Optimization of Variation in Wall Thickness of a Deep Drawn Cup using Virtual Design of Experiments

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***Abstract*— This paper presents an investigation of the effect of die draw radius, sheet thickness and blank holder force on the variation in wall thickness of a deep drawn cup using finite element simulations. The variation in wall thickness is minimized by carrying out analysis of variance (ANOVA) for individual factors and their interactions.**

Keywords- Metal forming process; Deep drawing; finite element simulations;design of experiments; Hyperform; ANOVA; Wall thickness Variation

I. INTRODUCTION

Deep drawing is one of the metal forming processes used to produce a cup like cylindrical component by radially drawing metal blank into the die cavity with the help of a punch. The cup shaped part produced by this process has the depth greater than half of its diameter. The change in cross-section of the metal is achieved by plastic deformation of the initial blank. Optimization of the process plays an essential role in improving industrial performance measures such as productivity and cost. In order to improve the process outcome, a number of process parameters such as blank shape, sheet dimensions, blank holding force, lubrication and punch/die design need to be controlled and optimized. [5] It is difficult yet essential to analyze the effect of various parameters on the process output and select their optimal values due to complexity of process and large number of factors involved in it. Finite element analysis is nowadays accepted and preferred by the industry over analytical and experimental approaches being more economic, time saving and equally effective in predicting the process output. Numerical simulation technology combined with optimization techniques has been applied in sheet metal forming processes in order to improve design quality and shorten design cycle. [29]

II. LITERATURE REVIEW

A. Review of Parameters Investigated

F. Ayari et al. (2009) [22] conducted a parametric study of deep drawing using FEM model which is built using ABAQUS/ Explicit standard code. In that they considered influential parameters such as geometric, material parameters and coefficient of friction and validated them against experimental results.

Kopanathi Gowtham et al. (2012) [24] studied the effect of variation in die radius on effective stress, effective strain, max. principal stress, max. principal strain, damage value and load required. They concluded that die radius is an important design parameter and they also optimized it using FE simulations.

Pandhare et al. (2012) [25] used FE simulations to optimize blank holder force in deep drawing process using friction property of CRDQ steel. They studied FLD for different values of μ and found that BHF first increases upto a certain limits and then decreases. For low BHF values, wrinkling defect is observed whereas high values of BHF result into failure, the optimum value is the one which reduces the probability of both the defects.

R. Padmanabhan et al. (2007) [30] studied the significance of three parameters die radius, blank holder force and friction coefficient on deep-drawing characteristics of a stainless steel axi-symmetric cup using finite element method combined with Taguchi technique. They carried out a reduced set of finite element simulations based on the fractional factorial design of L9 orthogonal array and analyzed the relative importance of the selected parameters on thickness distribution using ANOVA. From the analysis they concluded that die radius has the greatest influence on the deep drawing of stainless steel blank sheet which is followed by the blank holder force and then the friction coefficient.

P V R Ravindra Reddy et al. (2012) [32] have studied the effect of blank holding force and die draw radius on the limit strains in deep drawing process using an explicit finite element code LSDYNA. They have validated the results of the simulations with the strain values obtained by analytical formulae for power law plasticity models. The observations from the investigation were increase in limit strains with increase in die corner radius. They also concluded that even though safer deformation zone increases with blank holder force (BHF), limit strains are independent of BHF at lower ratio of principal strains.

R. Venkat Reddy et al. (2013) [33] have conducted a parametric study of BHF, sheet thickness, die profile radius, punch profile radius, initial yield stress, sheet anisotropy and imperfections. They found that maximum cup height at the onset of wrinkling increases with Blank Holding Force (BHF), sheet thickness and an increase in the die profile radius as well as punch profile radius. They also concluded that die profile radius is more significant and resistance to wrinkling also depends on anisotropy.

From above discussion and findings, it is clear that researchers have mainly worked towards improvement in formability and elimination of various defects such as wrinkling, fracture, thickness variation and other surface defects by careful selection of sheet material and process parameters such as friction, blank holder force, die draw radius, punch radius, blank shape and number of redrawing steps. It is also evident that researchers are successfully using FE approach to optimize the deep drawing process to reduce costly and time consuming experimental trial and errors and simulations can be combined with various optimization techniques such as design of experiments, analysis of variance, Taguchi's robust design for improving design quality and reducing design cycle time.

III. RESEARCH GAP

After a thorough analysis of the literature, it was found that researchers have investigated the effect of various process and design parameters on the process output using FE simulations but very few researchers have carried out a comprehensive parametric study to find the relative importance of the parameters using finite element method coupled with Taguchi’s techniques. There lies a future scope of conducting a more comprehensive parametric study of the deep drawing process parameters using finite element simulations and their interactions for optimizing the process using full factorial design of experiments. Hence, the aim of the present work is to investigate the effect of die draw radius, blank thickness and blank holder force on variation in wall thickness of the deep drawn cup and select their optimal values using full factorial design.

