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Investigation of the Effects of Pressure Path and Tool Parameters in Hydrodynamic Deep Drawing

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ABSTRACT

Hydrodynamic deep drawing assisted by radial pressure is one of the main types of hydroforming process. In this paper, forming of cylindrical cups is investigated numerically and experimentally in hydrodynamic deep drawing assisted by radial pressure. The effects of significant parameters such as pressure path, punch corner radius and die profile radius are studied on thickness distribution and punch force. Results showed that increasing maximum pressure affects the thickness reduction of the cup in critical regions. Applying pressure above a certain value does not have a considerable effect on thickness of the part. On the other hand, increasing maximum pressure increases the force required for forming a cylindrical cup. Also, it was found that by increasing the punch corner radius, thickness distribution will be more uniform while maximum punch force does not change. Increasing the die profile radius has a positive effect on the thickness distribution and the forming force.

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1. INTRODUCTION

Compared with conventional deep drawing, sheet hydroforming technology possesses many remarkable advantages [1, 2]. Many materials such as low carbon steel, stainless steel, aluminum alloys and copper can be used in this process [1, 3]. Researchers have proposed different techniques for sheet hydroforming such as rubber diaphragm hydroforming [1, 4], hydro-mechanical deep drawing [1], hydrodynamic deep drawing [1], and hydrodynamic deep drawing assisted by radial pressure (HDDRP) [5, 6]. Amongst different techniques of sheet hydroforming, HDDRP has given good results for forming parts with high drawing ratios.
Some studies have been done about forming these parts. Ozek and Bal [7] studied the effects of die profile radius, punch corner radius on limiting drawing ratio in conventional deep drawing. They found that drawing ratio increases by increasing the punch corner and die profile radii. Liu et al. [8] studied the effect of loading path on formability of cylindrical cups with hemispherical bottoms in hydrodynamic deep drawing. Wang et al. [9] studied forming of cylindrical cups using hydrodynamic deep drawing with independent radial pressure. They concluded that if the radial pressure becomes higher, thinning ratio and punch force will be lower but the compressive stresses and tendency to wrinkling on the flange will be higher. Lang et al. [10, 11] examined the effects of pre-bulging height and pressure on forming, limiting drawing ratio and geometrical precision of the cylindrical cups. They found that the higher the drawing ratio, the better the roundness at the same measured height. They also stated that the variation of pressure in the die cavity does not affect this tendency significantly. They stated that lower pre-bulging pressure can improve the accuracy of the formed part. In order to control the forming process, it is required to study the effects of different parameters on flow of material. Improving the effective parameters always has been considered by researchers. In this paper, forming of pure copper cylindrical cups is studied through hydrodynamic deep drawing assisted by radial pressure using finite element simulation and experiment. The effects of pressure path, punch corner radius and die profile radius on the thickness distribution and punch force are also investigated.

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2. EXPERIMENTAL PROCEDURE

In this study, pure copper (99.99%) circular sheet with a diameter of 80mm and a thickness of 1mm was used. The mechanical and physical properties of the sheet are shown in Table 1. E, υ and ρ were obtained from reference [12] and the flow stress equation was obtained from the tensile test. The true stress-strain curve of the copper sheet is shown in Figure 1. Because of small difference between the curves of 0, 90 and 45 degree directions, the copper sheet was assumed to be isotropic. The schematic of the die set is shown in Figure 2. Two cylindrical punches, one with flat bottom and the other with hemispherical bottom, were made. The punches and their dimensions are shown in Figure 3.

A DMG universal testing machine with 600kN capacity was used. The components of the die are shown in Figure 4. The typical pressure path used in this research is shown in Figure 5. In this path, OA is the pre-bulging pressure (2.5MPa) applied to the bottom of the blank before the movement of the punch. According to references [10, 11, 13], the pre-bulging pressure should not be too high, since it has negative effect on forming. Furthermore, a lower pre-bulging pressure improves accuracy of the cylindrical cup.

Thus, in this research a pre-bulging pressure of 2.5MPa was used. The path AB is the constant pressure (2.5MPa) applied after the punch moves down. BC is the linear pressure path, the slope of which will change with the punch velocity, shape of the part and thickness of the blank. In this study, thickness of the sheet (1mm) and punch velocity (200mm/min) were constant. Thus, the only factor that affects the slope of this path is the shape of the punch. Since two different punch shapes are examined in this paper, two different slopes for the path BC would exist. CD is a constant maximum pressure at which the liquid outflows from the pressure control valve. In this path, P1 is 2.5MPa and P2 is variable. The fluid pressure was applied to the bottom and also to the rim of the blank. Since there was no O-ring between the blank holder and die, the fluid could leak from this space.

