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Deep drawing of cup shaped steel component: finite element analysis and experimental validation

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ABSTRACT : The deep drawing process is one of the important sheet metal forming process. In this paper, different methods of analysis such as analytical, numerical and experimental techniques are employed to determine sheet blank size, formability and thickness distribution. The traditional sheet plate forming techniques used in industry is experimental, expansive and time consuming methods. Prediction of the formability, thickness distribution in deep drawing process will decrease the production cost and time of material to be formed.

With this regard, the numerical simulations were conducted using the finite element method for cup shaped components with flange. Thickness distribution is obtained for entire cup along with flange. The results obtained from this numerical analysis are compared with experimental findings and results of other researchers. Experimentally thickness distribution is obtained by measurement at various locations in half cut cup along with flange region. Also analytical relationship is suggested to obtain correct initial blank size for cup shaped components with flange on the basis of principal of constancy of volume.

As a result of this, 90-95% consistency is obtained between the finite element result and experimental, analytical findings for initial blank size, formability and thickness distribution. Analytical models are extensive and experimentation is time consuming and expensive. Thus one can rely on FEA and simulations can be carried out to control IBS, formability, thickness distribution for component of same family by taking initial guess of IBS from analytical formula to avoid time and cost in field trials by controlling parameters of tooling and press machine.

Keywords : Deep drawing, Finite Element Analysis, Formability.

NOMENCLATURE

μ	Coefficient of friction,
t_o	Initial thickness of the cup
r_p	Punch nose radius
r_d	Die corner radius
h	Die height
c	Clearance
K	Strength coefficient
D_b	Diameter of blank
D_p	Diameter of punch
D_f	Diameter of flange
IBS	Initial Blank Size
FEA	Finite Element Analysis
BHF	Blank holder force in tons
n	Work hardening exponent

I. INTRODUCTION

In order to see more clearly, what is happening to the blank as it is being formed; it is divided into three sections as shown in Fig. 1. (i.e. x, y, and z). The material in section x will form the base of the cup which is in contact with the face of the punch. This material stretches and slides over the surface of the punch; however, minimal variation in thickness of this section is expected. Section y represents the cup bottom radius, which has undergone bending around the die radius first, then unbending and then bending around the punch radius in the opposite direction. Finally, the material in section z forms the sidewall of the cup and the flange. It has undergone bending around the die radius and then unbending as it is drawn to become the sidewall.

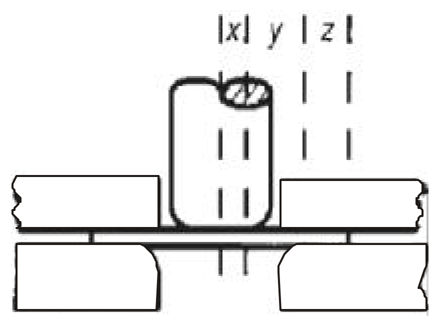


Fig. 1 : Schematic x, y, z sections.

Fig. 2 shows the typical shape characteristics and thickness variation of a partially drawn blank. Thickening occurs in the flange area and some stretching, necking occurs in the side wall and just above punch nose radius.

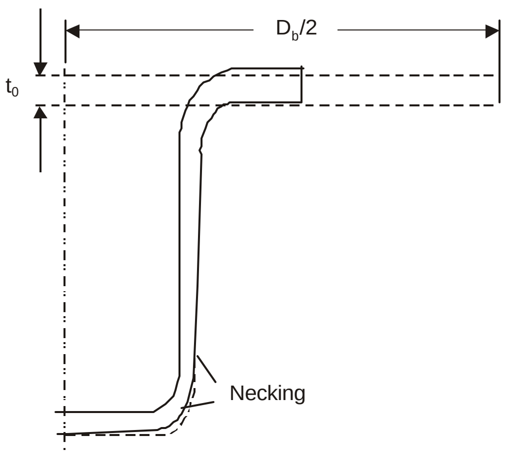


Fig. 2 : Deformation and necking of workpiece.

