An Investigation of Wrinkling and Thinning in Hydroforming Deep Drawing Process with Hemispherical Punch

Hamed Ziaei Poor *, Hasan Moosavi
Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran
*h.ziaeipoor@me.iut.ac.ir; h.moosavi@cc.iut.ac.ir

Abstract- In this paper, the effect of hydrostatic pressure on wrinkling phenomenon in the HDD process of hemispherical cups with material AL6111-T4 has been numerically investigated. The simulation results are in excellent agreement with the experimental results obtained from the work of Abedrabbo et al., [1]. ABAQUS/Explicit was used for simulations of processes, and failure criteria used in the analysis were based on forming limit diagrams (FLDs). Furthermore, Hill’s anisotropic material model implemented in ABAQUS/Explicit was used. The results showed that hydrostatic pressure causes the sheet to stretch in the flange area, and this external support provides a compressive stress that delays the onset of tensile instabilities and reduces the formation of wrinkles due to tensile frictional forces. In the second section of this paper, the effect of maximum counter pressure profile on the thinning distribution in HDD process has been studied numerically. Results of this work showed that minimum thinning can be obtained by using a maximum counter pressure profile of 17 Mpa. When the pressure exceeds this limit, rupturing will occur.

Keywords- Wrinkling; Hydroforming Deep Drawing; Hemispherical Cup; FE Simulation

1. INTRODUCTION

As a new technology, sheet hydroforming has been developing since before World War II. The early sheet hydroforming technology was a forming technology mainly using a rubber diaphragm and a rubber bag and was applied in the small batch production of automotive panels and aircraft skins in the 1980s. A great development and many applications were obtained in hydromechanical deep drawing technology in the 1960-1970s, and batch production was realized in the automotive industry [2]. In 1980-1990s, sheet hydroforming technology achieved extensive development. The integral hydro-bulge forming technology (IHBF) of shell products, the hydroforming of sheet metal pairs, and viscous pressure forming (VPF) appeared successively [3, 4].

Some advantages of sheet hydroforming are improvement of material formability, reduction of friction force, accuracy of the forming part, and reduction of forming stages because of improvement in limiting drawing ratio (LDR) and control in wrinkling [5, 6]. Wrinkling is one of the major defects that occur in sheet metals formed by the CDD process. Wrinkling may be a serious obstacle to a successful forming process and to the assembly of parts. It may also play a significant role in the wear of the tool. In order to improve productivity and the quality of products, wrinkling must be suppressed.

Wrinkling is a complex buckling phenomenon that is affected by many factors, including geometry, material properties, and boundary conditions, and it prevents the sheet from forming. If buckling takes place in the flange area it is well-known as wrinkling; if it takes place on the cup wall, it is called puckering. Furthermore, circumferential compressive stress in the flange area is the major reason for initiation and wrinkle growth in this region. The schematic diagram in Fig. 1 shows the mechanism of wrinkling initiation and growth in the cylindrical cup deep drawing process [7].

Numerous research has been performed to explain the critical condition of rupturing and wrinkling in the hydroforming process. Tseng et al. discussed several significant process parameters for the formability of Ti/Al clad metal sheets during sheet hydroforming [8]. Yossifon and Tirosh predicted rupture using the criterion of plane strain failure and wrinkling instability by energy method. They also obtained tearing and wrinkling diagrams for a process with radial pressure [9, 10]. Lee et al. extended the results of Yossifon and Tirosh for hemispherical cups [11]. Wu et al. obtained a rupture and wrinkling diagram for stepped punches through finite element simulation and experiments [12, 13]. Thiruvarudchelvan et al. performed theoretical analysis and an experimental approach of hydraulic pressure assisted deep drawing process [14]. Hama et al. developed an elasto-plastic finite element method for the sheet hydroforming of elliptical cups [15]. Zhang et al. investigated the effects of anisotropy and prebulging on dimension accuracy and thickness distribution in the hydromechanical deep drawing of hemispherical mild-steel cups by finite element simulation and experiments [16].

