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Experimental and Numerical Investigations of Hydromechanical Deep Drawing of a Bilayer Conical Cup

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Abstract

In hydromechanical deep drawing process, a space of liquid replaces the matrix and the final shape of part is established based on the form of stiff punch. The application of hydroforming process is forming complex parts with higher quality than traditional forming methods. The advantages of multi-layer sheets are using different material characteristics, achieve higher strength and consequently get better forming condition. Forming of poor formable light-weight metals like aluminum alloys is difficult, which can be made easy with using hydroforming process. Having suitable range of the effective parameters of the process is important and can help to form parts with higher quality. In this research, the hydromechanical deep drawing of the two-layer bimetallic Copper/Aluminum 3003 with conical shape was studied using the finite element method (FEM) and the effect of different parameters of the process such as final pressure, friction coefficient, pre-bulging pressure, and pre-bulging height on maximum thickness reduction and thickness distribution were inspected. The results showed that increasing of the friction between blank and die or blank and blank-holder increases the thinning ratio, while by increasing of the friction between blank and punch, the maximum ratio of thickness reduction declined. In addition, optimum range of the pre-bulging pressure and pre-bulging height of this case study was extracted by numerical simulations. A study was also carried out using experimental setup for verifying the FEM results. By comparison of experimental and numerical results, good reliability was seen between them.

1. Introduction

One of the best methods which is very applicable to form sheets with high quality is Hydromechanical deep drawing. Due to application of multi-layer sheets in industry, especially aerospace, forming of these sheets is very important. Multi-layer sheets consist of various kinds of sheet metals by various properties of each layer. Some of advantages of multi-layer sheets which make them popular are good efficiency of strength to weight, ability to absorb vibration, high ratio of thermal conductance, possibility to use in erodible spaces etc. But forming of these types of sheets is a little bit harder than single sheet which is because of different deformation behavior of layers. Pay attention to benefits of hydroforming method such as possibility to form parts with higher drawing ratio, forming complicated parts, and decreasing defects like wrinkling, necking, and rupturing. This method can be applied to form multi-layer parts.

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Amount of drawing ratio through this procedure in addition of material properties, relies on the oil chamber pressure that directly affects the blank holder force, clearance between oil chamber and blank holder, and interfacial conditions between parts. Blank-holder force and friction coefficient between surfaces confines slip at the interfaces and causes an increase in the tension of the blank.

In the last decade, many papers studied the hydromechanical deep drawing process. Alizad-kamran et al. [1] developed a theoretical model based on BBC2008 yield criterion including 8 and 16 parameters to determine critical pressure in hydromechanical deep drawing process. In their work, with applying uniaxial and equi-biaxial tensile tests and optimizing an error-function by using Levenberg-Marquardt method, the parameters of BBC2008 yield criterion could be determined.

Lou et al. [2] developed micro-hydromechanical deep drawing to take advantage of hydraulic force. With reduced dimensions, the hydraulic pressure development changes; accordingly, the lubrication condition changes from the macroscale to the microscale. A Voronoi-based finite element model was proposed to consider the change in lubrication in micro-hydromechanical deep drawing according to open and closed lubricant pocket theory. Their results showed that high hydraulic pressure can increase the maximum drawing ratio (drawn cup height), whereas the surface finish represented by the wear is not linearly dependent on the hydraulic pressure due to the wrinkles.

Öztürk et al. [3] proposed an improved approach to determine the optimal profiles of two controllable process parameters (hydraulic pressure and blank holder force), which improve the forming condition and/or make better use of forming limits in hydromechanical deep drawing process. A method was developed based on adaptive finite element analysis coupled with fuzzy control algorithm (aFEA-FCA) using LS-DYNA to determine the optimal loading profiles, thus the limiting drawing ratio is maximized.