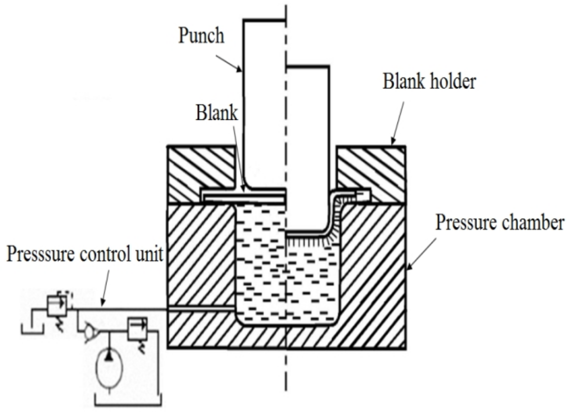


Figure 2. Schematic of the hydroforming die set

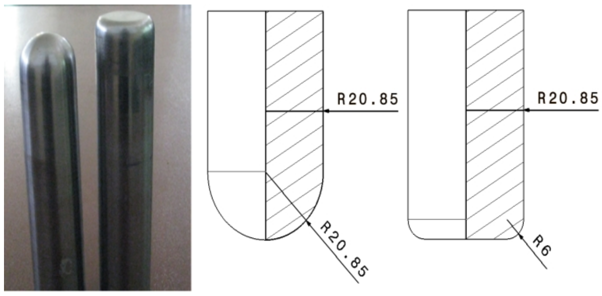


Figure 3. Punches used in experiments, dimensions in mm

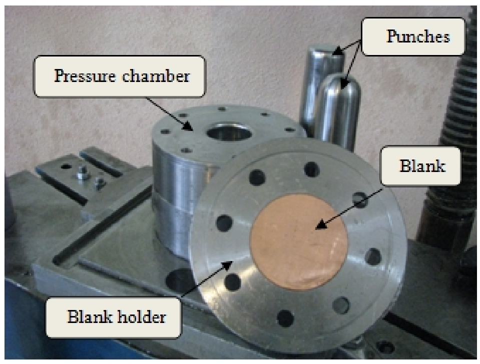


Figure 4. Components of the hydroforming die

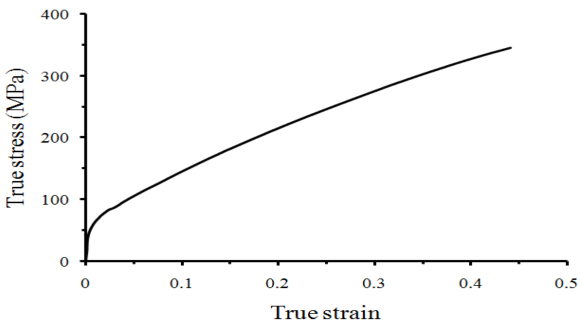


Figure 1. True stress- strain curve of the copper sheet

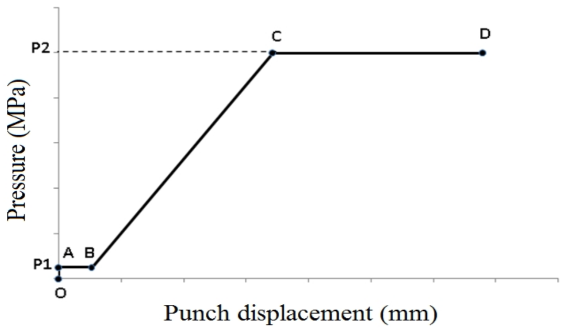


Figure 5. Typical pressure path used

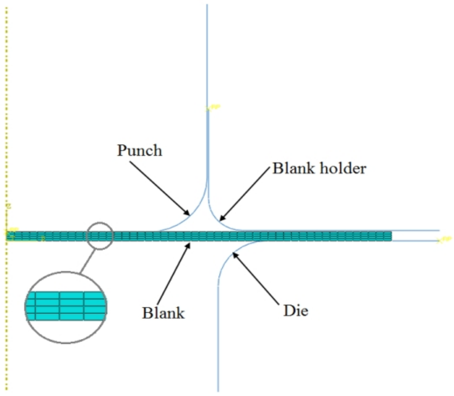


Figure 6. Finite element model of the die set

TABLE 1. Properties of the copper sheet

Flow stress [MPa]	Density [kg/m^3]	Young's modulus [GPa]	Poisson's ratio
$\sigma=531\varepsilon^{0.44}$	$\rho=8940$	$E=117$	$\nu=0.32$

3. FINITE ELEMENT SIMULATION

The software, ABAQUS 6.9/Explicit, was used for the simulations. Due to the axial symmetry, axisymmetric model was used. The blank was modeled as 2D deformable with CAX4R element, which is an axisymmetric 4-node reduced-integration element. Simulations were done with different mesh sizes, mesh types and number of meshes along the thickness. The convergence of the curves of strain-distance from center of part, and force-punch displacement were examined to determine the best model for simualtions. Eventually, 4 elements along the thickness and mesh size of 1mm were selected. The FE model of the die set is shown in Figure 6. The die set was modeled by 2D axisymmetric analytical rigid element. The die and blank holder were fully constrained and the punch could move in the vertical direction. Due to low space between the die and blank holder, and very low leakage of fluid, the pressure under the blank flange was assumed to be uniform and the same as that in the die cavity [6].

The friction coefficient for the blank and punch interface was considered to be 0.14 and for other surfaces 0.04 [14]. The process was set in one step.

The maximum thinning was used for fracture criterion in the simulation and experiment. According to [15], major engineering strain (e_θ) in plane strain condition is calculated by Equation (1):

$$e_\theta = \left(23.3 + \frac{360}{25.4}t_0\right)\left(\frac{n}{0.21}\right) \quad (1)$$

where, n is the strain hardening exponent and t_0 the initial blank thickness. The major true strain (ε_θ) and true strain in the thickness direction in plane strain condition are determined according to Equations (2) and (3).

$$\varepsilon_\theta = \ln\left(1 + \frac{e_\theta}{100}\right) \quad (2)$$

$$\varepsilon_t = -\varepsilon_\theta \quad (3)$$

After calculating ε_θ and substituting it into Equation (4), the value of t_f is obtained. By placing t_f into Equation (5), maximum thinning is obtained.

$$t_f = t_0 \exp\left(\varepsilon_t\right) \quad (4)$$

where, t_0 is the initial thickness of the blank and t_f the final thickness of the cup.

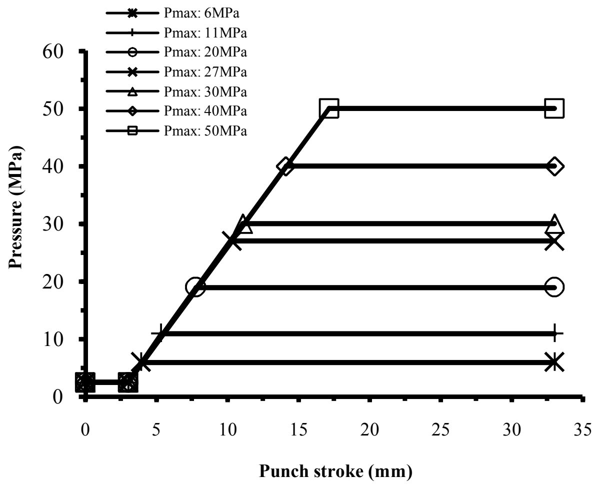
$$\%\,thinning = \frac{t_0 - t_f}{t_0} \times 100 \quad (5)$$

Maximum thinning obtained for the copper sheet was 44%, which means that if thickness of the cup in the simulation or experiment becomes less than 0.56mm, bursting occurs and forming of the cup fails.

