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Effects of surface roughness on micro deep drawing of circular cups with consideration of size effects

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ABSTRACT

Surface roughness, compared with tiny sizes of micro products, can be relatively large and has significant influences on micro forming processes and products' quality. In this study, a voronoi finite element model that considers size effects of material was developed. Next the surface roughness information was assigned to this voronoi model through different elemental thickness distributions. Furthermore, springback simulation was conducted for the micro deep drawn circular cups. Simulation results demonstrate that the surface roughness with consideration of size effects has significant influences on the overall springback, the drawability represented by the minimum thickness and products' quality regarding thickness evenness and shape accuracy. This study also shows that the results from the new models are close to the experimental results concerning the diameter of cup mouth and the maximum drawing force. The developed model for the micro deep drawing is accurate and beneficial for the development of micro deep drawing process.

1. Introduction

Driven by the urgent requirement on the miniaturised products that can bear harsh working environments, such as small or tiny devices, micro metal products have been required. Accordingly various metal micro forming methods have been developed. Moreover, micro forming has drawn increasing attention due to its advantages, such as the potential of mass production, the capacity to fabricate 3D products with a high aspect ratio and the power of (near) net producing [1,2]. However, micro forming is a budding technology compared to well-developed silicon based micro manufacturing technologies for Micro-Electro-Mechanical Systems (MEMS) products [3]. Several obstacles relating to tiny sizes need to be overcome to fulfil the superiority of micro forming processes. Once scaled down to a micro scale, influences of different impact factors in micro forming change from that in normal forming processes, and some ignorable factors in macro forming become obvious and significant [1,4–7]. One typical phenomenon is the change of material properties at the micro scale. The decrease of flow stress with small sample sizes has been observed and corresponding theories, such as the surface layer model and the modified surface layer model [8,9], have been developed as explanations. Additionally, modifications to the traditional material models, such as the Swift model and the Hall–Petch model [10,11], have been conducted to fit the strain–stress relationship in the micro scale. However, those developed or modified models can partly explain size effects and none of them can present deformation with size effects on the micro scale. Another phenomenon is the increase of data scatter of the material properties at the micro scale, which has been explained by the ratio of grain size to sample feature size. A large ratio meant that deformation behaviour was determined by a few grains and therefore, randomness was increased resulting in significant data scatter [12]. Thus, a finite element (FE) model that considers size effects on the micro scale is required.

Compared to the material's intrinsic properties, influences of non-intrinsic properties also change in the micro scale. Surface roughness, a non-intrinsic property, though being very slight, can be relatively large compared to the minute sizes of micro products. Hence, surface roughness can be considered as a part of the geometry and affects the micro forming process and then the products, whereas the research on surface roughness has mainly focused on the friction fields [13–15]. Corresponding models describing the change of friction coefficient, such as the open and

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closed lubricant pockets model and the normal pressure based dynamic friction coefficient model [13,16], have been developed. Consequently, the influence of surface roughness is primarily expressed by the friction coefficient in the normal micro forming FE models. However, effects of roughness on the forming process and products quality cannot be fully exhibited, although size effects on friction have been considered in those models. Moreover, a real surface topography or a simplified rough surface was introduced into FE models, and these models could exhibit detailed surface roughness information [17]. Nonetheless, the meshes based on this complex surface topography were of tetrahedron or triangular meshes. As a result, forming simulation could barely be conducted due to the large quantity and poor quality of meshes in these models. Therefore, a FE model that considers influences of the surface roughness from a geometry viewpoint and counts friction in the micro scale is highly needed.

In this study, micro deep drawing (MDD) of circular cups was chosen as the research objective as the cup-like micro products have been widely applied. A voronoi model that considers material size effects was generated. Furthermore, the surface roughness of the blank was considered and represented by thickness distribution in this voronoi model. Springback was also simulated after micro deep drawing calculation. Consequently, effects of roughness on the micro deep drawing process and the drawn cups were studied.

