Journal of Materials Processing Technology 212 (2012) 672–677

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Optimization of cushion conditions in micro multi-point sheet forming

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ARTICLE INFO

Article history:
Received 31 January 2011
Received in revised form 20 July 2011
Accepted 28 July 2011
Available online 4 August 2011

Keywords:
Micro multi-point forming
Size effect
Finite element simulation

ABSTRACT

Improvement of product quality is required more than ever for mass production of micro formed parts. The process of micro multi-point forming with cushion has been simulated in this paper by finite element model which incorporates a constitutive relation with consideration of size effect. The effect of the cushion material, cushion thickness and coefficient of friction on the surface quality of the deformed sheet has been investigated. It has been found that a proper selection of the cushion material and optimum cushion thickness can significantly improve the surface quality. In addition, this paper also discusses the influence of the cushion material and coefficient of friction on the sheet thickness distribution. Better surface quality and thickness distribution can be obtained with good lubricating condition.

1. Introduction

Because of the trend toward miniaturization, the so-called size effects (Armstrong, 1961) occur in sheet metal working processes. On the technological side, the need of micro-parts primarily drives the development in many fields, e.g. telecommunication, medicine and sensor systems. Researchers and manufacturers have paid more attention to study several key aspects of microforming, such as the applications and material behaviors of the micro-parts, various manufacturing processes at micro scale and the problems have encountered with microscale tooling, assembly and handling. However, when the size of mechanical parts is reduced smaller than 1.0 mm, the empirical knowledge and know-how in the macro forming processes cannot be applied to micro forming fields. Armstrong (1961) stated that size effects are responsible for the increased strength of a polycrystalline aggregate above the single crystal strength at low temperatures. Hansen (1977) has conducted tensile tests of aluminium to investigate the effect of the grain size on material properties. Messner et al. (1994) studied the size effect in the material of CuZn15 using the upsetting experiment and the simulation of ring forming and obtained the influence of length scale on flow stress. Fulop et al. (2006) have explained the effect of the grain size and the specimen size on the mechanical response according to the theory of rate-dependent crystal plasticity. As the results of tests and simulations were reported more widely in micro forming fields, the size effect of the tool dimension was also observed. Wang et al. (2007) have investigated the effect of the ratio of grain size to groove width on the microforming ability during a coining process. Mahabunphachai and Koc (2008) adopted the hydraulic bulge test to analyse the effect of the specimen thickness and the punch dimension on the material flow stress. A new constitutive model has been developed to predict the material behavior.

The sheet metal forming processes have played a significant role in many fields to manufacture the small parts with simple shapes. With a further development of microforming and a requirement of the 3D complex products, a series of the novel techniques appear to meet these demands. Saotome and Okamoto (2001) have developed an incremental micrforming system to fabricate micro-three-dimensional structures of foil metallic materials, but the major shortcoming of this technique is its low productivity. Vollertsen and Niehoff (2009) utilized an initiated plasma shock wave to manufacture the formed parts of deep drawing. They measured and optimized the pressure of the shock wave. However, the shape of formed parts manufactured by this method is simple. In macro forming processes, MPF[1] is a unique reconfigurable manufacturing technique rapidly developed for fabricating the various three-dimensional parts of sheet metal. In MPF, the conventional dies are replaced by a pair of matrices of punches with hemispheric domes. By controlling the height of each punch, the envelope surface of the punch matrices can be reconfigured according to the object shape. In order to improve the product quality, a rubber cushion layer is usually used between the punch matrix and the sheet. Walczyk and Hardt (1998) developed a reconfigurable discrete die system to compensate for spring-back and in-process variations during forming. Haas et al. (2002) described the design and test of a particular type of discrete die reconfigurable tool. The required design parameters were developed using a combination

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doi:10.1016/j.jmatprotec.2011.07.015

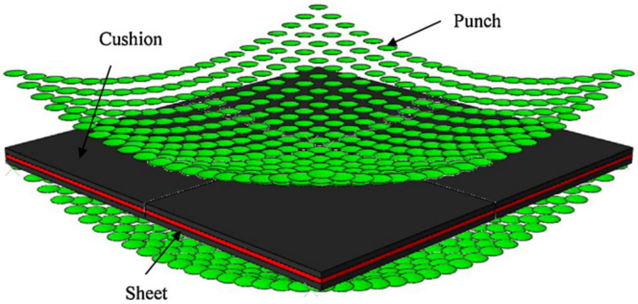

Fig. 1. The simulation model of micro MPF.