The experimental and theoretical investigation carried out by Chung and Swift [1] still remains the most comprehensive examination of cup drawing that has been carried out. The theory was restricted to an investigation of the stresses and strains in the radial drawing regions and no attempts are found reported to analyze the conditions in the region of stretch forming over the head of punch. The assumptions made mainly include blank holding force, which is exerted at the rim only, and variation of the material thickness can be neglected. Extensive experiments were conducted by Chung and Swift and found that the surface area of the drawn cup did not differ greatly from that of the original blanks. Some of the discrepancy in the experiments for the steel blanks was attributed to neglect the thinning that occurred over the base of the cup (approximately 10%). [1] The method of analysis applicable to both radial drawing and stretch forming was suggested by Woo. [2] The analysis was general in nature and does not involve assumptions mentioned by Chung and swift. It was found that blank holding force exerted only at the rim did not differ significantly from that applied over a certain area near the rim. Also study can be regarded as preliminary nature.

Chang et al [3] developed analytical model to evaluate the draw redraw process and to calculate sidewall thickness distribution. The analysis was based on radial drawing and plastic bending of blank at die radius and punch nose radius. The extensive models are then developed into computer subroutines. It was shown that the predicted wall thickness distributions are very close to the experimental measurements. It was also concluded that methodology is needed to optimize the thickness profile. The analytical models become extensive as material properties, tooling geometry and process parameter are all taken into consideration in the formulation and then it is followed by tooling and shop floor trials. These trials are time consuming and nowadays are very expensive. Mamalis et al[4, 5] investigated the deep drawing of cylindrical cups using explicit finite element method. The simulation result was punch force, obtained by using different simulation parameters such as punch velocity, sheet material density, columb friction coefficient; for galvanized and aluminum sheet. Good consistency was observed with experimental results. FEA provide clearer picture of sheet metal forming which describes by a sequence of discrete steps, the manner in which component is formed and calculations are continued until the final shape is realized. For this two software programs are used one step and incremental. In first program, geometry is unfolded back to obtain flat blanks where as in second program; full process simulation is done[6]. Several researchers investigated the deep drawing process employing finite element analysis method[8 – 12, 14, 15]. Factors influencing deep drawing process like punch and die radii, punch velocity, clamping force, friction, drawing force, effect of element type on forming load, variation in thickness strain, strain distribution improving deep drawability, determination of optional blank shape, were some of the objective considered by previous researchers in performing FEA of the process.

Parameters selected in this study are initial blank size, formability and thickness distribution in entire cup. Finite element simulations were performed by using shell element to obtain initial blank size, formability, thickness distribution. Experimental work is carried out for validating the findings of analytical and simulation outcome.

Analytical relationships are suggested for the prediction of initial blank size based on the principle of constancy of volume between the drawn cup and the blank. For simplifying the calculation, constant wall thickness is assumed. The component selected was cylindrical cup with flange.

Assuming that the total area of a drawn cup is equal to the summation of the primitive elements like as base of cup, bottom fillet area, and sidewall area, top flange fillet area and flange area. The surface area of drawn cup is equated with surface area of blank to obtain initial blank diameter D_b.

Surface area,

$$\begin{aligned} S.A = {} & \pi/4(D_d - 2(r_p + t_o + c))^2 + \pi D_d (h - r_d - (r_p + t_o + c)) \\ & + \pi/4\{2\pi (r_p + t_o + c)(D_d - 2(r_p + t_o + c)) \\ & + 2\pi(r_p + t_o + c)^2\} + \pi/4\{D_f^2 - (D_d + 2r_d)^2\} \\ & + \pi/4\{2\pi\, r_d D_d + 2\pi r_d^2\} \end{aligned} \quad ...(1)$$

$$D_b = SQRT\ \{(4*S.A)/\pi\} \quad ...(2)$$

II. NUMERICAL SIMULATION AND EXPERIMENTATION

Numerical simulations of the process were conducted in FEA software: Hyperform-LSDYNA.® The configuration of the punch, die, blank and blank holder modeled in the software is shown in Fig.No.3. Shell type of element (quadra) was employed to model the blank. Deep drawing quality steel sheet (IS 573:1994) [13] of initial thickness 0.8 mm was used as blank material. Yield stress, K, and n were taken as 250N/mm^2, area 600 N/mm^2 and 0.21 respectively. The coefficient of friction is taken equal to 0.125. Results obtained from FEA were thickness distribution and formability by varying blank holder force.