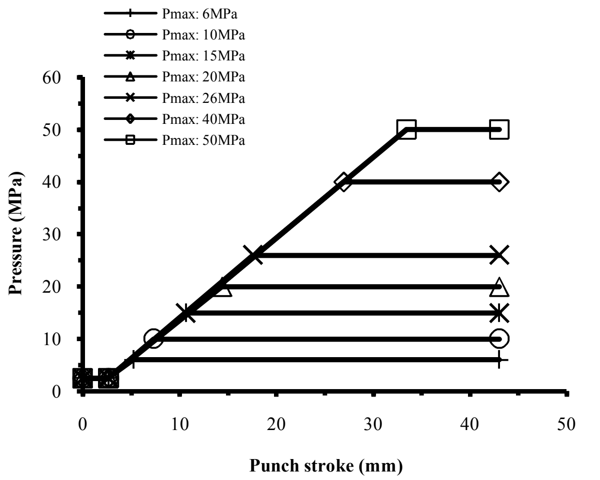
4. RESULTS AND DISCUSSIONS

The pressure paths used in this research are shown in Figure 7, based on the path illustrated in Figure 5. In order to examine the effect of pressure path, some preliminary paths were selected and the process was simulated. Based on the changes of the thickness distribution, the appropriate maximum pressures were selected. Then, experiments were performed with the pressure paths obtained. Since the pressure control valve could be adjusted manually, the actual applied pressure paths were recorded and finally selected for further examination. In order to study the thickness distribution, the cup was divided into parts, as shown in Figure 8.

Figure 9 shows the flat part formed. Figure 10 shows the thickness distribution and punch force curves of the cylindrical part with flat bottom formed. As it is seen, there is a good correlation between the experimental results and simulation. Thickness reduction at the bottom of the cup (region A) is small. This is because of tensile strains. The highest thickness reduction occurred at the corner radius of the cup (region B). This is because of bending occurring in this region. At the end of the cup wall, thickening occurs which is because of compressive strains in the flange area.

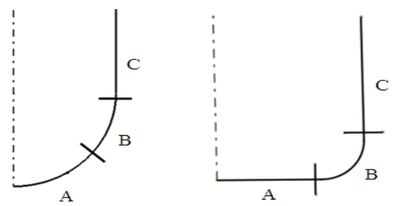


(a)

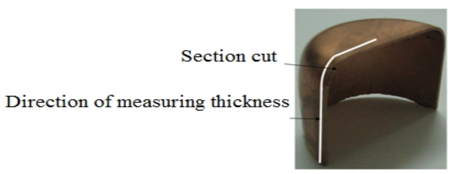


(b)

Figure 7. Pressure paths used, (a) the punch with flat bottom, (b) the punch with hemispherical bottom

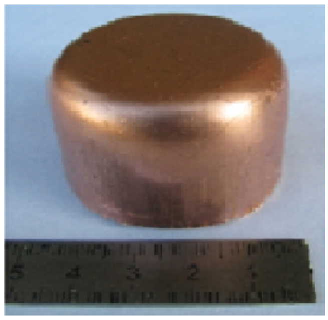


(a)



(b)

Figure 8. (a) Different regions on the formed parts, (b) Direction of measuring thickness



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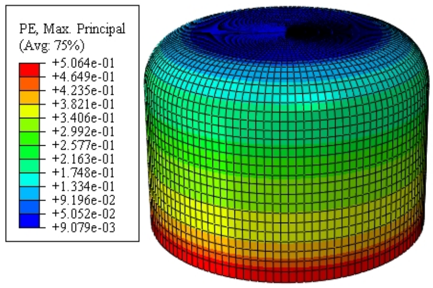
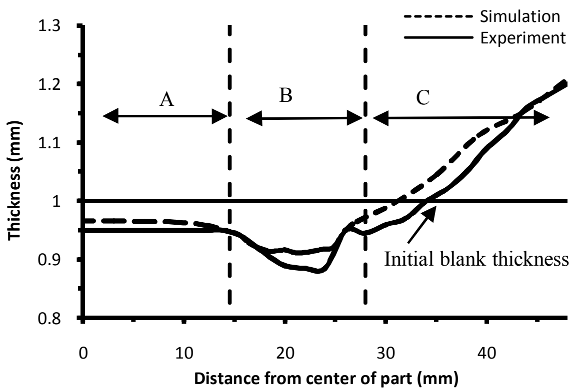
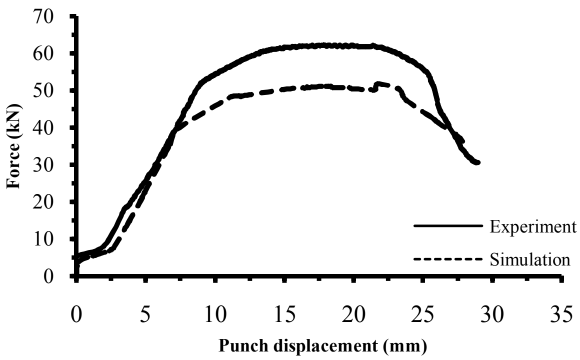


(b)

Figure 9. Cylindrical cup with flat bottom formed with the maximum pressure of 20MPa, (a) Experiment, (b) Simulation



(a)



(b)

Figure 10. Thickness distribution and punch force curves of the cup with flat bottom, maximum pressure 20MPa

