Research on the effect of the local constraints on sheet hydroforming with the movable die

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Abstract. An improved Sheet Hydro-forming process was put forward, which was researched in the Institute of Metal Research (Chinese Academy of Sciences) and Aalborg University jointly. In this paper, the effects of local constraints on the sheet deformation were researched experimentally. For this case, the local constraints include rigid tools (movable die) and surface roughness of the movable die, especially around the shoulder of the movable die. Finally, ASAME system and FEM are used to analyze the forming process to explain some results that were found in the experiment. In the simulation, the effects of the friction between the movable die and the blank and the movable die on the deformation of the blank are investigated in detail by using the FEM code LS-DYNA. For the sheet hydroforming with local constraints, the contact between the sheet and the dies affects the material flow and the fracture of the sheet can be avoided. Moreover, the forming limit of sheet metal can be remarkably improved. This process meets the need of the deformation of complicated parts as well as forming of low-formability and light-weight materials, such as aluminum lithium alloys and magnesium alloys. The die can be replaced with other die of various shapes, and can also be made of very cheap materials. Thus complex-shaped sheet parts can be formed with less expensive tool systems.

Keywords: Sheet hydroforming; Movable die; ASAME; Local constraint

INTRODUCTION

Sheet hydroforming (SHF) has gained increasing interest around the world in the automotive and aerospace industries recently. Sheet hydroforming has many advantages that meet the needs in reality very well, such as improvement of the sheet formability, good surface quality, higher dimensional accuracy, reduction of spring-back amount compared with the conventional sheet metal forming processes. Furthermore, the process chain could be simplified and energy will be saved [1].

In sheet hydroforming with local constraints, one of the active sheet hydroforming processes, combined dies are used, which consists of a fixed part and a movable part. This may realize the complicated deformation of the combination of deep drawing and stretching [2]. During forming, the movable die (MD) is firstly moved to one position, while increasing the internal pressure, the movable die is forced to move backward under controlled force in order to ascertain continuous contact with the sheet. The contact between the sheet and the dies affects the material flow and the cracking of the sheet can be avoided. Moreover, the forming limit of sheet metal is increased. This process meets the need of the deformation of complicated parts as well as forming of low-plasticity and light-weight materials, such as aluminum lithium alloys and magnesium alloys [3,4].

EXPERIMENT DESCRIPTIONS

Figure 1 shows a scheme of the experimental tool setup used for performing SHF tests and producing...
hemi-toroidal components similar to the one in Figure 2. Tests were undertaken adopting a fixed gap (spacers highlighted in Fig.1) between the blank holder and the container. Main process parameters are the pressure \((p)\), the spacer height \((s)\), the counter force of the movable die \((f)\) and the distance between the movable die and the fixed die \((d)\).

FIGURE 1. Sheet hydroforming using a movable die.

Wrinkling and rupture are the two main failure modes in the SHF with the movable die. The experiments showed that too high pressure or too fast growing of the pressure could lead to premature rupture; too small distance \(d\) and unreasonable surface roughness for the movable die also could lead to rupture. But large distance \(d\) could lead to body wrinkling. So the proper process parameters (pressure, counter force and MD initial position) and equipment characteristics (surface roughness of the MD) are very important in carrying out the process successfully.

ANALYSES OF THE EXPERIMENTAL RESULTS

SHF tests were aimed to investigate the effect of both the main process parameters and the friction conditions. In particular, during the experimental activity, the surface roughness of the MD was changed several times. The regions whose roughness were changed are indicated in Figure 3 while the corresponding values are shown in Table 1.

### Table 1. Analyzed surface roughness conditions.

<table>
<thead>
<tr>
<th>Test label</th>
<th>Surface roughness, (R_a(\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
</tr>
<tr>
<td>Time 1</td>
<td>6.11</td>
</tr>
<tr>
<td>Time 2</td>
<td>1.10</td>
</tr>
<tr>
<td>Time 3</td>
<td>1.10</td>
</tr>
<tr>
<td>Time 4</td>
<td>1.10</td>
</tr>
</tbody>
</table>

FIGURE 3. Movable die regions.

The effects of different surface roughness conditions on the thickness distribution are shown in Figure 4.
FIGURE 4. Thickness distribution in the radial direction.

It can be seen that the thickness distribution for Time 1 is more uniform than that of Time 2, Time 3 and Time 4. Analyzing synthetically, the surface roughness in Time 1 is very helpful for the deformation of the sheet. Using this surface roughness the formability of the sheet can be improved. The thickness strain distribution is more uniform.

The grid analysis for the thickness strain with the surface roughness in Time 2, Time 3 and Time 4 are shown in Figure 5. Comparisons of the thinning ratio in area A (around the shoulder of MD) measured by using different methods for Time 2, Time 3 and Time 4 are shown in Table 2.

TABLE 2. Thinning ratios in area A for the different surface roughness (d=9.2mm).

<table>
<thead>
<tr>
<th>Times</th>
<th>Measuring Methods</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Time 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured by Zeiss coordinate measuring machine</td>
<td>28%</td>
<td>20%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Measured by ASAME</td>
<td>24%</td>
<td>21%</td>
<td>20%</td>
</tr>
</tbody>
</table>

FIGURE 5. Comparison of the thickness strain distribution for the different surface roughness of movable die (d=9.2mm, measured by ASAME).

