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Establishment of size-dependant constitutive model of micro-sheet metal materials

Xiao-juan LIN[1,2], Guang-chun WANG[1], Wei ZHENG[2], Hua JIANG[1], Jin LI[2]

1. Key Laboratory for Liquid−Solid Structural Evolution and Processing of Material, Ministry of Education, Shandong University, Ji'nan 250061, China;
2. School of Materials Science and Engineering, Shandong Jianzhu University, Ji'nan 250101, China

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Abstract: The inherent mechanism of size effect in micro-sheet material behavior of plastic forming was explained by the surface layer model and theory of metal crystal plasticity. A size-dependant constitutive model based on the surface layer model was established by introducing the scale parameters and modifying the classical Hall−Petch equation. The influence of the geometric dimensions and the grain size on the flow behavior of the material was discussed using the new material constitutive model. The results show that, the flow stress decreases while the sheet metal thickness decreases when the grain size keeps constant, and the micro-sheet metal with a larger grain size is more easily to be influenced by the size effects. The material constitutive model established is validated by the stress−strain curve of the micro-sheet metal with different thicknesses derived from the tensile experiments. The rationality of the material model is verified by the fact that the calculation results are consistent with the experimental results.

Key words: sheet metal; micro-forming; constitutive model; scale parameters; pure copper foil

1 Introduction

With the rapid development of electronic industry and precision devices, miniaturization is the trend of the modern manufacture [1]. Micro-forming technology refers to the technology to produce parts with sizes less than 1 mm at least in two dimensional directions using the material plastic forming [2,3]. This technique inherits the characteristics of the traditional plastic processing technology with high productivity, minimum or zero material loss, excellent mechanical properties of the products and small error, and can be used to form tiny parts of a variety of complex shapes. Therefore, the micro-forming technology has very important application prospects in meeting the needs of micro-system technology (MST) and micro parts used in the fields of aerospace, military, medical, microelectronics, textiles and fuel cell, etc [4].

Material flow behavior shows strong size effect during micro-forming process due to the miniaturization of specimen [5,6]. The existing finite element numerical analyzing software based on traditional plastic forming theory is not directly suitable for the micro-forming process simulation because the material model does not include scale parameters.

In the numerical simulation of micro-sheet metal forming process, KU and HWANG [7] simulated the milli-structure rectangular cup drawing using the SPEC plastic forming data and designed the forming process using a systematic approach. KIM and KU [8] proposed a new numerical approach to simulate the micro-strip rolling, by which the polycrystalline material was composed of regular hexagonal crystal grains and the grain unit was connected by the grain boundary unit accounting for shear deformation between grains. This approach was also introduced to laser micro drawing and bulging process. A mixed stress−strain material model was proposed by LAI et al [9] to describe the fine material forming. Combining the theory of material forming in grain and grain boundary based on the surface layer theory, the mechanical properties of the different

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Corresponding author: Guang-chun WANG; Tel: +86-531-88392315; E-mail: wgc@sdu.edu.cn
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thicknesses of the stainless steel sheet were obtained through experimental data.

The Taylor factors were given different values to estimate the conditions under which the material properties were likely to be influenced by single grain orientations considering the shear stress of the slip systems for FCC crystal structure by JUSTINGER and HIRT [10] in the aspect of grain orientations. Stated thus, researching on the micro-forming is in its beginning stage and many problems have not yet been explained by the traditional plastic forming theory and molecular dynamics. So, a material constitutive model that can reflect the size effects needs to be established to reveal the micro-sheet metal deformation mechanism and material flow behavior.

In this work, micro-sheet metal is taken as the research object; Hall−Petch equation, a traditional polycrystalline material model, based on the surface layer theory and the crystal plasticity theory of metals, is revised by introducing scale parameters to guarantee accurate numerical simulation of micro-sheet plastic forming process.

2 Scale-dependent material model

2.1 Traditional polycrystalline material constitutive model

The dislocation slip inside a grain needs to overcome the resistance of the grain boundary caused by dislocation pile-up besides the lattice resistance and the resistance of impurity atoms in the slip plane to dislocation as the polycrystalline material formed. The smaller the grain is, the more the grain boundaries are, and the greater the resistance is. Hall−Petch equation is the empirical formula derived from the dislocation pile-up theory, reflecting the effect of the grain size on the material stress−strain relationship [11].

$$\sigma_s = \sigma_i + Kd^{-1/2} \tag{1}$$

where σ_i is the frictional resistance that the dislocation slip plane sliding needs to overcome inside a separate individual grain, independent of the grain size; $Kd^{-1/2}$ is the resisting stress near the grain boundary from the dislocation pile, influenced by the grain size. Taking into account the hardening effect of the plastic forming process, the flow stress of the strain is

$$\sigma(\varepsilon) = \sigma_i(\varepsilon) + K(\varepsilon)d^{-1/2} \tag{2}$$

where $\sigma(\varepsilon)$ and $K(\varepsilon)$ are functions of strain ε without considering the strain rate and temperature effect; d is the average grain size of the material.

2.2 Surface layer theory

GEIGER et al [12,13] found that the flow stress of the material reduced with the reduction of the specimen size when the grain size kept constant in the brass unidirectional compression experiment. This phenomenon can be explained by the surface layer model. Material can be divided into the surface layer grains and the internal grains. In the case of small scale, the ratio of the surface layer grains to the whole grains increases and size of the surface layer becomes thick. In the case of small scale, the surface layer is relatively thick and the number of surface grains has a relative increase when the sample dimensions were scaled down according to the ratio of grain size and deformation scale, just as shown in Fig. 1. Compared with the internal grains, surface grains can deform under a lower flow stress because of less restriction according to the physical principle of metal. This leads to reduction of the flow stress of the total deformed body. This tendency is more obvious when the reduction of the specimen size and its specific surface area increases as the grain size keeps constant.

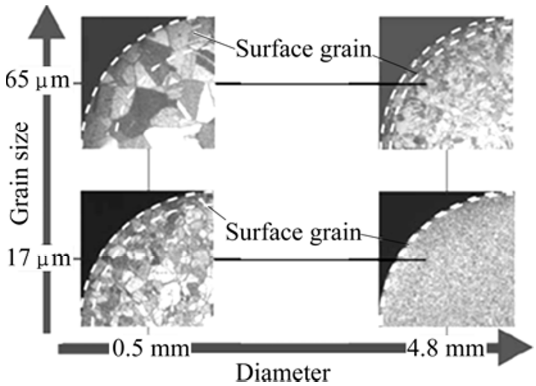

Fig. 1 Surface layer model

2.3 Analysis of size effects in material flow based on surface layer theory

The difference between the material surface layer grain and internal grain can be ignored since the geometry of the part is much larger than the grain size for macroscopic forming.

However, it is necessary to consider the effects of surface layer grains in the entire deformation since the part is miniaturized. This results in the relative increase in the number of grains of the surface layer during the micro-forming process. For a micro-sheet forming process, when the whole thickness of the sheet only has two or three or even less layers of grains, it can be considered that the whole material is on the surface layer [14,15], as shown in Fig. 2.

A micro-sheet specimen and the longitudinal sectional grain distribution are given in Fig. 3, where L, b and t represent the length, width and thickness of the specimen, respectively. For convenience of description, the grain shape is simplified to quadrilateral in