of theory and experiment. Outstanding work in this area was Li and his co-workers who have conducted in-depth research in the past two decades. Peng et al. (2006) presented two methods for NURBS surface extension to design the blending surface between the surfaces of the blank holder and the workpiece. Tan et al. (2007) applied multi-point forming equipment with blank-holder device to process titanium alloy retiary sheet into cranial prosthesis. Qian et al. (2007) achieved the numerical simulation in the process of dish head by sectional and multi-step multi-point forming method. Cai et al. (2009) carried out multi-point stretching processes for parabolic cylinder, toroidal saddle and sphere parts. Liu et al. (2010) achieved the process of multi-point forming for tube by dynamic explicit finite element analysis. Compared with the conventional die forming processes, MPF can satisfy the requirement of low-loss, high-efficiency and the complex structures of sheet metal. The purpose of the present study is to introduce a novel process of micro multi-point forming (micro MPF), which uses a pair of matrices of punches with hemispherical domes as the micro dies. It is attractive due to the flexibility of the technique. This work reports a study to optimize the parameters of micro MPF process which considers the size effect.

2. FE simulation of micro MPF

2.1. Simulation model

Both the explicit dynamic finite element code ABAQUS/Explicit and the implicit finite element code ABAQUS/Standard have been used in the simulation of micro MPF. The former is carried out for the stamping process of micro MPF, while the latter is utilized to model the subsequent springback process. The simulation model consists of two pairs of matrices of punches, a flat sheet and two cushion layers, as shown in Fig. 1. Due to symmetry, a quarter of the system is simulated and the symmetric boundary conditions are applied to two sides of the simulated sheet and cushions. The punch diameter D_c is set to 1.0 mm and each punch is simplified to the spherical crown. The distance between two adjacent punches is 1.0 mm. The location of each punch along the vertical direction is adjusted so that an interface layer with radius of 30 mm can be formed. The planar area of the simulated sheet is the same as that of cushions, which is 20 mm × 20 mm. The sheet material is stainless steel 304. There are several factors influencing the surface quality of the products, including the sheet thickness (t_0), sheet grain size (d), cushion material, cushion thickness (t_c) and coefficient of friction (f) between the sheet and the cushion. In order to investigate the effects of these factors, they are altered in this study. The sheet thickness varies between 0.1 mm and 0.3 mm, cushion thickness between 0.05 mm and 0.75 mm and coefficient of friction between 0 and 0.2. Two grain sizes of 51 μm and 135 μm (Kim et al., 2008) and three different cushion materials (polyurethane (Zhang et al., 2008), black rubber (Zhang et al., 2008) and typical synthetic rubber (Zhuang et al., 2005)) have been compared.

C3D8R element has been used to mesh the sheet and the cushion. The elements used for the punches are the bilinear quadrilateral three-dimensional rigid element (R3D4). At the initial state, the flat blank and the cushion were located between two punch matrices. During the simulation of the stamping process of micro MPF, the bottom punch matrix is fixed and the top one moves downward with a constant speed of 1 mm/s. The flat sheet sample is finally formed into a hemispheric shape with a radius of 30 mm. Then the punch matrices and the cushion were removed, the deformed sheet is subjected to the springback process. The finite element model used in the present study has been previously validated with experimental results in Qian et al. (2007).

2.2. Materials model

Mahabunphachai and Koc (2008) have investigated the size effects on the material flow curve of thin sheet metals under hydraulic bulge testing conditions. The ratio of the sheet thickness to the material grain size ($N = t_0/d$) was used as a parameter to characterize the interactive effects between the specimen size and the grain size at the micro-scales, while the ratio of the bulge die diameter to the sheet thickness ($M = D_c/t_0$) was used to represent the effect of the feature size in the bulge test. Based on the experimental results, Mahabunphachai and Koc (2008) have proposed a constitutive model to explain the size effect, which is expressed as follows:

$$\sigma = \left(1658 + 148.2\sqrt{N} - 0.02973\frac{M^2}{e^{\varepsilon}}\right)\varepsilon^{0.5436} \tag{1}$$

where σ is the equivalent stress, ε is the equivalent strain and e is the constant. In this study, Eq. (1) was adopted as the stress–strain relation for sheet.