In recent years, several researches have concentrated on forming of multi-layer sheets using different methods that some of them are presented in following sentences. Habibi Parsa et al. [4] worked on mechanical properties behavior of two-layer aluminum/stainless steel bilayer sheets in traditional deep drawing of cylindrical cups. It was deduced that in direct drawing, contact of stainless-steel and the punch leads to the maximum drawing ratio and in reverse drawing, to achieve the highest drawing ratio, aluminum layer should be in contact with punch Atrian and Saniee [5] put upon stainless steel/brass laminated sheets in the conventional deep drawing of cylindrical cups. It was presented the effects of efficient parameters on the final part shape the stress and strain distribution along radial distance of cup. Lang et al. [6] discussed the effect of some parameters on the forming process of multilayer sheets with a very thin middle layer in sheet hydroforming process and the ways to improve the sheet formability using both the experiment and simulation Zafar et al. [7] studied process variables of three-layer semi-spherical part with numerical and experimental method. Barlat 2000 yield criterion was used to estimate forming capability of layers in LS-DYNA software. Khandeparkar and Liewald [8] investigated the effect of various parameters on maximum applicable drawing ratio of complex parts with two different materials and two different pressure paths in hydro-mechanical deep drawing process. Zhang et al. [9] analyzed the production of cone boxes by rectangular section using hydromechanical deep drawing method. Simulations were done with circular and octagonal blank shapes; subsequently, the results were compared. Bagherzadeh et al. [10] studied about instability of bimetal sheets with Al1050/St13 layers and extracted some theoretical relations to predict the safe working zone of the HMDD process for cylindrical cups. It was concluded that wider working zone was achievable by decrease in drawing ratio. Hashemi et al. [11] proposed an adaptive finite element algorithm to validate experimental tests of hydroforming of bilayer sheets and also predict the forming condition of parts with different shapes. To form the parts with highest drawing ratio, finding a suitable oil pressure range, control of slip between the blank and die, and punch and blank-holder are necessary. In this research, hydromechanical deep drawing of a bilayer conical cup was studied experimentally and numerically. Also, the effects of process parameters such as final pressure, friction coefficient, pre-bulging pressure, and pre -bulging height were investigated on limit drawing ratio, thickness distribution, and maximum thinning ratio of manufactured specimen with hydromechanical deep drawing process. To verify the simulation results, free rupture parts forming condition was investigated with some experimental tests. There was good agreement between experimental and simulation results. The main novelty of this paper is hydromechanical deep drawing process of two-layered sheets with different materials and thicknesses in order to manufacture a conical specimen. To the authors knowledge, there are not any researches on the hydromechanical deep drawing of two-layered conical specimens with different materials and thicknesses.

2. Process Modeling

Abaqus/CAE was used to analyze the forming process. The material behavior was considered isotropic. The simulations were done fixed by considering die-blank holder gap of 1.45mm. In all of the simulations, the effect of fluid pressure was applied uniformly. The pressure changes linearly in the pre-bulging and forming stages. Internal pressure of the fluid chamber versus punch movement into the oil chamber is named pressure path that is very effective parameter on hydroforming process and especially limiting drawing ratio. Amounts of 10, 20, 30, 40, and 50MPa were considered as a final pressure which were applied with tabular amplitude. The FE model of the die set is shown in Fig. 1. The blank was created deformable by solid element (C3D8R). To investigate a secure result along thickness and control hourglass defect, three elements were considered along the thickness. The die set was shaped using a rigid four- node shell element (R3D4). The initial thicknesses of the Aluminum and Copper were 0.5mm and 0.8mm respectively. The whole blank contained 5000 elements. To avoid movement of the die and the blank holder during the analyses, Encaster type of boundary condition applied to their reference point and the punch could move to the die holes axis. Pressure load was applied on the bottom surface and also on the rim of the blank as a radial pressure.

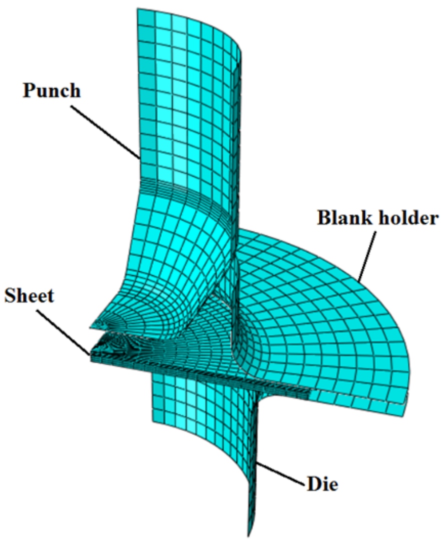

Fig. 1. Finite element model of hydromechanical deep drawing of a conical cup.