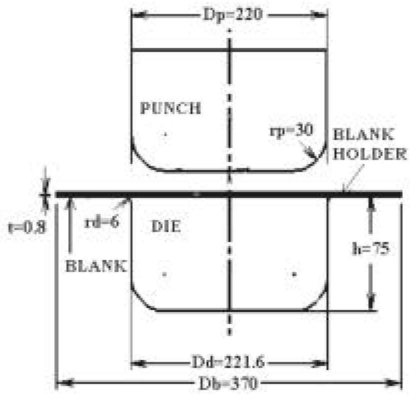


Fig. 3 : The configuration and dimensions of tools and workpiece modeled in FEA [16]

In experimentation; experiments were carried out with initial blanks of size ϕ370 mm. To obtain thickness distribution, half cut drawn cup was taken and thickness was measured at various locations as shown in Fig. 4.

III. RESULT AND DISCUSSION:

A. Initial blank size & Formability

Initial blank size obtained from analytical formula was ϕ 367mm. During experimentation good quality cups were obtained at ϕ 370 mm as shown in Fig. 5.

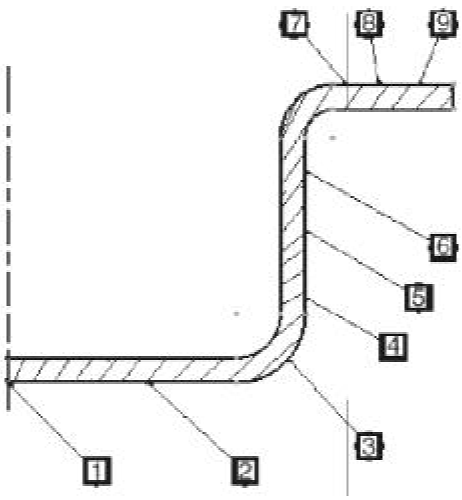


Fig. 4 : Thickness measurement locations.

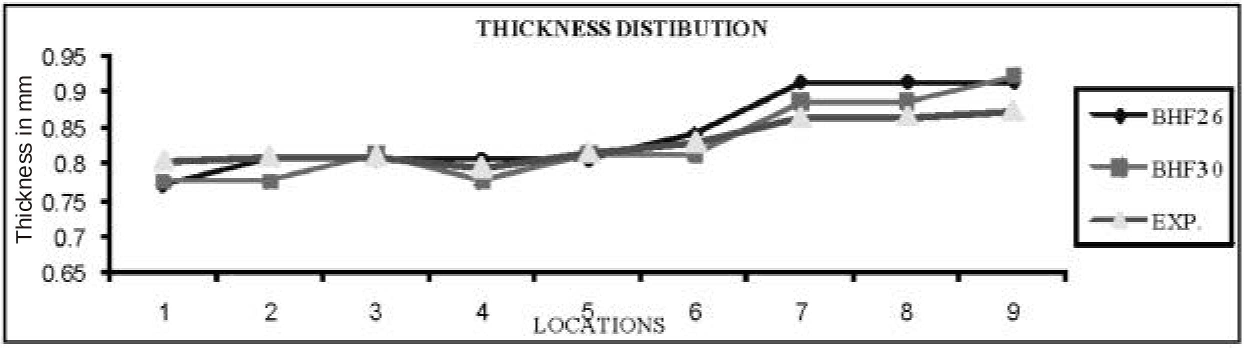
With ϕ 367 mm as initial guess FEA shows good formability at ϕ 370 mm. As shown in Fig. 6, green color in cup except at flange predicts good quality of formability. Pink color in flange predicts wrinkle tendency. In comparison with practically drawn cups good formability is observed in cup except at flange, where thickening is observed. This shows good agreement between FEA and experimental results. Thus FEA can be done to check feasibility of drawing of cup.

