Investigation of holder pressure and size effects in micro deep drawing of rectangular work pieces driven by piezoelectric actuator

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A B S T R A C T
Micro forming is a manufacturing process to fabricate micro parts with high quality and a cost effective manner. Deep drawing could be a favorable method for production of complicated parts in macro and micro sizes. In this paper piezoelectric actuator is used as a novel approach in the field of micro manufacturing. Also, in current work, investigations are conducted with four rectangular punches and blanks with various thicknesses. Blank holder pressure effects on thickness distributions, punch force, and springback are studied. According to the results of this work, increasing of blank holder pressure in scaled deep drawing, in contrast to thickness of drawn part, leads to decrease in the punch forces and springback. Furthermore, it is shown that in micro deep drawing, the effects of holder pressure on mentioned parameters can be ignored.

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1. Introduction

It is anticipated that micro electro-mechanical system (MEMS) will take on more and more importance as an integration technology in the fields of mechanics and electronics, hence leading to a rise in application of micro parts. Micro metal forming is a technique to produce micro parts with high quality and cost efficiency. Micro deep drawing is one of the forming methods which have great potential for fabrication of mechanical components with varying shapes. Micro deep drawing produces some micro parts which are useful in the field of bio-MEMS applications and biological engineering. These parts could be used in medical devices, bio-sensors, bio-robot, microelectronic chips, and so on. When scaling down the part dimension, the ratio of the mean grain size to the part dimension will be changed. This is named size effect. Aminzahed et al. investigated drawn radius effects on thickness distributions, punch force, and springback [1]. Lou et al. developed a finite element model that considers size effects of the material. They attributed surface roughness properties to the model through different element thickness distributions. Their results indicated that the surface roughness, taking the size effects into consideration, has major impact on springback [2]. Gong et al. investigated effects of lubrication on micro deep drawing of micro conical-cylindrical cups. Their experimental results demonstrated that a microconical-cylindrical cup with internal conical bottom diameter of only 0.4 mm was fine formed [3]. Sato developed a micro-hydromechanical deep-drawing apparatus for fabrication of micro-complex-shape components and increased accuracy of the drawn part. They concluded that the size accuracy and the forming limit could be improved using this device [4]. Irihiea et al. presented a new method in which an initial gap is utilized between an adjustment ring and a blank holder employed in the developed forming system. Results showed the ability of this technique on manufacturing of micro parts with high quality and large aspect ratio [5]. Gau et al. implemented experimental work by using sheets of 200 μm thickness annealed at four different temperatures to discover the impact of size effects on this process. They demonstrated that this process was very powerful as long as the sheets were annealed at the temperature 900 °C or less during 3 min or more [6]. Behrens et al. investigated drawing capability of skinny magnetron sputtered Al–Zr foils in micro deep drawing process. They showed that magnetron sputtering is a favorable process for micro deep drawing [7]. Gong et al. implemented experimental micro deep drawing at a drawing velocity of 0.1 mm/s with three conditions: without lubrication and under the lubrication of castor oil and DLC film. Their work proved that the parts were fine formed with DLC film [8]. Fu et al. examined size effect by preparing the copper sheets with different grain sizes and various punch radii. According to their results, the deformation load diminishes with the increase of grain size [9]. Hu used scaled deep drawing and realized that the friction coefficients increase significantly with decreasing specimen size. He studied the tribological size effect on deep drawing of rectangular work. Furthermore, he implemented size dependent FE-simulation for this operation, in which the friction functions from scaled deep drawing of circular parts in previous work were used. He compared both the simulated and experimental results and proved that the friction functions from deep drawing of circular parts is also valid for rectangular micro cups [10].

In current study, four different rectangular punches and four Al99.5 blank sheets with different thicknesses are studied. To this end, different blank holder pressures (from 1 Mpa to 2 Mpa) are applied to analyze
output parameters of micro deep drawing of rectangular parts such as blank thickness distribution, punch force-stroke curves, and springback. Also, friction functions of circular parts are derived and used to simulate the scaled deep drawing of rectangular work pieces. Finally, Simulation results are compared with experimental punch force-stroke curves of Hu’s work [10] which validates the results of the simulation.

2. Methods of study

Different scales of rectangular deep drawing setups are used in this analysis (four scales). The geometrical specification which is applied to the forming setup and the blank are scaled based on the theory of similarity [11] and was shown in Tables 1 and 2. The geometry of the forming setup and the blank is illustrated in Figs. 1 and 2 respectively. The blank is made of Al99.5 for all of the four scales. Different blank holder pressures from 1 N/mm² to 2 N/mm² is applied for each scale to study the pressure effects on micro deep drawing parameters of rectangular parts such as thickness distributions, punch force, and springback.

