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Size effect on deformation behavior and ductile fracture in microforming of pure copper sheets considering free surface roughening

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ABSTRACT

In meso/micro-scaled plastic deformation, material deformation and ductile fracture are quite different from those in macro-scale. The roughness of the free surfaces of workpiece increases with deformation and the decrease of grain number in the sample thickness direction, leading to the nonuniformity of specimen thickness. The so-called size effect and free surface roughening may in turn affect the deformation behavior, ductility and fracture morphology of the samples. To explore the coupled effect of workpiece geometry and grain size on material flow behavior in meso/micro-scaled plastic deformation, uniaxial tensile test of pure copper sheets with different thicknesses and comparable microstructure was performed. The experimental results reveal that the material flow stress, fracture stress and strain, and the number of microvoids on fracture surface are getting smaller with the decreasing ratio of specimen thickness to grain size. In addition, the modified Swift's equation and the corrected uniform strain are closer to the experimental ones considering the thickness nonuniform coefficient induced by the free surface roughening. Furthermore, the observation of fracture morphologies confirms that the local deformation caused by the free surface roughening leads to strain localization and a decreased fracture strain when there are only a few grains involved in plastic deformation.

1. Introduction

With the ubiquitous trend of product miniaturization, meso/micro-scaled parts have been widely used in many industry clusters such as electronics, automobiles, healthcare, aerospace, and biomedicine [1–3]. Particularly, the copper alloy microparts are widely used in electronic and communication industries due to the excellent conductivity and good ductility of copper alloy. To fabricate copper alloy microparts efficiently, microforming is used due to its high productivity, low cost, and the good mechanical properties of microformed parts [4–6]. However, when the workpiece geometry is scaled down from macro-scale to meso/micro-scale, the material deformation behavior, fracture toughness and surface roughening may also change accordingly. The deformation behavior and ductile fracture can further affect the forming performance and defect formation due to the fewer grains in the deformation zone and the random orientation and property distributions of individual grains. Thus, understanding of the size effect and its affected material deformation behavior is crucial to product quality and defect avoidance in meso/micro-scaled sheet metal forming.

To explore the size-dependent material flow and fracture behavior, many attempts have been carried out. Fan [7] investigated the grain size effect on the ductile fracture toughness of polycrystalline metals and alloys, and proposed a semi-empirical equation to describe the dependence of fracture toughness on grain size. Michel and Picart [8] conducted the tensile and hydraulic bulging tests to evaluate the thickness-dependent flow stress of brass sheets, and established a constitutive model by taking into account the size effect. Kim et al. [9] studied the feature/specimen size effect and quantified it via relating the size effect to the fundamental properties of single and polycrystalline deformation. Sinclair et al. [10] explored the grain size dependent work-hardening of copper polycrystals. They found that the grain size effect is related to the interaction between dislocation and grain boundary, and this effect on work hardening disappears at a large strain owing to the dynamic recovery. Peng et al. [11,12] developed different material models considering the size effect in microforming process. They believed that the flow stress in meso/micro-scale falls in between those of single crystal and polycrystal. In addition, Molotnikov et al. [13,14] established a physically based constitutive model to represent the size effect on tensile strength considering both material microstructure and

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sheet thickness. They studied the effect of sheet thickness in micro deep drawing process of coarse-grained and ultrafine-grained copper sheets. Vollertsen [15] summarized the size effect on flow stress, tribology, sheet formability and forming processes in meso/micro-scaled plastic deformation. Chan and Fu [16,17] examined the geometry and grain size effects on the deformation behavior and ductile fracture of copper sheet via uniaxial tensile test. They found that flow stress, fracture stress and strain, and the number of microvoids decrease with the ratio of sheet thickness (t_0) to grain size (d_0). Chen and Ngan [18] investigated the coupled effect of grain and specimen sizes on the tensile strength of Ag wires. They revealed that the strengthening effect depends on the specimen shape as the ratio of t_0/d_0 decreases from about 3. Lu et al. [19] presented a new material model for micro-scaled plastic deformation based on the grained heterogeneity and specimen dimension, and conducted finite element (FE) simulation to validate this model by using Voronoi tessellation to describe the polycrystalline microstructure. Ran et al. [20,21] reported that the ductile fracture on the flanged surface of the flanged cylindrical parts is easier to occur in macro-scale flanged upsetting process. Furthermore, they proposed a hybrid model to characterize the size effect on fracture surface morphology and fracture formation by considering the phase composition and distribution of material. Wang et al. [22] performed the uniaxial compression test of pure nickel polycrystals with a constant thickness and various grain sizes to investigate the size effect on flow stress. They found that the conventional Hall–Petch law is not applicable when the specimens have only a few grains across the thickness direction. Xu et al. [23,24] explored the effect of geometry and grain sizes on the forming limit of sheet metals, and developed a coupled damage model based on the Gurson–Tvergaard–Needleman and the Thomason models via considering size effect on void evolution. Meng et al. [25] studied the grain size effect on deformation behavior, dimensional accuracy, defect formation and surface quality in progressive microforming by directly using sheet metals.

