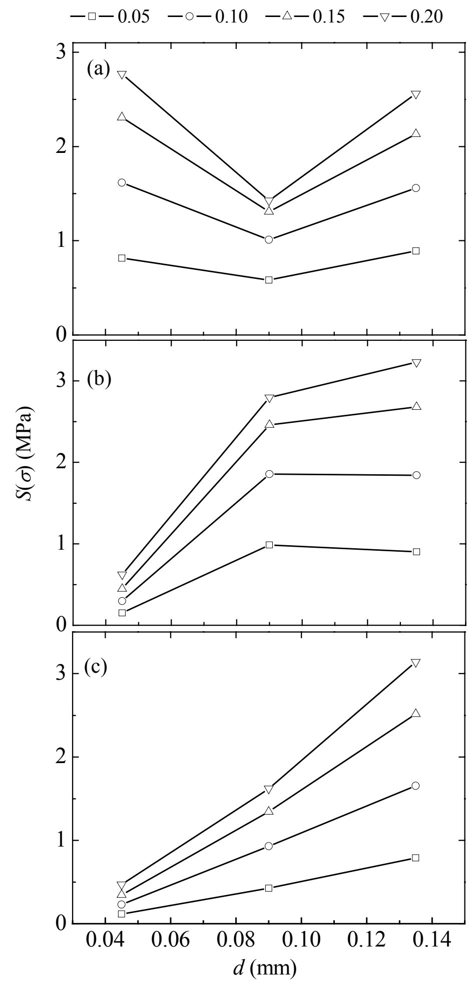

Fig.6 Relation of flow stress standard deviation to grain size. (a) *D*=0.49 mm; (b) *D*=0.98 mm; (c) *D*=1.47 mm

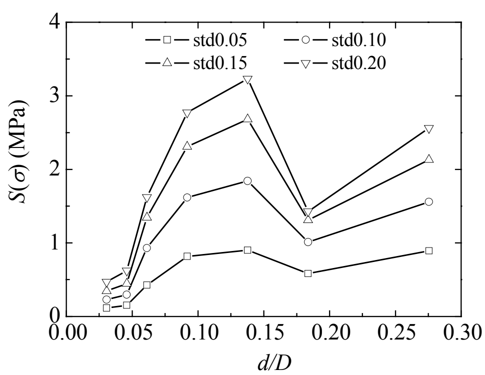

Fig.7 Relation of flow stress standard deviation to grain quantity

Characteristics of the flow stress fluctuation mentioned above can be explained with the crystal plasticity theory and the surface layer theory proposed by Geiger and Eckstein (2002). According to the surface layer theory, grains on free surface are constrained less, so their flow stress can be regarded as the single grain flow stress, and varies in grains. As a result, the flow stress of surface layer fluctuates in a certain extent, and its fluctuation is mainly influenced by the grain quantity in the surface layer. Similarly, for the inner part of a billet, due to random orientations and constraints of grains, the inner part flow stress fluctuates. Compared with the flow stress surface layer, the fluctuation of inner part flow stress is larger. The flow stress fluctuation of the whole billet can be regarded as an integration of fluctuations in surface layer and inner part.

When billet dimensions are larger, or grain size is less, the grain quantity of surface layer and inner part are both large, deformation is more homogeneous, so fluctuation is less. With the decrease of billet dimensions or the increase of grain size, the grain quantity of billet is decreased, so the fluctuation is increased. At the same time, with the decrease of grain quantity, the proportion of inner part is decreased. When the effect of grain quantity on the fluctuation is less than that of the inner part proportion, the flow stress fluctuation is decreased. When the grain quantity is decreased further, the effect of grain quantity is the main factor, so the fluctuation is increased gradually.

CONCLUSION

Crystal plasticity theory was used to simulate upsetting tests of different grain size and diameter micro copper cylinders, and the fluctuant flow stress scale effect was studied, the relation of grain size and billet dimensions to the fluctuation of flow stress was discussed. Conclusions are drawn as given below:

When grain size is less, with the decrease of billet dimensions, the fluctuation of flow stress is increased gradually; when grain size is larger, with the decrease of billet dimensions, the fluctuation of flow stress is increased first and then decreased.

When billet dimensions are less, with the increase of grain size, the fluctuation of flow stress is increased first and then decreased gradually; when billet dimensions are larger, with the increase of grain size, the fluctuation of flow stress is increased gradually.

Even if there is a maximum of flow stress fluctuation, on the whole, with the decrease of billet grain quantity, the fluctuation of flow stress is gradually increased.

Work of this paper gives a deeper understanding about the fluctuant flow stress scale effect, and provides necessary relevant information for prediction and control of the fluctuant flow stress scale effect, as well as the design of process and die structure in microforming.

References

Balendra, R., Qin, Y., 2004. Research dedicated to the development of advanced metal forming technologies. *Journal of Materials Processing Technology*, **145**(2): 144-152. [doi:10.1016/S0924-0136(03)00665-4]

Cao, J., Krishnan, N., Wang, Z., Lu, H.S., Liu, W.K., Swanson, A., 2004. Microforming: experimental investigation of the extrusion process for micropins and its numerical simulation using RKEM. *Transactions of the ASME*, **126**:642-652.

Engel, U., Eckstein, R., 2002. Microforming—from basic research to its realization. *Journal of Materials Processing Technology*, **125**:35-44. [doi:10.1016/S0924-0136(02)00415-6]

Engel, U., Egerer, E., 2003. Basic research on cold and warm forging of microparts. *Key Engineering Materials*, **236**(1):449-456.

Geiger, M., Eckstein, R., 2002. Microforming. Advanced Technology of Plasticity. Proceedings of the 7th ICTP. Yokohama, Japan, p.327-338.

Geiger, M., Engel, U., 2002. Microforming—a challenge to the plasticity research community. *Journal of the JSTP*, **43**(494):171-172.

Geiger, M., Engel, U., Vollertsen, F., Kals, R., Meßner, A., 1994. Metal forming of micro parts for electronics. *Production Engineering*, **2**(1):15-18.

Geiger, M., Vollertsen, F., Kals, R., 1996. Fundamentals on the manufacturing of sheet metal microparts. *Annals of the CIRP*, **45**(1):277-282.

Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N., Engel, U., 2001. Microforming. *Annals of the CIRP*, **50**(2):445-462.

Peirce, D., Asaro, R.J., Needleman, A., 1983. Material rate dependent and localized deformation in crystalline solids. *Acta Metall. Mater.*, **31**(12):1951-1976. [doi:10.1016/0001-6160(83)90014-7]

Raulea, L.V., Govaert, L.E., Baaijens, F.P.T., 1999. Grain and Specimen Size Effects in Processing Metal Sheets. Advanced Technology of Plasticity. Proceedings of the 6th ICTP. Springer, Nuremberg, p.939-944.

Tiesler, N., Engel, U., 2000. Microforming—Effects of Miniaturization. Metal Forming 2000. Balkema, Rotterdam, p.355-360.

Tiesler, N., Engel, U., Geiger, M., 2002. Basic Research on Cold Forming of Microparts. Advanced Technology of Plasticity. Proceedings of the 7th ICTP. Yokohama, Japan, p.379-384.

Wang, Z.Q., Duan, Z.P., 1995. Meso-Plasticity Mechanics. Science Publishing House, Beijing, p.263-305 (in Chinese).