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Procedia Manufacturing
Volume 15
Page range 1170-1176
Year 2018-08-11

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URL http://hdl.handle.net/10297/00026426
17th International Conference on Metal Forming, Metal Forming 2018, 16-19 September 2018, Toyohashi, Japan

Incremental sheet metal formed square-cup obtained through multi-stepped process

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Abstract

In this paper, we present a new strategy for the single point incremental forming (SPIF). This process involves the use of non-horizontal path planes of a tool tip and is oriented to produce steep wall portions. In the most SPIF operations, a set of closed contour tool paths existing on horizontal planes or a spiral tool path interpolated from the contours was used. When the process is single-step operation, the final thickness after forming can be predicted using the sine law. The law suggests that the final thickness of a vertical wall becomes zero. Therefore, steep or vertical walls are impossible to produce through the single-step SPIF. The vertical wall was produced only by the multi-step approach. The aim of this study is to control the material translation by modifying the direction of the path planes of a tool tip and develop the process to produce the steep wall portions. This multi-step approach was applied to the process for a square cup and the thickness distribution was examined in detail.

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Peer-review under responsibility of the scientific committee of the 17th International Conference on Metal Forming.

Keywords: Incremental forming; Sheet metal forming;

1. Introduction

Recent demands for small-lot production of various shapes introduce a requirement for new flexible forming processes not requiring the use of any expensive dies. The incremental sheet metal forming technique, which uses a
CNC forming stylus, has been developed [3-8]. In the typical process, the outer side of a blank is held in a blank holder and a forming stylus indents the blank by a given pitch and travels along a closed contour or a spiral tool path. After traversing on all path lines, the sheet metal fits on the tool envelope surface.

The aim of this paper is to study the feasibility of the sine law in the non-horizontal approach and the effect of the direction control on the thickness change in the new process. This approach was applied to the process for a square cup and the thickness distribution was examined in detail.

### Nomenclature

- $p_z$: vertical tool feed
- $r_p$: tip radius of forming tool
- $n$: surface normal of objective shape
- $t$: surface normal of tool-path plane

### 2. Multi-stepped process for single-point incremental sheet metal forming

#### 2.1. Sine's law

In the most of the incremental sheet forming processes, horizontal paths are used as shown in Fig. 1(a). Assuming idealized deformation mechanism as shown in Fig. 1(a), the wall thickness and the thickness strain after forming are given by,

$$ t = t_0 \sin \theta , $$

$$ \varepsilon_t = \ln(\sin \theta) . $$

The formulas suggest that the final thickness of a vertical wall becomes zero and the strain is infinite. Therefore, steep or vertical wall is impossible to produce through the single-step SPIF. Several researchers reported on the multi-step approach for steeper wall portions [1, 2, 5].

Recent 3-dimensional motion control technology allows non-horizontal path approach in SPIF, and the control of the direction allows the process to modify the material translation. The sine law could be also used to predict the thickness change as shown in Fig. 1(b). The thickness strain would be given by,
\[ \varepsilon_t = \ln(n \cdot t), \quad (3) \]

where \( t \) is the normal vector of the path plane, and \( n \) is the surface normal of the product. Assuming the intermediate parts consist of flat surfaces, the strain in multi-step approach is given by,

\[ \varepsilon_t = \sum_i \ln(n_i \cdot t), \quad (4) \]

2.2. Process for square cup with vertical walls

A square cup has four vertical walls. In order to produce the shape successfully, multi-step strategy should be employed. Fig. 2 shows the multi-step process for a square cup. The process consists of forming operations for a square pyramid (1st step), two triangular pyramids (2nd step), two square pyramids (3rd step), and four triangular pyramids (4th step). Every step except 1st one has several sub-steps, and the process includes nine sub-steps. All intermediate shapes consist of flat planes, and the Eq. (3) and Eq. (4) would be valid.

\[ \text{Fig. 2. Multi-step approach for square cup.} \]

3. Multi-step forming of square cup

3.1. Experimental Method

The experiments were conducted on a four-axis incremental forming machine, which consists of X-Y table, Z table and \( \phi \) table attached on the Z table. The radius of the hemispherical tip of a carbide forming tool was 2 mm. The outer side of a blank is held on the table through the blank holder. The material used was pure aluminum (JIS: A1050-H18) sheet, and the thickness was 1.0 mm and grid marks were printed on it to observe the local deformation. The sheets were lubricated with molybdenum disulfide (MoS\(_2\)). The thickness after forming operations was measured by optical 3D coordinate measuring machine (ATOS core, GOM mbH) and checked using a point micrometer.
Table 1. Experimental conditions.

<table>
<thead>
<tr>
<th>Blank</th>
<th>Pure aluminum (JIS:A1050-H18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness:</td>
<td>$t_0 = 1.0$ mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tip radius of forming tool: $r_p$</th>
<th>1.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical tool feed: $p_z$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Mineral oil (includes 10% MoS$_2$)</td>
</tr>
</tbody>
</table>

3.2. Experimental Result

Fig. 3(a) shows the photos after the every step. The square cup was successfully formed without failure. As can be seen in Fig. 3(b), in which the view after 4th step are shown, the circle marks in the corner triangle sections of the top were enlarged significantly. Every section was subjected to different forming operations and the circles distort in a complicated way.

Fig. 3(b) shows the grid mark printed on the specimen. The grid lines are boundaries of the sections, which are undergo uniform deformation. The strains measured at the centre of the triangle or quadrangular sections are shown in Fig. 3(a). Although the experimental results are slightly smaller than the theoretical values as reported by Young [8], the thickness changes were approximated using the sine law.

Fig. 4 shows thickness after the every step. The thickness of intermediate and final product is not uniform. The section V is extremely thin. Fig. 5 shows thickness variation along AA' after the every step. The broken lines are thickness calculated by using sine law. The thickness after 1st step is almost constant, however, after the 2nd step there exists thick ridge which has two peaks. The local thicker portion remains until 3rd and 4th steps.

Fig. 3. Square cup obtained through multi-step approach ($r_p = 2.0$ mm, $p_z = 0.1$ mm/rev., cup width $W = 54$ mm, cup height $H = 25$ mm).
4. Discussion

Though the BB’ is constant thickness crest after 1st step, in the 2nd step the crest is opened by neighboring forming operation. The opening operation results in the thick ridge line.

In order to specify thickness distribution, the mapping from a blank to a final product should be determined. The mapping is determined by use of least-squares approach. For example, when constant thickness product in Fig.4 is...
required, the thickness is one third of original thickness. The mapping is optimized by use of least-squares approach. Fig. 6 shows one of the solutions for the problem.

However the mapping is determined, the exact multi-stepped forming process that realizes the mapping (material translation) is not easy to designed. The above process in Fig. 2 is a simplest solution consisting minimum number of steps under the constraints, in which the intermediate shapes are all convex. Because it is minimum process, the thickness distribution isn't able to be modified. If the local weak concavity is tolerated, the approximate solution in could be proposed as shown in Fig. 7. The process includes redundant control points and sub-steps to control the material translation.

5. Conclusions

The direction control of the path planes in incremental sheet forming was introduced. It was applied to obtained the square-cup and the thickness was examined in detail. For the experiments the following conclusions are obtained:

- A square cup can be formed successfully through the multi-step approach with non-horizontal path planes;
- In the minimum process for a square cup, extremely thin area exists, and the thicker ridge line remains after the steps in which the crease gets opened;
- The mapping from a blank to a constant thickness product is determined by use of the least-squares approach. The multi-stepped process could be designed approximately when the local weak concavity tolerated;
References


