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Effect of Sheet Thickness and Punch Roughness on Formability of Sheets in Hydromechanical Deep Drawing

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The importance of hydromechanical deep drawing is due to certain advantages over conventional deep drawing such as better formability, reduced number of manufacturing steps, improved surface finish, etc. Due to this, the potential applications of hydromechanical deep drawing have increased in the recent years. In this process, sheet metal parts are formed with the assistance of fluid pressure. The present work addresses the effect of sheet thickness and punch roughness on the formability of interstitial-free steel sheets in hydromechanical deep drawing. Experimental work has been done to study the influence of counter pressure on drawability by varying the sheet thickness and punch roughness. Finite element method has been used to simulate the process, and the results have been found to be in good agreement with the experimental results. It has been found out that the minimum required counter pressure for successful drawing increases with increase in sheet thickness. Drawability of 1.2 mm thick sheet improved with increase in punch roughness. As the punch roughness increases, the minimum required counter pressure decreases because of improved friction holding effect. For the same punch roughness, the minimum required counter pressure increases with increase in draw ratio.

Keywords counter pressure, drawability, hydromechanical deep drawing, interstitial-free steel sheet, punch roughness, sheet thickness

1. Introduction

In hydroforming of sheets, hydromechanical deep drawing is an important process. In hydromechanical deep drawing or counter pressure deep drawing, the punch deforms the blank to its final shape by moving against a controlled pressurized fluid (Ref 1). Blank is held between the blank holder and the die. A pressure chamber is attached to the lower die in which the fluid is injected so that the blank comes in contact with punch prior to drawing and it causes upward bulging of the blank which is called prebulging. The prebulging gives more uniform elongation in the sheet and cups with more depth can be obtained (Ref 2). As the punch is moved downward, it displaces the fluid in the cavity and hence pressure is built up in the cavity. The counter pressure induces compressive stress on the blank reducing thinning and hence improving formability. The friction between the die and the blank holder is reduced because of the oil film. Figure 1 shows the principle of hydromechanical deep drawing (Ref 1). The advantages of this process over conventional deep drawing can be outlined as follows (Ref 3, 4):

1. Very high limiting draw ratio can be achieved due to continuous action of counter pressure.
2. Better surface finish can be obtained due to lubrication between the lower die and the blank.
3. Thickness distribution is more uniform due to prebulging of the sheets.
4. More complex parts can be formed because of enhanced formability.

In hydromechanical deep drawing, the influence of various process parameters on drawability and failure mechanism has been studied (Ref 5, 6). The counter pressure path has an important effect on formability, and the variation of sheet thickness is expected to influence counter pressure path and hence the safe working zone (Ref 7, 8). Also in hydromechanical deep drawing, it is expected that the punch roughness affects drawability and the minimum required counter pressure (Ref 9, 10). In view of this, the present work is aimed at studying the combined effect of sheet thickness and counter pressure on drawability of interstitial-free (IF) steel sheets in the hydromechanical deep drawing and to determine their influence on optimum working zone for the process. The effect of punch roughness on the required counter pressure in hydromechanical deep drawing has also been studied.

2. Experiments

In the present work, IF steel sheets have been used as they possess excellent formability due to their high strain hardening ability and normal anisotropy. To study the effect of sheet thickness on counter pressure in hydromechanical deep drawing, sheets of four different thicknesses 0.8, 1.0, 1.2, and

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1.5 mm have been used. A minor variation in the mechanical properties of these four sheets was observed and hence the mean values are presented in Table 1.

The experimental setup used for hydromechanical deep drawing include a drawing die, a 30 mm diameter flat bottom cylindrical punch, a blank holder, and a pressure chamber attached to the drawing die. A die entry radius of 8 mm and punch corner radius of 4 mm were used. The tools were mounted on a hydraulic press of 310 tons capacity as shown in Fig. 2. Oil gap refers to the additional clearance between the punch and the cup wall in hydro mechanical deep drawing. The oil gap (clearance between the blank and the die), peak fluid pressure, and initial pressure in the chamber are the important process parameters in hydromechanical deep drawing. The details of the design and development of the experimental setup and the influence of these process parameters on formability of IF steel sheets (of same thickness) have already been reported (Ref 11). A modified die was designed with a taper at the die entry to take advantage of the large oil gap at the beginning and then with a straight cylindrical portion with much less clearance. The optimization of design parameters such as die lip diameter and draft angle using finite element analysis have been reported (Ref 12). In order to capture the load-displacement and pressure-displacement data during experiments, a computerized data acquisition system is used. The data acquisition system consists of a load cell, a rotary encoder, and a pressure transducer. A load cell of 30 tons capacity (with a resolution of 10 kg) was used in these experiments. The rotary encoder (with a resolution of 0.1 mm) and the pressure transducer (with a resolution of 10 Pa) were used to measures the displacement of the punch and the fluid pressure in the chamber, respectively. SAE40 oil was used as the working media in all the experiments.

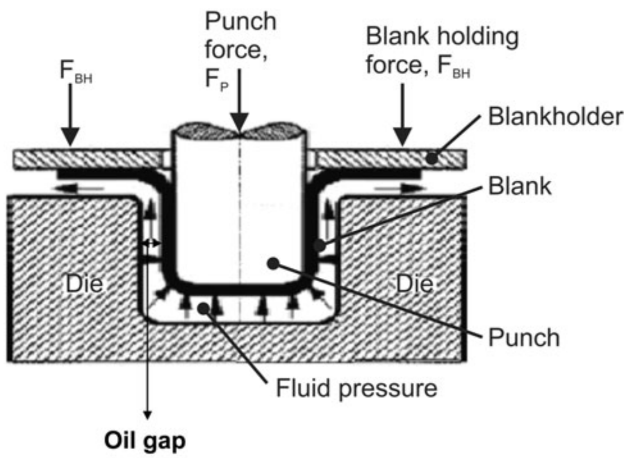


Fig. 1 Principle of hydromechanical deep drawing

Table 1 Mechanical properties of IF steel sheets

	Orientation of specimen with respect to rolling direction		
	0°	**45°**	**90°**
Yield strength, MPa	144	135	131
UTS, MPa	250	265	252
Elongation to fracture, %	50	48	50
Strain hardening exponent, *n*	0.28	0.25	0.26
Strength coefficient, *K*, MPa	550	503	490
Plastic strain ratio, *r*	1.75	1.50	3.07

Initially experiments were done by conventional deep drawing (without using any lubricant) on blanks of all thicknesses to check whether they could be drawn successfully. In conventional deep drawing, suitable blank holding force was applied to prevent wrinkling of the blank during drawing. The blank holding force was applied on the upper die (blank holder). Cups were drawn using hydromechanical deep drawing to determine the maximum draw ratio that can be achieved. Experiments were conducted starting with a draw ratio of 2.3 and then blank diameter was gradually increased to achieve the draw ratio of 2.4, 2.5, and 2.6. With every draw ratio, sheets of four different thicknesses were drawn to study the effect of sheet thickness on the required counter pressure.