The material characteristics and process parameters which were used in the simulations are shown in Table 1 and Table 2. The Coulomb friction was implemented to define contact interfaces between surfaces and Penalty contact algorithms were used between the sheet metal and the tooling elements. The friction coefficients between the blank and blank-holder was 0.05, between the blank and punch was 0.1, and between the blank and die was 0.05 and Penalty contact algorithms were used between the sheet metal and the tooling elements. The drawing ratio of conical part is the ratio of initial blank diameter to the average diameter of the conical potion. An adaption mass scaling scheme in which the ratio of the kinetic energy to the internal energy is negligible was utilized to reduce the simulation time. Plastic strain of the final product with 2.2 drawing ratio extracted from the simulation is shown in Fig. 2 to predict the failure time, different failure criteria can be used. As it is seen in Fig. 2, the values of the effective strain of the inner layer of the cup are much greater than those of the outer layer. The reason is that the outer layer is thicker and stronger than inner one. In this article, based on reference [12] the maximum thinning of each layer was considered as a fracture criterion.

Table 1
Mechanical properties of Al-3003 and Copper sheets.

Properties	Symbol	Al 3003	Copper
Thickness (mm)	t	0.5	0.8
Young's module (GPa)	E	70	117
Poisson's ratio	ν	0.33	0.32
Yield stress (MPa)	σ_y	62	123
Ultimate stress (MPa)	σ_{UT}	116	370
Strain hardening exponent	n	0.25	0.44

Table 2
Dimensions of the die set and the punch.

Items	Symbol	Dimension
Punch's large diameter (mm)	D_p	32
Punch's small diameter (mm)	d_p	16
Punch's tip angle	$\circ$	60
Punch tips fillet (mm)	r_p	3
Drawing ring inside diameter (mm)	D_d	37
Drawing ring inside fillet (mm)	r_d	3.5

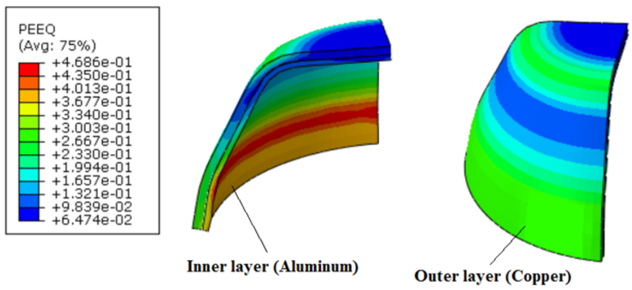

Fig. 2. Plastic strain of simulated bilayer conical cup drawing of ratio=2.2.

3. Experimental Equipment

To verify the numerical results, an experimental setup of HMDD process was designed, which is shown in Fig. 3. The schematic of employed die set geometry with utilized hydraulic circuit is also shown in Fig. 4. A constant gap with 1.45mm distance between the blank holder and the die was set by using different spacers which are shown in Fig. 5. Pay attention to wide industrial applications of Aluminum/Copper laminated sheets; in this research, two-layer sheets of Copper and Aluminum alloy 3003 were considered and bonded by polyurethane adhesive. These sheets combination performs suitable formability, corrosion resistance, low density against high strength, and electrical conductivity. In HMDD, to form the blank into the final shape, with moving the punch into oil chamber, the blank is forced into the oil chamber and the pressurized oil pushes the blank onto the punch surface. At the forming phase, oil pressure would increase rapidly by entering the punch into the die cavity. After reaching the desired final pressure limit, the operation continues at the stable oil pressure.