The rubber cushion behaves in a non-linear hyperelastic manner and can be generally assumed to be virtually incompressible. The Ogden model ($N = 3$) (Abaqus Analysis User's Manual) was adopted to represent the constitutive relation of the cushion. The Ogden strain energy potential U (Abaqus Analysis User's Manual) is defined in terms of the principal stretches λ_1, λ_2 and λ_3:

$$U = \sum_{i=1}^{N}\frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_1} + \bar{\lambda}_2^{\alpha_2} + \bar{\lambda}_3^{\alpha_3} - 3\right) + \sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \tag{2}$$

where $\bar{\lambda}_i$ are the deviatoric principal stretches, and μ_i, α_i and D_i are temperature-dependent material parameters. Due to the material incompressible, D_i is equal to 0. The details of the parameters for three cushion materials are shown in Table 1. Fig. 2 shows the model prediction curve of three kinds of materials.

Table 1
The material parameters of rubber.

Material	Parameter					
	μ_1	α_1	μ_2	α_2	μ_3	α_3
Typical synthetic	6.400	2.000	2.341e-5	4.000	1.600	−2.000
Black	1.257	1.099	4.08e-4	11.983	5.61e-5	−10.055
Polyurethane	−475.63	1.285	203.851	2.312	281.391	0.108

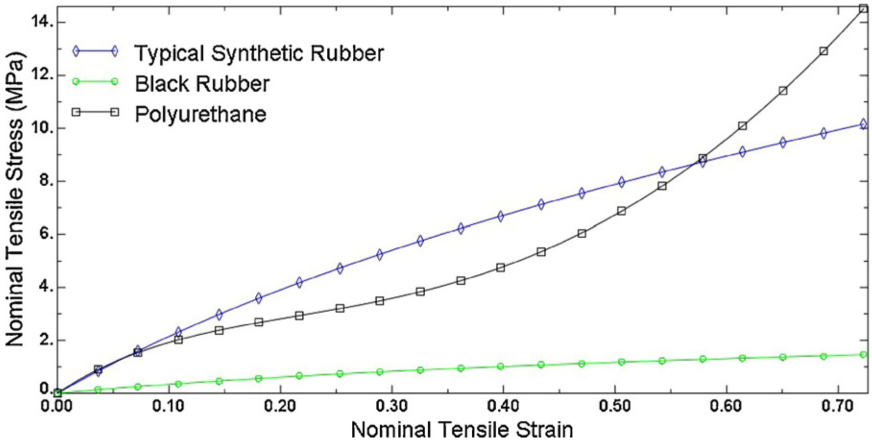

Fig. 2. Uniaxial tensile stress–strain curve for three kinds of rubbers.

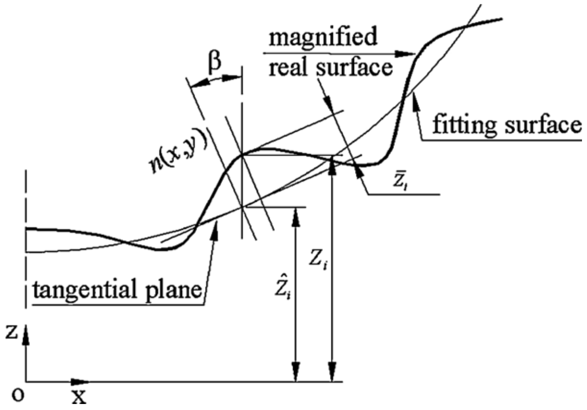

Fig. 3. Sketch to analyse the local surface.

2.3. Characterization of surface quality

In micro MPF, dimple is a typical surface defect, which results from the small contact area between punches and the sheet. A schematic of the real surface calculated from the FEM simulation is shown in Fig. 3. A parabolic surface described by Eq. (3) is used to fit the real surface.

$$f(x, y) = Ax^2 + By^2 + Cxy + Dx + Ey + F \tag{3}$$

where A, B, C, D, E and F are the fitting parameters.