3. FEM simulation of forming process

FEM simulation of deep drawing process with different scales is implemented with ABAQUS 6.12. In this model, a discrete rigid shell part is used for the punch, die, and blank holder and a deformable part is defined for the blank sheet. The ‘4-node doubly curved thin or thick shell, reduced integration (S4R)’ is used for blank meshing. In order to make the simulation easier to complete, only a quarter of the parts is simulated. For the purpose of obtaining valid results for FEM-simulation of micro scale, the size effects must be taken into account. Both the size effect on the material properties [12] and the size effect on tribology such as friction functions [13] are the most important consideration for forming process. Without considering these factors, the FEM-simulation results become invalid. Because of the need for having knowledge of the flow stress properties for the FEM-simulation, the tensile tests results are extracted from Hu’s work [10] to obtain the flow curves of Al99.5 in each thickness. To define the mechanical properties of Al99.5 in this model for different thicknesses, Table 3 is utilized.

Friction functions of the deep drawing process with scales of 0.075, 0.1, 0.5 and 1 are demonstrated in Table 4. These friction functions show the tribological size effect within deep drawing operation. The friction coefficient between the blank and the drawing setup in micro-scale.

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**Table 1**

Geometrical specification applied to forming setup (Unit: mm).

<table>
<thead>
<tr>
<th>Scale</th>
<th>Punch size ((L_p \times W_p))</th>
<th>Punch edge radius (R_p)</th>
<th>Punch corner radius (R_{pc})</th>
<th>Material flow radius (R_z)</th>
<th>Drawing clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 × 10</td>
<td>3</td>
<td>2</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>10 × 5</td>
<td>1.5</td>
<td>1</td>
<td>0.65</td>
<td>0.1</td>
</tr>
<tr>
<td>0.1</td>
<td>2 × 1</td>
<td>0.3</td>
<td>0.2</td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td>0.075</td>
<td>1.5 × 0.75</td>
<td>0.23</td>
<td>0.15</td>
<td>0.1</td>
<td>0.015</td>
</tr>
</tbody>
</table>

**Table 2**

Geometrical specifications which are implemented for blank (Unit: mm).

<table>
<thead>
<tr>
<th>Scale</th>
<th>Punch dimension</th>
<th>Blank thickness</th>
<th>Blank length ((a))</th>
<th>Blank width ((b))</th>
<th>Chamfer ((c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 × 10</td>
<td>0.2</td>
<td>28</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>0.5</td>
<td>10 × 5</td>
<td>0.1</td>
<td>14</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>0.1</td>
<td>2 × 1</td>
<td>0.02</td>
<td>2.8</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>0.075</td>
<td>1.5 × 0.75</td>
<td>0.015</td>
<td>2.1</td>
<td>1.35</td>
<td>0.375</td>
</tr>
</tbody>
</table>

**Table 3**

Flow stress properties of Al99.5 blank sheet.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Contact pressure ((\text{Mpa}))</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.25</td>
<td>0.16</td>
<td>0.24</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.18</td>
<td>0.14</td>
<td>0.22</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.15</td>
<td>0.135</td>
<td>0.17</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>0.14</td>
<td>0.132</td>
<td>0.18</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.13</td>
<td>0.13</td>
<td>0.17</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4**

Friction Coefficient between the blank and the drawing setup with different scale factors.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>t = 0.02 mm</td>
<td>t = 0.1 mm</td>
<td>t = 0.2 mm</td>
<td>Plastic strain</td>
</tr>
<tr>
<td>Yield stress ((\text{MPa}))</td>
<td>Plastic strain ((\text{MPa}))</td>
<td>Plastic strain ((\text{MPa}))</td>
<td>Plastic strain ((\text{MPa}))</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>0</td>
<td>39</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>60</td>
<td>0.01</td>
<td>55</td>
<td>0.01</td>
<td>52</td>
</tr>
<tr>
<td>70</td>
<td>0.02</td>
<td>60</td>
<td>0.02</td>
<td>61</td>
</tr>
<tr>
<td>80</td>
<td>0.03</td>
<td>70</td>
<td>0.03</td>
<td>68</td>
</tr>
<tr>
<td>85</td>
<td>0.04</td>
<td>72</td>
<td>0.04</td>
<td>70</td>
</tr>
</tbody>
</table>

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Fig. 1. Geometrical specifications and assembly of micro deep drawing components.

Fig. 2. Blank geometrical specification for micro deep drawing.

