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Effects of grain size and heterogeneity on the mechanical behavior of foil rolling

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ABSTRACT

When the part size is scaled down to micro-scale, the material consists of only a few grains and the material properties and deformation behaviors are quite different from the conventional ones in macro-scale. This paper focuses on the effect of grain size and heterogeneity on the mechanical behavior of foil rolling using a grain level finite element analysis in combination with a rate dependent crystal plasticity constitutive model. Voronoi tessellation has been applied to describe the polycrystalline aggregate. Based on a heterogeneity crystalline plasticity model identified for metal foil, simulations of rolling tests were performed for samples with different grain orientations and sizes. The simulation results have been validated by comparing with the experimental observations. It is predicted that detrimental effects on the mechanical performance will generate by reducing the number of grains through the foil thickness and changing the grain orientation sets. The simulations correctly reproduce the softening effect which has been experimentally characterized linked to decreases in the number of grains through the thickness. The analysis of the plasticity deformation mechanisms shows that the softening is due to surface grain effect which is discussed in terms of grain orientations, activity of slip systems and strengthening of interior grains versus weakening of surface grains.

1. Introduction

In recent years, a lot of efforts have been made by the material science community to understand the plasticity deformation mechanisms of metallic materials at micro-scale due to the strong trend of miniaturization dedicated to the micro-scale products used in many industries including automotive, bio-medical, aerospace and electronic. As the dimensions of such micro-parts are reduced, they usually involve the use of metallic parts with dimensions typically between 1 μm and 100 μm. Miniaturization is a general trend in micro-system industry and a significant progress has been made in the fabrication of micro-parts via various methods. In these methods, plastic micro-forming technology becomes the first choice of mass production of miniature parts due to its advantages including efficiency, high quality and low cost. The metal forming in macro-scale has been developed for many years and a series of classic theories have been established. However, when the part's geometry size is scaled down to micro-scale, the design of micro-parts fabricated by micro-forming cannot be conducted based on the knowledge transfer from macro-forming to micro-forming due to size effect [1–5]. For these micro-products, the size of the microstructure is generally as the same order as the geometry dimensions, leading to different size effects. These size effects modify the mechanical behavior of the micro-parts and can be classified as (i) intrinsic size effects, (ii) statistical size effects, (iii) strain gradient effects and (iv) surface constraint effects [6]. Statistical size effects (ii) arise when the geometric dimensions of the polycrystals approach those of their metallic grains. Then a limit of the grains will be located in the deformation zone and as a result, the overall mechanical response of the polycrystal will be determined to an increasing extent by the mechanical properties of relatively few individual grains [7–9]. Upon miniaturizing a component, the total grain boundary fraction inherently decreases, whereas the volume of grains with a free surface gradually increases. Surface constraint effect (iv) is related to the ability of dislocations to glide out of the free surface of miniaturized parts and can lead to either weakening effect or strengthening effect with further miniaturization, depending on the surface condition and specimen dimension versus grain size [10–12].

The research on micro-scale material deformation behavior in micro-forming has been conducted and many efforts have been made to observe and explain the size effect. Shen et al. [13] established the relationship between the flow stress, specimen dimension and grain size using surface layer model and crystal

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plasticity constitutive model. Gau et al. [14] investigated the springback behavior of sheet metal in micro-forming process. Results showed that the ratio of sheet thickness to grain size has important influence on the amount of springback. Mahabunphachi et al. [15] investigated the grain size effect in hydraulic bulge test at micro/meso-scales. They concluded that the interaction and interplay among grain size, feature size and specimen size significantly affected material deformation behavior in micro-forming process. A mixed material model in micro-forming has been developed to describe flow stress in sheets in tension as a function of applied strain and the ratio of surface grains to internal grains [16–19]. These new material models assumed surface grains to be weaker than the internal grains. Lin et al. [20] established a similar approach in developing a constitutive model, with flow stress again depending on the ratio of volume of free surface grains to internal grains. Chan et al. [21] investigated the decrease of flow stress and scatter of mechanical behavior due to different grain sizes, shapes and orientations through explicit modeling of individual grains with different stress–strain behaviors. Lu et al. [22] developed a new material model in micro-forming with consideration of grain heterogeneity and specimen dimension. Özdemir [23] studied the grain size effect in the micro-expansion by using crystal plasticity constitutive model. They concluded that the deformed geometry converges to limiting values and the scatter of mechanical properties diminished as the number of grains through the thickness is increased. Yoshida [24] studied the surface roughness and necking in micro-forming by consideration of grain heterogeneity and using crystal plasticity constitutive model. They found that the magnitude of surface roughness became large and the shear band changed as the ratio of specimen thickness to grain size decreases. Grogan et al. [25] studied the statistical size effect on the plastic deformation behavior of coronary stents in tension and bending through explicit modeling of individual grains with crystal plasticity theory.