The deviation of the real surface from the fitting surface is used to characterize the surface quality. The root mean square of the surface deviation is defined as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\bar{Z}_i^2} \tag{4}$$

where $\bar{Z}_i$ is the shortest distance between the real surface and the fitting surface at the ith point.

3. Results and discussion

3.1. Surface quality

In macro MPF, dimple and wrinkle have been found to be the major surface quality problems (Qian et al., 2007). Fig. 4 shows a typical sheet deformed by micro MPF. It can be seen that wrinkle does not exist in micro MPF, while dimple is still significant. RMSE will be chose as a criterion to characterize dimple on the surface of the deformed sheet in the following context.

Fig. 5 shows the effect of the initial sheet thickness on RMSEs of both top surface and bottom surface of the deformed sheet. The size effect is obvious in the figure, namely RMSEs decrease with the increase of the initial sheet thickness. The MPF process incorporates two forming processes: coining and bending. The coining process introduces the pile-up around the punch, which is the

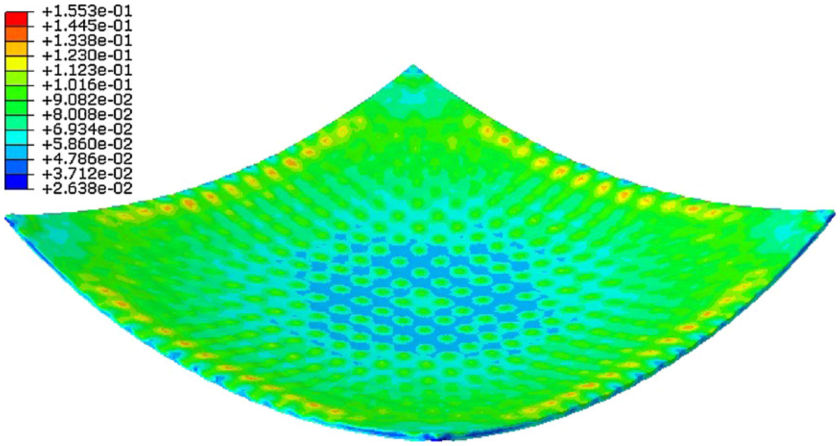

Fig. 4. Equivalent plastic strain distribution in a typical sheet deformed by micro MPF without cushion.

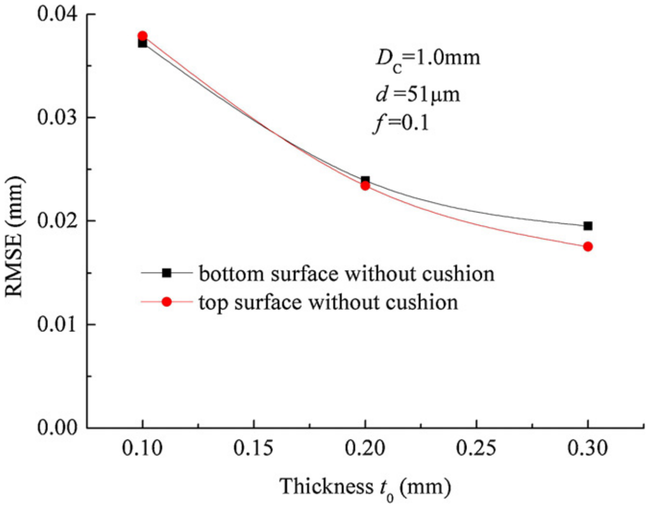

Fig. 5. Effects of the initial sheet thickness on RMSEs of both top and bottom surfaces of the deformed sheet.

major contributor to dimple. Eq. (1) indicates that the materials become harder as the initial sheet thickness increases. The harder material tends to remain in the vicinity of the punch rather than moving away from the punch. The harder material makes the fluctuation of both surfaces low. This results in a higher pile-up and a lower RMSE with a thicker sheet. It can be seen from Fig. 5 that RMSEs of both top surface and bottom surface exhibit similar values except for the highest initial sheet thickness of 0.3 mm. More simulations show that the bottom surface quality is in general superior to that of the top surface. So the top surface quality will be regarded as a primary object in the following analyses.

