Finite Element simulation and Optimisation of blank holder force and rectangular drawbead geometry using Taguchi method for hemispherical cup

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Abstract. In sheet metal forming process for obtaining good component one of the important practices is to controlling the sheet material flow into the die cavity. This is possible by applying the proper blank holding force and optimized drawbead geometry on the surface of the die. This paper aims to investigate the effect of drawbead geometry and blank holding force on thickness of formed component and restraining force using the Taguchi optimized technique. FE simulation is carried out by hyperform software and L9 orthogonal array design of experiments is used for simulation. Furthermore the values of thickness and drawbead forces predicted by developing a linear regression model. From the result, it is noticed that the shoulder radius and drawbead height are more influencing parameters for controlling the restraining force and thickness variation. The obtained results are validated by conducting conformation test and values obtained are the good agreement with the literature data and simulated results.

1. Introduction
In the manufacturing of sheet metal components, roll of blank holder and drawbead is very crucial. Both elements help to control the flow of material in the die cavity to avoiding the wrinkling and stretching, tearing formation during deformation of the sheet. The drawback is acting as the speed breaker for material while flowing in to die cavity and it forms the restraining force due to bending, unbending and friction between drawbead and sheet. This restraining force can be altered by changing the geometry of drawbead. Blank holder used to create the frictional resisting force between the tools and die. Key for controlling of material flowing in die is proper dimension of the shoulder radius, drawbead height, drawbead radius and also blank holding force, hence many researchers are highlight the issue of effect of blank holder force and drawbead geometry.

Author Doege et. al. [1] investigated the blank holder force optimization in the deep drawing process of rectangular parts. In addition to the blank holder force, they studied the effect of material selection and lubrication to avoiding fracture and wrinkling. Yellup and Painter [2] investigated the effect of shallow drawbead on restraining forces using the finite element simulation. Cao et.al. [3] worked on nonlinear finite element analysis for various draw bead configurations to study the mechanics of draw bead restraint. Sanchez et.al. [4] proposed an analytical and experimental study of the flow of sheet metal between Circular Drawbeads. Keum et.al [5] finding out the expert drawbead model for analyzing the effect of restraining force on sheet forming. Han et.al.[6] studied
computational inverse technique for finding out effect of drawbead parameters on sheet metal forming. Chen et. Al.[7] introduced the simulation of the blank holding process by considering the blank holder gap (BHG), which is fixed distance between the blank holder and the die surface and find an optimization approach for determining the optimum blank holding gap and indicate that how the BHF is correlated with the BHG. Author Naceur [8] developed inverse approach method for finite element analysis for optimizing drawbead restraining force in sheet forming. Lee et. al.[9] presented numerical method for rapid estimation of drawbead restraining force based on non-linear, anisotropic constitutive equations. Duarte [10] carried out hybrid approach for estimating the drawbead restraining force by considering semi-circular drawbead geometry. Guangyong Sun [11] proposed multiobjective robust optimization technique for the effects of uncertainties in drawbead geometry, where the six sigma method is used to measure the variations, a dual response surface method is used to construct surrogate model and a multiobjective particle swarm optimization is developed to generate robust Pareto solutions. Sena et.al.[12] worked on Position and the Size of Drawbeads for improving formability in Sheet Metal Forming using finite element analysis. Zhang [13-14] constructed an optimization method for drawbead geometry based on an iterative learning control model and geometry is adjusted by to a learning updating law and also he utilized theoretical optimization method for developing drawbead restraining forces in automotive panel based on plastic flow principles. Kitayama [15] presented optimization process of blank shape and variable blank holder force of front side member manufacturing by deep drawing process. Preedawiphat et.al. [16] Studied the effect of localized friction on sheet thinning through lubricated conditions with the use of Finite Element Analysis (FEA) to evaluate the sheet thinning of AISI 1020 sheet under six segmented blank-sheet interfaces. Hence there is no any investigation is carried out between the drawbead parameters and blank holding force so this paper is focused on analyzing the effect of rectangular bead geometrical parameters and blank holding force using Taguchi L9 array optimization process is used to reduce the effort of trial and error experiment while forming part in industry. In the current study three levels of rectangular drawbead geometry parameters like drawbead height and shoulder radius and blank holding force is used for numerical simulation on thickness of formed part and restraining force which will use to slowdown the metal flow in to die cavity. Work is carried out by hyperform software to finding out the thickness and forces. Figure 1 show the experimental results of location of drawbead from center of die [17] to validate numerical findings. The location of drawbead is fixed for optimizing the values of drawbead geometry and blank holding force. The percentage error between experimental result and numerical findings are an average of 11% is observed.