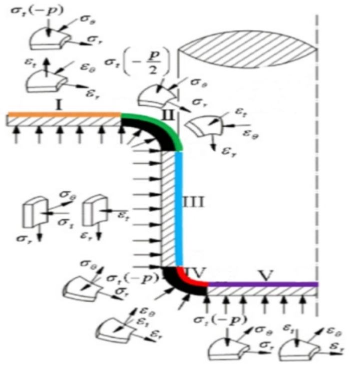


Figure 11. Stresses and strains of regions of the cup [16]

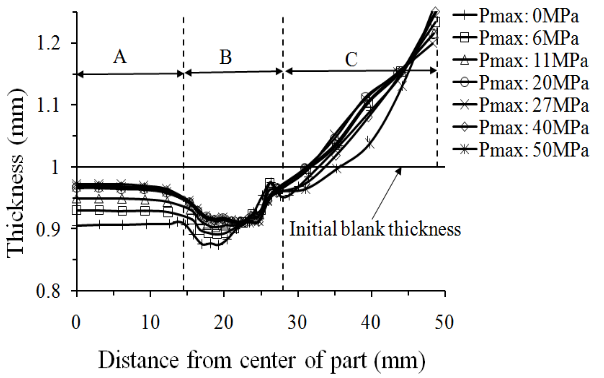
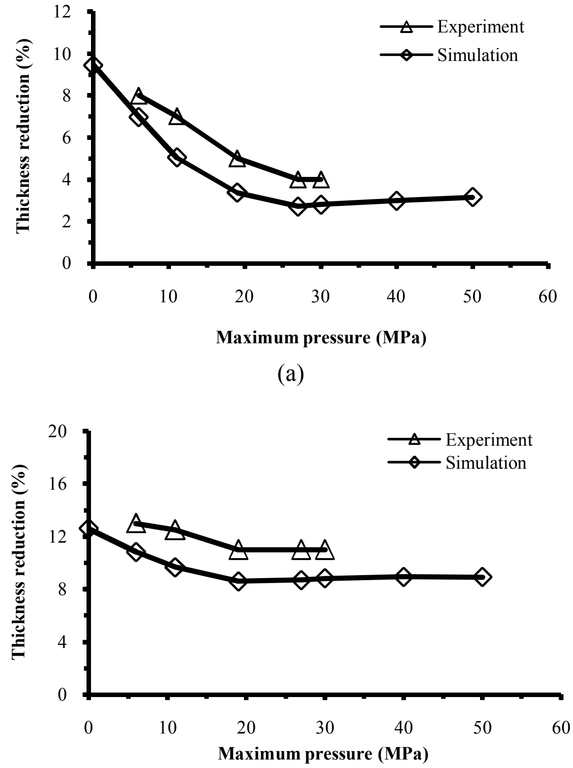


Figure 12. Thickness distribution curves of cylindrical cups with flat bottom, obtained from simulation



(b)

Figure 13. Thickness reduction curves versus maximum pressure, (a) region A, (b) region B

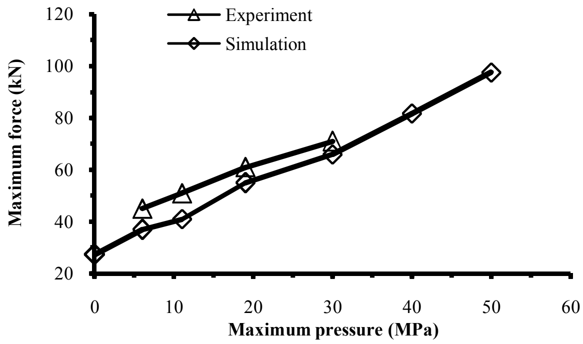


Figure 14. Maximum punch force versus maximum pressure, corresponds to cylindrical cup with flat bottom

Figure 11 shows the cross section of a cylindrical cup with stresses and strains in its different regions. As it is seen, circumferential strain (ε_θ) in region I tends to thicken the sheet on the flange, but the strain created by the fluid pressure (ε_t) prevents excessive thickening of the sheet. ε_r is the tensile strain created by the friction force. Bending of the sheet around the punch profile in region IV causes thinning in this region. Because of tensile strains in region V, thinning occurs in this region, too. The strains created by fluid pressure prevent excessive thinning in regions IV and V. So, thinning decreases in these regions by increasing fluid pressure. Increasing fluid pressure results in increasing vertical force applied to the surface of the sheet, which prevents the sheet from sliding on the surface of the punch.

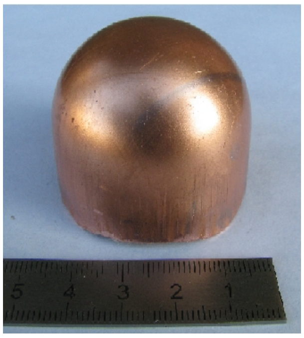
The thickness distribution curves of the cups formed with different paths are shown in Figure 12. Maximum pressure greatly affects the thickness of regions A and B. Figure 13 shows the thickness reduction in regions A and B. Maximum thickness reduction in these two regions occurs when there is no pressure under the blank. By increasing the maximum pressure to 27MPa, thickness reduction of region A decreases with a sharp slope.

Maximum pressure of higher than 27MPa does not have a significant effect on thickness reduction of that region. On the other hand, by increasing maximum pressure, thickness reduction in region B decreases with low slope and from the maximum pressure of 20MPa, pressure does not have effect on the thickness. In hydroforming process, liquid pressure pushes the blank to the surface of the punch and creates a large surface contact between the punch and sheet. This causes more friction force which prevents the sheet from slipping on the punch surface. So, by increasing pressure, thickness reduction in critical areas decreases.