In the experiments, the applied blank holding pressure ranged from 2.5 to 5 MPa. No predetermined fluid pressure

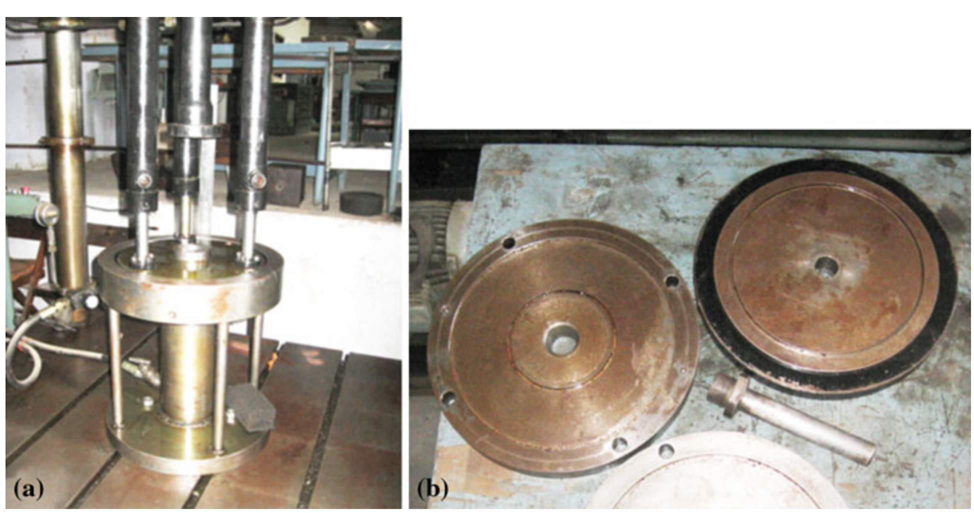


Fig. 2 Experimental setup used for hydromechanical deep drawing experiments. (a) Pressure chamber and the blank holding system and (b) tools (Dies and Punch)

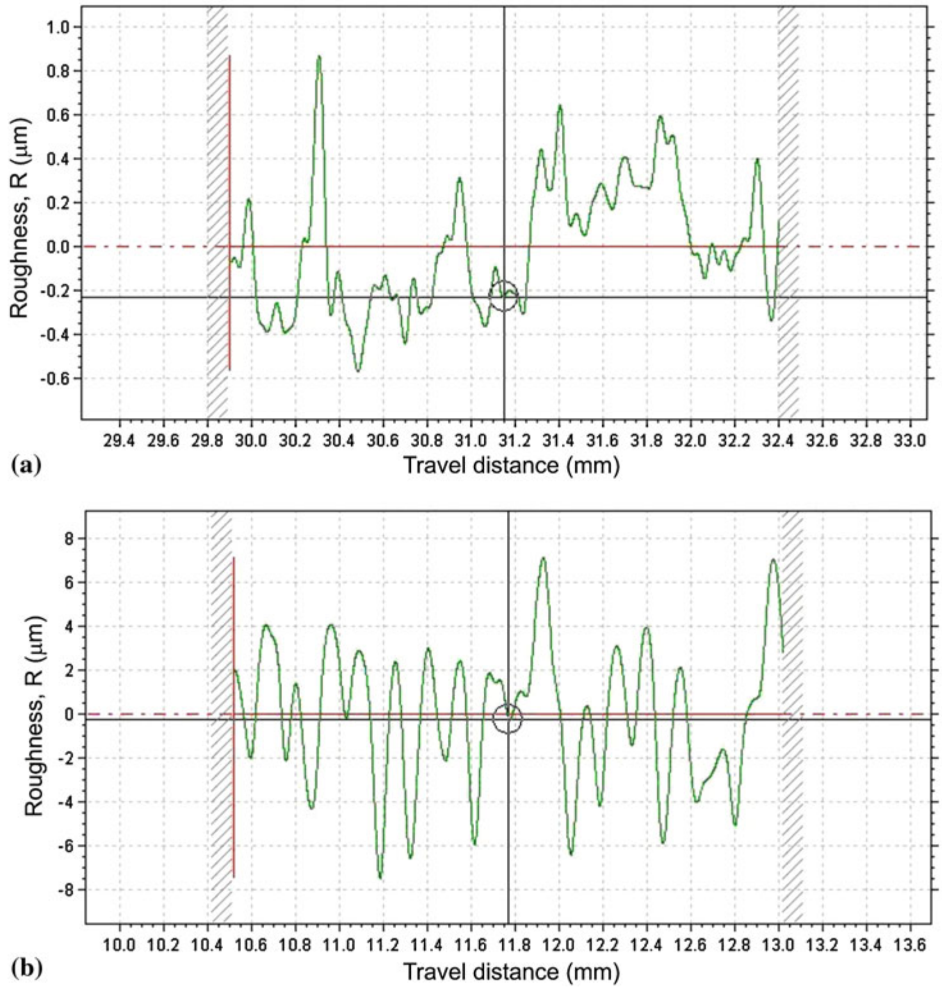


Fig. 3 Roughness profiles of the punches (a) R_a = 0.39 µm; (b) R_a = 2.98 µm; (c) R_a = 5.23 µm, and (d) R_a = 8.24 µm, used in hydromechanical deep drawing experiments

path was used but an initial prebulging pressure was applied by opening the valve connected to the pressure chamber. The applied pressure was measured using a pressure gauge connected to the pressure transducer. The prebulging pressure applied in the present work was in the range of 0.5-1 MPa. During the course of drawing, the chamber pressure increased almost linearly and a relief valve was adjusted to the set cut off pressure. Punch speed of 10 mm/s was used to draw the blanks. The oil leakage was prevented by using the high pressure rubber oil seals. No lubricant was used in conventional deep drawing experiments and in hydromechanical deep drawing, there was forced lubrication due the presence of fluid between the die and the blank.

The effect of punch roughness has been studied using four punches of different roughness for two draw ratios (2.5 and 2.6). In these experiments, sheet thickness was kept constant. The initial chamber pressure and the blank holding pressures applied were the same as those in the above experiments. The thickness of the blanks used in these experiments was 1.2 mm. The variation in roughness was obtained by using different combinations of machining parameters such as feed and also the type of polishing technique after final machining. With fine polishing of the punch by emery paper after final machining, the average roughness (R_a) was found out to be 0.39 µm. The roughness was increased by changing the feed rate in machining and R_a increased to 5.23 µm. High roughness of R_a = 8.24 µm was obtained by fine knurling on the punch. The roughness of the punch was measured on Talysurf texture measuring system with a travel distance of 2.5 mm. To ensure the uniformity, measurement was performed at three locations on the punch wall and the punch bottom and the average was determined. The roughness profiles are shown in Fig. 3.

