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Modelling of size effects in microforming process with consideration of grained heterogeneity

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ABSTRACT

Size effect is a special phenomenon in metal micro-forming process. As the deformation process is scale down to micro/mesoscale, the characteristics of single grain involved in the deformed region play a significant role on the material mechanical behaviours resulting in the invalidation of classical theories in microforming. This paper presents a newly developed material model in microscale on the basis of the grained heterogeneity (e.g. grain size, shape and deformability) and specimen dimension. Voronoi tessellation has been employed to describe the polycrystalline aggregate. The grain shape is controlled by the centroidal-voronoi algorithm to drive grains into steady state. Hardness of the grains obtained from Nano-indentation is used to identify the scatter of the grained deformability. Applying the new material model, the micro-compression test of pure copper is numerically simulated by finite element method (FEM). The influences of grain size and feature size on the deformation behaviours are discussed. The numerical simulation results are in good agreement with the experimental results in terms of the flow stress curves and profile of deformed parts. Based on the novel material model, a FE model of microcross wedge rolling is established and the obtained results show the strain of specimen core region increases with the magnification of grain size.

1. Introduction

In recent years, microsystem technology, a prominent technology to fabricate microparts, is attracting more and more attention due to the increasing demand on micro-scale products. The metal forming in conventional scale has been developed for hundreds of years and previous researchers have established a series of classic theories for macro-scale deformation, however, many of which do not work when the metal deformation scales down to a certain geometrical scale [1–3] due to size effect. The most common phenomena of size effect associated with miniaturisation are related to the deformation behaviour which is normally described by flow stress model [4].

Many explorations on this issue were conducted using both experimental and numerical methods and the corresponding constitutive models were developed as well. Hall [5] and Petch [6] 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. Miyazaki et al. [7] investigated the effect of specimen size on the flow stress of rod specimen of polycrystalline Cu–Al alloy and an affect zone model is proposed to explain why the flow stress decreases with the dimensional reduction of specimen. Leu [8] established a flow stress model as a function of the ratio of the sheet thickness to grain size based on the affect zone model, the pile-up theory of dislocation and Hall–Petch relationship.

Engle and Eckstein [9] 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. A systematic influence of the sample size was proposed by Kals et al. [10] by defining a quantitative value for the share of surface grains. The influence of the surface grain was shown in Fig. 1. Lai et al. [11] developed a mixed model by combining the modified Hall–Petch relation and surface layer model. Based on the composite and surface layer models, Liu et al. [12] developed a constitutive model considering the grain boundary strain strengthening.

The grained heterogeneity was taken into account by Chan et al. [13] to investigate the decrease of flow stress and scatter of grained behaviour due to different grain size, shape and orientation. The grained heterogeneity was identified using nanoindentation test by the authors to simulate the microcross wedge rolling process and an inhomogeneity coefficient has been introduced [14].

The voronoi tessellation was introduced to generate polycrystalline aggregate using probability theory. This method subdivides

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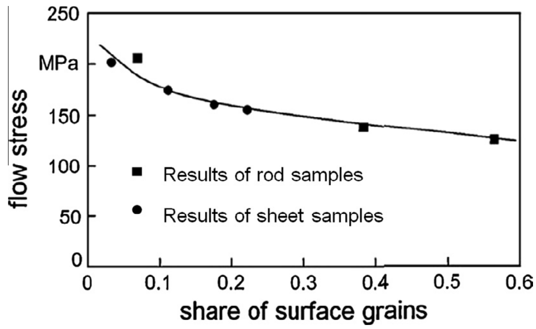

Fig. 1. Change of flow stress with increasing share of surface grains [10].

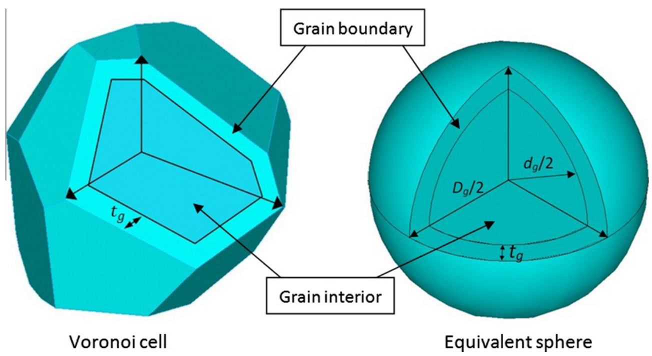

Fig. 2. Grain interior and grain boundary model.