![Figure 1. Graph of results of validation study [17].](image)

2. Numerical Modeling

Modeling of all elements in the deep drawing process is done in hypermesh software and pre-processing post processing were done in hyperform software. While simulations punch, die, binder acts as rigid material and it acts as slave surface while blank is acts as master surface. Model is meshed with shell element and the blank meshing size is maintained 2.5 mm because more size of mesh indicate variation in the result while less value takes more time to simulation. Size of punch is
100 mm and inner diameter of die is 102.2 mm with entry radius 4mm. The blank size of 174 mm diameter was assigned with hill orthotropic tabulated model with uniform thickness of 1.02 mm is attained. The material used for the study is AISI 1020 steel. The properties of material are shown in table 1. [17].

| Properties          | AISI1020 Steel |
|---------------------|----------------|
| Young’s Modulus (Gpa) | 207            |
| Mass density (kg/m3)     | 7830           |
| Poisson’s Ratio        | 0.28           |

Table 1. Mechanical Properties of materials

2.1. Numerical Simulation

During the simulation of sheet metal forming process there is always maintaining the contact between the binder-blank, punch-blank, die-blank and using AUTOPOSITION option the uniform gap is maintain between punch die, binder etc. The coefficient of friction between the sliding surfaces is 0.14 and during simulation process the blank is acts as master surface while die, punch is acts as slave surface. The velocity of 5 m/s was given to punch with negative Z direction with stroke distance of 40mm.[sheriff] Numerical model of set up of drawing process is shown in the figure 2.

![Figure 2. Numerical model for set up of drawing process](image)

2.2 Taguchi Method

Design of experiment is carried out by adapting Taguchi method to investigate the effect of three parameters of die like blank holder force and drawbead geometry on two important responses of thickness and drawbead restraining force on which the quality of finished part is depends. Hence to analyse the effect selecting appropriate three levels and parameters has been selected for the study which is shown in table 2.

| Process Parameters | Levels |
|--------------------|--------|
| Blank holding Force (Tonns) | 6.5    | 7.5 | 8.5 |
| Drawbead Height (mm)      | 2.5    | 3.5 | 4.5 |
| Sh.Radius (mm)            | 1.5    | 2.5 | 3.5 |

According to Taguchi principle three levels and three parameters will form L9 array in which Taguchi is divided S/N ratio into three categories namely smaller- the better, larger-the- better and medium-the-better. In the present study thickness and restraining force was considered as responses in which thickness of formed parts is always required as maximum so for thickness S/N ratio is considered as larger is the better and for restraining force always considers/N ratio smaller the better because as restraining force is larger causing tearing or failure in the finished part.Eq.1 applies for calculating
S/N ratio as larger-the-better and eq.2 is applied for finding the S/N ratio as smaller the better[19]. Different responses and S/N ratio of thickness and force are obtained from Taguchi analysis is shown in the table 3.