Fig. 6 compares RMSEs for three different cushion materials and no-cushion case. It can be seen that the use of the polyurethane cushion significantly improve the surface quality. The typical synthetic rubber can also improve the surface quality for the sheet thickness of 0.1 mm. However, the black rubber cushion makes the surface quality worse. It is clear that the cushion material plays an important role on the surface quality. Therefore, it should be careful to select a proper cushion material for a real application. Fig. 2 implies that the typical synthetic rubber cushion and polyurethane cushion are harder than the black rubber cushion. The harder cushion can enlarge the contact area and spread out the concentrated loads, leading to reduction of the surface indentation and improvement of the surface quality. The cushions deform at higher strain (>60%) than the sheet. At higher strain the polyurethane cushion is harder than the typical synthetic rubber cushion. Therefore, the polyurethane cushion exhibits a better surface quality than typical synthetic rubber cushion. As seen in Fig. 2 the black rubber is very soft. It deforms severely between the punch and the sheet. The load is more concentrated at the center of contact between the punch and the sheet since the soft cushion releases the load between the punch and the pile-up. This directly results in a higher RMSE for the black cushion.

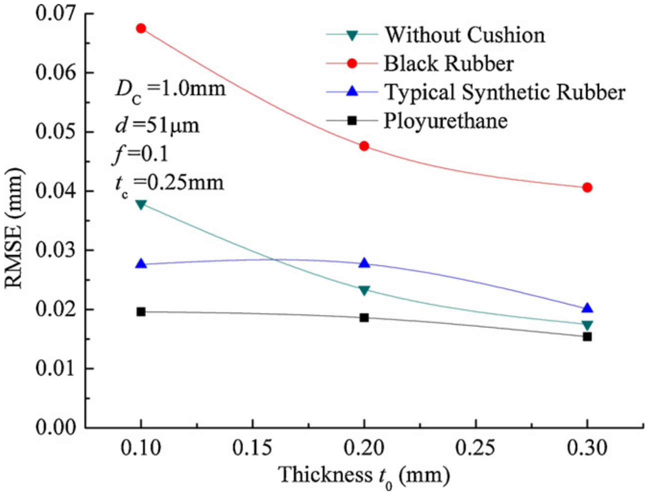

Fig. 6. Effect of the cushion material on RMSE.

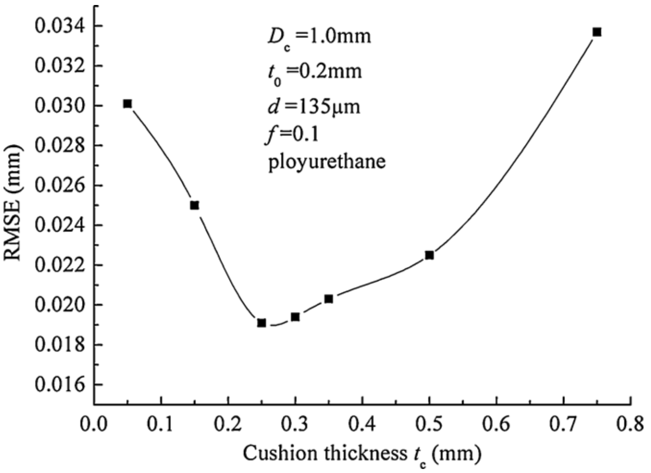

Fig. 7. Effects of the cushion thickness on RMSE.

Fig. 7 shows the dependence of RMSE on the thickness of the polyurethane cushion. The detailed simulation conditions are shown in the figure. The cushion thickness varies from 0.05 mm to 0.75 mm. It can be found that the cushion thickness significantly affects the surface quality. As the cushion thickness increases, RMSE decreases and reaches the minimum value at the thickness of 0.25 mm, and then increases. This indicates that t_c = 0.25 mm is the optimum cushion thickness for the condition listed in Fig. 7 in term of improvement of the surface quality. When the cushion is adopted between punches and the sheet, the punch and the sheet will not contact directly. The cushions under great pressure will product the large non-uniform deformation in the thickness direction. It consists of two types: envelope indentation and surface indentation. When the cushion thickness is lower than 0.25 mm, envelope indentation is dominant with thinner cushion thickness and the

