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Geometry and grain size effects on the fracture behavior of sheet metal in micro-scale plastic deformation

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ABSTRACT

The demand on micro-parts is significantly increasing in the last decade due to the trend of product miniaturization. When the part size is scaled down to micro-scale, the billet material consists of only a few grains and the material properties and deformation behaviors are quite different from the conventional ones in macro-scale. The size effect phenomena occur in micro-scale plastic deformation or micro-forming and there are still many unknown phenomena related to size effect, including geometry and grain size effects. It is thus critical to investigate the size effect on deformation behavior, especially for the fracture behavior in micro-scale plastic deformation. In this research, tensile test was conducted with annealed pure copper foils with different thicknesses and grain sizes to study the size effects on fracture behavior. It is found that flow stress, fracture stress and strain, and the number of micro-voids on the fracture surface decrease with the decreasing ratio of specimen size to grain size. Based on the experimental results, dislocation density based models which consider the interactive effect of specimen and grain sizes on fracture stress and strain are developed and their accuracies are further verified and validated with the experimental results obtained from this research and prior arts.

1. Introduction

The demand on micro-parts and micro-products is increased significantly due to the trend of product miniaturization. To efficiently fabricate micro- parts and products, micro-forming is one of the promising approaches due to the advantages of high productivity, low production cost and the good mechanical properties of micro-formed parts. In design and development of micro-parts via micro-forming, understanding of material deformation behaviors in the process is critical to produce quality parts and products. For macro-scaled metal forming process, the analyses have been extensively conducted [1,2] and widely used in metal forming industries to design and evaluate metal forming systems [3–5]. When the part size is reduced to micro-scale such as sub millimeter range, the deformation behavior changes due to size effect [6–8]. The conventional material models are no longer valid in analysis of micro plastic deformation behavior [9,10].

To explore micro deformation behavior and mechanics, a lot of prior researches have been conducted. Geißdörfer et al. [11] proposed a model concerning the grain boundary condition and anisotropic material behavior to simulate micro-forming process. Their model was implemented in FE simulation system and validated by the experiment of cylinder compression. Kang et al. [12] investigated the micro-formability of Al5083 by using micro-forging method. They concluded that the micro-formability increases with the decreasing grain size. Parasiz et al. [13] conducted the experiment to study the size effect in micro-extrusion process. They found that the extruded pin is curved and the distribution of plastic strain and hardness along the section of the extruded pin is not uniform when the material with coarse grain size is used. Kim et al. [14] established a model to analyze the micro-scale deformation based on Hall–Petch relation. Fan [15] described the grain size effect on fracture behavior based on the composite model with the consideration of grain boundary and grain interior. Zhao et al. [16,17] examined the specimen size effect for the ultrafine- and coarse-grained copper foils via tensile test. They found that the fracture strain, post-necking elongation and strain hardening rate increase with the increasing specimen thickness and the decreasing gauge length. With the increase of specimen thickness, the failure mode changes gradually from shear to normal tensile failure. Kals and Eckstein [18] studied the material size effects in the tensile test, air bending and the punching of sheet metal. They found that the ductility decreases with the increase of grain size and the decrease of specimen size. The decrease of specimen size leads to the substantial necking and localized shearing. Ma et al. [19] examined the grain size effect on the fracture behavior in deep drawing process. It is shown that the limit drawing ratio is significantly decreased with the decreasing grain size. Joo et al. [20] investigated the size effect in punching process. They revealed that when there are only a few grains constituting the workpiece

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