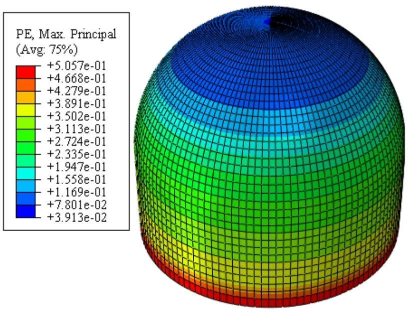
Figure 14 shows the effect of maximum pressure on maximum punch force. As it can be found from Figures 13 and 14, the pressure path with the maximum value of 27MPa is the best pressure path for forming a cup with the punch corner radius of 6mm. Increasing the pressure above 27MPa does not have a significant effect on thickness distribution, while increases the force.

Figure 15 shows a model of cylindrical cup with hemispherical bottom formed with the maximum pressure of 20MPa. This form of the cup is a form of a cylindrical cup with flat bottom, the corner radius of which is 20.85mm. Figure 16 shows thickness distribution and punch force curves of the hemispherical part formed with the maximum pressure of 20MPa. As it is seen, there is a good correlation between the results of experiment and simulation. For this form of the cup, the highest thickness reduction occurs in regions A and B. This thickness reduction is due to stretching of the sheet and tensile strains in these regions. At the top of the cup wall, thickening occurs which is because of compressive strains in the flange area.

In Figure 17, the thickness distribution curves of hemispherical parts formed with different maximum pressures are displayed. By applying pressure paths with low maximum pressures, maximum thinning occurs in region A. At low maximum pressures, the sheet slides much more on the surface of the punch.



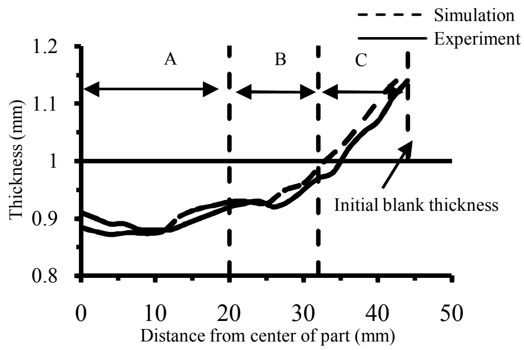
(a)



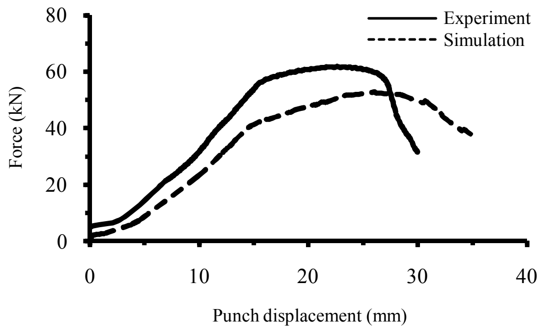
(b)

Figure 15. Cylindrical cup with hemispherical bottom, (a) Experiment, (b) Simulation, correspond to maximum pressure 20MPa

This results in tensile strains in region A and creates more thickness reduction in this region. By increasing the maximum pressure, contact surface of the sheet and punch increases and due to more applied perpendicular force to the surface of the punch, friction force increases. This prevents sliding of the sheet on the surface of the punch. So, when the maximum pressure is high, the thickness reduction decreases in regions A, while it increases in regions B and C.



(a)



(b)

Figure 16. Thickness distribution and punch force curves of cylindrical cup with hemispherical bottom, maximum pressure 20MPa

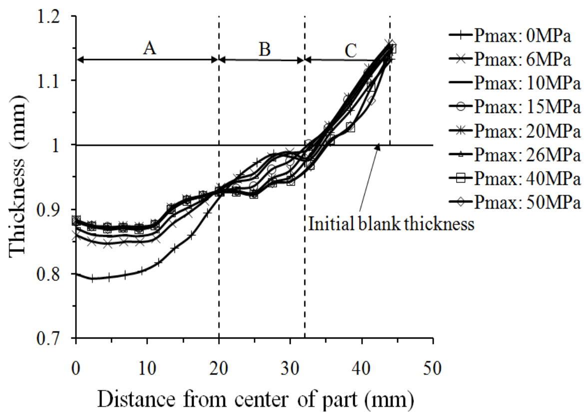
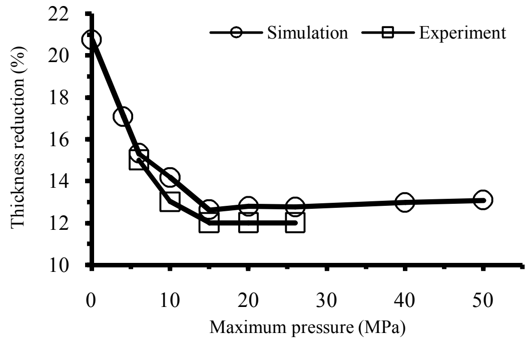
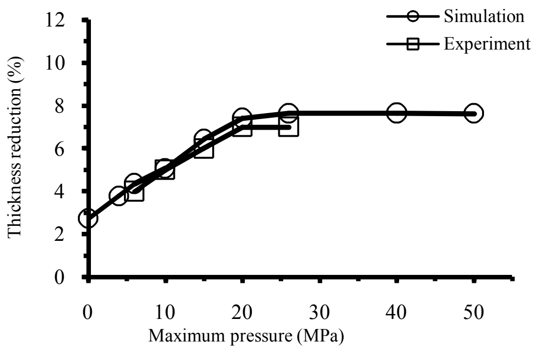


Figure 17. Thickness distribution curves of cylindrical cups with hemispherical bottoms, obtained from simulation

Figure 18 shows thickness reduction percent in regions A and B corresponding to different maximum pressures. As it can be seen, by increasing the maximum pressure to 15MPa, thickness reduction decreases in region A. From the maximum pressure of 15MPa, the fluid pressure does not have a significant effect on thickness reduction of this region. On the other hand, by increasing maximum pressure to 20MPa, thickness reduction increases in region B. From the maximum pressure of 20MPa, pressure does not have any effect on thickness of this region.