3. Finite Element Analysis

Finite element analysis was carried out using the commercially available code LS-DYNA to simulate both conventional and hydromechanical deep drawing processes. A typical FE model of the tools used in simulations is shown in Fig. 4. A fine mesh was preferred because it ensures that the geometry is adequately defined. Typically around 1000 (quadrilateral and triangular) shell elements were used to mesh the blank and the exact number depends on the blank dimensions. Belytschko-Tsay shell elements were used and number of integration points through thickness was taken to be 5. The shell thickness was taken equal to the thickness of the blank. The die and the punch

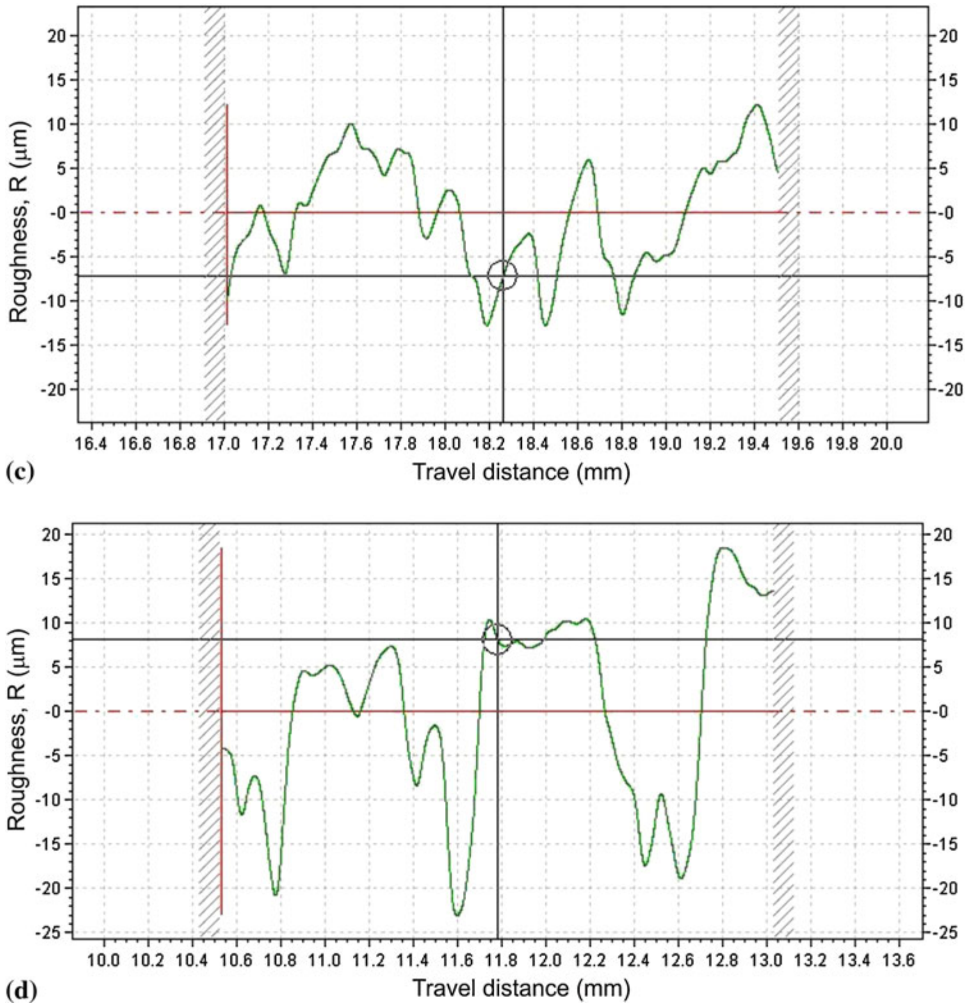


Fig. 3 Continued

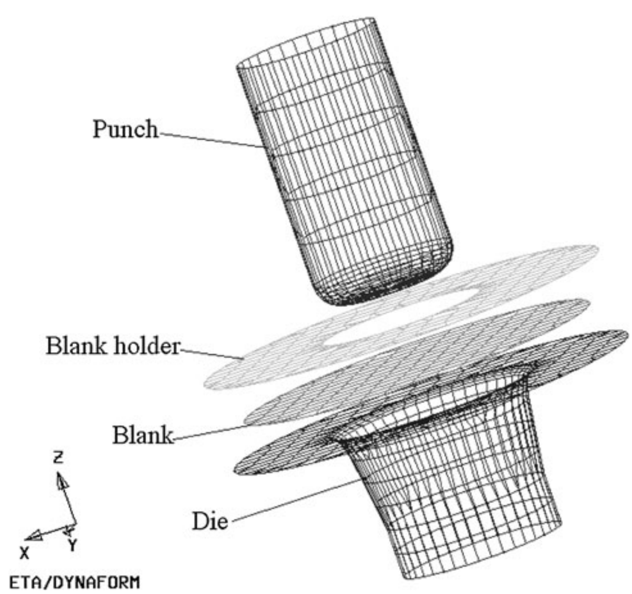


Fig. 4 A typical FE model of the tools used in simulations

were modeled as rigid bodies and the blank as a deformable body.

The material was assumed to be rigid plastic obeying the power law of hardening during strain hardening (Ref 13). The yielding behavior of the material was defined using Barlat's three parameter anisotropic criterions (Ref 14). It incorporates the influence of both normal and planar anisotropy. The anisotropic material parameters in the criterion are determined from the Lankford coefficients r_0, r_{45}, and r_{90} which were given as input to define the material behavior along with the other properties (as given in Table 1).

The Barlat's exponent (M) in the yield criterion was taken to be 6.

In the process parameters, the punch velocity was specified using a trapezoidal profile (punch velocity versus time). This curve was used to define the motion of the punch to a depth of 55 mm as the depth of drawing was approximately 45 mm. The total punch displacement was divided into 25 time steps. To reduce the computational time, the punch velocity was taken as 1000 mm/s which is 100 times the actual punch speed. Several simulations were carried out in order to arrive at the optimum blank holding force to prevent wrinkling and cracking and it has been found to be in the range of 25 to 55 KN depending on the process, blank size, and thickness. Because of the counter pressure in hydromechanical deep drawing, the applied blank holding force was higher compared to conventional deep drawing.

The friction between the blank and the rigid surfaces was modeled using Coulomb's law of friction. Since no lubricant was used in conventional deep drawing, coefficient of friction was taken to be 0.125 in simulations of conventional deep drawing at all contacts between the tools and the blank. In hydromechanical deep drawing the lubrication can be approximated to semi-fluid film lubrication between the die and the blank because of the influence of fluid under pressure as suggested in an earlier work (Ref 15). The coefficient of friction was taken as 0.05 between the dies and the blank and between punch and the blank, it was taken as 0.125 (Ref 15).

In the case of hydromechanical deep drawing, a counter pressure was specified on the blank in the opposite direction of the punch travel by applying pressure boundary conditions. The counter pressure path was also specified in the input conditions. This path depends on volume of cavity, punch speed, and prebulging pressure. The pressure path used in simulations was approximated from the pressure path obtained in the experiments.

Using the parameters discussed above, a large number of simulations were carried out to study the effect of sheet thickness and to predict the minimum possible pressure at which a particular sheet can be drawn successfully. Simulations were carried out for draw ratios of 2.3, 2.4, 2.5, and 2.6 to compare the results with the experimental results.

In the simulations, forming limit diagrams (FLDs) were used to identify the step at which the deformation in the sheet reaches a stage where the strains at some locations exceed the maximum safe strains. The limiting draw ratio was obtained by carrying out several simulations gradually increasing the blank diameter (draw ratio). Simulations were carried out to study the thickness variation in the successfully drawn cups with the same parameters used in the experiments for comparison.

