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A review of geometrical and microstructural size effects in micro-scale deformation processing of metallic alloy components

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A B S T R A C T

Plastic deformation at the macroscopic scale has been widely exploited in industrial practice in order to obtain desired shape and control the requested properties of metallic alloy parts and components. The knowledge of deformation mechanics involved in various forming processes has been systematically advanced over at least two centuries, and is now well established and widely used in manufacturing. However, the situation is different when the physical size of the workpiece is scaled down to the micro-scale (μ-scale). In such cases the data, information and insights from the macro-scale (m-scale) deformation mechanics are no longer entirely valid and fully relevant to μ-scale deformation behavior. One important reason for the observed deviation from m-scale rules is the ubiquitous phenomenon of Size Effect (SE). It has been found that the geometrical size of workpiece, the microstructural length scale of deforming materials and their interaction significantly affect the deformation response of μ-scale objects. This observation gives rise to a great deal of research interest in academia and industry, causing significant recent effort directed at exploring the range of related phenomena. The present paper summarizes the current state-of-the-art in understanding the geometrical and microstructural SEs and their interaction in deformation processing of μ-scale components. The geometrical and grain SEs in μ-scale deformation are identified and articulated, the manifestations of the SE are illustrated and the affected phenomena are enumerated, with particular attention devoted to pointing out the differences from those in the corresponding m-scale domain. We elaborate further the description of the physical mechanisms underlying the phenomena of interest, viz., SE-affected deformation behavior and phenomena, and the currently available explanations and modeling approaches are reviewed and discussed. Not only do the SEs and their interaction affect the deformation-related phenomena, but they also induce considerable scatter in properties and process performance measures, which in turn affects the repeatability and reliability of deformation processing. This important issue has become a bottleneck to the more widespread application of μ-scale deformation processing for mass production of μ-scale parts. What emerges is a panoramic view of the SE and related phenomena in μ-scale deformation processing. Furthermore, thereby the outstanding issues are identified to be addressed to benefit and promote practical applications.

Contents

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1. Introduction

With the increasing demand for micro-scale (μ-scale) parts and components in connection with product miniaturization in microelectronics, biomedical engineering, and consumables industries, the spotlight of attention and development effort has once again fallen on manufacturing technology, at the μ-scale in particular. Several generic approaches can be identified to producing miniature, or μ-scale parts and components. One approach is the Micro-Electro-Mechanical Systems (MEMS) manufacturing methods, such as X-ray lithography [1,2], ink-jet printing [3], etc. Another is mechanical-based μ-manufacturing processes that include micro-machining [4,5], micro-injection molding [6–8], powder injection molding [9,10], and micro-forming [11–13].

Micro-forming (μ-forming) is a prominent manufacturing technology for fabricating μ-scale parts with at least two dimensions less than one millimeter. μ-forming can be used to produce bulk (approximately equiaxed) parts, or to produce components that are thin in one dimension using sheet metal (foil) as initial material form. Fig. 1 shows some μ-scale parts made by μ-forming processes. μ-forming has some clear advantages, such as high productivity, low-cost, ability to fabricate complex geometries, extensive range of materials to which the methods can be applied, superior mechanical properties of the finished product, and the net-shape or near net-shape fabrication capability [14]. μ-forming, however, also has some inherent disadvantages, such as challenges in the manipulation of billets and preforms in between different processing operations, and the ejection of the final formed part from the die cavity, as well as the fluctuation of dimensional accuracy, geometry rendering, and property variability due to the inhomogeneous and random nature of grain distribution and orientation, referred to in this paper as process performance scatter.

The principles and theory of μ-forming processing are based on the μ-scale plastic deformation analysis. While the conventional m-scale material properties, flow behavior, formability, fracture behavior and friction in plastic deformation processing are well understood and are routinely practiced by the industrial community to provide solutions for part design, process configuration, parameter specification, tooling development, and product quality control and assurance [15,16], these existing approaches cannot be applied directly to μ-scale deformation processes, since the emergence of the so-called size effect (SE) impedes direct transfer of methodology from m-scale to μ-scale [17–19].

Comprehensive research activities conducted in the past two decades were aimed at elucidating different aspects of the problem, such as the influence of plastic deformation on the apparent SE(s), the elucidation of the underlying physical mechanisms and advanced numerical modeling of μ-scale deformation, process development and optimization, and the assessment of performance and quality of μ-scale parts. Reported investigations of SE-related material behavior are partially listed in Fig. 2 and include studies of SE manifestations in the flow stress [17,20,21], fracture behavior [22–27], flow behavior [28], elastic recovery [29–31], frictional behavior [32], surface roughening [33–35], and the hardness of μ-formed parts [36,37]. The mechanisms underlying these SEs were investigated through simulation using the surface layer model [11,38], mixed material model [39], composite constitutive model [40,41], etc. These modeling approaches were proposed in order to describe quantitatively the consequences of SEs on the μ-scale deformation parameters, such as the force, temperature, strain rate and die geometry required for optimum outcomes. In respect of μ-forming processing quality, the influence of SEs on the dimensional accuracy [29,42,43], the occurrence of deformation defects [44–47], product mechanical properties [48,49], and surface finish [50,51] of μ-formed parts are reviewed.

Although studies of μ-scale deformation behavior of materials have been conducted over several decades, and the modeling approaches incorporating SEs have been developed, many unknowns and uncertainties persist in relation to SEs. Significant challenges remain, e.g. predicting material deformation behavior at correct scale, enhancing the performance of μ-scale deformation processing, improving the mechanical properties of μ-formed parts and the quality of tooling, and optimizing process parameters.

This paper is distinct from previous reviews of μ-forming and the associated size effects (SEs) in that it introduces a systematic approach to the identification of the underlying origin of SE as a