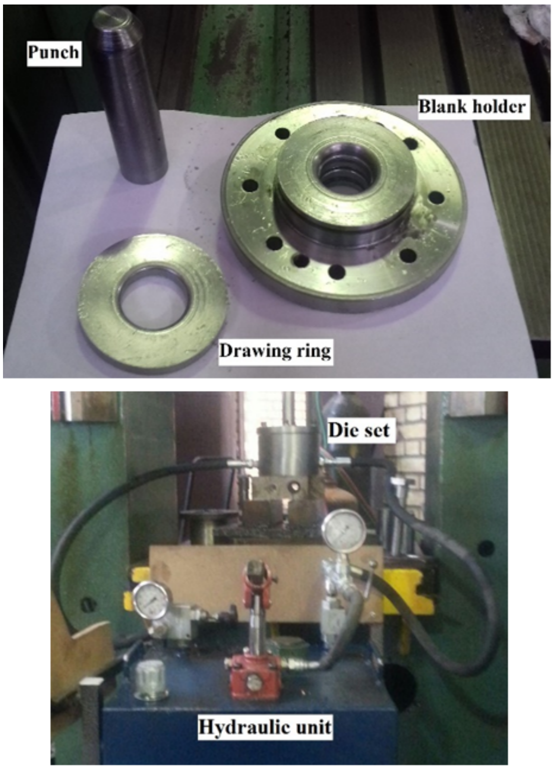

Fig. 3. Experimental equipment for hydromechanical deep drawing of a bilayer conical cup.

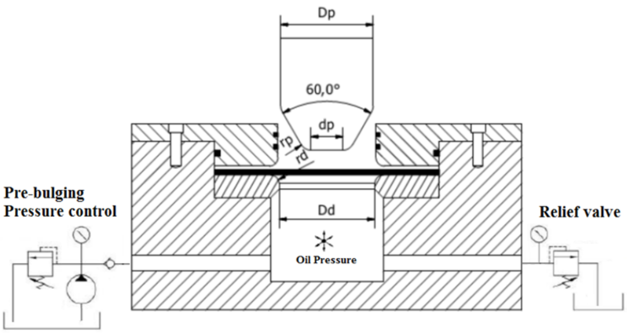

Fig. 4. The geometries of employed die set.

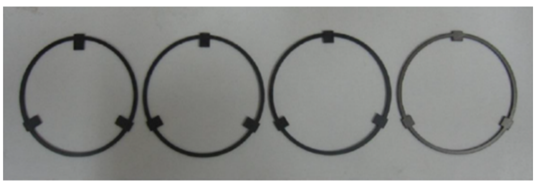

Fig. 5. Different spacers used in experiments.

4. Results and Discussion

4.1. Working Zone and Thickness Distribution

To verify the simulation results, the hydromechanical deep drawing of the Aluminium 3003/Copper laminated sheet at different drawing ratios and pressures of the fluid chamber was done with experimental tools. Amount of pre-bulge pressure applied in experimental and simulations was 4MPa. In order to determine the allowable working zone for specific conditions, all process parameters except final pressure and drawing ratio were kept fixed in simulations. For a specific final pressure, simulation was done with different drawing ratios and the limit drawing ratio was achieved at that pressure. The process window for thickness combination of 0.5mm and 0.8mm for the Aluminium and Copper layers, respectively, is shown in Fig. 6.

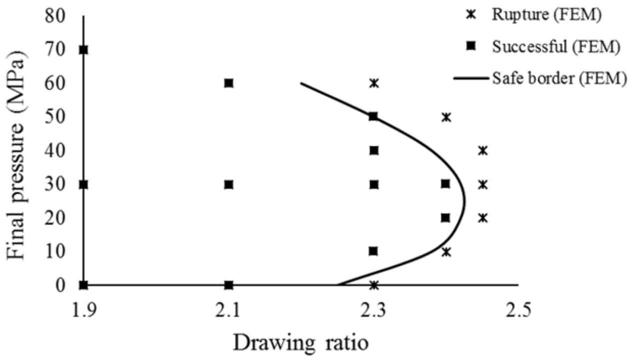

Fig. 6. Working zones extracted from numerical simulations for a bilayer conical cup.