From the comparisons as shown in Figure 5 and Table 2, it can be seen that the thickness strain distribution in Time 4 is more uniform than others. Moreover, the thinning ratio in area A for the surface roughness in Time 4 is very small.
FINITE ELEMENT ANALYSES

Model description

To investigate the deformation secrets that cannot be observed directly in experiments, FEM was used. The commercial explicit finite element code LS-DYNA [5], 2D and 3D, was used. Due to the symmetric character of the forming, only a quarter of the model was used. For 3D simulation, all tools were modeled using rigid elements with a four-node shell and the material meets the elasto-plastic properties. The blank was meshed using four node quadrilateral, Belytschko-Lin-Tsay element [6]. By using shell element, the sheet blank consists of 4470 nodes and 4321 elements. In order to accord with the process of the sheet hydroforming, the rim of blank was modeled as a solid element with a width of 1.0 mm. Here, the model has two layers through the thickness of the rim of blank. The rim of the blank is meshed with 531 nodes and 232 elements. Penalty contact interfaces were used to enforce the intermittent contact and the sliding boundary condition between the sheet metal and the tooling elements. The material parameters used for the blank were from the uni-axial test. The die and blank holder were constrained fully and the movable die (punch in Ingrid files) could move only along the Z-direction, corresponding to the central axis of the punch. The gap between the die and the blank holder was fixed.

For computing the effect of bending and unbending, 2D simulation is used. The effect of constraints around the shoulder of the movable die on the stress-strain distribution along the sheet was investigated. The local constraints affect the types of the fracture. The movable die (punch in the Ingrid file) was modeled using rigid elements with a four-node shells and the material meets the elastic property. The die and the blank holder were modeled using elastic elements with four-node shells and the material meets the elastic property. The model of the blank has 6 layers through the thickness of the blank in 2D simulation.

Effect of friction coefficient on SHF

In the simulation, the friction coefficients between the die and the blank and between the blank holder and the blank are 0.005. But the friction coefficient between the blank and the movable die, $f_{B-MD}$, may be different. The distributions of the shell thickness with the radial pressure under different friction coefficient are shown in Figure 6 and Figure 7.

FIGURE 6. Distributions for the shell thickness with the radial pressure under different friction coefficients.
FIGURE 7. Effect of the friction coefficient on the shell thickness distribution.

From Figure 6 and Figure 7, it can be seen that the friction coefficient $f_{B-MD}=0.1$ is the critical condition for wrinkling. If $f_{B-MD}>0.1$, wrinkling will occur. But when reducing the friction coefficient to 0.05 or 0.009 all over the MD, the blank thickness reduction is not contrasted anymore (in particular see area B) and high thinning values can be noted (red and black curve).

When increasing the friction coefficient to 0.2 all over the MD as shown in Figure 7, the minimum thickness reduction moves outside which is very helpful for the uniform thickness distribution. From Figure 7, it can be also seen that there are two areas along the 1/4 part where it is more obvious for the effect of friction coefficient on the thickness distribution, area B (from point 1 to point 6) and area C (from point 7 to point 11). Area B is the area for MD contacting with the blank and around the shoulder of the movable die. Area C is the hanging part. In area B, the larger the friction coefficient, the smaller the thinning ratio, which is very helpful for the sheet deformation. But for area C, the blank is in the instable state for the larger friction coefficient such as $f_{B-MD}=0.15$ and $f_{B-MD}=0.2$. Analyzing synthetically from area B and area C, it is better for the distribution of shell thickness when $f_{B-MD}=0.1$.

Effect of MD on SHF

In 2D simulation, the distributions for the plastic strain around the shoulder of MD are shown in Figure 8. From Figure 8 (a), the deformation without the MD, it can be seen that the plastic strain reaches the maximum at the early deformation ($t=0.0033s$). Moreover, the plastic strain in inner and outer along the shell thickness gets to the maximum at the same time and its distribution is concentrated, which is why it is very difficult to deform the blank without the movable die and fracture occurs frequently. But for the deformation with the MD as shown in Figure 8 (b), the plastic strain is very small at the early deformation ($t=0.0033s$). Even if it is very large at the end of deformation, but the distribution area for the plastic strain is also very large. Moreover, the distribution for the plastic strain is more uniform. In addition, at this deformation stage, the blank almost contacts the die completely and the crisis for fracture is passed by. So, to find the way for blank covering the shoulder of MD, it is very helpful for analyzing the types of fracture.
CONCLUSIONS

The SHF using the MD mainly lies in the advantageous friction between the blank and the die component. Tests on hemitoroidal parts, performed at IMR and Aalborg University using a in-home designed equipment, have highlighted that using the MD the SHF process can be effectively improved. Friction conditions play a fundamental role, since a proper surface roughness for movable die is very helpful for the uniform thickness distribution.

Numerical simulations, 2D and 3D, are performed by using the software LS-DYNA. When reducing the friction coefficient to 0.05 or 0.009 all over the MD, high thinning values can be noted. But when increasing the friction coefficient to 0.2 all over the MD, the minimum thickness reduction moves outside which is very helpful for the uniform thickness distribution. But if $f_{B-MD}>0.1$, wrinkling will occur. Analyzing synthetically, it is better for the distribution of shell thickness when $f_{B-MD}=0.1$.

The movable die delays the maximum thickness strain to the contacting die stage. So the formability of blank can be improved by adopting the movable die.

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