Materials & Design 83 (2015) 14–25

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Ductile fracture and deformation behavior in progressive microforming

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ARTICLE INFO

Article history:
Received 1 January 2015
Revised 29 May 2015
Accepted 30 May 2015
Available online 19 June 2015

Keywords:
Progressive microforming
Ductile fracture
Size effect
Material flow
Fracture criterion

ABSTRACT

With the increasing demand for the quality and quantity of miniaturized parts, fabrication of microparts directly using sheet metals is proven to be promising and efficient for mass production. In this process, however, there are many unknowns in terms of size effect and its affected fracture and deformation behavior. This study is thus aimed at investigating the micromechanical damage and deformation behavior in progressive microforming and establishing a systematic knowledge to support the microformed part design, process configuration and tooling design. In detail, a micro cylindrical part is fabricated via shearing process and a multi-level flanged part is produced via progressive micro extrusion and blanking. To explore the effect of material microstructure on the deformation behavior, ductile fracture and the product quality of microformed part, the original sheet metals are annealed under different temperatures. To realize the microforming process, a progressive microforming system is developed and its characteristics are investigated. The effect of grain size on dimensional accuracy, microstructure evolution and fracture behavior in microforming is also studied. The ductile fracture and its induced defects are identified and the damage accumulation is predicted. In the end, the validity and applicability of different fracture criteria in microforming is discussed.

1. Introduction

Micro/meso-scaled parts have been widely used in electronics, automobiles, dyeing textile, aerospace and biomedicine in tandem with the ubiquitous trend of product miniaturization [1,2]. To meet the increasing market demand and product quality requirement for microparts, micro-manufacturing technologies including micromachining, laser processing, microinjection, lithography and microforming have been developed to fabricate the micro-scaled parts and components. From manufacturing perspective, microforming fabricates microparts with the desirable geometries via plastic deformation and has been proven to be promising for mass production for its high productivity and excellent mechanical properties of microformed parts, together with low production cost [3,4].

Nowadays, the development of micro/meso-forming system is generally conducted through trial-and-error based on the scaling down and modification of the conventional macro-forming system design. In microforming, the design and fabrication of microparts cannot be simply conducted via leveraging the knowledge of macroforming to microforming since the size effect could be a barrier to this knowledge transfer [5,6]. Therefore, the researches on some issues and phenomena induced by size effect such as deformation behavior, damage accumulation, dimensional accuracy, friction, springback and deformation defects in microforming have been performed for the efficient development of microparts by this promising micro-manufacturing process [7–11].

On the other hand, the microforming for mass production of microparts and its process chain have not yet been studied extensively. To realize the batch production of microparts using microforming, the difficulty in handling, transporting, stripping and positioning of billet, preform, semi-finished or final part must be overcome [12,13]. One way of handling and positioning microparts is using robot and advanced gripper system, which is proven to be complicated, tailor-made, less efficient and costly [14]. To address the handling, transportation and ejection issues in microforming, Hirota [15] put forward a new method to fabricate micro billet via extruding the sheet metal in thickness direction, and studied the effect of constraint condition on the height of the extruded billet. Based on this, the concept of progressive microforming by directly using sheet metal was developed by Fu and Chan [16,17]. They further examined the feasibility of this process to fabricate meso/micro-scaled parts with more complex features and explored the process characteristics using different microformed part sizes and the materials with different grain sizes. Ghassemali et al. [18–20] also used this process to manufacture micro-pins directly using copper strip.

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http://dx.doi.org/10.1016/j.matdes.2015.05.088
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In progressive microforming, the knowledge of deformation and fracture behavior are very important, which supports defect-free micropart design, process determination, die design and product quality assurance. In macroforming, huge efforts have been provided to reveal the ductile fracture behavior of different materials under different stress conditions. To name a few, Wierzbicki et al. [21] presented a thorough comparative study of seven commonly used fracture criteria to identify their suitability in the prediction of fracture, and they found that Xue–Wierzbicki model agrees well with the experimental results. Li et al. [22] investigated the reliability and validity of two categories of fracture criteria, viz. coupled and uncoupled fracture models, in ductile failure scenarios and revealed that the applicability of fracture criteria depends on the damage evolution and the factors including pressure stress, stress triaxiality, Lode parameter, equivalent plastic strain and shear stress. Mori et al. [23] developed a slight clearance punching process using a small round edge to improve the quality of the sheared edge, and they found that the delayed fracture did not happen and the fatigue strength was enhanced due to the large compressive stress around the sheared edge in such punching process. In addition, Achouri et al. [24] investigated the physical damage mechanisms in punching operation, and further established an improved numerical formula to predict the fracture location based on the micromechanical approach. Furthermore, Liu and Fu [25,26] proposed a modified ductile criterion for fracture prediction of sheet metal forming, and verified its validity by flexible die forming and hemispherical bulging.