2. FE simulation models

2.1. Basic models

A normal deep drawing FE model was firstly developed as a fundamental model in LS-DYNA. Fig. 1 displays (a) the fundamental deep drawing model and (b) its geometry sketch. There were a punch, a die, a blank holder and a blank which was the only deformable part in this model. One quarter of the machine was modelled to accelerate computational speed. Accordingly, symmetrical boundaries were applied on the symmetrical lines of the blank. Moreover, all the parts were modelled on shell elements, and the blank was meshed with high quality quadrilateral meshes through carefully allocating mesh seeds on each line of the blank. These high quality quadrilateral meshes are beneficial for forming simulation with great deformation. Additionally, the blank applied a fully integration elemental formula while others were assigned a default elemental formula. Seven integration points through thickness direction were employed to accurately capture thickness direction stress–strain distribution and provide accurate and adequate information for subsequent springback simulation. Regarding the friction, a surface-to-surface forming contact algorithm specialised for metal forming simulation was applied. Further, a constant friction coefficient was utilised and its value was tested by a Universal Tribometer from ©Rtec Instruments. A 3-parameter-Barlat material model was employed for the blank with a thickness of 50 μm [18], while all the other parts were of a rigid material model. The parameters of each blank material model were tested 10 times using repeated tensile tests. According to the plane stress assumption of the material model, a plane anisotropy index (the R-value), defined as the instantaneous strain ratio of width to thickness (Eq. (1)), was utilised to update thickness. Moreover, a yield stress criterion, defined as Eq. (2), was employed for the blank.

$$R=\frac{\frac{dW}{d\varepsilon}/W}{\frac{dT}{d\varepsilon}/T} \tag{1}$$

$$\Phi=a|K_1+K_2|^m+a|K_1-K_2|^m+c|2K_2|^m=2\sigma_Y^m \tag{2}$$

$$K_1=\frac{\sigma_x+h\sigma_y}{2} \tag{3}$$

$$K_2=\sqrt{\left(\frac{\sigma_x-h\sigma_y}{2}\right)^2+p^2\tau_{xy}^2} \tag{4}$$

where σ_Y is the yield stress, σ_x and σ_y are stress along x and y directions respectively, τ_{xy} is the shear stress, a, c, h and p are the material parameters which can be obtained by Eqs. (5)–(8). Moreover, p can be searched by iterations of Eq. (8) at the condition of $\phi=45°$. For isotropic material, $a=c=h=p=1$. Further, $M=8$ for face centred cubic (FCC) material.

$$a=2-2\sqrt{\frac{R_{00}}{1+R_{00}}\frac{R_{90}}{1+R_{90}}} \tag{5}$$

$$c=2-a \tag{6}$$

$$h=\sqrt{\frac{R_{00}}{1+R_{00}}\frac{1+R_{90}}{R_{90}}} \tag{7}$$

$$g(p)=\frac{2m\sigma_Y^m}{\left(\frac{\partial\Phi}{\partial\sigma_x}+\frac{\partial\Phi}{\partial\sigma_y}\right)\sigma_\phi}-1-R_{45}=0 \tag{8}$$

where R_ϕ is the R value at angle of ϕ.

This model employed normal material model for the blank and therefore cannot represent any size effects. Furthermore, the blank had a constant thickness, thus surface roughness and its influences cannot be revealed.

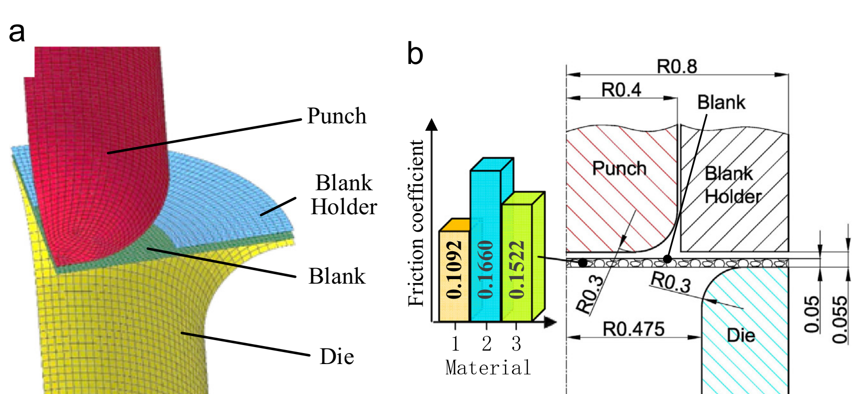

Fig. 1. (a) Basic deep drawing model and (b) its geometry illustration.