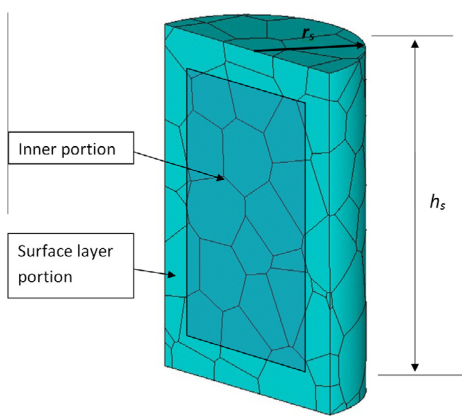

Fig. 3. Surface layer and inner portion of a cylindrical spencimen.

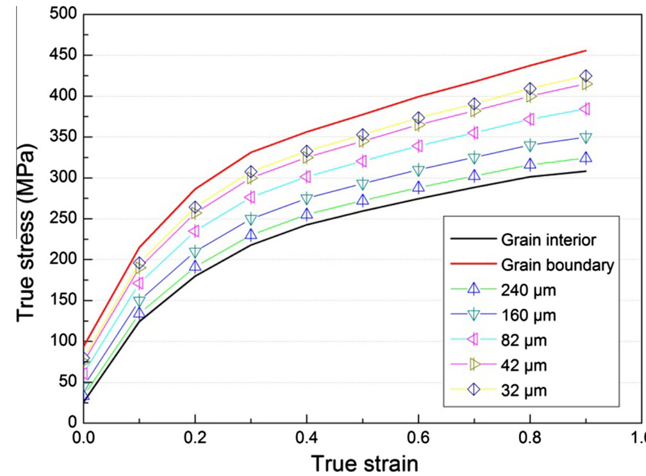

Fig. 4. Strain–stress curves determined according to Eq. (11).

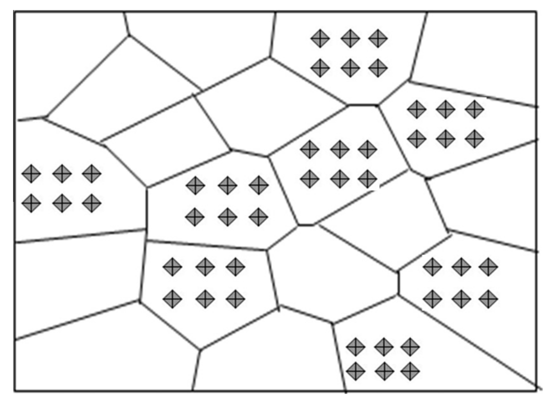

Fig. 5. Illustration of nanoindentation.

a space tessellation into voronoi polyhedral, which is similar to morphogenetic process of nucleation and growth from random seeds [15]. The concept of the voronoi polygon has been used extensively in material science, especially for modelling random microstructure of grain aggregates [16]. Zhang and Tong [17] presented the numerical computation of 3D as a general investigation tool that featured an aggregate computation including element type and geometrical representation of grain boundary. Based on voronoi tessellation, lognormal and gamma distribution were used to describe the distribution of grain size in polycrystalline by Zhu et al. [18] and Dalla et al. [19].

The main objective of this study is to introduce a constitutive material model based on the surface layer model and intragranular heterogeneities that involves the difference between the grain interior and boundaries and the scatter of deformation behaviour among grains. The 3D aggregate of polycrystalline is represented by a voronoi tessellation. Applying the novel material model and 3D full scale polycrystalline structure, the micro-compression test of pure copper is numerically simulated by finite element method (FEM). In order to validate the accuracy of the presented material model, physical experiments are conducted to compare the simulation results with experimental ones. The scatter of grained heterogeneity is analysed in terms of flow stress and free surface asperity of the deformed part. A FE model of microcross wedge rolling is established based on the new material model and the influence of grained heterogeneity on strain distribution is discussed briefly.

2. Scatter of constitutive model in microforming process

The most common used parameter to describe the behaviour is the flow stress curve. In this paper, a mixed material model based on modified Hall–Peth relationship, surface layer model and grained heterogeneity is proposed.

2.1. Hall–Peth relationship

The effect of grain size on flow stress is an important aspect of polycrystalline metal plastic deformation. The Hall–Petch equation is the most widely accepted empirical theory describing the effect of grain size on the yield stress and a linear relationship between the yield stress and reciprocal of the square root of the grain size