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Size effect affected formability of sheet metals in micro/meso scale plastic deformation: Experiment and modeling

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ABSTRACT

Ductile fracture of metallic materials in micro/meso scale plastic deformation is influenced by geometry and grain sizes and the so-called size effect thus exists. To reveal how the size effect affects the formability of sheet metals in micro/meso scale plastic deformation, the forming limit of sheet metals was studied by experiment and modeling. An extended coupled damage model was first developed based on the Gurson–Tvergaard–Needleman and the Thomason models via considering the geometry and grain size effects on void evolution. In modeling process, the void nucleation was analyzed by taking account the phenomenon that the number of voids decreases with the ratio of thickness to grain size of workpiece. For the void growth, the widely used surface layer model was employed to describe the size effect on the flow stress of material. The grain size effect on void spatial arrangement was also modeled during the coalescence of micro voids. The model was then implemented into finite element simulations and the predicted forming limit curves under different scale factors were constructed. On the other hand, the forming limit experiments were conducted based on the miniaturized Holmberg and Marciniak tests to estimate the formability of sheet metals under different conditions. Both the physical experiments and finite element simulations show a significant size effect on the micro/meso scaled fracture behavior: The forming limit curve shifts down with the decreasing ratio of the thickness to grain size. The simulation results were also corroborated and verified by experiments. In addition, when the ratio is two or less than two, the very scattered limit strain results are observed in the experiments and the strain localization tends to occur at the beginning of deformation. The research conducted advances the understanding of size effect on the formability of micro/meso scaled sheet metals and thus helps the development of the successful and reliable microforming processes.

1. Introduction

Due to the development of product miniaturization in many industry clusters, micro-manufacturing technologies such as micromachining, micro laser machining and LIGA, are widely studied and well developed recently. Microforming is one of the most attractive approaches to fabricating micro-parts for its unique advantages such as high productivity, low cost and the good mechanical properties of microformed parts (Geiger et al., 2001; Vollertsen et al., 2004). In microforming,

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one of the key issues is that the properties and deformation behaviors of the microformed parts are affected by the so-called size effect (Engel and Eckstein, 2002; Vollertsen et al., 2006). The size effect is mainly caused by the significant reduction of grain number in deforming zone. Therefore, the deformation and the properties of individual grains play an important role in the deformation and ductile fracture (DF) of micro-parts and many macroscopic rules may no longer be valid. The DF in microforming is a critical research topic closely related to the manufacturing reliability and quality. How the geometry and grain sizes affect the fracture behavior is thus an eluded and tantalized research issue in microforming arena and attracts a lot of efforts to explore it.

The preliminary researches on the size effect of DF are focused on the effect of specimen size and geometry. Decamp et al. (1997) and Besson et al. (2000) found that the mean ductility decreases with the increase of dimension size through the experiment of different materials with multi-phases. In addition, a significant scatter of ductility is also observed with the decrease of specimen size. Their studies are mainly conducted in millimeter-scale. Regarding the ductility of materials in micro/meso scale forming, bulging test was conducted by Diehl et al. (2010) and revealed that the forming limit decreases with the thickness of fine-grained copper sheet from 500 to 25 μm. Later on, some researchers noticed that the DF in micro/meso scale is also associated with grain size and microstructure. Vollertsen et al. (2010) carried out the pneumatic bulge tests of aluminum foils with the thickness of 20 μm. The highly irregular local distribution of strain is observed and the fracture appears randomly in the deformation zone. They attributed this phenomenon to the significantly different plastic flow behaviors of local microstructures. Similarly, Zhuang et al. (2010) provided an intuitive observation of the strain localization in hydroforming of the micro-tube with about 1–2 grains across the thickness of tube section using crystal-plasticity finite element (FE) simulation. They pointed out that the localized necking is highly related to the directions of crystal slip system and external load.