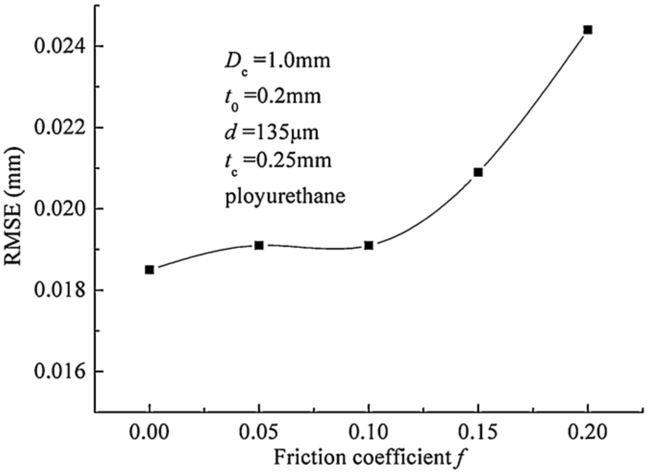

Fig. 8. Effect of the coefficient of friction between the cushion and the sheet on RMSE.

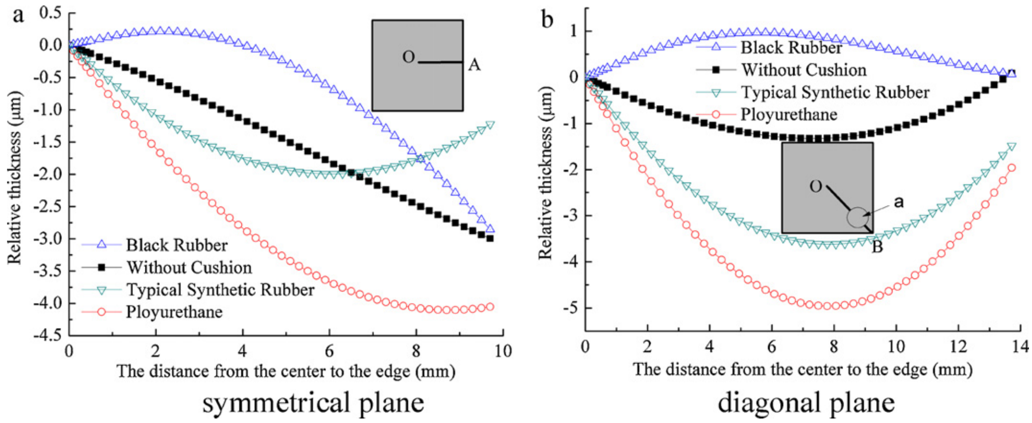

Fig. 9. Distributions of relative thickness for different cushion materials and no-cushion with conditions: $D_c = 1.0$ mm, $d = 51$ μm, $t_0 = 0.2$ mm, $t_c = 0.25$ mm, $f = 0.1$: (a) symmetrical plane and (b) diagonal plane.

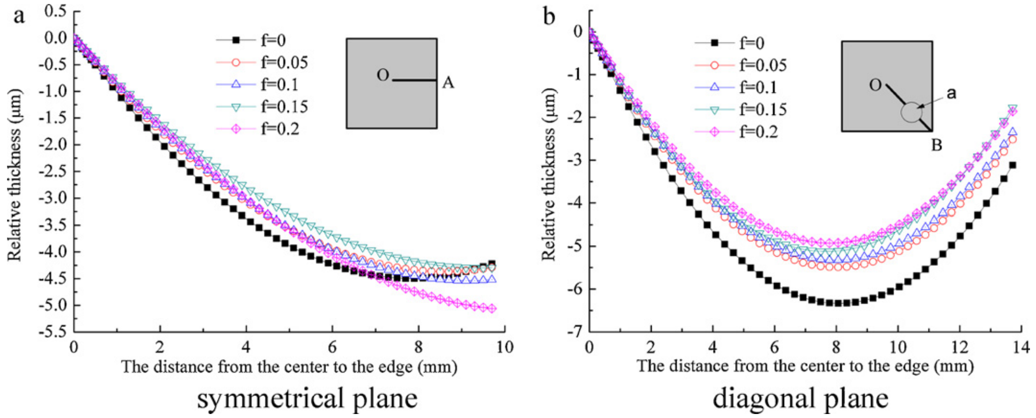

Fig. 10. Distributions of relative thickness for different coefficients of friction with conditions: $D_c = 1.0$ mm, $d = 135$ μm, $t_0 = 0.2$ mm, $t_c = 0.25$ mm and polyurethane cushion: (a) symmetrical plane and (b) diagonal plane.