Abedrabbo et al. also investigated numerically and experimentally the wrinkling behavior of aluminum alloy
during the sheet HDD process. They implemented Barlat’s anisotropic material in LS-Dyna code [1]. Azodi et al. performed an analysis of tensile instability in the hydromechanical deep drawing process of cylindrical cups. In their paper, they compare theoretical results with results obtained from experiments to verify the validity of their proposed analytical approaches [17]. Singh et al. predicted the thickness along a cup wall in hydromechanical deep drawing, using an artificial neural network (ANN). When they compared the results of HDD and CDD, they found that higher draw ability and a more uniform thickness distribution can be obtained using the HDD process [18].

A schematic of the sheet hydroforming process used for forming deep-drawn hemispherical cups is presented in Fig. 2. At the start of the process the blank is placed on top of the die (see Fig. 2-a). The blank holder is then lowered and a gap of specified distance (e.g. 4mm) is maintained between it and the die (see Fig. 2-b). The fluid is then injected into the die and pressurized (see Fig. 2-c). As the fluid pressure is increased, the blank is raised and clamped against the blank holder (see Fig. 2-d). In this process, creating a seal is a vital section because the fluid shouldn’t leak a lot into the upper part of the die.

The initiation and growth of wrinkles are influenced by many factors such as stress ratios, the mechanical properties of the sheet material, the geometry of the work piece, and contact condition. It is difficult to analyze wrinkling initiation and growth while considering all the factors, because the effects of the factors are very complex and a study of wrinkling behavior may show a wide scattering of data even for small deviations in factors. Therefore, this paper is focused on the fluid pressure profile, and the other factors are ignored.

In the first section of this paper, the procedure of wrinkle initiation and growth in the flange area was discussed. The results of CDD and HDD process were compared, and the height of wrinkles in the flange area and major and minor strain distribution for HDD and CDD processes were determined. In the next section, a numerical investigation of the effect of hydrostatic pressure on thinning in the HDD process was done. The counter pressure profile was applied according to experimental work that was accomplished by Zhang and et al. [19]. Finally, the optimum value of maximum counter pressure profile for minimum thinning was obtained.

II. CONDITIONS

To form a wrinkle-free deep-drawn hemispherical cup with sheet hydroforming, a numerical analysis on the work of Abedrabbo et al. [1] has been done. Fig. 3 depicts the optimum counter pressure profile proposed by Abedrabbo et al. [1].

Hill’s anisotropic material model was implemented in ABAQUS/Explicit. The anisotropic characteristics (r-values) of Al6111-T4 were obtained according to ASTM E517 standard. The other process parameters used in simulation are shown in Table 1. The material behavior was determined from Hollomon’s hardening equation. Failure
criteria used in all simulations were based on the forming limit diagrams (FLDs).

### TABLE 1 MECHANICAL MATERIAL PROPERTIES AND PROCESS PARAMETERS FOR THE SIMULATION

<table>
<thead>
<tr>
<th>Material</th>
<th>AL6111-T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank Diameter, (mm)</td>
<td>177.8</td>
</tr>
<tr>
<td>Blank Thickness, (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Young’s Modulus, E (Mpa)</td>
<td>71000</td>
</tr>
<tr>
<td>Density (gr/cm^3)</td>
<td>2.7</td>
</tr>
<tr>
<td>Yield Stress (Mpa)</td>
<td>180</td>
</tr>
<tr>
<td>Ultimate Tensile Strength, (Mpa)</td>
<td>370</td>
</tr>
<tr>
<td>Strain Hardening Exponent, n</td>
<td>0.21</td>
</tr>
<tr>
<td>Strength Coefficient, K</td>
<td>456.7</td>
</tr>
<tr>
<td>Punch Diameter, (mm)</td>
<td>101.6</td>
</tr>
<tr>
<td>Inner Diameter Of Blank Holder, (mm)</td>
<td>103.6</td>
</tr>
<tr>
<td>Outer Diameter Of Blank Holder, (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Inner Diameter Of Draw Binder, (mm)</td>
<td>103.6</td>
</tr>
<tr>
<td>Outer Diameter Of Die, (mm)</td>
<td>210</td>
</tr>
<tr>
<td>Gap Between Die and Blank Holder, (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Die Profile Radius, (mm)</td>
<td>8</td>
</tr>
<tr>
<td>Friction Coefficient (Blank and Die)</td>
<td>0.05</td>
</tr>
<tr>
<td>Friction Coefficient (Blank and Blank Holder)</td>
<td>0.05</td>
</tr>
<tr>
<td>Friction Coefficient (Blank and Punch)</td>
<td>0.15</td>
</tr>
<tr>
<td>R_0</td>
<td>0.832</td>
</tr>
<tr>
<td>R_{45}</td>
<td>0.861</td>
</tr>
<tr>
<td>R_{90}</td>
<td>1.422</td>
</tr>
</tbody>
</table>