From this working zone diagram, one could extract the optimum chamber pressure to make maximum accessible limit drawing ratio and rupture free part. The maximum of drawing ratio was obtained at $P = 250$bar, which is reduced by decrease or even increase of the final pressure. Fig. 7 illustrates the experimental process window that has suitable similarity to numerical results. It can be seen that amount of pressure obtained in simulation to achieve maximum drawing ratio is lower than experimental ones. Pay attention to the prediction of simulation results, It can be found that as the drawing ratio increases, the safe working zone becomes narrower.

Figs. 8 and 9 show the rupture free and failed parts achieved from experimental tests. The experimental results accept and validate the predicted safe working zone well. Indeed, in a few samples that were deep drawn in Cu/Al layer combination, the lower maximum drawing ratio achieved, which shows when copper is the outer layer, there is better condition to achieve a higher drawing ratio. The reason is that the outer layer sustains more deformations and tensile stresses, so according to higher strength and formability of copper, higher LDR could be achieved when the Cu layer is arranged to be the outer layer.

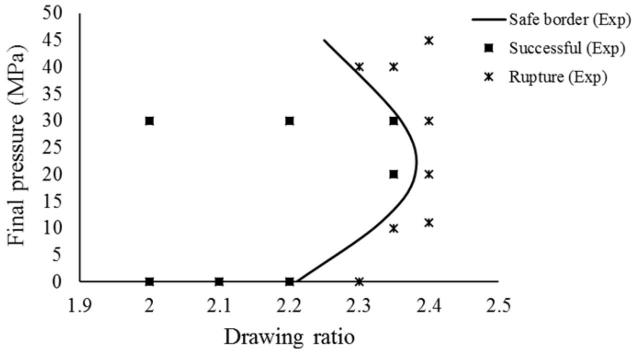

Fig. 7. Working zones extracted from experimental tests for a bilayer conical cup.

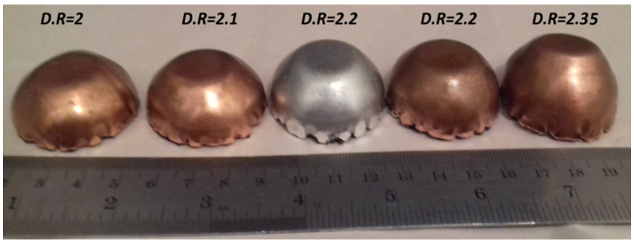

Fig. 8. Experimental samples without rupture.

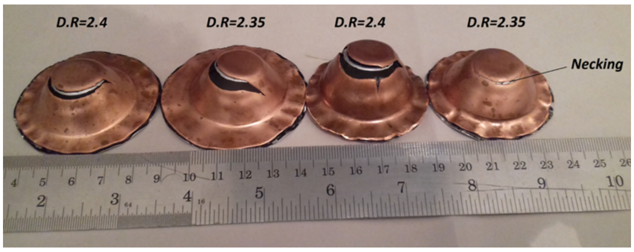

Fig. 9. Experimental samples with rupturing and necking.

As it is shown in Fig. 10, to investigate the thickness distribution of both layers and parts critical zone, the punch and subsequently deformed parts were divided into different regions. Fig. 11 shows the thickness distribution curve of both layers. It is clear from this figure in the top of the conical head, region A, that the thickness reduction is not too much. The most thickness reduction occurred in B region. The most important point in forming of bilayer cups is this point where the outer layer has the maximum thinning. So, for the cases that have been studied in this paper, it is better to put the layer with higher strength and formability as outer layer. However, this is not a general conclusion, and more investigations need to be done for other cases.

