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Influence of size effect on the springback of sheet metal foils in micro-bending

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ABSTRACT

To analyze the unloading springback of sheet metal foils after micro-bending process, a constitutive model is proposed based on the surface layer model by which the sheet foil is divided into surface layer and inner portions. For the inner portion, each grain is envisaged as a composite, comprised of grain interior and grain boundary work-hardened layer. The classical composite model is then used to calculate its flow stress. For the surface layer portion, a model without grain boundary strengthening is constructed to represent the flow stress in this zone. The developed method is verified through the comparison of the calculated strain–stress curves with the tensile test results of four kinds of pure copper sheet foils with different thicknesses ranging from 0.1 mm to 0.6 mm. To investigate the effect of thickness and grain size on the springback of pure copper sheet foils, three-point bending tests are carried out. A finite element (FE) model for predicting the springback in micro-bending process is further developed, which takes into account the deformation behavior and orientation of each grain. The influences of grain size and thickness on the springback of sheet foils are investigated. The research results show that the decrease of sheet foil thickness or the increase of grain size results in a big springback. The scatter of springback angle is mainly attributed to the elastic anisotropy of surface grains and increases with the reduction of grains along the thickness direction. A good agreement between the experimental results and the analytical calculations shows that the developed FE model can predict the springback of sheet metal foils well in micro-bending process.

1. Introduction

Bending is a major sheet forming process commonly used in fabrication of sheet metal parts. Springback refers to the elastic recovery caused by the release of the non uniformly distributed stress in a deformed part after the deformation load is removed. Springback significantly affects the accuracy of deformed parts. Over the past decades, it has been widely investigated for sheet metal bending at macro-scale. Many methods have been developed to predict the unloading springback of sheet metals, such as analytical method [1,2], numerical method with finite element (FE) analysis [3–5], and the semi-analytical method [6]. Some factors affecting springback such as mechanical properties, tooling geometry and shape, and process parameters, have also been extensively studied [7–10].

When the geometry of sheet metal bending part is downscaled to micro-scale, its bending process, however, is quite different from the macro one due to size effect. The micro-bending experiments of copper alloy and pure aluminum have shown that the grain size and thickness of sheet metal foils, especially for the ratio of sheet foil thickness t to grain size d, are the key factors affecting bending force and springback angle [11]. If there is more than one grain locating over the thickness of sheet metal, the bending force and springback behavior are mainly determined by t/d. The three-point bending experiment for brass conducted by Gau et al. [12] has shown that the springback angle decreased with the increase of t/d. But the investigations carried out by Diehl et al. [11] has drawn a different conclusion through defining a scaling factor λ (which is used to scale down the thickness of sheet foil and the geometry size of tool according to similarity rule, $0 \leqslant \lambda \leqslant 1$) to multiply the bending radius and foil thickness for the given grain size specimens. For copper sheet foils, the increasing share of surface grains is dominant for the scaling factor greater than 0.2. At the smaller scaling factor, an increasing influence of strain gradient can be observed. For aluminum sheet foil, the influence of strain gradient is decisive, leading to a constant increase of springback angle with the decreasing scaling factor.

Based on the available literature, most of the researches conducted on the springback of micro-bending process are experiment-based. Very few on numerical simulation and analytical analysis are conducted to investigate the deformation behavior of sheet metal foils with more than one grain locating over the thickness. The numerical simulations conducted by Diehl et al. [11] showed that the difference between the simulation and experimental results increases with the decreasing scaling factor. This is

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because the constitutive model they used cannot represent the deformation behavior well. The constitutive equation has thus been identified as one of the most important factors, which affects the accuracy of springback prediction via analytical computation or FE simulation [13–16]. Although this conclusion is drawn at macro-scale, it is also suitable for the springback prediction at micro-scale. In order to accurately evaluate the springback in micro-bending, a proper material model must be developed firstly. When there is only one grain locating over the thickness of sheet foils in micro-bending process, the strain gradient greatly affects the material strength and deformation behavior, instead of the size effect. To analyze this process, the existing analysis methods such as the FE based crystal plasticity approach [17] and the strain gradient based FE approach [18], provide a basis and fundamental for this research.

