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Study of size effect in micro-extrusion process of pure copper

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ABSTRACT

The size effect on material deformation behaviors are characterized by grain size, part feature size, forming material size and interfacial condition. These factors have a close relationship with material flow behavior, which in turn affects the geometry accuracy of micro-formed parts. In this study, a general-purpose tooling set for realization of micro-forward, backward, combined forward rod-backward can and double cup extrusions is developed and the micro-extrusions of pure copper with different grain sizes are conducted. The size effect phenomena are analyzed based on the deformation load, interfacial friction behavior and microstructure evolution. It is found that the interfacial friction is high in micro-extrusion processes and the grain size effect on deformation load is sensitive to the friction force at the tooling–workpiece interface. The microstructures of the extruded parts show the occurrence of inhomogenous deformation and a large number of slip bands passing through the grain boundaries to accomplish the strain continuity in the cases with coarse grains. In addition, the flow stress curves obtained from micro-compression are used to model the micro-extrusion processes using finite element (FE) simulation based on the conventional material model. It is found that the conventional material model is not applicable in simulation of the material deformation behavior and evaluation of the interfacial friction in micro-extrusion processes due to the size effect. This research therefore provides an in-depth understanding of size effect in micro-extrusion processes, which is critical to further formulate design rules to facilitate the development of micro-parts.

1. Introduction

The trend of product miniaturization and multi-function integration makes the demand of micro-parts increase significantly in the last decade. Metal forming process presents a promising manufacturing process for mass production of micro-parts due to its characteristics of high productivity, high material usage, net/near-net shape and good mechanical properties of the formed parts [1]. The knowledge and tools for analysis of the metal deformation behavior in macro-scale have been well developed [2,3] and widely used in metal forming industries to design and evaluate metal forming systems [4–6]. However, when the part geometry size is scaled down from macro- to micro-scale, the design and development of micro-parts fabricated by micro-forming cannot be conducted based on the knowledge transfer from macro-forming process to micro-forming due to the occurrence of size effect. Nowadays, the design and development of micro-parts are usually based on the experience and know-how obtained via trial-and-error. Therefore, the understanding of deformation behavior and the properties change of material in micro-forming process is critical in predicting the quality of micro-formed parts and optimizing the process parameters at up-front design stage.

To develop micro-extrusion technology for micro-parts fabrication, Egerer and Engel [7] investigated the micro-backward extrusion at moderate temperature. They found that homogenous deformation can be achieved in warm forming process. Hirota [8] proposed a novel micro-extrusion process that micro-part could be extruded by pressing the sheet material in thickness direction. Atsushi et al. [9] and Lim et al. [10] have further developed this method to fabricate micro-parts with internal structure. Rosochowski et al. [11] and Chang and Wang [12] found the uniform material flow can be achieved in micro-backward extrusion process using ultra-fine grained material. Eichenhüller et al. [13] revealed that the forming temperature, pin diameter and lubrication significantly affect the aspect ratio of the extruded pin in micro-backward extrusion process. Krishnan et al. [14] found that the friction is nonuniform in micro-extrusion process and changes with the size of forming material. Parasiz et al. [15] identified that the size and orientation of individual grain significantly affect the deformation behavior in micro-forward extrusion process.

Based on the above literature review, it can be seen that different micro-extrusion processes have been investigated independently and the focus is on a few factors in those studies. There is a lack of comprehensive research on different size effects in differ-

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