4.2. Effect of Coefficient of on Maximum Thinning

According to the large effect of coefficient of friction on the forming process such as deep drawing, rolling etc. Effect of friction between the blank and the blank-holder and also between the blank and the punch on the limit drawing ratio was investigated for two different thickness combinations. Fig. 12 shows the effect of friction between the punch and the blank on the limit drawing ratio. As shown in Fig. 12, as coefficient of friction between the blank and the punch increases, the LDR increases as well. This is due to better attachment of the blank to punch and consequently prevention of blank slide by punch. Fig. 13 shows the effect of friction between the blank and the blank holder on the limit drawing ratio (obtained from numerical simulation). It can be seen that by increasing the friction between the blank holder and the blank, probability of part necking rises considerably and lower limit drawing ratio becomes accessible. It is clear that due to large blank holding force which is caused by increasing chamber pressure and creating larger frictional force by increasing friction coefficient between blank and blank holder, effect of coefficient of friction between the blank holder and the blank at higher chamber pressures is more than low pressures. Another important point that is distinguished form Figs. 12 and 13 is effect of each material thickness portion on the forming condition. Higher limit drawing ratio is accessible when portion of sheet with higher strength is more than the other layer.

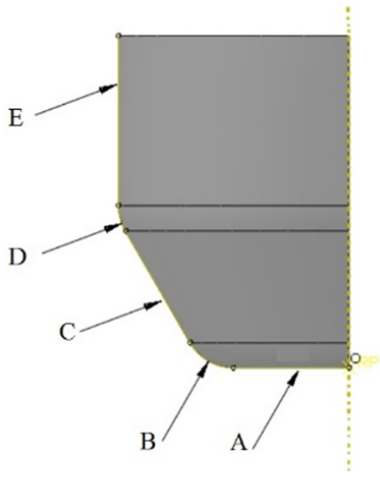

Fig. 10. Different regions of final conical cup.

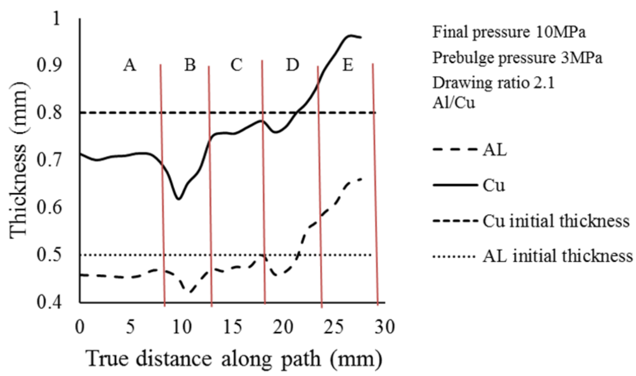

Fig. 11. Thickness distributions of the both layers for a bilayer conical cup.

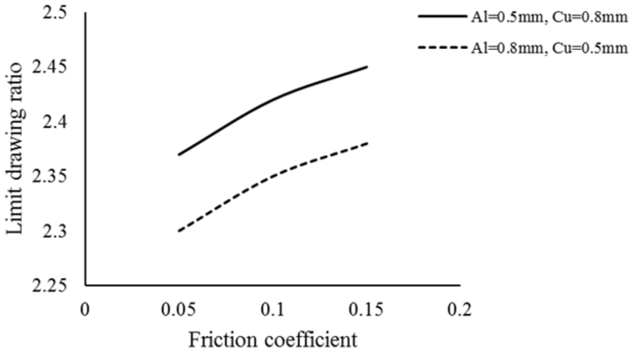

Fig. 12. Effect of coefficient of friction between punch and sheet on LDR of a bilayer conical cup.

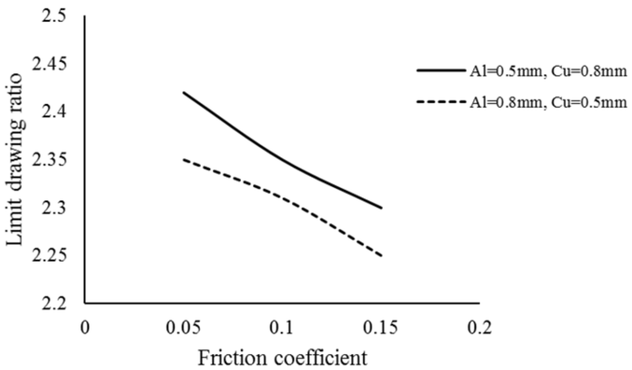

Fig. 13. Effect of coefficient of friction between blank holder and sheet on LDR of a bilayer conical cup (numerical simulation).