The DF affected by both the geometry and grain sizes has not yet been explored and studied until the recent past. Among the researches, the tensile tests of the annealed copper foils with different thicknesses and grain sizes were studied by Fu and Chan (2011) to reveal the size effect on fracture behavior. The number of micro-voids, as well as the fracture stress and strain, were identified to decrease with the reduction of thickness-to-grain-size ratio (t/d). A dislocation density based model considering size effect was also developed to predict the DF behavior. Furthermore, Ben Hmida et al. (2013) conducted the single point incremental forming process of copper foils with the thickness of 0.21 mm and various grain sizes. The formability deteriorates with the decrease of t/d according to their investigations. In addition, Ran et al. (2013) and Ran and Fu (2014) studied the DF of micro and macro scale flanged upsetting. They concluded the fracture in the flange surface is easier to form in macro scale flanged upsetting process. The size effect has a significant effect on the dimple size at the transgranular fracture surface and the fracture behavior. A hybrid model considering multiphase and size effect was also proposed to predict the fracture in microforming.

Regarding the DF of sheet metals, forming limit diagram (FLD) developed by Keeler and Backofen (1963) and Goodwin (1968) has been the most widely used tool to evaluate the formability of ductile sheet metals. In addition, numerous studies were conducted to predict the FLC in macro scale. The traditional methods for construction of theoretical FLD include Swift (1952) diffuse criterion, Hill (1952) localize criterion, bifurcation theory based instability prediction developed by Stören and Rice (1975), M–K model proposed by Marciniak and Kuczyński (1967), etc. A lot of recent research efforts have been made to improve and verify these theories under different conditions. Among them Khan and Baig (2011) considered the effects of strain-rate and temperature on the formability of aluminum alloy based on the M–K model. Eyckens et al. (2011) extended the M–K model for anisotropic sheet metals with consideration of through-thickness shear. They pointed out that the effect of through-thickness shear is significant and needs to be considered in sheet metal forming process. The prediction of forming limit coupling crystal plasticity and M–K model was done by John Neil and Agnew (2009), Kim et al. (2013) and Signorelli et al. (2009) with different materials. They also revealed a strong dependency of limit strains on the initial texture of sheet metals.

In addition to the classical models for forming limit prediction, DF criteria have also been widely-employed to predict the FLD recently. The DF criteria can be mainly classified into the uncoupled and coupled categories depending on whether the model incorporates the damage accumulation into the constitutive equation (Liu and Fu, 2014a, b). In the uncoupled criteria field, Luo et al. (2012) investigated the DF response of aluminum sheets under both tension- and shear-dominated loadings to cover a wide range of stress states. An anisotropic fracture criterion was also proposed and the criterion provides an accurate prediction of the onset of fracture using the Modified Mohr-Coulomb stress state weighting function. Khan and Liu (2012a, b) established an accurate and efficient fracture criterion to predict the fracture of Al 2024-T351 alloy under different loading conditions. The criterion was also extended to include strain rate and temperature dependence. The developed criterion is considered to be more accurate compared with others. Furthermore, Li et al. (2011) analyzed the deformation and DF behavior of Al 6061 alloy using various DF criteria. The predicted results of different criteria were compared and the applicabilities of the criteria were verified under different conditions. Regarding the coupled criteria, Brünig et al. (2013) developed a continuum damage model (CDM) by taking into account stress intensity, stress triaxiality and the Lode parameter. The model was verified by comparing with the numerical results obtained by the unit cell calculation of different conditions. In addition, Malcher and Mamiya (2014) considered the stress triaxiality and the third invariant of deviatoric stress tensor into the Lemaitre's CDM. The numerical results were compared with the experimental ones upon a wide range of stress triaxiality and the accuracy of the model is improved significantly compared with the origin one.

The well-known Gurson model (Gurson, 1977) is one of the most attractive coupled DF models. It provides a realistic description of material microstructure and associates DF to the micromechanical parameters directly (Besson, 2009;