Table 2 Summary of the experimental results with blanks of different thickness for draw ratios (a) 2.3, (b) 2.4, (c) 2.5, and (d) 2.6

Sheet thickness, mm	Process and peak counter pressure, MPa	Remark
(a) Draw ratio 2.3		
0.8	CDD	Success
1.0	CDD	Success
1.2	CDD	Success
1.5	CDD	Failure
	HDD (14)	Failure
	HDD (15, 17, 19, 21)	Success
(b) Draw ratio 2.4		
0.8	CDD	Success
1.0	CDD	Success
1.2	CDD	Failure
	HDD (1.5, 4.5, 7.5, 15.0)	Success
1.5	CDD	Failure
	HDD (9.0, 17.0, 19.0)	Failure
(c) Draw ratio 2.5		
0.8	CDD	Success
	HDD (0.5, 1.5, 14.0)	Success
1.0	CDD	Success
	HDD (1.5)	Success
1.2	CDD	Failure
	HDD (6.0, 7.0, 9.0)	Failure
	HDD (12.5, 17.0)	Success
1.5	CDD	Failure
	HDD (9.0, 15.0, 16.0)	Failure
(d) Draw ratio 2.6		
0.8	CDD	Success
1.0	CDD	Failure
	HDD (2.5, 7.0, 9.0, 16.0)	Failure
1.2	CDD	Failure
	HDD (10.0, 15.0)	Failure

CDD, Conventional deep drawing; HDD, hydromechanical deep drawing

4. Results and Discussions

The summary of the results on drawability of IF steel sheets of four different thicknesses obtained from conventional deep drawing and hydromechanical deep drawing experiments for different draw ratios are given in Table 2. The peak counter pressures reached in hydromechanical deep drawing are also given and success or failure is indicated.

As can be seen from Table 2, for the draw ratio of 2.3, sheets of thicknesses 0.8, 1.0, and 1.2 mm have been drawn successfully by using conventional drawing itself. Therefore, the sheets were not drawn using hydromechanical deep drawing for this draw ratio. The 1.5 mm sheet could not be drawn in conventional deep drawing indicating that its limiting draw ratio in conventional deep drawing is lower than 2.3. When this was drawn by using hydromechanical deep drawing with pressures up to 21 MPa, it was found that the minimum counter pressure required for successful drawing was 15 MPa.

For the draw ratio of 2.4, sheets with thickness 0.8 and 1.0 mm were successfully drawn in conventional deep drawing but sheets of higher thickness showed failure at the cup bottom in conventional deep drawing. By applying counter pressures up to 15 MPa in hydromechanical deep drawing, 1.2 mm thick sheet was drawn successfully. The minimum pressure at which it could be drawn was found out to be 1.5 MPa.

The 1.5 mm sheet could not be drawn even in hydromechanical deep drawing by varying the counter pressure in the possible range. The pressure did not rise beyond 19 MPa because of the occurrence of fracture during deformation at the cup bottom. Successfully drawn cups from 1.2 mm thick sheet with different draw ratios using hydromechanical deep drawing are shown in Fig. 5. The results obtained from conventional deep drawing and hydromechanical deep drawing experiments for the draw ratio of 2.5 are similar to those discussed above for the draw ratio of 2.4. The sheets of thickness 0.8 and 1.0 mm could be drawn in conventional deep drawing and also in hydromechanical deep drawing with very low counter pressures of 0.5 and 1.5 MPa, respectively. The 1.2 mm sheet could not be drawn in conventional deep drawing, but the experiments were successful in hydromechanical deep drawing with a counter pressure of 6 MPa and above like in the previous case. The 1.5 mm thick sheet could not be drawn successfully even at higher pressures. For the highest draw ratio of 2.6, only 0.8 mm thick sheet could be drawn successfully with a counter pressure of 1.5 MPa. Failure was observed in all the other sheets even at much higher counter pressures. The summary of the experimental observations are shown in Fig. 6 for draw

Fig. 5 Successfully deep drawn cups from 1.2 mm thick sheet with different draw ratios using hydromechanical deep drawing

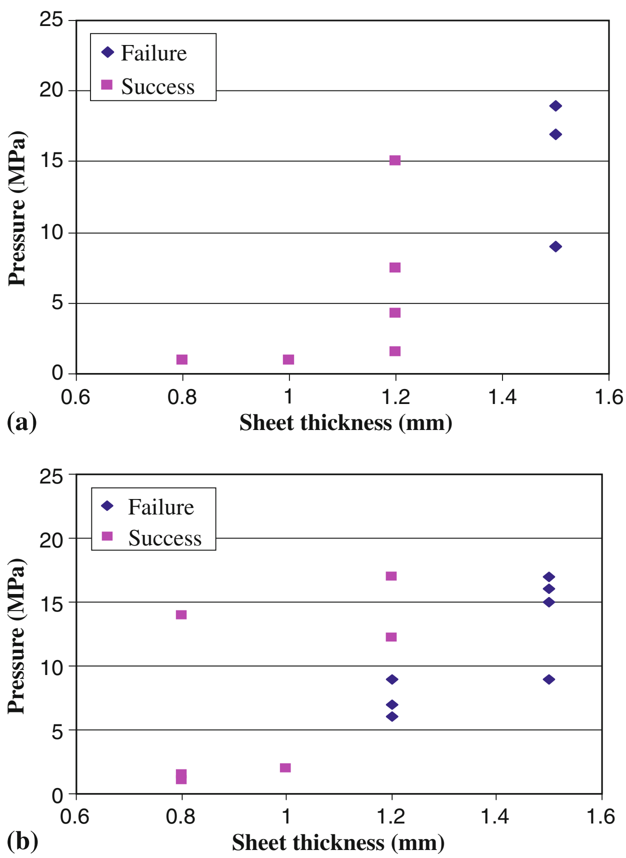


Fig. 6 Variation of counter pressure with sheet thickness for draw ratio of (a) 2.4 and (b) 2.5

ratios 2.4 and 2.5. Some typical failures occurred in hydromechanical deep drawing are shown in Fig. 7.

As discussed in an earlier work (Ref 16), as the oil gap increases, drawability increases. This is due to larger area of the blank being subjected to prebulging pressure leading to more uniform strain distribution. In this work, the same experimental setup has been used for all the sheets and so, as the sheet thickness increases, the oil gap decreases and hence the drawability decreases. To achieve higher draw ratios for thicker sheets (for the same punch-die clearance), higher counter pressures are required as demonstrated in this paper.

Fig. 7 Typical failures observed in hydromechanical deep drawing

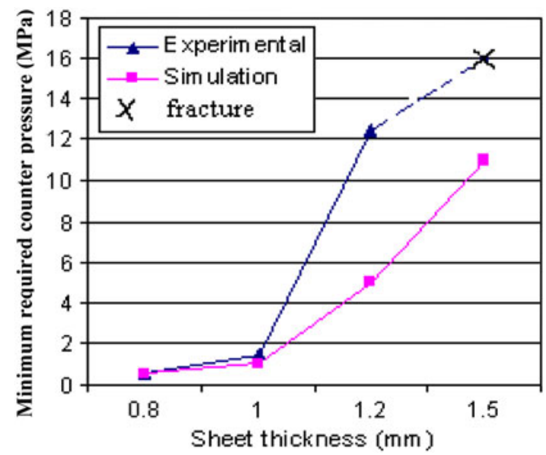


Fig. 8 Effect of sheet thickness on minimum required counter pressure with 2.5 draw ratio

It has been found out in the experiments that the minimum required counter pressure for successful drawing increases with increasing sheet thickness. The variation of this minimum required counter pressure with sheet thickness for a draw ratio of 2.5 is shown in Fig. 8. The predicted values from simulations are also shown in the figure for comparison. Such plots have not been shown for the draw ratios of 2.3 and 2.4 at which most of the sheets could be drawn in conventional deep drawing and for the draw ratio of 2.6 at which only one sheet could be drawn successfully in hydromechanical deep drawing.