III. FINITE ELEMENT SIMULATION

Modeling of HDD and CDD processes were developed using Abaqus/CAE. The path of the counter-pressure was defined using “Amplitude” which employs forming-time as a variable. The punch, blank holder, and drawing die were modeled using rigid surface-elements R3D4 for a 3D model. The Coulomb friction was assumed for contact conditions. Fig. 4 shows the finite element model [20].

Energy output is often an important part of an Abaqus/Explicit analysis. Comparisons between various energy components can be used to help determine whether an analysis is yielding an appropriate response. Generally the kinetic energy should be a small fraction of the internal energy (less than 5 to 10%) until the least dynamic effect is reached, and the analysis procedure will be Quasi-static (Abaqus/CAE User’s Manual). Fig. 5 shows the internal energy and kinetic energy during process analysis. It is obvious that kinetic energy is far less than five percent of internal energy; therefore the problem was solved with the quasi-static procedure, and simulations results are valid [20].

![Fig. 4 Simulated model by Abaqus/explicit](image)

![Fig. 5 Comparison of total Kinetic and internal energies during FEM analysis](image)
energy in this analysis (see Fig. 6). Artificial energy should usually be a small fraction of internal energy (about 5%) so that the hourglass phenomenon does not occur during analysis (Abaqus/CAE User's Manual [20]). Large values of artificial energy indicate that meshing must be refined or other changes in meshing are necessary [20].

Fig. 6 Comparison of artificial and internal energies during FEM analysis

IV. RESULTS AND DISCUSSION

Several finite element simulations (FES) were performed, and for each FE simulation, the forming depth at which the sheet started to wrinkle was recorded.

Fig. 7 shows experimental and simulation results of the cup formed by CDD process. The height of wrinkles that developed in the flange area reached 3mm. The initial wrinkles were made in the flange area. With developments in punch displacement, the height of wrinkles was increased to the maximum gap between die and blank holder. In this paper the U2 parameter has been defined as vertical displacement.

Wrinkles developed in the region of the cup wall by more punch displacement. Fig. 8 shows the cup formed by HDD process. It can be seen that the height of wrinkles that developed in the flange area reached 1.64 mm. The initial wrinkles happened in the die corner, and with developments in the punch stork, wrinkle height was increased to the gap between die and blank holder. The results showed that while hydrostatic pressure was lost, height and number of wrinkles increased.

Fig. 7 Simulation and experimental results of CDD process
draw depth in simulation= 51.17 mm; draw depth in experimental = 50.8 mm [1]

Fig. 8 Simulation and experimental results of HDD process
Draw depth in simulation= 56.56 mm; draw depth in experimental = 53.4 mm [1]
The onset point of wrinkling of the sheet was measured, and the results of the finite element analysis were compared. In Fig. 9, the history of one node in 4-node square elements with maximum displacement in the flange area is displayed. Fig. 9 also shows that by using HDD process, it is possible to delay the initiation and growth of wrinkles in the part’s flange area.