Table 3. Simulation layout and S/N ratio results using $L_9$ array

| Runs | Process Parameters | Thickness | Restraining force | S/N ratios |
|------|--------------------|-----------|-------------------|------------|
|      | Blank holder force(T) | DB height mm | DBRF | Thickness mm | F (KN) |   |
| 1    | 1                  | 1 | 1 | 0.8260 | 94.7 | -1.66040 | -39.5270 |
| 2    | 1                  | 2 | 2 | 0.8440 | 84.8 | -1.47315 | -38.5679 |
| 3    | 1                  | 3 | 3 | 0.8469 | 82.1 | -1.44336 | -38.2869 |
| 4    | 2                  | 1 | 2 | 0.8749 | 55.6 | -1.16083 | -34.9015 |
| 5    | 2                  | 2 | 3 | 0.8704 | 59.2 | -1.20562 | -35.4464 |
| 6    | 2                  | 3 | 1 | 0.3624 | 189.0 | -8.81624 | -45.5292 |
| 7    | 3                  | 1 | 3 | 0.8874 | 38.6 | -1.03761 | -31.7317 |
| 8    | 3                  | 2 | 1 | 0.6065 | 141.0 | -4.34338 | -42.9844 |
| 9    | 3                  | 3 | 2 | 0.7489 | 115.0 | -2.51152 | -41.2140 |

Signal to noise ratio for the smaller-the-better = $-10 \log \frac{1}{n} \sum (R)^2$

Signal to noise ratio for the larger-the-better = $-10 \log \frac{1}{n} \sum \frac{1}{(R)^2}$

Where n = No. of observations and $R$ is Observed data for each response.

2.3 Optimisation results of process parameters on performance characteristics

From Taguchi analysis and numerical simulation it is noticed that the blank holding force, drawbead height is reduced with increasing the shoulder radius.

From figure 3 it is observed that, as blank holding force raised causing friction between sheet and die which result of tearing or stretching and if reducing force cause wrinkling in the formed part. Similarly from figure 3 it is contemplated drawbead height preferably as minimum as possible because large height or penetration shows sharp effective bending radius as well as large sliding angle hence creating large restraining force which restrict the flow of metal in die cavity causes tearing and reduce the thickness of the formed part.[18]
Third parameter is the shoulder radius which refers as large as possible to reduce bending angle with bending stresses thereby decreasing the restraining force and allow flowing metal in die cavity for increasing the thickness of formed part.[18]

2.4 Analysis of S/N ratio

For maximum thickness SN ratio is considered as larger-the better. Table 4 indicate that analysis of SN ratio for thickness. From table it is clear that most influencing factor for getting the maximum thickness during process is shoulder radius of rank1 followed by drawbead height of rank 2 and then blank holding force (binder force) of rank 3. From figure 3 it is also observer that binder force is of 6.5 T, DB height is 2.5 and shoulder radius is obtained as 3.5 and optimum combination is $L_{11}^{-}L_{21}^{-}L_{33}^{-}$ which is highlighted in table 4.

![Figure 4. Mean S/N ratio of thickness](image)

Table 4. Max.thickness by SN ratio factor level

| Level | Binder force | DB height | Sh. radius |
|-------|--------------|-----------|------------|
| 1     | -1.526       | -1.286    | -4.940     |
| 2     | -3.728       | -2.341    | -1.715     |
| 3     | -2.631       | -4.257    | -1.229     |
| Delta | 2.202        | 2.971     | 3.711      |
| Rank  | 3            | 2         | 1          |

Similarly for restraining force SN ratio is considered as smaller-the better. Table 5 indicates that analysis of SN ratio for restraining force and it is clear that most influencing factor for getting the minimum restraining force during process is shoulder radius of rank1 followed by drawbead height of rank 2 and then blank holding force (binder force) of rank 3. From figure 4 it is observer that binder force is of 6.5 T, DB height is 2.5 mm and shoulder radius is obtained as 3.5 mm and optimum combination is $L_{12}^{-}L_{21}^{-}L_{33}^{-}$ which is highlighted in table 5.

![Figure 4. Mean S/N ratio of thickness](image)

Table 5. Restraining force by S/N ratio factor level

| Level | Binder force | DB height | Sh. radius |
|-------|--------------|-----------|------------|
| 1     | -38.79       | -35.39    | -42.68     |
| 2     | -38.63       | -39.00    | -38.23     |
| 3     | -68.64       | -41.68    | -35.16     |
| Delta | 0.17         | 6.29      | 7.53       |
| Rank  | 3            | 2         | 1          |