Even though the existing fracture criteria have been proven to be accurate in macro-scaled deformation, the geometry and grain size effects on the criteria in micro/meso scale deformation should be considered to represent how the scale factor affects failure behavior. Among those efforts, Shim et al. [27] investigated the shearing mechanism in blanking of thin foils by finite element method, and examined the Cockroft and Latham's fracture criterion to predict the fracture location. Furushima et al. [28] examined the ductile fracture and free surface roughening behavior for pure copper foils and sheets with initial thicknesses spanning from 0.05 to 0.3 mm, and evaluated the applicability of various ductile fracture criteria for fracture prediction during the stretch forming. Yu et al. [29] explored the fracture behavior and the shear fracture angles of aluminum 6061 sheets, and also discussed the fracture mechanism and size effect during tensile test. Ran et al. [30,31] addressed the size effect on ductile fracture in micro-scaled plastic deformation, and further proposed a hybrid flow stress model to predict the ductile fracture in microforming. Xu et al. [32] extended the GTN-Thomason model by considering the geometry and grain size effects in micro/meso scale, and investigated the size effects of scale factor on the failure behavior of sheet metals.

Based on the above brief review, the prior researches on fracture and deformation behavior of sheet metals are mainly focused on the individual forming operation under different stress conditions. For progressive microforming, however, the ductile fracture and its induced defects resulted from a great amount of damage accumulation and deformation inhomogeneity in different operation stages, have not yet been sufficiently explored and studied. This is due in large part to the nascent state of progressive microforming technology. The concept of using sheet metals as the billet material in progressive microforming is novel and advantageous. A few typical micro-parts have already been fabricated by such process. The unique deformation behavior and damage accumulation effect, however, remain unknown and need to be explored in general. The process performance and the final product quality, on the other hand, depend on the deformation and ductile fracture behavior. Moreover, there is a lack of the detailed investigation into dimensional accuracy, material flow behavior and microstructure evolution of the formed parts by progressive microforming. This research is thus aimed at addressing these issues and exploring how the factors including material property, microstructure and process variables affect the fracture behavior and product quality via experiment and finite element analysis. Meanwhile, the validity and applicability of the existing ductile fracture criteria in progressive microforming will also be investigated and discussed.

2. Experimental details and numerical simulation

2.1. Testing material

Pure copper sheet metal with the thickness of 1.52 mm was used as the testing material. To explore how the original microstructure of sheet metal affects the ductile fracture and deformation behavior in progressive microforming, the material was annealed at different temperatures and holding times, viz., 500 °C for 2 h, 600 °C for 2 h and 750 °C for 3 h in vacuum environment. The average grain sizes of the sheet metal are 11.1, 21.9, 23.3 and 37.8 μm corresponding to the conditions of the as-received and annealed at 500, 600, and 750 °C, respectively. To obtain the flow behavior of the used materials with different states, uniaxial tensile tests were performed to obtain the flow stress curves, as shown in Fig. 1. It can be seen that the flow stress of the as-received sample is greater than that of the annealed one, which can be explained based on the decrease of grain boundary strengthening effect with the increase of grain size. However, the fracture strain of the as-received sheet metal is lower than that of the annealed ones. The grain size effect can be represented by the Hall–Petch relation, which articulates that the flow stress grows linearly with the reciprocal square root of grain size [17].

2.2. Progressive microforming system

The schematic illustration of the developed progressive microforming system for the fabrication of the micro flanged part is shown in Fig. 2, which consists of shearing, blanking and extrusion operations. The copper sheet with the dimension of 80 × 10 × 1.52 mm is used. There are four processing operations in each stroke. In the first step, the sheet metal undergoes shearing deformation. A cylindrical part is blanked out and a hole in the sheet metal is pierced, which is used for positioning in the subsequent operations. In the second and third operations, the workpiece is extruded in thickness direction to form the multilevel flanged features, and a portion of the material is further pressed into the die orifice. It is noted that the formed part at the first three stages is attached to the sheet metal, which makes it easier for handling, positioning and transferring to the next step. In the last operation, the flanged part is removed from the strip by blanking operation. Considering the machine capacity and the mechanical

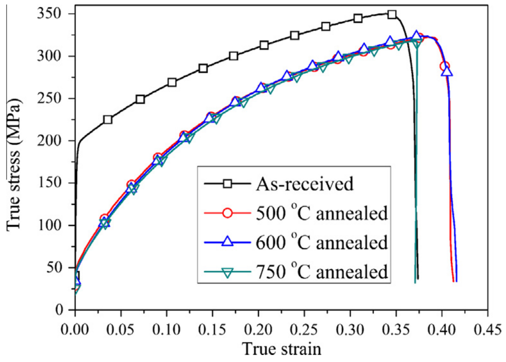

Fig. 1. Flow stress curves of the testing material under different states.