(a)



(b)

Figure 18. Thickness reduction curves versus maximum pressure, (a) region A, (b) region B

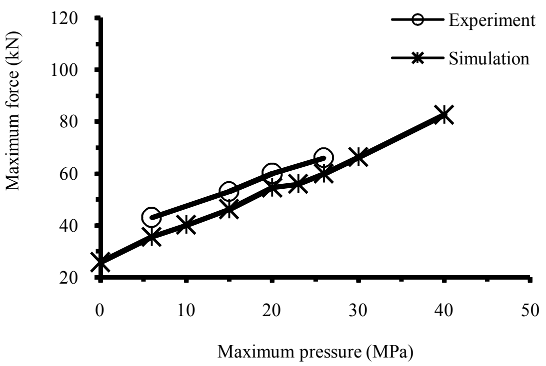


Figure 19. Maximum punch force versus maximum pressure for the cylindrical cups with hemispherical bottoms

Figure 19 shows the effect of maximum pressure on maximum punch force. As it can be found from Figures 18 and 19, the pressure path with the maximum pressure of 15MPa is the best pressure path for forming a hemispherical part. Increasing pressure above 15MPa does not have a significant effect on thickness reduction of region A, but increases thickness reduction of region B and also increases the force needed for forming the cup. To evaluate the effect of punch corner radius on forming a cylindrical cup, different radii (3, 6, 9, 12, 15, 18, 20.85 mm) were studied. The value of die profile radius was kept constant at 5mm. Figure 20 shows thickness distribution curves of the cups with different punch corner radii. By increasing punch corner radius, thinning increases at the bottom of the cup. For the case when the punch corner radius equals 20.85 mm, the punch would have a hemispherical shape. Therefore, the most thinning occurs in hemispherical punches due to more stretching occurring in the sheet.

The thickness reduction percent of the bottom of the cup versus the punch corner radius is shown in Figure 21. It can be seen that by increasing punch corner radius, thinning increases at the bottom of the cup. It is because of more sliding of the sheet on the punch surface and increasing tensile strains in this region. The reduction in the thickness of the corner versus the punch corner radius is shown in Figure 22. By increasing the punch corner radius up to 12mm, thinning decreases in region B due to reduction of sheet bending around the punch profile. By increasing the radius above 12mm, thinning increases in this region. It is because of more sliding of the sheet on the punch surface which results in more stretching of the sheet. Figure 23 shows punch force versus stroke corresponding to different punch corner radii. As it is seen, maximum punch force does not change with increasing punch corner radius, but maximum force occurs at greater punch displacements.

To investigate the effect of die profile radius, punch corner radius was kept constant at 6mm and different die profile radii (1, 2, 3, 5, 7, 9 mm) were simulated. Figure 24 shows the simulated cups of two different die profile radii (3 and 7mm) at the same step. At both maximum pressures of 6 and 30MPa, when the die profile radius is small, the sheet contacts with the surface of the blank holder and die. Friction and bending/unbending of the sheet on the surface of the die profile radius causes thickness reduction. By increasing die profile radius, at maximum pressure of 30MPa, the sheet contacts the blank holder and does not have any contact with the die profile radius. At high maximum pressures, increasing die profile radius above a certain value does not affect thickness reduction at maximum pressure of 6MPa, the sheet always contacts the die profile radius. Thus, thickness reduction decreases at low maximum pressures by increasing die profile radius that results in less bending of the sheet in this region. Thickness distribution of the cup for different die profile radii at maximum pressure of 30MPa is shown in Figure 25. As it can be seen, thickness reduction decreases in all regions of the cup by increasing die profile radius to a certain value.

Thickness reduction of bottom of the cup (region A) and corner radius of the cup (region B) corresponding to the maximum pressure of 30MPa is shown in Figure 26. The greatest thickness reduction is related to the radius of 2mm. It is because of too bending of the sheet in this region. By increasing die profile radius to 5mm, thickness reduction decreases in both regions. Increasing die profile radius over 5mm does not affect the thickness of regions A and B. This is because of high pressure that pushes the sheet onto the blank holder and prevents its flow on the die profile radius surface. Figure 27 shows maximum punch force corresponding to different die profile radii. As it can be found from Figures 26 and 27, die profile radius of 5mm is the best radius for forming a cup with the maximum pressure of 30MPa.

Figure 28 shows thickness distribution of the cups with different die profile radii at maximum pressure of 6MPa. By increasing die profile radius, thickness reduction in all regions of the cup decreases. Thickness reductions of bottom of the cup (region A) and corner radius of the cup (region B) are shown in Figure 29. Sheet and die corner contact with each other in different die profile radii. So, by increasing die profile radius and less bending of the sheet in large radii, thickness reduction decreases in both regions. Figure 30 shows maximum punch force corresponding to different die profile radii. As it can be found from Figures 29 and 30, the more the die profile radius, the better the thickness distribution and the less the punch force at low maximum pressures.

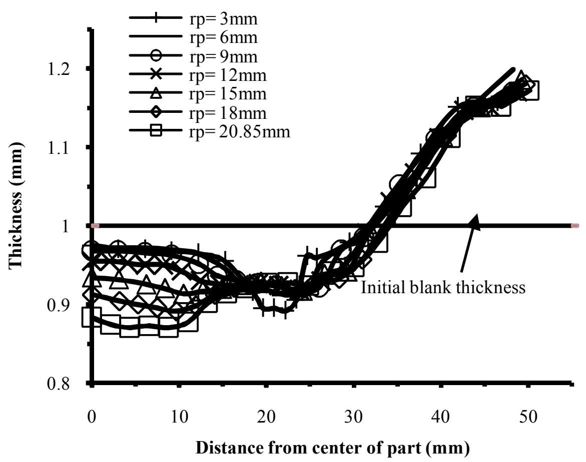


Figure 20. Thickness distribution of the formed cups, maximum pressure: 30MPa, obtained from simulation