Fig. 5 : Drawn cup.

Fig. 6 : Formability obtained from FEA.

B. Thickness distribution

It is of great importance to know the wall thickness profile of drawn cup since thickness distribution will not only influence the material consumption but also dictate structure performance. Using thickness profile as a criterion, comparison of FEA prediction with experimental measurement and with work of other researchers is made to verify predictive capability of FEA. The comparisons of FEA and experimental shown in Fig. 7 shows that in cup bottom and punch nose radius severe thinning is not observed due to large value of punch nose radius. After the punch nose radius thickening of cup wall starts. Near the die open, wall is thickened since radial drawing is dominant. Also tendency of wrinkling is observed at flange and maximum prediction error at flange is 2-4 %. Author also worked with cup shaped component without flange and obtained maximum prediction error 1-4 % in the regions of cup except at cup open due to thickening it was 9 %. [17]



BLUE – BHF 26, MANGETA-BHF 30, EXP-RED

Fig. 7 : Thickness Distribution.

The comparison of methodology and results of various researchers along with Author is given in following Table 1.

Table 1 : Comparison of methodology and results of various researchers for Thickness [1, 3, 8, 14].

Nameof	Region of Cup					Methodology Used			PredictionError
researchers and Blank Material	Bottom	Punch nose radius	Cup wall	Cup open	Flange	An a	FEA	Exp	
Swift & Chung[1] Mild steel	√	√	√	√	√	√	—-	√	Max.10 % at cup bottom
Chang[3]Steel blanks	√	√	√	√	√	√	—-	√	Max. 4.2 % at cup open
I. Demirci[14] Aluminum	√	√	√	√	√	——	√	√	Average 10%
Colgan[8] Mild steel EN10130FeP01	√ 2.4%	√ 2.7%	√ 6.7%	√ 12.2%	√ 2%	——	√	√	Max.12.2% at cup open
Author'sDeep drawing Steel IS573: 1994	√ 2-4%	√ 1-2%	√ 1-2%	√ 1-2%	√ 2-5%	——	√	√	Max.5% at flange end.

This shows good agreement with work of other researchers.

Thus analytical models are extensive since material properties, tooling geometry; process parameter must be taken in to consideration for formulation. Instead of that, one can rely on FEA prediction.

IV. CONCLUSION

To understand deep drawing process cylindrical cup with flange is selected. Parameters studied are calculation of initial blank size, formability and thickness distribution from industry point of view. For this methodology adopted consists comparison between FEA, analytical, experimental measurements & work of others researchers.

(A) To obtain correct initial blank size author derived mathematical formula on the basis of calculation of area of every primitive of component, assuming constant wall thickness. Initial blank size obtained from mathematical formula shows good agreement with that of FEA & experimental result. Also formability obtained from FEA shows good agreement with experimental results. Thus FEA can be done to check feasibility of component & IBS for early quotation.

(B) Thickness distribution is obtained experimentally & by FEA & compared with work of other researchers. Maximum errors in prediction are 2-4 % in cup bottom and 1-2 % in cup wall. In flange region maximum prediction error obtained is 2-5 %. Thus FEA results are showing 90-95 % consistency with experimental findings as well as with results of some researchers. So that one can relay on FEA results, as analytical models are extensive and experimentation is time consuming.

(C) On this basis simulations can be carried out to control IBS, formability, thickness distribution for component of same family (Ex. Cylindrical cup with varying dimensions) by considering initial guess of IBS from analytical formula, to avoid time and cost losses in practical trials by controlling various parameters of tooling and press machine.

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