In order to predict the springback accurately, appropriate constitutive models considering size effect need to be developed. Over the past years, many efforts have been devoted to this and a number of constitutive models have been established based on surface grain model, composite model, passivation layer model or the affected zone model. Geiger et al. [19] proposed the surface layer model, which is the most commonly used model for representing size effect. Based on this model, a micro-part is divided into two portions, viz., inner and surface layer portions. The share of surface grains increases with the increasing grain size or the miniaturizing part geometrical dimensions [20]. In addition, it is known that the grains locating at the free surfaces show less strain hardening effect compared with the inner grains due to the different mechanisms of dislocation movement, pile-up and the fact that they are less subject to the compatibility restriction. Therefore, how to represent the deformation behaviors of the two portions in the deformation body lies in the development of appropriate constitutive models. Based on the assumption that the surface layer and inner portion of the deformation body can be treated as single crystals and polycrystals, respectively, Kim et al. [21] and Lai et al. [22] developed a mixed material model by combining the surface layer model and the modified Hall–Petch relation. Miyazaki et al. [23] found that the flow stress decreases with the reduction of specimen size and explained this finding by using an affected zone model. Based on the affected zone model and the Hall–Petch relation, Leu [24] proposed a simple flow stress model, which introduces a function with the ratio t/d of sheet thickness t to grain size d defined as a measure of size effect. Molotnikov et al. [25] developed a physically based constitutive model, in which the flow stress of inner portion grains is described by the dislocation-density theory initiated by Estrin et al. [26] and that of the surface layer grains is thus considered as the image force of free dislocation at the grain boundary being attracted to the surface. Furthermore, a few phenomenological models have also been proposed through fitting the strain–stress curves obtained from tensile or upsetting test [27–31]. Based on some classic material models via introduction of correction terms, which considers factors such as specimen size and grain size, the developed material models can take size-dependent factors into account for handling simple microforming processes. The detailed overviews of these developed constitutive models are given by Vollertsen et al. [32]. The main disadvantage of these developed constitutive models is that these models predict a uniform flow stress, which depends only on the homogeneous strain, strain rate, temperature, but does not account for any strain localization. Therefore these models are not applicable in prediction of the mechanical response in complex microforming processes such as micro-bending.

In this research, the pure copper sheet foils with the thickness ranging from 0.1 mm to 0.6 mm (0.1, 0.2, 0.4 and 0.6 mm) are used. Through annealing treatment, the sheet foils with different average grain size are obtained. The tensile tests are conducted to measure the strain–stress curves and the effect of t/d ratio on the strain–stress curves is investigated. Based on the surface layer model, the sheet foil is divided into surface layer portion and inner portion. For the inner portion, each grain is envisaged as a composite, comprised of the grain interior and grain boundary work-hardened layer. The classical composite model is used to calculate the flow stress. For the surface layer portion, a model without grain boundary strengthening is constructed to represent the flow stress in this zone. By using the developed method, a FE model for springback prediction is developed. Three-point bending tests for all the sheet foils are carried out and FE simulations to explore the unloading springback are conducted. The relationships between thickness, grain size and springback angle are investigated. The prediction results are compared with the experimental ones and the efficiency of the developed models is verified.

2. Microstructure of the experimental material

The pure copper is used to investigate the size effect in micro-bending process in this research. Four kinds of pure copper sheet foils with the thickness ranging from 0.1 mm to 0.6 mm are employed. To investigate the influence of grain size effect, the sheet foils with different grain sizes are obtained via the annealing heat treatment of sheet foils at different temperatures with different holding times. To avoid oxidation, the heat treatments are conducted in vacuum condition. The annealing conditions and the obtained grain sizes are listed in Table 1. The microstructures of the copper sheet foils along the sheet plane after the annealing treatment are shown in Fig. 1. All the microstructures are obtained through etching the sheet foil samples using $FeCl_3$ (5 g) + HCl (15 ml) + H_2O (85 ml) solution for 30 s. Under the first annealing condition, the average grain sizes are ranging from 45 μm to 55 μm for the four different foils. For the second annealing condition, the average grain size is about 60 μm when the sheet thickness is 0.2, 0.4 and 0.6 mm. But for the sheet foils with the thickness of 0.1 mm, the average grain size is 92 μm. For the third annealing condition, the average grain size for the sheet foils with the thickness of 0.4 mm is 132 μm.

According to the prior researches, the average number of grains (calculated by t/d) along the thickness direction of sheet foils is a prime factor, which affects the mechanical properties of sheet foils [20]. The optical microstructures of pure copper sheet across its thickness are shown in Fig. 2. The number of grains along the cross-section of thickness decreases with the increase of annealing temperature and holding time. When the thickness of sheet foils is 0.1 mm, there are less than three grains over the cross-section in the thickness direction for the three heat treatment cases. The t/d ratios for all the sheet foils are listed in Table 1 and its values vary from 1 to 12. The grain orientations of copper foils with the grain size of 50 μm are determined by electron backscatter diffraction (EBSD) technology, as shown in Fig. 3. It can be seen that the grain orientation distributed randomly. In the present study, three types of grains with the orientation of [0 0 1], [1 0 1], and [1 1 1] to the loading axis, are considered.

3. Mechanical properties analysis and the constitutive model

3.1. Tensile test

The mechanical properties of the annealed treatment sheet foils are determined by the tensile tests conducted in a MTS material testing machine. For each category of sheet foils, three tests are done to decrease the experimental error. The dimensions of the test specimen are shown in Fig. 4, which is designed based on the ASTM-E8 standard. A standard extensometer with the length of 25 mm is used to measure the strain accurately. The crosshead velocity is 0.033 mm/s for all the testing.