cushion is not subjected to the external pressure of the punch. This results in a non-uniform deformation on the sheet surface and a higher RMSE. When the cushion thickness is larger than 0.25 mm, surface indentation appears on the cushion and the forming error of the sheet increases.

Fig. 8 shows the relationship between the surface quality and the coefficient of friction when the blank thickness is 0.2 mm, the grain size 135 μm, the punch size 1.0 mm, the cushion thickness 0.25 mm and the cushion material polyurethane. The value of RMSE is small if the coefficient of friction is below 0.1. However, it increases sharply with the coefficient of friction when the coefficient of friction is higher than 0.1. With increasing the coefficient of friction, the relative motion between the sheet and the cushion becomes difficult. This limits the sheet deformation and will produce the concentrated load when the micro forming is carried out. The less relative slip makes the surface of formed part rough and the surface quality becomes worse. The coefficient of friction is usually higher than 0.1 for the dry contact condition, while it will be significantly reduced when the lubrication is applied. This means that the lubrication can improve the surface quality in micro MPF and a better lubricating condition is helpful to reduce the value of RMSE.

3.2. Sheet thickness distribution

Except for the surface quality, it is also expected that the deformed sheet has a uniform thickness. The effects of the cushion material and coefficient of friction on the sheet thickness distribution will be discussed below. In this paper, the relative thickness is used as a parameter to characterize the thickness distribution along with the symmetrical plane and the diagonal plane. It is the thickness difference between the center of sheet and any point of the deformed sheet on the symmetrical plane or the diagonal plane.

Fig. 9a and b describes the relative thickness distributions on the symmetrical plane (OA) and the diagonal plane (OB), respectively. It can be seen that the relative thickness of sheet formed without cushion varies linearly from the center to the edge on the OA plane, while it changes parabolically on the OB plane. All the cushions cause the non-linear thickness variations on both the OA and OB planes. Opposite to the surface quality, the polyurethane cushion induces the largest thickness variation, while the black rubber cushion causes the smallest one, which is better than the non-cushion case. The effect of the typical synthetic rubber cushion sits between those of other two cushions except for the area near point A. Since the gap between two punch matrices is set to be uniform in the simulation, the above results indicate that the softer cushion has more uniform thickness reduction after deformation than the harder one, resulting in smaller thickness variation in the formed sheet.

Fig. 10a and b shows the influence of lubricating condition on the relative thickness distribution on the OA and OB planes, respectively. From the figures, it can be seen that the relative thickness distribution becomes slightly more uniform with increasing coefficient of friction although the effect is small, which is similar to the observation in macro MPF (Zhang et al., 2007). In the case of the symmetrical plane, around the center, the smaller the friction coefficient is, the larger the relative thicknesses are, while it is reversed near the edge. In the case of the diagonal plane, the smaller the friction coefficient is, the more obvious the relative thickness varies.

The results indicate that the smaller coefficient of friction leads to larger thickness variation on both section planes.

4. Conclusion

A finite element model with consideration of size effect has been developed to simulate the micro multi-point sheet forming process. The influence of parameters on surface quality and relative thickness distribution has been investigated. The results show that the good quality surface can be achieved by properly selecting the cushion material. If the cushion material is soft, the surface quality of formed sheet becomes worse. The cushion thickness has a significant effect on the surface quality. When the cushion thickness is less than 0.25 mm, the surface quality is improved with increasing cushion thickness. It has been found that the relative thickness distributions are non-uniform from the center to the edge in the deformed sheets. Furthermore, friction also affects the surface quality and relative thickness distribution in micro MPF. A lower friction coefficient produces a better surface quality and makes the thickness variation of the formed sheet larger.

Acknowledgement

This work was supported by State-Sponsored Scholarship Program for Graduate Students.

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