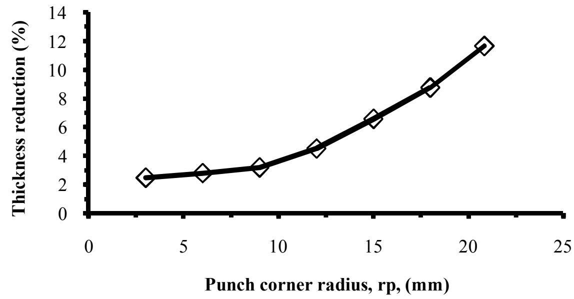


Figure 21. Thickness reduction percent at the bottom of the cup (region A)

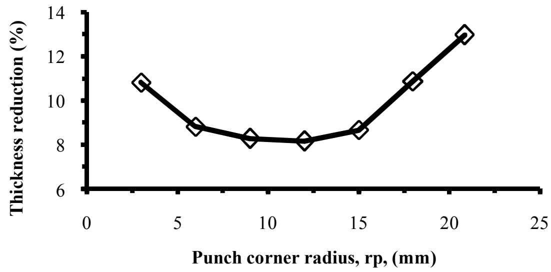


Figure 22. Thickness reduction percent at the punch corner radius (region B)

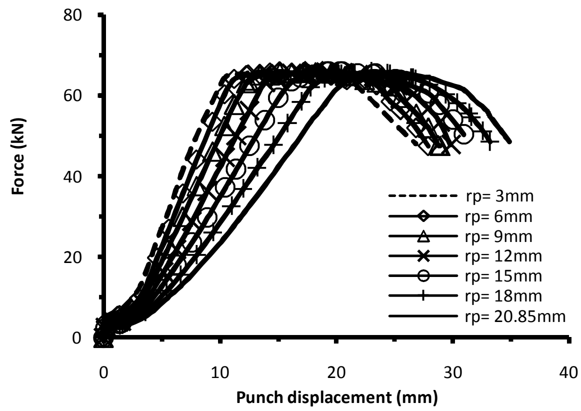


Figure 23. Punch force for different punch corner radii (rp)

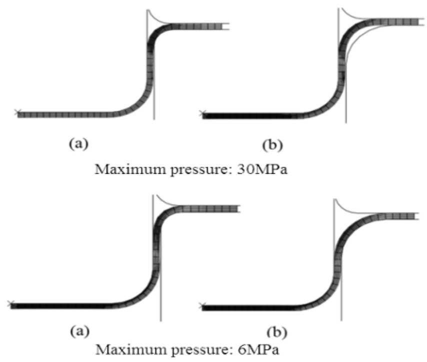


Figure 24. Simulated cups of two die profile radii at the same step, (a) rp= 3mm, (b) rp= 7mm

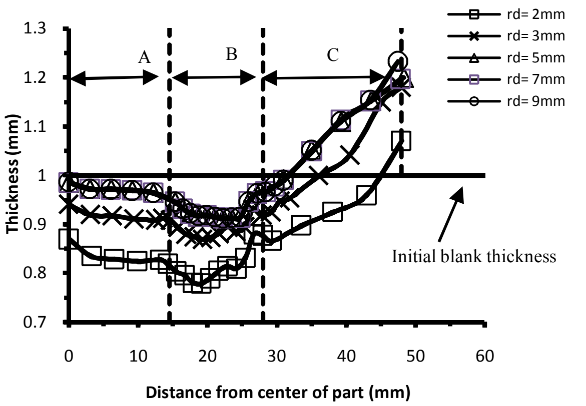


Figure 25. Thickness distribution for the different die profile radii (rd), maximum pressure 30MPa

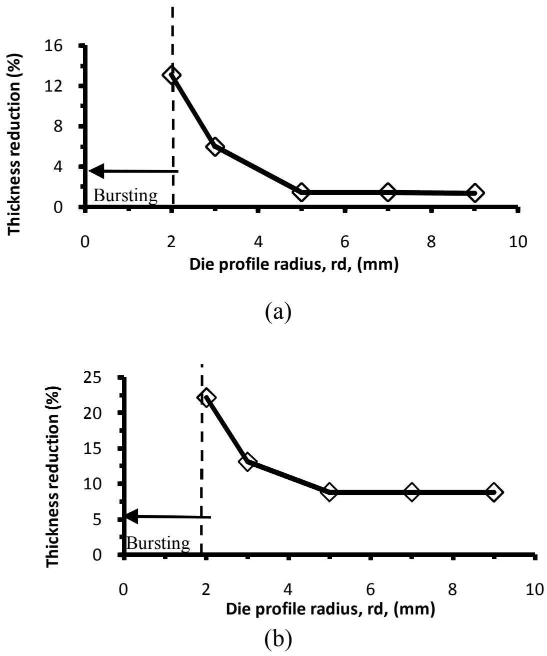


Figure 26. Thickness reduction in critical regions for different die profile radii (rd), maximum pressure 30MPa, obtained from simulation, (a) region A, (b) region B

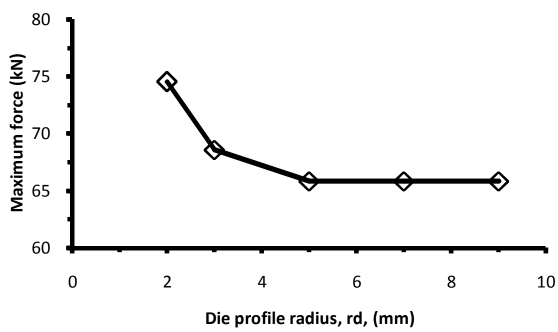


Figure 27. Maximum punch force for different die profile radii (rd), maximum pressure 30MPa, obtained from simulation