Meanwhile, some studies are focused on size-dependent free surface roughening phenomenon and its affected deformation behavior and ductile fracture. Mahmudi and Mehdizadeh [26] investigated the surface roughening behavior of brass sheets under uniaxial and equi-biaxial stress states. They found the roughness increment is proportional to the applied strain and the grain size irrespective of stress state. Wittridge and Knutsen [27] reported that the ribbing profile of sheet metal during uniaxial deformation is attributed to the grain anisotropy roughening, which further produces strain localization. Simons et al. [28] systematically studied the size effect on the tensile properties of copper sheets, and emphasized that the increase in surface roughness is moderate for as-received samples and very apparent for the annealed specimens. This is because there are only a few grains across the thickness of the annealed sample. These grains are less constrained and can rotate out of their initial position by gliding along grain boundaries, leading to a remarkable increase of surface roughness. Furushima et al. [29–31] conducted a series of studies to explore the effect of free surface roughening on the ductile fracture of copper sheet and foil via experiment, modeling, and FE simulation. They found that fracture strain and the number of dimple on the fracture surface decrease for the metal foil, and the ductile fracture criteria are invalid in prediction of the fracture of metal foil with the thickness of 50 μm. Suh et al. [32] studied the combined effect of sample thickness and surface roughness on the uniaxial tensile property of aluminum sheet, and found the effect of surface roughness increases with the decrease of sheet thickness. Romanova et al. [33] numerically investigated the effects of grain shape, loading state and boundary condition on the meso-scaled surface roughening of polycrystalline aluminum alloy under uniaxial tension deformation. They pointed out that the surface ridge and valley are caused by the developed micro-scale normal and shear stresses. Abe [34] proposed a surface roughening model to describe the plastic deformation of polycrystalline metal via introducing the anisotropic coefficient of individual grain, and analyzed the formability of sheet metal under biaxial stretching based on the free surface roughening phenomenon caused by different grain orientations. Khoddam et al. [35] estimated the surface wrinkling during the uniaxial straining of TWIP steel with an initial grain size of 160 μm. Shimizu et al. [36] investigated the surface roughening at the corner of a drawn cup made of ultrathin metal foil, and indicated that the thickness nonuniformity exacerbates with the reducing thickness, which in turn affects the instability and limiting strain of metal foils.

Based on the above brief review, it can be seen that the specimen and grain size effects on the micro-scaled plastic deformation behavior and ductile fracture of sheet metal have been sufficiently investigated. However, there is still a lack of knowledge on the comprehensive influence of the geometry size and material microstructure on deformation behavior, ductile fracture and free surface roughening. Actually, the size-dependent free surface roughening could in turn affect the material deformation behavior, ductile fracture, and further the dimensional accuracy and surface quality of the microformed parts. Therefore, this effect should be also considered in addition to the size effect. This research is thus aimed at addressing the former issues and exploring how the geometry and grain size effects affect flow behavior, fracture stress and strain, surface roughness, and fracture morphologies via uniaxial tensile tests. Meanwhile, the surface roughness of the deformed specimens under different material conditions was measured and characterized. The factor of free surface roughening is introduced into the constitutive model and the plastic instability criterion to explore its effect on material flow stress, uniform strain, and fracture strain.

2. Experimental details

2.1. Sample preparation

Pure copper sheets with the thicknesses of 0.2, 0.4 and 0.6 mm were used as the testing material in this research. The copper sheets with the thicknesses of 0.2 and 0.4 mm were heat treated to release the internal residual stress after rolling, whereas the sheets with the thickness of 0.6 mm were not heat treated. The test specimen was cut along the rolling direction by electrical discharge machining method. The dimension of the test sample and the surface roughness requirement are presented in Fig. 1(a). After cutting, the samples were ready for tensile test, which are termed as the "as-received" in this paper. Meanwhile, some machined samples were heat treated to explore the effect of material microstructure on deformation behavior and free surface roughening phenomenon. Since the recrystallization temperature of pure copper is about 380 °C, the annealing temperatures and dwelling times are 500 °C and 2 h, 600 °C and 2 h, and 750 °C and 3 h in the vacuum environment, respectively. These samples are thus identified as the "annealed" in this research. The flow chart of sample preparation process is presented in Fig. 1(b). The metallographic observation was conducted on the microscope (Epiphot 200, Nikon) after the specimens were etched with a solution of 5 g of $FeCl_3$, 15 ml of HCl and 85 ml of H_2O for 10 s. The microstructure along the thickness direction and the average grain size under different thicknesses and heat treatment conditions are shown in Fig. 2 and Table 1, respectively. It is observed that the grain size increases with the annealing temperature. There are only 2–3 grains in the thickness of the samples with the thickness of 0.2 mm annealed at 750 °C. In addition, the grain distribution of the as-received