4.3. Effect of Pre-bulging Height and Pre-bulging Pressure on the Maximum Thinning

Fig. 14 shows the effect of pre-bulging height on the maximum percent of thinning (obtained from numerical simulation). In the pre-bulging stage, the punch is fixed at a special point, the chamber pressure increases, the blank bulges up and is pushed to punch head. The distance between the punch head and the blank at the initial stage of the process is called pre-bulge height and amount of chamber pressure before punch movement is called pre-bulging pressure. Due to reverse drawing in the Pre-bulging stage, stress status in bulged zone is changed, which prevents the failure at the early stages of forming. According to Fig. 14, increases of pre-bulging height from 0 to 1mm has a small effect on decreasing maximum thinning of the part. But by increasing the pre-bulge height from 1 mm to 4mm, probability of the rupture will increase due to rise in the tensile stress effects.

Fig. 15 shows maximum thinning ratio when pre-bulging pressure considered as a variable in a constant condition. It is obvious that better forming with higher quality is achievable with applying pre-bulging pressure than doing process without pre-bulging pressure. The best range of pre-bulging pressure in the above-mentioned condition is between 2MPa to 4MPa.

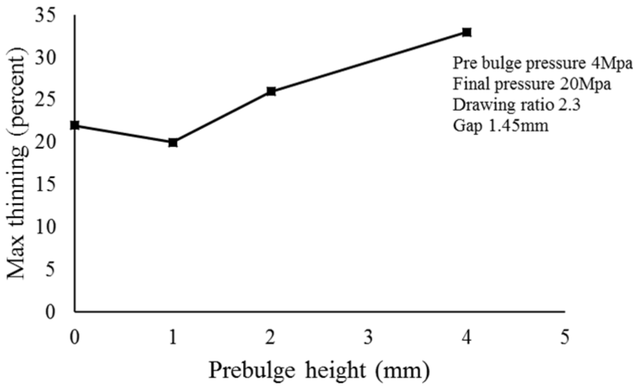

Fig. 14. Effect of pre-bulging height on maximum thinning of a bilayer conical cup (numerical simulation).

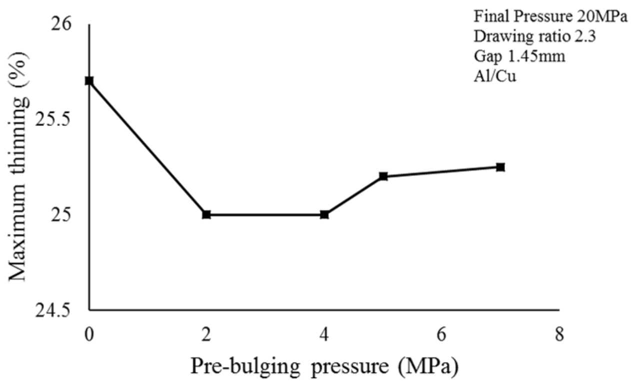

Fig. 15. Effect of pre bulge height on maximum thinning of a bilayer conical cup.

4.4. Effect of Final Pressure on Punch Force

As shown in Fig. 16 because of applying pressure in reverse direction of the punch move direction, amount of punch force and subsequently hydraulic press capacity needed in hydromechanical deep drawing process increases.

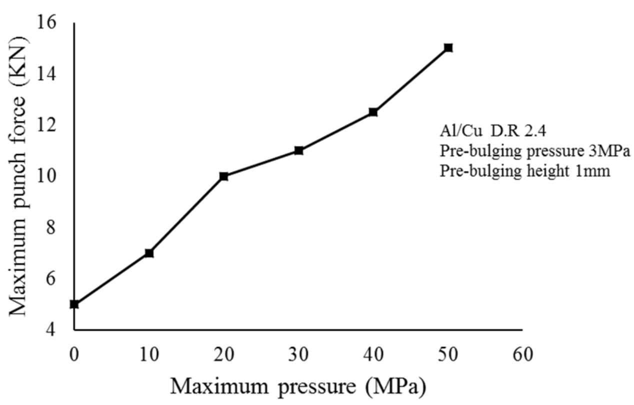

Fig. 16. Maximum punch force against different chamber pressure of a bilayer conical cup.