The successfully drawn cups in finite element simulations of hydromechanical deep drawing for each sheet thickness at the minimum possible pressure are shown in Fig. 9. The corresponding strain data super imposed on the FLD at the last step is also shown. The figures indicate the presence of few wrinkles in the predicted results of finite element simulations. This is a very common feature of deep drawing when the cup is completely drawn into the die cavity. Very few wrinkles at the top of the cup (due to primary wrinkle in the flange) cannot be considered as a failure in cup drawing as the most of the deformed region lies in safe region.

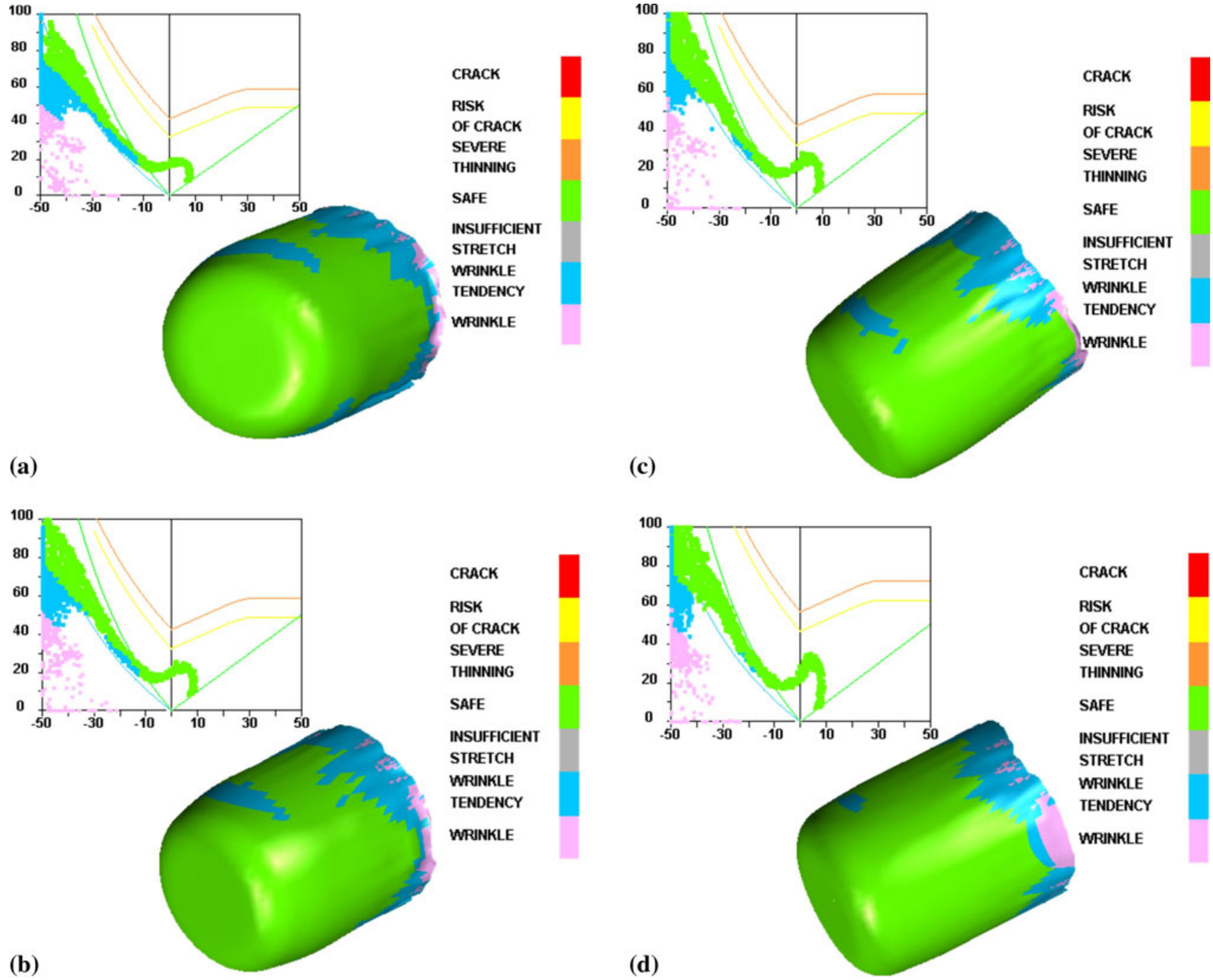


Fig. 9 Simulation results for hydromechanical deep drawing process with draw ratio 2.5 for sheet thickness of (a) 0.8 mm; (b) 1.0 mm; (c) 1.2 mm, and (d) 1.5 mm. The strain data from cups are superimposed on the corresponding forming limit diagrams

As shown in Fig. 8, the predicted minimum counter pressure by FLD simulations for the draw ratio of 2.5, agreed well with the experimental data for the sheets of lower thicknesses (0.8 and 1.0 mm). But for the sheets of higher thickness of 1.2 mm, the variation between the experimental and the predicted value is large. This could be due to experimental errors leading to faster rise in pressure.

For 1.5 mm sheet thickness, simulation showed successful drawing at a counter pressure of 11 MPa, where as in experiments failure was observed even at a pressure of 16 MPa.

Thickness variation was obtained from both experiments and simulations for all the sheet thicknesses for a fixed draw ratio of 2.5. Successful cups which were drawn at the minimum possible pressures were taken for observation. Simulations were carried out with the same minimum pressures obtained in experiments, and the thickness variation was taken from these thickness contours and the percentage change in thickness was calculated. The thickness measurements in the deep drawn cups were always made along the rolling direction in all the cases (in both simulations and experiments). The percentage change in thickness obtained from experiments and the simulations for each thickness are shown in Fig. 10. Two typical thickness contours obtained from simulations for sheets of 0.8 and 1.0 mm are shown in Fig. 11. From the plots, it is observed that the variation in thickness observed from experiments and simulations are in good agreement. As expected, the maximum thinning is near the cup wall bottom close to the punch corner because of stress concentration due to small punch corner radius and plane strain stretching of the cup wall. The thickness increases from the center of the cup as we move up along the cup wall. Significant thickening was observed near the top portion of the cup wall due to compressive stresses in the flange leading to wrinkling. Though higher oil gap increases drawability in hydromechanical deep drawing, it also leads to wrinkling and shape distortion (Ref 16). For the same punch-die combination, higher wrinkling is expected for thinner sheets. This has been observed in the present work also (as shown in Fig. 11 for sheets of lower thickness, i.e., 0.8 and 1.0 mm). This can be avoided by combining ironing with drawing in the same die as proposed in an earlier work (Ref 12).

