Materials and Design 49 (2013) 774–783

Contents lists available at SciVerse ScienceDirect

Materials and Design

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

Micro-scaled progressive forming of bulk micropart via directly using sheet metals

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ARTICLE INFO

Article history:
Received 9 December 2012
Accepted 9 February 2013
Available online 24 February 2013

Keywords:
Microforming
Process design
Plastic deformation
Progressive forming

ABSTRACT

In our prior study, a progressive forming system to fabricate meso-scaled bulk cylindrical and flanged parts by using sheet metals has been developed. In this forming system, the cylindrical part is formed via blanking, while the flanged part is formed via the progressive punching, extrusion and blanking. In forming of the flanged part, the preform is attached to the metal strip and positioned based on the geometry of preform. The formed part is finally trimmed out by shearing in the last operation. In such a way, the transporting, positioning and ejecting of preform/part are facilitated. In this paper, the research is aimed at further studying the feasibility of forming microscaled parts by using the previously developed forming system and examining its characteristics based on the material flow behavior, microstructure evolution, the quality and property of the final formed parts. It is revealed that the length of blanked cylinder decreases with the increase of grain size. When the grain size is large compared to the workpiece thickness, an inclined fracture surface is formed on the blanked cylinder and the rollover surface on the flanged part becomes rough. A rough fracture surface with microvoids is formed after shearing operation. The number of microvoids on the fracture surface decreases with the increase of grain size. The developed process is proved to be promising and efficient for mass production of bulk microparts directly using sheet metal.

1. Introduction

With product miniaturization, the demand on quality and quantity of microparts is increasing significantly. The mass production of quality metallic microparts at low cost and high productivity is still a challenging and non-trivial issue. Microforming process, which fabricates the parts with the desirable geometries via plastic deformation, offers attractive characteristics of low production cost and high productivity. Many microforming processes, such as coining, heading, upsetting, bending, deep drawing, extrusion, embossing and blanking, have been extensively explored. It is found that the well-established knowledge of the conventional metal forming processes [1] is not applicable in microforming processes. The design of microforming processes is generally conducted via trial-and-error approach based on the scaling down and modifying the conventional macroforming systems. Such a design and development paradigm is time-consuming and costly, and the product quality is not assured. Therefore, the researches on the development of scaled down forming processes, the size effect on material deformation behavior, and the performance of microforming processes are thus needed for development of microparts.

In the last two decades, the research on microforming has been focused on the change of flow stress, fracture behavior, flow behavior, elastic recovery and surface finish with the decrease of forming material size. The change of flow stress not only affects the deformation load, but also the material flow, as revealed in the double cup extrusion [2,3]. It has been shown numerically and experimentally that the amounts of upward and downward material flow change with flow stress. In addition, it is found that the flow stress decreases with the specimen size [4,5], which is attributed to the increase of surface grain fraction [6,7] and the decrease of grain boundary fraction [6]. The surface grains have less constraint and lower flow stress. The decrease of specimen size leads to the increase of surface grain fraction. Furthermore, the flow stress of material is also related to grain boundary strengthening behavior. Grain boundary acts as a strong obstacle to stop dislocation movement. Grain boundary fraction could decrease with the ratio of specimen size to grain size, leading to the decrease of flow stress. The size effect on the fracture behavior has been investigated via tensile [7] and upsetting [8] tests with different specimen and grain sizes. Understanding the mechanism of fracture behavior in microforming process is critical to avoid the thinning, fracture and cracking defects of the microformed parts. It is revealed that the amount of deformation up to fracture decreases with the thickness of sheet metal. It is due to the fact that non-uniform deformation takes place along the gauge length of specimen when the specimen size is decreased. Significantly large deformation is localized at the section with large fraction of grains which are favorable to deform in tensile direction. It further results in the small fracture strain.

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0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.02.045

Single grain deforms via slipping. For a given stress direction, there is a preferred slip plane and direction. This deformation mechanism makes the mechanical properties of grain anisotropic. When the material size is in macroscale, it is composed of a large number of grains. Different grains with different sizes, orientations and forms can be evenly distributed in the material. This leads to the isotropic properties of macro-scaled materials. However, the forming material could have only a few grains in microforming processes and the properties of individual grain could be dominant in the overall deformation behavior. It could further lead to the inhomogeneous deformation and irregular shape of the formed part [9].