![Graph showing punch depth at beginning of wrinkling (mm) in CDD and HDD processes](image)

**Fig. 9** Punch depth at beginning of wrinkling (mm) in CDD and HDD processes

Figs. 10 and 11 show that results of FE simulations have good agreement with experimental results. The application of fluid pressure caused the sheet to stretch everywhere, including underneath the blank holder, according to the results. This stretching strain helped prevent the sheet from wrinkling in the blank holder region. Therefore an optimum fluid pressure profile should induce enough stretching strain in the sheet to prevent it from wrinkling, while being low enough not to cause the sheet to fail by tearing. Thus the pressure profile shown in Fig. 3 should be further modified to iron out wrinkles developing in the die corner region.

If the flange region in the hemispherical cup deep drawing process remains perfectly flat and is constrained by reducing the gap between die and blank holder to 1.1mm, wrinkling does not take place in this area. Therefore in this section, the effect of the optimized counter-pressure profile on appropriate thickness distribution is investigated. Fig. 12...
shows a normalized counter-pressure profile obtained from experimental work by Zhang et al. [19].

![Normalized counter-pressure profile](image)

Fig. 12 Normalized counter-pressure profile adopted from experimental work [19]

The ideal condition is to produce a part with uniform thickness distribution, however in fact this target cannot be reached, because there are circumferential compressive stresses in the flange area that lead to an increase in the cup’s thickness. Furthermore, there are tensile stresses in the cup wall that cause thinning to take place in this region. Several finite element simulations were performed and thickness distribution of the cups measured. A comparison of the percentage of thinning distribution between the HDD process and CDD process in the radial direction of the cup wall with different maximum counter-pressure profile are shown in Fig. 13.

It can be seen that the thickness is remarkably reduced near the punch’s head, and also the thickness is gradually increased in the radial direction in the flange area. Moreover, the thickness distribution of the cup in HDD process is more uniform than in CDD process.

![Measured thinning distribution](image)

Fig. 13 The measured thinning distribution in CCD and HDD processes at various maximum counter pressure profiles

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**Interpolated line in CDD process**  
\[ y = -40.69x + 27.40 \]

**Interpolated line in HDD process (17Mpa)**  
\[ y = -28.78x + 16.9 \]
A better thickness distribution will be obtained by getting less slope of line and a y-intercept close to zero. Considering Fig. 14, it can be seen that by increasing the maximum counter-pressure profile from 0 to 17Mpa, the slope of interpolated lines and the y-intercept of lines are reduced; hence thickness distribution is better. By increasing the maximum counter-pressure profile from 17Mpa to 27Mpa, the slope of interpolated lines and y-intercept are increased.

When maximum counter pressure becomes more than 17Mpa, the blank starts to thin due to an increase in the friction force between blank and blank holder. When this pressure exceeds this criteria, the cup ruptures (see Fig. 15).

V. CONCLUSION

Results of the numerical analysis are in good agreement with the results of experimental work performed by Abedrabbo et al. [1]. Draw-in with CDD process caused the material to wrinkle in the flange area at a punch depth of 18.36 mm, while draw-in with HDD process allowed the material to be drawn to a depth of 34.01 mm without any wrinkling or rupturing. This represents an 85% improvement in depth forming. Also in HDD process, compressive stresses developed in the flange area and the die corner, causing the material to wrinkle due to the loss of pressure on the sheet. Furthermore using hydrostatic pressure in HDD process, a 10% improvement in depth forming was obtained. The effect of maximum counter-pressure profile on the thinning distribution of the cup in HDD process was investigated. Using a maximum counter-pressure profile of 17 Mpa, the quality of the cup is improved, and uniform deformation of the sheet is achieved.

The results showed that by applying higher pressure, maximum thinning was increased (due to an increase in the frictional force between blank and blank holder), and rupturing occurred near the die radius. Using optimal maximum counter-pressure profile, the maximum thinning had a 10% improvement. Moreover, by HDD process, the multi-pass forming process for conventional complicated sheet parts can be decreased to one or two passes. Thus higher efficiency and lower cost can be achieved. The distribution of wall thickness can be controlled, and thinning can be decreased.
REFERENCES