4.5. Effect of Drawing Ratio on Thickness Distribution

In Figs. 17 and 18 thickness distribution diagrams of both layers extracted from simulations for different drawing ratios are shown. It can be found that maximum and minimum thickness reductions of the layers belong to regions B and A respectively. This is because the region A is in contact with a rigid body from the beginning of the process and behaves like it, hence it has the minimum thickness reduction. Furthermore, Region B is in contact with the punch radius and is applied to the highest tensile stress. Therefore, it has the maximum thickness reduction. Moreover, it can be concluded that the amount of maximum thinning rised with higher drawing ratio.

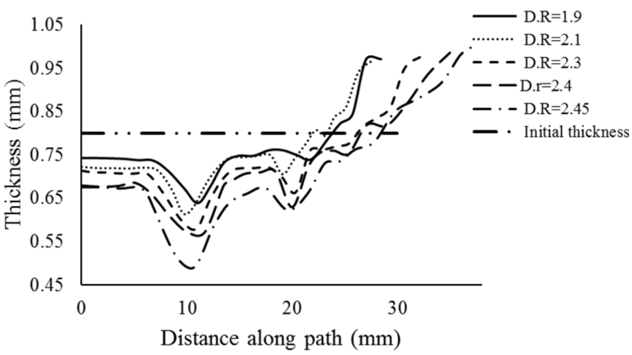

Fig. 17. Thickness distribution of Copper for different drawing ratio with constant condition. Final pressure= 20MPa, Pre-bulging pressure= 4MPa.

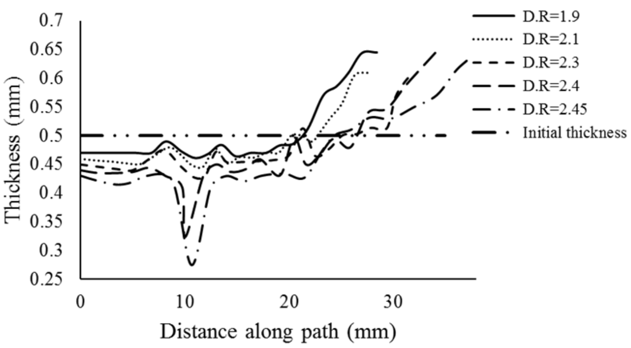

Fig. 18. Thickness distribution of Aluminum for different drawing ratio with constant condition. Final pressure= 20MPa, Pre-bulging pressure= 4MPa.

5. Conclusions

In this paper, experimental study and FE simulation of bilayer sheet hydroforming of conical parts were performed. In the FEM, effects of the process parameters such as coefficient of friction, pre-bulging pressure, and pre-bulge height on the maximum thinning were investigated. In addition, thickness distribution of the both layers after forming was compared with simulation results. To validate the working zone that achieved from FE simulations, some experimental tests were done, where there was good adaption between them. The following conclusions were drawn:

- Higher drawing ratio can be achievable when the layer with higher strength and higher formability is considered as an outer layer.

- As the coefficient of friction between the punch and the blank increases, maximum thickness reduction is confined, while increasing friction coefficient between the blank holder and the blank increases maximum thinning.

- There is an optimum pre-bulge height and pre-bulging pressure for producing a part with minimum thinning that in this case study, the best pre-bulge height is 1mm and optimum pre-bulging pressure rate is between 2MPa to 4MPa. By increasing the pre-bulge height and pre-bulge pressure from optimum value, the maximum thinning in the critical region of the part increases.

- In forming process of the bilayer conical cups, maximum thinning occurs in outer layer and specially punch tip zone, and the minimum thinning occurs in a punch head area.

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