From the review above, it can be concluded that the material deformation behavior in micro-forming has a close relationship with the characteristics of grain heterogeneity (grain size, shape and orientation). When the sheet thickness is scaled down to micro-scale and the number of grains through the thickness generally becomes less, especially for the metal foil. The distribution of different grain sizes, shapes and orientations plays a significant role in the size effect related to inhomogeneous deformation behavior and the scatter of mechanical properties. The models and researches considering these factors in foil rolling remains lacking. It is difficult to research the influence of grain size and heterogeneity on polycrystal plasticity behavior with experiments, as changing ratio of specimen to grain size will introduce other size effects. Therefore, the computational modeling is a wonderful method of gaining insight into their influence on mechanical behavior. In this research, the deformation behavior of pure copper foils with different grain size is investigated via rolling process. Voronoi tessellation has been applied to describe the polycrystalline aggregate. Finite element analysis of grain size effect based on rate dependent crystal plasticity theory is established to incorporate heterogeneity by the variation of grain size, shape, orientation and to examine its effect and evolution.

2. Rolling experiments

The grain size effect and heterogeneity were investigated by rolling of pure copper foil due to its excellent formability and widespread use in industry. The dimensions of foils were 100 mm (length) × 20 mm (width) × 0.1 mm (thickness). The foils were annealed at the temperatures ranging from 800 to 900 °C at the vacuum condition for 3–7 h in order to produce various grain sizes. Then the heat-treated samples were etched with a solution of 5 g of $FeCl_3$, 15 ml of HCl and 85 ml of H_2O for 5–8 s. The microstructures of tested foils were obtained using optical microscope as shown in Fig. 1. From the figure, it could be concluded that the mean grain size increases and the grains with different sizes were unevenly distributed in the foil complied with the increase of annealing temperature and holding time. The interaction effect between the specimen and grain sizes was discussed by the ratio of the specimen thickness (t) to grain size (d) in the following:

$$\varphi = \frac{\text{specimenthickness} \quad (t)}{\text{grainsize}(d)} \tag{1}$$

Rolling test was used to produce the metal foils and investigate the deformation behaviors. Cold rolling was carried out on a multi-function rolling mill, as shown in Fig. 2. The maximum roll force is of 50 kN and the work rolls of 50 mm diameter were independently driven by two 5.5 kW motors. The upper roll speed remains

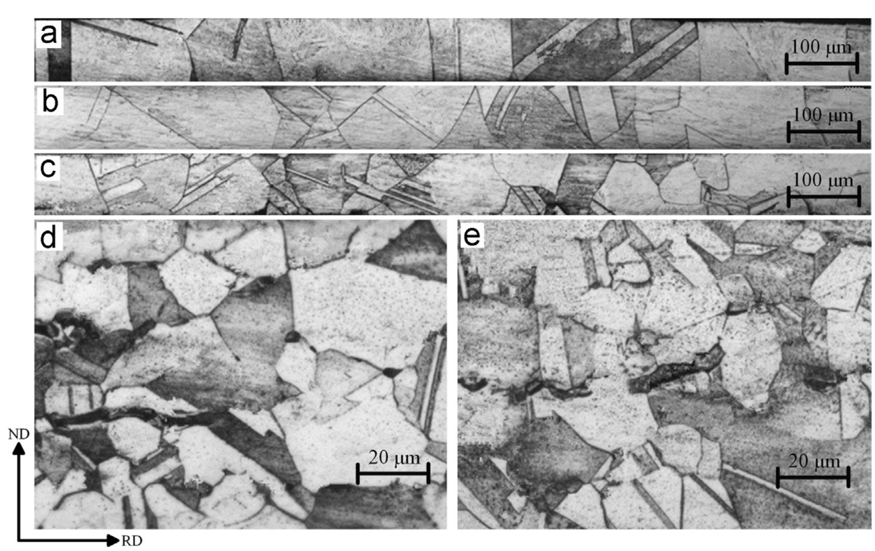

Fig. 1. Microstructure of the annealed pure copper foil: (a): t=100 μm, d=100 μm; (b): t=100 μm, d=50 μm; (c): t=100 μm, d=34 μm; (d): t=100 μm, d=25 μm; (e): t=100 m, d=20 μm.