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The influence of size effect on the ductile fracture in micro-scaled plastic deformation

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ABSTRACT

In macro-scaled plastic deformation processes, viz., macroforming, the so-called ductile fracture has been extensively studied in terms of the physics, mechanisms, affecting factors and the prediction criteria of ductile fracture. In micro-scaled plastic deformation processes, or microforming, all of these are relatively new and have not yet been extensively investigated. In tandem with this, the applicability of the traditional fracture criteria in micro-scaled plastic deformation and how the size effect affects the deformation and fracture in the microforming processes are critical. Using micro scale flanged upsetting as a case study process, the fracture in the process is studied via experiment and finite element (FE) simulation. The FE simulation is conducted using the established model based on the widely accepted surface layer model in microforming. Both the physical experiment and simulation show that the size factor has a significant effect on fracture formation in micro-scaled plastic deformation. Based on the proposed surface layer model, the fracture in micro scaled plastic deformation is predicted by considering the size factor in Cockcroft fracture criterion and the results are corroborated and verified by experiments. It is found that the ductile fracture affected by size effect is difficult to occur in microforming in the same deformation conditions under which the fracture happens in macroforming scenario. The research thus provides an in-depth understanding of the fracture in micro-scaled plastic deformation.

1. Introduction

Due to the massive demands on micro-scaled parts, components and products in many industrial clusters, microforming has become a more and more important micro manufacturing process recently compared to other micro manufacturing processes such as micro machining, micro injection molding, powder injection molding and Micro-Electro-Mechanical-Systems (MEMS)-based lithography processes. Microforming is a plastic deformation process to manufacture the small parts with at least two dimensions in sub-millimeter scale and with the advantages of high productivity, low production cost, good mechanical properties, and the rational grain flow texture in the microformed workpieces (Geiger et al., 2001). Micro scale flanged upsetting is one of the microforming processes to fabricate the workpieces with different cross sections and high material utilization. In this process, billet material is compressed and a flange is formed in the middle of workpiece. Similar to other micro upsetting processes, the basic deformation of micro scale flanged upsetting process is to form a radically expended flange under punch pressure. In this microforming process, the material flow mechanism is different from that in the conventional macro flanged upsetting process due to the so-called size effect in microforming process. The size effect is mainly caused by the significant reduction of grain number in billet material. As a result, the fracture formation in micro flanged forming could be different from that in macro forming in terms of fracture behavior, mechanism, and affecting factor (Wen et al., 2005).

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In microforming researches, many prior arts are basically focused on material flow behaviors in the process with the consideration of size effect. Few efforts are provided to explore fracture and its formation mechanism in this process. Regarding the flow and deformation behaviors, the pioneer researches include the exploration done by Pawelski (1992), who presented that the rules for macroforming are not fully applicable in the manufacturing of the scaled-down parts using the same process. The so-called size effect is thus proposed to define the limitations induced in the scaled down forming process. Michel and Picart (2002) and Picart et al. (1998) conducted the evaluation of size effect on the flow stress of material using the tensile test experiment of brass samples. The material parameters are implemented in a constitutive model for sheet metal specimen based on the experimental results to evaluate the stress–strain model. Chan and Fu (2011) have done a systematic research on the influence of size effect on the deformation behavior and friction variation in microforming processes. In their researches, a series of flow stress curves are generated for the scaled down specimens and the applicability of these curves are validated via experiments and simulations. To present the panorama of the whole research status of microforming, Vollertsen (2003, 2008) conducted a comprehensive review and succinctly figured out the issues to be addressed in development of microforming processes and micro scaled parts.

Regarding the forming limit and the defect formation in microforming, Gouveia et al. (1995) investigated the applicability of four ductile fracture criteria in metal forming processes. The accuracy of the fracture prediction is examined and compared with the experimental results. Ogawa et al. (2002) conducted the research on the forming limit of magnesium alloy. It is found that the magnesium alloys have different workability after heat treatment due to oxidation. A tensile stress related fracture criterion is proposed to predict the forming limit of the alloy. Sljapic et al. (2002) investigated the fracture of cold upsetting process of brass. The axi-symmetric brass forming experiments are modeled by finite element method (FEM). The maximum plastic strain coincident with the fracture initiation is identified via simulation. Murty et al. (2004) examined the adequacy of some commonly used criteria which are used to predict ductile fracture in metal forming process. By considering the triaxiality, a stress-function-based ductile fracture model was proposed. In addition, Li et al. (2011) provides a panoramic review of numerous ductile fracture criteria in macro scaled plastic deformation. By implementation of those criteria in simulations and verified by physical experiments, the most applicable conditions are identified for each criterion. However, the research did not address the applicability of the criteria in micro-scaled plastic deformation. Furthermore, Li and Karr (2009) proposed a methodology to predict ductile fracture initiation in tensile test. The one dimensional quasi-static simple tension test is focused and the example of the Lambert W function in material analysis is provided. The feature size effect on ductile fracture initiation is considered in their model. Using the single crystal plasticity model, Kadkhodapour et al. (2011) employed both the experimental and numerical methods to explain the failure mechanism in the tensile test of steels. It is found that the deformation localization is most probably the root-cause of failure in the final stage of the test. Recently, the stress state dependence is found to be an important effect in the macroscopic fracture research. Bao and Wierzbicki (2004) and Bai and Wierzbicki (2008) revealed the relationship between the equivalent strain and stress triaxiality via experiment and FEM simulation. Fracture models for both the negative stress triaxiality and large triaxiality are proposed. As discussed by Brünig et al. (2008, 2011), this stress state dependence effect is caused by the stress state dependence of the damage mechanisms occurring at micro-scale.

Through literature review, it is found that fracture in microforming process and how the size effect affects the fracture in the process have not yet been paid much attention and explored. The forming limit and fracture defect formation in the process need a systematic research considering size effect. There is a need to verify whether the conventional fracture theory can be used in micro-scaled plastic deformation. Therefore, this paper aims at addressing this issue via development of a surface layer model considering the size effect in microforming process to model and represent the formation of micro fracture in the process. To realize these thoughts, the physical experiments and numerical simulations considering size effect are conducted. The simulation and experiment results are compared and the proposed size effect based surface layer model is verified.

2. Research methodology

2.1. Research procedure

Fig. 1 presents the research procedure in this research. The stress–strain relationship of the testing material (brass) is first established through macro and micro scale upsetting experiments. After the size factor, which represents the percentage of the surface grains among all the grains in the workpiece, is calculated according to the specimen dimension, a micro-scaled upsetting stress–strain model is established. The simulations of micro scale flanged upsetting are then conducted using the model and the corresponding simulation results are compared with the experimental ones to determine whether the forming process is influenced by size effect. Finally, the micro fracture prediction is provided using these results. By implementing the stress–strain model into Cockcroft fracture criterion, the fracture energy of the testing specimen is calculated and the fracture initiation strain is predicted and compared with the experimental results.

2.2. Material behavior modeling considering size effect

In microforming process, material deformation behavior is affected by size effect. The size effects are classified into grain and geometry size effects. Grain size effect happens when the grain size of billet material is changed while the workpiece