The springback caused by the elastic recovery of the forming material affects the dimensional accuracy of the formed parts. In bending test with different foil thicknesses and grain sizes, it is found that the amount of springback increases with the decreasing ratio of specimen size to grain size [10]. In addition, the surface roughness of the forming material keeps changing throughout the deformation process. It is found that the size of surface asperity relative to the part size generally increases with the increase of grain size and the decrease of formed part size. This phenomenon could be explained by the incompatibility of deformation among grains with different properties [11], such that the free surface grains move normal to the surface. This eventually leads to the occurrence of surface roughening.

Based on the above brief review of the researches on size effects and the deformation behaviors, it is found that less effort has been made in development of microforming process for mass production of microparts, in which formed part quality and productivity are two of critical concerns. In microforming, the adhesive forces on micropreform or part surface make it prone to stick on the forming or handling tool. This results in the difficulty in handling and transporting. The prior studies [12,13] on microforward extrusion have shown that the extrudate is distorted, as shown in Fig. 1a. In addition, the high tooling-workpiece interfacial friction in the process results in the difficulty in part ejection [14]. The formed part could be damaged by ejection force, as shown in Fig. 1b. To overcome the difficulty in part ejection, separating the extrusion die into two halves was proposed by Krishnan et al. [13]. The authors also conducted the similar experiments. However, such design leads to the formation of flash at the parting line, as shown in Fig. 1c. It also increases tooling cost and affects productivity.

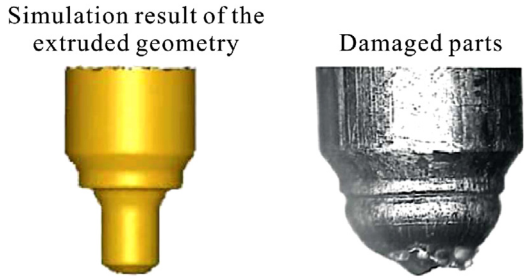
Bulk micropart is usually formed from bulk microbillet, which is usually fabricated by costly micromachining process. Two alternative approaches have been proposed to substitute the micromachining process. The first one is to cut microbillet from metal wire by simple shearing [15], while the second approach is to form the micropart directly using sheet metal [16]. However, it is difficult to control the quality of the fracture surfaces in the first approach. In addition, the stress in micropunch could be unevenly distributed when the billet with the inclined fracture surface is used in the subsequent extrusion process, resulting in early failure of tooling. The second approach seems to be more promising as it facilitates the material handling, transportation and ejection in forming of meso-scaled parts in our prior study [17]. In this research, the objective is to further study the feasibility of the process to fabricate the microparts and identify its characteristics via scaling down the formed part size and using materials with different microstructures.

2. Experimental details

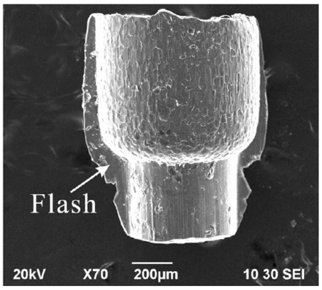
2.1. Testing material preparation

Copper is widely used for manufacturing microparts due to its excellent formability and conductivity. Pure copper is thus selected as the testing material in this research. The copper sheets with the thicknesses of 1.5 and 0.8 mm are used in two size-scaled forming systems, respectively. To obtain different grain sizes, the copper sheets are annealed using different temperatures and holding times, viz., 500 °C for 2 h, 600 °C for 2 h and 750 °C for 3 h. The samples are then cooled down to room temperature gradually in the furnace. The entire heat treatment process is conducted in an argon gas-filled chamber to avoid oxidation. The obtained microstructures of the testing materials are shown in Fig. 2. To obtain the flow stress curves, the dog bone shaped specimens are used in tensile test which complies with the standard ASTM: E8/E8M. An extensometer with the gauge length of 25 mm is used to measure the elongation of the testing specimens. The tensile test is conducted using a slow crosshead speed of 1 mm/min and the specimens are deformed until fracture.

(a) Distorted extrudate [12]



(b) Damage in part ejection [14]



(c) The formed flash on the extruded part

Fig. 1. The quality issue in the microextruded parts.

2.2. Fabrication of bulk microparts

Two size-scaled forming systems are developed to examine the part size effect in this study. Three microforming operations are conducted and the schematic illustration of tooling structure and the corresponding dimensions in the two size-scaled cases are shown in Fig. 3. They are realized using different punches, blank holders and die inserts on the same tooling platform. In the first forming operation, the workpiece is subject to shear deformation, and then a hole is pierced and a cylinder is blanked out. In the second operation, the workpiece is positioned based on the guide hole pierced in the first operation. The material is pushed to flow towards die cavity. In the last operation, the flanged part is blanked out via shearing. The experiment is conducted in a MTS testing machine. To minimize the friction effect in the forming process,