IV. RESEARCH METHODOLOGY

The research methodology used for the current work is as shown in the figure 1 below.

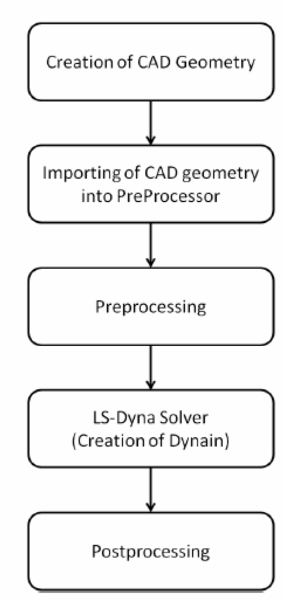


Figure 1: Deep Drawing Simulation Methodology

The geometry of the die and blank is prepared using modeling software PRO-E and then is imported into the preprocessor Hyperform. There all the preprocessing steps are carried out and then the analysis is carried out using LSDYNA solver. The output of the analysis stage is viewed using postprocessor Hyperview. The simulations are carried out based on full factorial design of L27 orthogonal array and then the relative importance of the selected parameters and their optimal values are analyzed using ANOVA.

The parameters selected for the investigation are as follows:

Dependent Variables

Dependent variables are the ones that depend on other variables. The dependent variable selected for the present work is percent thickness variation which gives the variation in the wall thickness of a deep drawn cup as a percent of original blank thickness. During deep drawing, tensile and compressive stresses developed in them metal result into uneven thickness of the formed component, which may result into failure of the component in working condition. Hence the aim is to always select design parameters and control the process variables such that variation in the wall thickness is minimum.

Independent Variables

Independent variables are not dependent on any other parameter. These are the inputs to the analysis and mainly contribute to measurement of model.

In the present work, independent variables selected are as follows:

- Die draw radius
- Blank thickness
- Blank holder force

The model of the deep drawing process, which is the outcome of the preprocessing step, used for the finite element analysis is as shown in the figure 2 below:

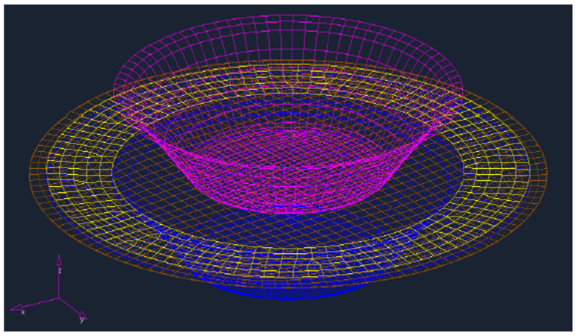


Figure 2: Outcome of the preprocessor used for FE analysis

V. DATA COLLECTION AND ANALYSIS

Full factorial design is used for analysis of variance in the present work. The material of the deep drawn componenet selected for the study is CRDQ steel. Three parameters with their three levels selected for this purpose are given in the table 1 below:

Table 1: Factors and their levels selected for simulation

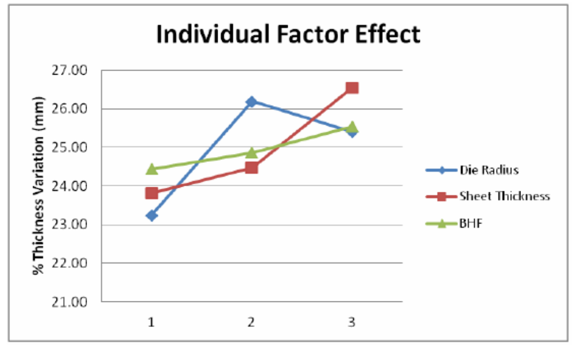
FACTORS		LEVELS		
		1	2	3
A	Die Draw Radius (mm)	4	5	6
B	Sheet Thickness (mm)	1	1.2	1.4
C	Blank Holder Force (KN)	20	30	40

The results for average response of percent thickness variation for individual factors are as given in the table 2 below.

Table 2: Average Response of Percent Thickness Variation for individual Factors

FACTORS	Average Response (% Thickness Variation)		
	Level 1	Level 2	Level 3
A	23.6449	26.9151	26.1466
B	24.7633	25.0861	26.8571
C	24.8685	25.5394	26.2987

The chart below clearly indicates that, percent thickness variation first increases as the level of factor A (die draw radius) changes from 1 to 2 and then decreases as the level changes from 2 to 3. Whereas % thickness variation increases as the level changes from 1 to 2 and from 2 to 3 for both factor B (Sheet thickness) and factor C (BHF).