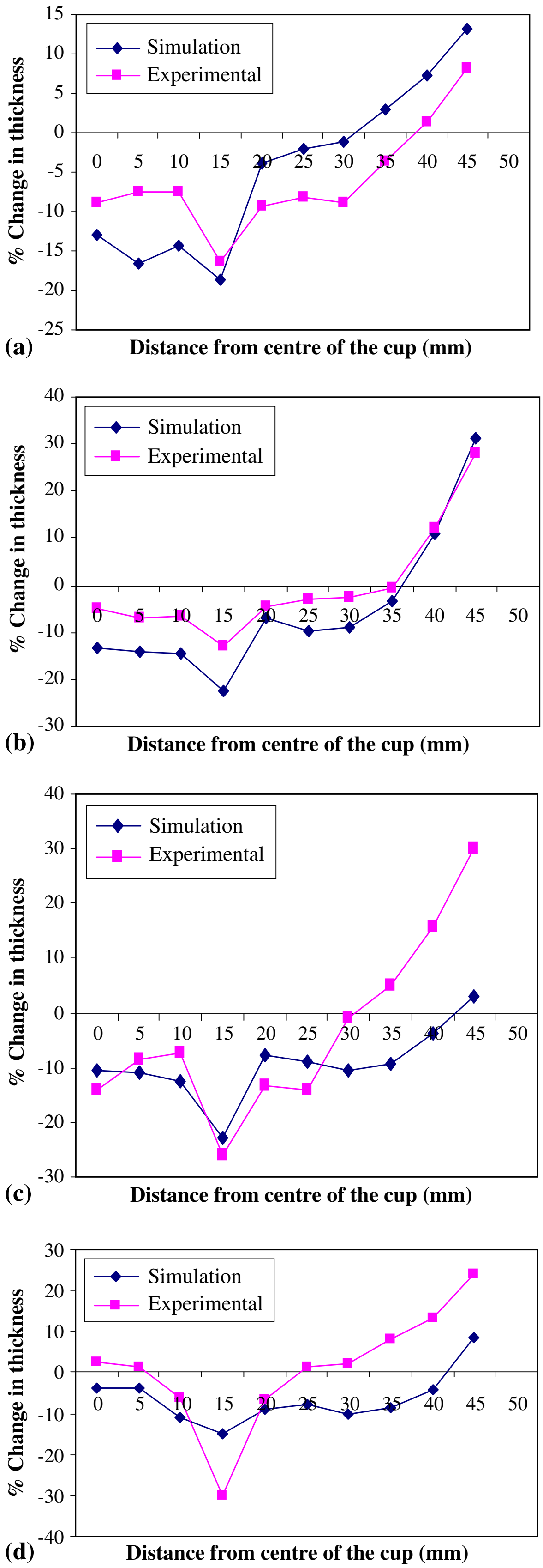


Fig. 10 Comparison of experimental and predicted thickness variations in the drawn cups by hydromechanical deep drawing of sheet thickness (a) 0.8 mm; (b) 1.0 mm; (c) 1.2 mm, and (d) 1.5 mm

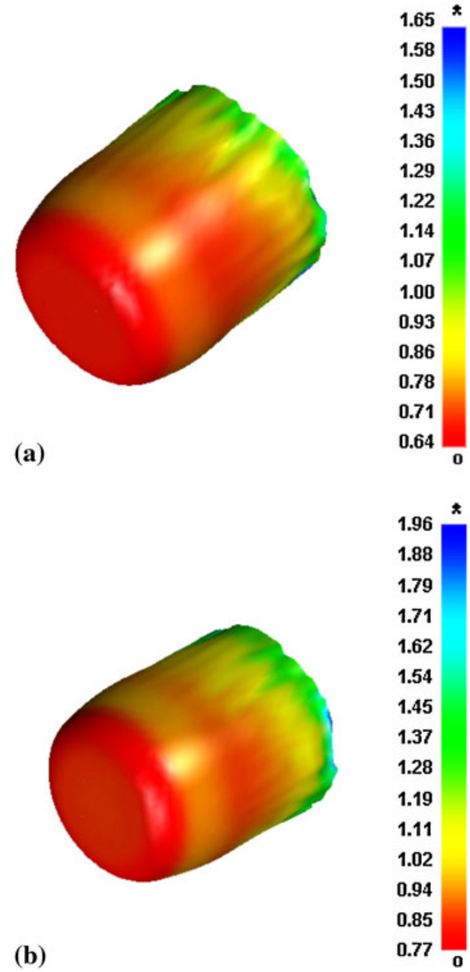


Fig. 11 Thickness contours from finite element simulation of hydromechanical deep drawing process at minimum possible counter pressure with sheet thickness of (a) 0.8 mm and (b) 1.0 mm

Figure 12 shows typical variations of load and counter pressure with displacement for all four sheets of different thickness in hydromechanical deep drawing. In hydromechanical deep drawing, additional drawing force is required to overcome the counter pressure and because of this, the total force required in hydromechanical deep drawing is significantly higher than the force required in conventional deep drawing for the same conditions. As discussed earlier, both load and the pressure increase in hydromechanical deep drawing with increase in sheet thickness. The peak loads observed are 2.6, 3.5, and 5.6 t for sheets of 0.8, 1.0, and 1.2 mm, respectively, for the constant draw ratio of 2.5 and in the case of 1.5 mm sheets, the peak load was 5.6 t for the draw ratio of 2.3.

5. Effect of Punch Roughness

The summary of the results obtained from experiments using punches with different values of roughness in both conventional deep drawing and hydromechanical deep drawing are shown in Fig. 13 for draw ratios of 2.5 and 2.6. All the tests were done for 1.2 mm thick blanks.