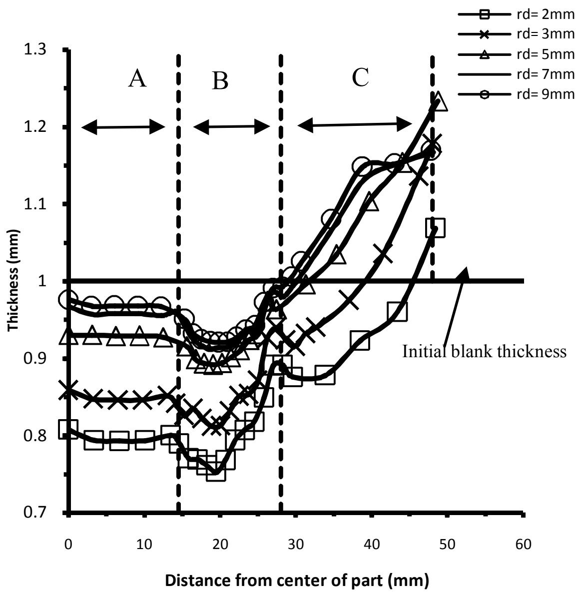


Figure 28. Thickness distribution for different die profile radii (rd), maximum pressure 6MPa, obtained from simulation

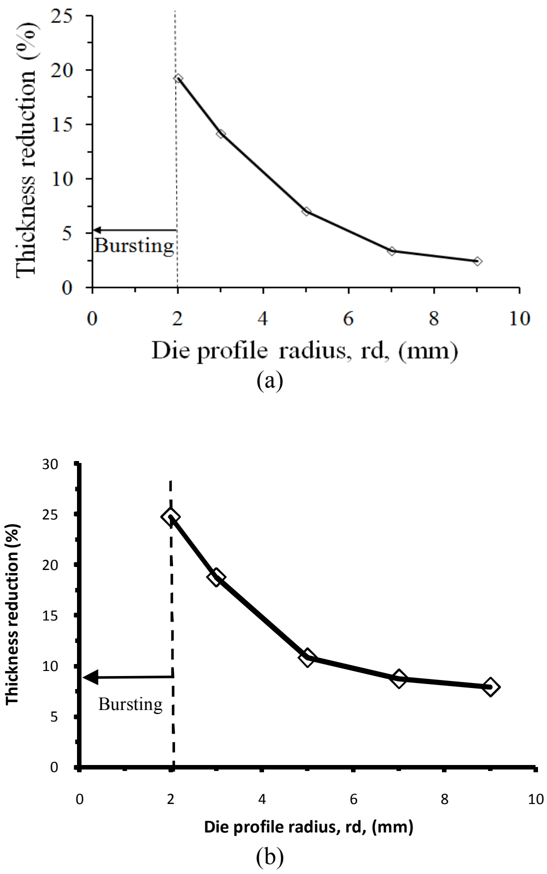


Figure 29. Thickness reduction in critical regions for different die profile radii (rd), maximum pressure 6MPa, obtained from simulation, (a) region A, (b) region B

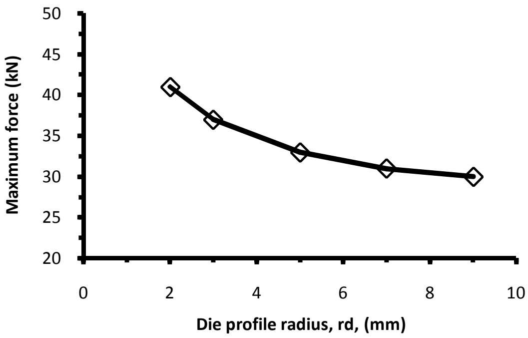


Figure 30. Maximum punch forces for different die profile radii (rd), maximum pressure 6MPa, obtained from simulation

5. CONCLUSIONS

In this paper, forming of pure copper cylindrical cups has been studied using finite element simulation and experiment. Several pressure paths were examined and their effects studied on thickness distribution and punch force. It was concluded that quality of the part improves at certain maximum pressure. Increasing pressure above this value does not improve thickness distribution, but increases punch force. The best pressure paths obtained from this study are the pressure path with the maximum of 27MPa for the flat part, and of 15MPa for the hemispherical part. The effect of punch corner and die profile radii were investigated, as well. By increasing punch corner radius, thickness distribution of the cup will be more uniform while maximum punch force does not change. Also, it was found that increasing die profile radius has a positive effect on thickness distribution of the cup and the required forming force.

6. FUTURE WORKS

In this paper, some of the effective parameters are studied on forming cylindrical cups. The authors suggest the investigation of other important factors such as the clearance between the die and punch, pre-bulging parameter, punch velocity and different kinds of pressure paths as future work.

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Investigation of the Effects of Pressure Path and Tool Parameters in Hydrodynamic Deep Drawing

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چکیده

روش کشش عمیق هیدرودینامیکی با فشار شعاعی یکی از انواع اصلی فرآیند هیدروفرمینگ است. در این مقاله، شکل‌دهی قطعات استوانه‌ای در فرآیند کشش عمیق هیدرودینامیکی با فشار شعاعی به صورت تجربی و شبیه سازی اجزای محدود بررسی شده و اثر پارامترهای مهم یعنی مسیر فشار، شعاع گوشه سنبه و شعاع لبه ماتریس بر توزیع ضخامت قطعه و نیروی سنبه مورد مطالعه قرار گرفته است. نتایج حاصل نشان داد که افزایش سطح فشار موجب کاهش نازک‌شدگی در نواحی بحرانی می‌شود. افزایش فشار ورای یک مقدار معین، تاثیری بر ضخامت قطعه ندارد. به علاوه، افزایش فشار بیشینه سیال موجب افزایش نیروی لازم برای شکل‌دهی قطعه می‌شود. همچنین، با افزایش شعاع گوشه سنبه ضخامت ورق در گستره فنجان یکنواخت‌تر می‌گردد، در حالی که حداکثر نیروی سنبه تغییری نمی‌کند. افزایش شعاع ورودی ماتریس تاثیر مثبتی بر توزیع ضخامت و نیروی شکل‌دهی قطعه دارد.

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