2.5 Linier regression analysis

Linear regression analysis is carried out to develop the predictive equation for response of maximum thickness and minimum restraining force. The linear regression equation for thickness and restraining force is finding out by using Minitab software tool is shown in eq.3 and eq.4 respectively.
Thickness = 0.809 - 0.0457 blank holding force - 0.0827 DB height + 0.113 Sh. Radius \hspace{2cm} eq. (3)

DBRF = 100 + 5.50 blank holding force + 32.9 DB height - 40.8 Sh. Radius \hspace{2cm} eq.(4)

A performance characteristic of developed regression model is verified by using coefficient of determination $R^2$. In the current study the value of $R^2$ for thickness and restraining force is 85.9% and 90.4% respectively. From figure 5 it is conclude that residuals points are falls near to the straight line for both the responses which has an indication of model is in significant one.

![Normal Probability Plot of the Residuals](image)

Figure 5. Residual plots for thickness and restraining force

2.6 Confirmation test:

For validating the result of current study the confirmation test is performed. To estimate and verify the responses at predicted condition, predicted SN ratio is calculated by using equation 4. \cite{19}

$$
\varepsilon_{\text{predicted}} = \varepsilon_i + \sum_{i=1}^{\chi} \varepsilon_0 - \varepsilon_i
$$

Where $\varepsilon_i$ = Total mean S/N ratio, $\varepsilon_0$ = Mean S/N ratio at optimal level, $\chi$ = No. of input process parameters.

The result of conformation test for thickness and drawbead restraining force is shown in the table 5 and table 6 respectively. From the table 6 it is observed that considerable improvement is seen in SN ratio and thickness, it is improved by the value of 2.574 and 11 % respectively.

| Table 6. Conformation test results for thickness |
|-----------------------------------------------|
| Initial process parameter | Optimal process parameters |
| -- | -- |
| Level | Prediction | Simulation result |
| $L_{13}, L_{22}, L_{31}$ (random level) | $L_{11} L_{21} L_{33}$ | $L_{12} L_{21} L_{33}$ |
| Thickness | 0.8101 | 0.8990 |
| S/N ratio | -1.8292 | 1.21 |
| Improvement in S/N ratio | 2.754 | -0.9248 |
| Improved Thickness | 11.00 % |

Also from table 7 it is observed the there is no improvement in case of restraining force because optimized level which is same as in the design of experiment in case of last two parameters i.e. drawbead height and shoulder radius but blank holding force is different. Both drawbead geometry and binder force are independent hence the restraining force will be same. If bead height and shoulder radius is different than DOE then certainly there will be change in restraining force.
From figure 6 it is observed that the thickness of randomly selected parameters i.e. (blank holding force is 8.5 tonn, bead height of 3.5 mm and shoulder radius is 1.5 mm) is of 0.8101 at the bottom portion of cup but optimized result having (Blank holder 6.5 tonn, bead height 2.5 mm and shoulder radius is 3.5 mm) will have better improvement in thickness at the bottom of cup obtained as 0.8990 mm.

Table 7. Conformation test results for draw bead restraining force

| Initial process parameter | Optimal process parameters |
|---------------------------|---------------------------|
| Level                     | Prediction                | Simulation result |
| Draw bead restraining force| L_{13}, L_{22}, L_{31} (random level) | L_{12}-L_{21}L_{33} |
| S/N ratio                 | -31.7317                  | -30.46            |
| Improvement in S/N ratio  | 0                         | 0                 |
| Reduction of DBRF         | 0                         | 0                 |

3. Conclusion

Following are the conclusions from the current study.

- The maximum thickness of cup and restraining force is observed for optimum process parameters using Taguchi method are blank holding force 6.5 Ton, bead height is 2.5 mm and shoulder radius is 3.5 mm is obtained and for restraining force the same values are obtained except different level of blank holding force. It is found that the geometrical parameters of drawbead are independent to blank holding force.
- From the SN ratio table it is observed that, the most influencing parameter for increasing thickness or reducing the restraining force is shoulder radius and then drawbead height.
- The regression equation shows excellent agreement with the predicted and simulated results. Hence, the regression equation developed can be used for the proper selection of draw bead geometry in the sheet metal forming process.

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