Fig. 3. Final formed part of the simulation for scale factor of 0.1.
scale deep drawing is commonly greater than macro-scale deep drawing. The friction functions are validated by Hu et al. work [14], where the simulated punch force vs. stroke curve agrees very well with the experimental curve for deep drawing of circular parts with the same scale factors (see Fig. 6). For implementation of these friction functions in scaled deep drawing of rectangular parts, an assumption should be made: The friction functions from deep drawing of circular parts are also credible for deep drawing of rectangular parts and the other operation parameters such as blank material type and lubricant condition are the same. Fig. 3 shows the final formed part of the simulation for scale factor of 0.1.

Piezoelectric actuators are used in systems in which precise displacement is required. So it makes piezoelectric highly useful in micro systems. Moreover, piezoelectric actuators are more cost effective and easier to handle than any other micro actuators such as linear motors and screw-drive actuators. Deep drawing process is carried out with four different scales and consequently four punch force vs. stroke curves have been obtained. Based on obtained curves and maximum required stroke for the forming processes, appropriate piezoelectric actuators are designed for each scale of deep drawing in previous work [1]. Fig. 4 shows the designed piezoelectric actuator for scale factor of 1. Also, the actuators are manufactured and maximum stroke and blocking force are measured experimentally. The manufactured actuator with scale factor of 0.1 is illustrated in Fig. 5.
4. Results and discussions

4.1. Simulation validation

Four different punch force vs. stroke curves are obtained from simula-
tion conducted in this study. These curves are compared to the exper-
imental obtained curves in Hu’s work [10]. For a valid comparison
between different scales, the proportion of punch force to section area
\((L_s \times W_p)\) and stroke to scale factor are used to illustrate the curves
(Fig. 6). There are totally favorable agreements between simulation
and experimental results. In addition, simulation results could be vali-
dated in ABAQUS by evaluating the proportion of drawing kinetic ener-
gy to drawing internal energy. Deep drawing is a quasi-static operation,
but because of complicated interactions in simulation, the Dynamic-Ex-
plicit step has been used. In order to prove that this operation is valid,
the proportion of forming kinetic energy to internal energy should be
less than 0.1 in the forming operation. Fig. 7 demonstrates that the op-
eration is quasi-static.

4.2. Holder pressure effect on blank thickness

Holder pressure effect on blank thickness distribution for scaled
deep drawing is investigated in this section. The minimum blank thick-
ness distribution versus holder pressure curve for different scales is
shown in Fig. 8. Regarding the obtained curve, thickness of the drawn
part decreases with the increase in holder pressure. Furthermore, it is
obvious that in macro scales, this decline is more than in micro scales,
therefore, holder pressure has a slight effect on the thinning of the
micro drawn part.

4.3. Holder pressure effect on punch forces

The stroke versus punch force curves for different holder pressures
in scaled deep drawing are shown in Fig. 9. According to the obtained
curve, punch force increases with the increase in holder pressure. This
increase in macro deep drawing is more than in micro deep drawing. The reason is that while the scale factor is diminishing, the variations of stroke versus punch force curve decrease. It means that overlapping curves in micro scales are more than in macro scales. As shown in Fig. 9-d, the strokes versus punch force curves for different holder pressures overlap each other. In conclusion, holder pressure does not have a considerable effect on the micro deep drawing process.

4.4. Holder pressure effect on springback

Springback is an angle change made to a part in the final step of sheet forming operation immediately after the part has been relieved of the punch forces. Fig. 10 shows the angle deviation of the formed part, before and after the forming process, with different scales under different holder pressures. The results clearly indicate that by increasing the holder pressure, the angle deviation increases which leads to increase in the springback. The reason behind springback phenomenon is the difference between the outer layer and the inner layer plastic deformation of the sheet in the punch corner. In other words, it could be noted that the deformation at the outer layer is of tensile type and at the inner one it would be a compression deformation, which leads to occurrence of springback. As it is obvious in Fig. 10, when the scale goes from macro to micro, the effect of holder pressure on springback decreases.

5. Conclusion

In this study, various scales of deep drawing operation driven by piezoelectric actuator for rectangular cups were investigated. Piezoelectric actuator employed in this work is a new approach in deep drawing operation. In addition, blank holder pressure effects on thickness distributions, punch force, and springback were examined. Results indicate that thickness of the drawn part decreases with the increase in holder pressure and in macro scales this decrease is more than in micro scales. Moreover, punch force rises with the increase in holder pressure and this increase in macro deep drawing is more than in micro deep drawing. Finally, springback goes up with the increase in holder pressure. Also the holder pressure effect on springback decreases, when the scale of forming goes from macro to micro. Generally, the holder pressure does not carry much weight in micro scale deep drawing process.

References