Results of Analysis of variance considering the effect of individual factors and their interactions are as given in Table 3 below:

Table 3: Modified ANOVA Summary Table for Percent Thickness Variation

MODIFIED ANOVA SUMMARY TABLE						
	SS	D. F.	M.S.S.	F	$F_{critical}$ at α= 0.05	
Total	99.0161	26				
A	52.6270	2	26.3135	811.75228	4.46	Significant
B	22.8743	2	11.4372	352.8282	4.46	Significant
C	9.2158	2	4.6079	142.1500	4.46	Significant
AXB	12.0718	4	3.0179	93.1013	3.84	Significant
AXC	0.4653	4	0.1163	3.5886	3.84	Insignificant
BXC	1.5026	4	0.3756	11.5885	3.84	Significant
Error	0.2593	8	0.0324			

For studying the interaction effects pair-wise comparisons are useful. For this study, we need to make a distinction between focal independent variable and moderate variable. The focal independent variable can be 'assigned-active distinction'. The assigned independent variable i.e. a characteristic intrinsic to the participant such as sheet thickness in this case and the active independent variable i.e. the one assigned or designed by the researcher such as die radius or blank holder force will be considered as the focal variable. In the current analysis, sheet thickness is designated as moderator variable and die draw radius and blank holder force are designated as focal independent variables.

From the above analysis, it is clear that interaction AXC (die radius with BHF) is insignificant. Hence interaction effect of AXB and BXC is studied further. For each sheet thickness one-way ANOVA is carried out for interactions AXB and BXC for each sheet thickness to conclude on the effect. From the analysis, it is clear that the interaction effect AXB is significant at each level of sheet thickness and hence post-hoc analysis by doing pairwise comparison is carried out to determine the optimal values. The details are given in table 4 to 6 below.

Table 4: Pairwise Comparison (AXB) for % Thickness Variation for 1 mm Sheet Thickness

Pairwise Comparison	Difference	95 % confidence interval (difference ±0.3336)
Level1 - Level2	22.8733 - 25.5400 = -2.6667	(-3.0419, -2.2914)
Level2 - Level3	25.5400 - 25.8767 = -0.3367	(-0.7119, 0.0386)
Level1 - Level3	22.8733 - 25.8767 = -3.0033	(-3.3786, -2.6281)

It is clear that the differences between level 2 and level 3 is insignificant and the mean for level 1 of factor A (die draw radius - 4 mm) is significantly lower (22.8733) than the other two values

Table 5: Pairwise Comparison (AXB) for % Thickness Variation for 1.2 mm Sheet Thickness

Pairwise Comparison	Difference	95 % confidence interval (difference ±0.3336)
Level1 - Level2	22.1806 - 26.9194 = -4.7389	(-5.1141, -4.3636)
Level2 - Level3	26.9194 - 26.1583 = 0.7611	(0.3859, 1.1363)
Level1 - Level3	22.1806 - 26.1583 = -3.9778	(-4.3530, -3.6025)

It is clear that all the three differences are significant and the mean for level 1 of factor A (die draw radius - 4 mm) is the lowest (22.1806).

Table 6: Pairwise Comparison (AXB) for % Thickness Variation for 1.4 mm Sheet Thickness

Pairwise Comparison	Difference	95 % confidence interval (difference ±0.3336)
Level1 – Level2	25.8810 - 28.2857 = -2.4028	(-2.7800, -2.0295)
Level2 - Level3	28.2857 - 26.4048 = 1.8810	(1.5056, 2.2562)
Level1 - Level3	25.8810 - 26.4048 = -0.5238	(-0.8991, -0.1486)

it is clear that all the three differences are significant and the mean for level 1 of factor A (die draw radius - 4 mm) is the lowest (25.8810).

Similarly One-way ANOVA of BXC for each sheet thickness shows that optimal value of blank holder force is not different for different sheet thicknesses and there is not much difference in the group means. Hence it is advisable to select the blank holder force as calculated by the empirical formula.

VI. CONCLUSION

Summary of the optimal combination of selected parameters for minimum percent thickness variation is tabulated in table 7 below.

Table 7: Summary of Optimal Combinations for Minimum Percent Thickness Variation

Sr. No.	Details of the Requirements	Optimal Combination of Factors and levels for Minimum Percent Thickness Variation
1.	When any sheet thickness is permitted	Factor A - Level 1 Factor B - Level 2 Factor C - Level 1
2.	When Sheet Thickness of 1 mm is permitted	Factor A - Level 1 Factor B - Level 1 Factor C - Level 1
3.	When Sheet Thickness of 1.2 mm is permitted	Factor A - Level 1 Factor B - Level 2 Factor C - Level 2
4.	When Sheet Thickness of 1.4 mm is permitted	Factor A - Level 1 Factor B - Level 3 Factor C - Level 3

To conclude, in the present paper the effect of die draw radius, sheet thickness and blank holder force on the material thinning in deep drawing, individually and interactions is analyzed by using finite element analysis coupled with design of experiments. Optimal combination of the parameters is suggested based on ANOVA of the results obtained.

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