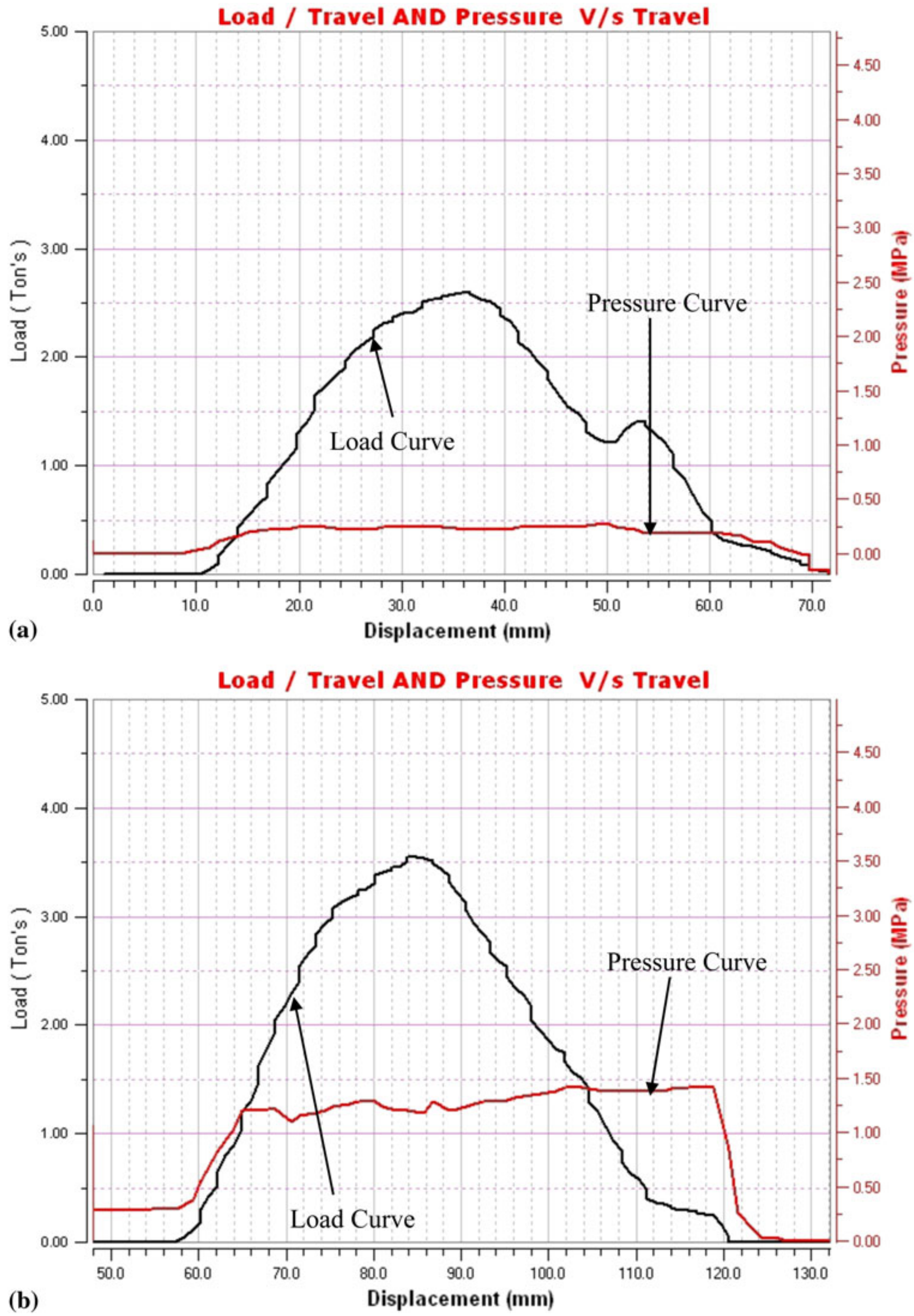
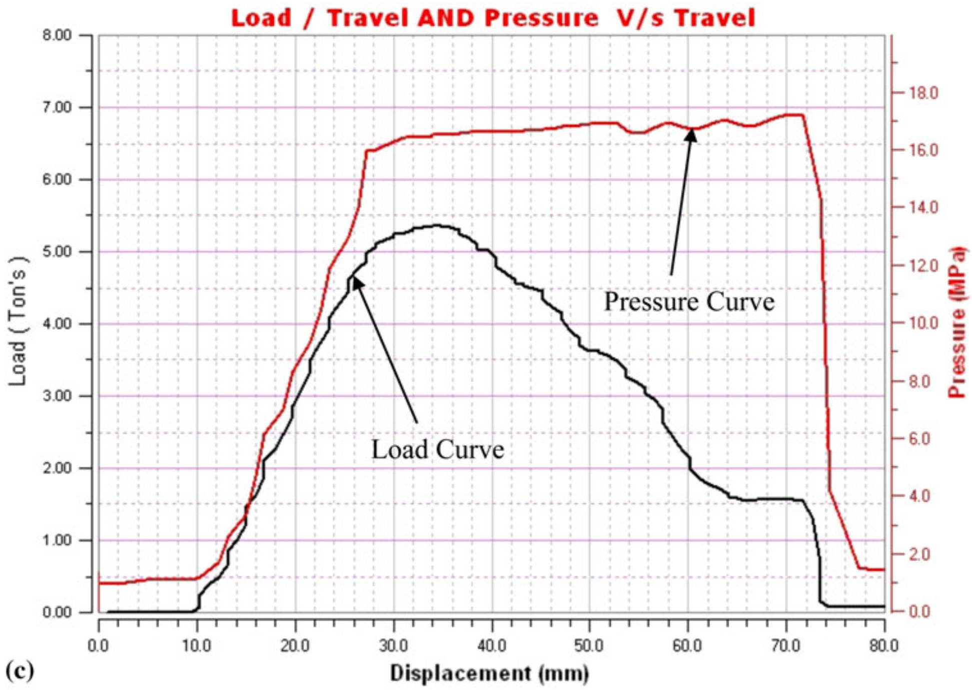
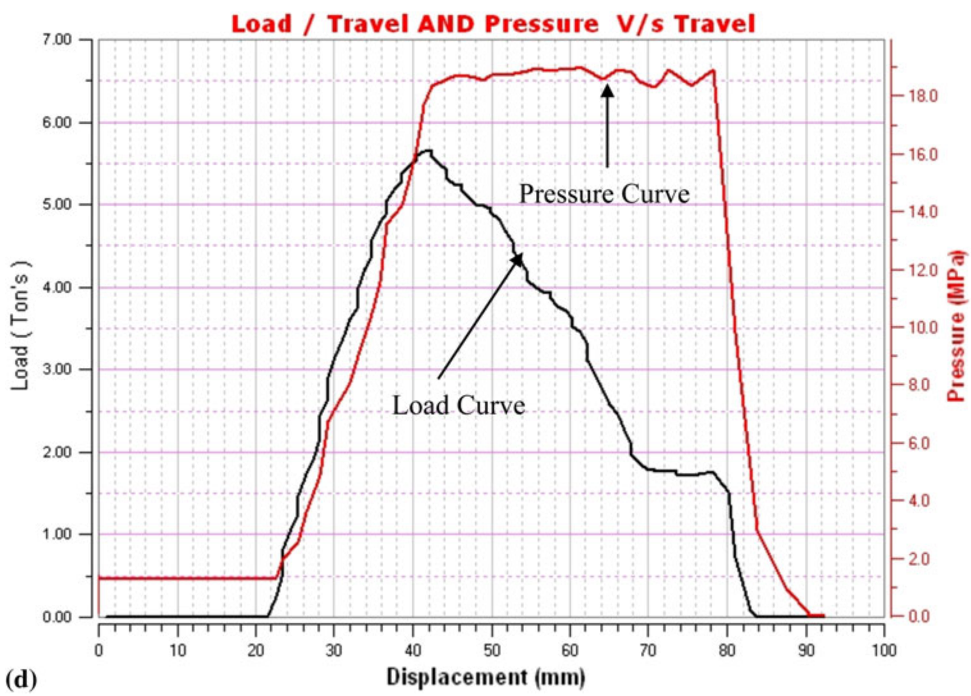


Fig. 12 Variation of load and counter pressure with displacement for sheets of thickness (a) 0.8 mm; (b) 1.0 mm; (c) 1.2 mm, and (d) 1.5 mm

It has been observed that punch roughness improves drawability in hydromechanical deep drawing as indicated by the experiments done with punch roughness values (R_a) of 5.23 and 8.24 μm. For the roughness values of 0.39 μm, cups could not be drawn successfully in both conventional deep drawing and hydromechanical deep drawing at both the draw ratios of 2.5 and 2.6. When the roughness is increased to 2.98 μm, with counter pressures of 12.5 MPa and above, cups were drawn successfully in hydromechanical deep drawing. But at higher roughness (5.23 and 8.24 μm), the cups were drawn successfully even at very low pressures of 1-1.5 MPa for the draw ratio of 2.5. This is due to improved friction holding effect when the punch roughness is higher. Improvement in drawability can be obtained by shifting the failure site up the cup wall by mechanical factors such as gripping the cup more firmly around the punch (Ref 13). Both roughening the punch and application of counter pressure help to achieve this better friction holding effect. Therefore, the cups can be drawn successfully even at



(c)



(d)

Fig. 12 Continued

lower pressures if the punch roughness is higher. For a given draw ratio, the minimum required counter pressure decreases with increasing punch roughness as observed in the experiments (Fig. 13). It was also found out that for the same roughness value, the minimum required pressure in hydromechanical deep drawing for successful drawing increases with increase in draw ratio. It can be seen that the minimum required pressures for 2.6 draw ratio are 22 and 18 MPa for roughness values of 5.23 and 8.24 µm, respectively. These values are much higher when compared to the corresponding values for the draw ratio of 2.5.

6. Conclusions

Based on the present work, the following conclusions are drawn. It has been found out from the hydromechanical deep

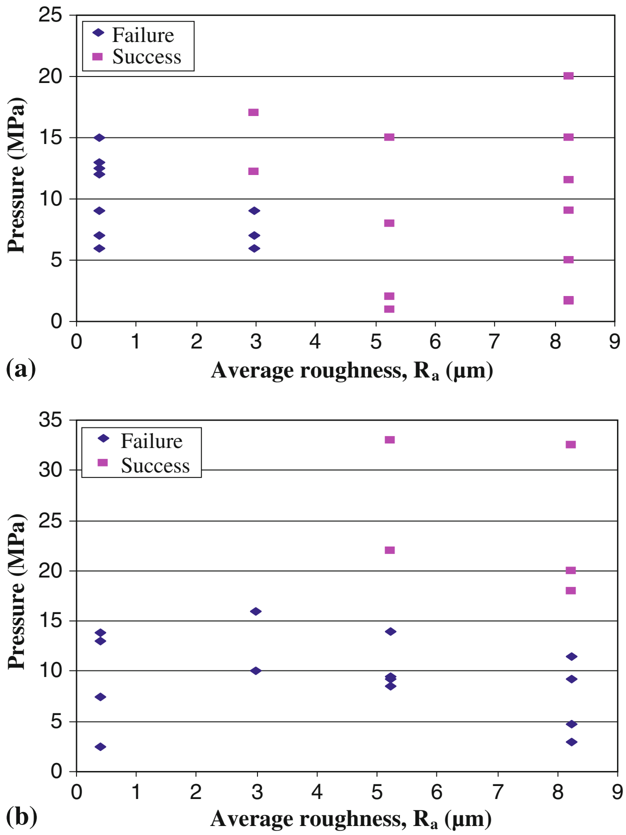


Fig. 13 Summary of the experimental results on 1.2 mm thick sheet with different punch roughness values for draw ratio (a) 2.5 and (b) 2.6

drawing experiments on IF steel sheets of four different thicknesses that the minimum required counter pressure for successful drawing increases with increase in sheet thickness. The predictions from finite element simulations also showed similar trend, and the predicted values have agreed well with experimental data for the sheets of thickness 0.8 and 1.0 mm. The thickness variations in the deep drawn cups from both experiments and simulations showed maximum thinning of about 15-25%. Drawability of 1.2 mm thick sheet in hydromechanical deep drawing improved with increase in punch roughness value. As the punch roughness increases, the minimum required counter pressure decreases because of improved friction holding effect. For the same punch roughness, the minimum required counter pressure increases with increase in draw ratio.

References

1. S.H. Zhang and J. Danckert, Development of Hydromechanical Deep Drawing, *J. Mater. Process. Technol.*, 1998, **83**, p 14–25
2. A. Kandil, An Experimental Study of Hydroforming Deep Drawing, *J. Mater. Process. Technol.*, 2003, **134**, p 70–80
3. K. Nakamura and T. Nakagawa, Sheet Metal Forming with Hydraulic Counter Pressure in Japan, *Ann. CIRP*, 1987, **36**(1), p 191–194
4. K. Nakamura, H. Amino, and T. Nakagawa, Counter Pressure Deep Drawing and Its Applications in the Forming of Automobile Parts, *J. Mater. Process. Technol.*, 1990, **23**, p 243–265
5. S.H. Zhang, M.R. Jensen, J. Danckert, K.B. Nielsen, D.C. Kang, and L.H. Lang, Analysis of the Hydromechanical Deep Drawing of Cylindrical Cups, *J. Mater. Process. Technol.*, 2000, **103**, p 367–373
6. A. Fazli and B.M. Dariani, Theoretical and Experimental Analysis of the Axisymmetric Hydromechanical Deep Drawing, *Proc. Inst. Mech. Eng.*, 2006, **220**, p 1429–1437
7. J. Wu, R. Balendra, and Y. Qin, A Study on the Forming Limits of the Hydromechanical Deep Drawing of Components with Stepped Geometries, *J. Mater. Process. Technol.*, 2004, **145**, p 242–246
8. S.H. Zhang, M.R. Jensen, J. Danckert, K.B. Nielsen, D.C. Kang, and L.H. Lang, Effect of Anisotropy and Prebulging on Hydromechanical Deep Drawing of Mild Steel Cups, *J. Mater. Process. Technol.*, 2003, **142**, p 544–550
9. L.H. Lang, J. Danckert, and K.B. Nielsen, Analysis of Key Parameters in Sheet Hydroforming Combined with Stretch Forming and Deep Drawing, *Proc. Inst. Mech. Eng.*, 2004, **218**, p 845–855
10. L. Lang, J. Danckert, and K.B. Nielsen, Investigation into Hydrodynamic Deep Drawing Assisted by Radial Pressure, Part II: Numerical Analysis of the Drawing Mechanism and the Process Parameters, *J. Mater. Process. Technol.*, 2005, **166**, p 150–161
11. S.K. Singh and D. Ravikumar, Numerical Predictions of Limiting Draw Ratio and Thickness Variation in Hydromechanical Deep Drawing, *Int. J. Mater. Product Technol.*, 2004, **21**, p 106–123
12. S.K. Singh, A. Dixit, and D. Ravikumar, Optimization of the Design Parameters of Modified Die in Hydromechanical Deep Drawing Using LS-DYNA, *Int. J. Adv. Manuf. Technol.*, 2008, **38**, p 32–37
13. W.F. Hosford and R.M. Caddell, *Metal Forming Mechanics and Metallurgy*, 2nd ed., Printice Hall, New Jersey, 1993
14. F. Barlat and Lian, Plastic Behavior of and Stretchability of Sheet Metals. Part 1, *Int. J. Plast.*, 1989, **5**, p 51–66
15. S. Thiruvarudchelvan and W. Lewis, A Note on Hydroforming with Constant Fluid Pressure, *J. Mater. Process. Technol.*, 1999, **88**, p 51–56
16. S.K. Singh and D. Ravikumar, Effect of Process Parameters on Product Surface Finish and Thickness Variation in Hydromechanical Deep Drawing, *J. Mater. Process. Technol.*, 2008, **204**, p 169–178