# Optimization of Forming Process Parameters for Appropriate Distribution of Wall Thickness in Car Wheel Disk using FEM and Taguchi

Rohit S. Birajdar<sup>1</sup>, P. D. Kamble<sup>2</sup>,

<sup>1</sup>M.Tech. Scholar, Yeshwantrao Chavan College of Engineering, Wanadongri, Nagpur 441110, India *rohitsbirajdar@gmail.com* 

<sup>2</sup>Assistant Professor, Yeshwantrao Chavan College of Engineering, Wanadongri, Nagpur 441110, India *pdk121180@yahoo.com* 

Abstract: The defects occurring in general sheet metal forming are bound to occur in the wheel disk forming process and these defects are reduced by varying the forming process conditions (trial and error method). This causes loss terms of money and time. There are various parameters included in the forming process which affect the final products quality. The final part in its desired quality limits is obtained by selection of some critical parameters which affect more on the total process and varying their values to their optimum values. This requires expertise in the tool design and thorough knowledge of the behavior of process according to these parameters. This trial and error methods are replaced by the virtual simulations of these trials using Finite Element Method (FEM) based software and optimization is carried out by the Design of experiments (DOE) techniques. This method will replace the need of industrial expertise and also save a lot of cost and time. In this paper simulation of the multi-stage forming of wheel disk by using Altair's Hyperform. The most effective parameters are identified using Analysis of variance (ANOVA). The optimization of these process parameters is done using Design of experiments (DOE) by Taguchi's orthogonal arrays in Minitab software. The results of optimization are validated by actual formed wheel disk at industry using same optimized parameters.

Keywords: Multi-stage forming, Thinning, Finite element method, Design of experiments (DOE), Taguchi, ANOVA, Minitab.

#### 1. Introduction

Metal forming process is the base process for almost every metal component which are produced in industries. The sheet metal forming process has a wide range of applications in the current engineering industries. Every industry uses metal forming process at least once for any component. Majority of metal forming processes involves plastic deformation of the metal by application of the forces.

In metal forming, the form change is accomplished by plastic deformation only and therefore there is no waste of metal. This is the primary advantage compared to machining practices. In machining processes the shape modification is done by removing material from the part. Engineering research and improvement is to decide the ideal resources of producing complete products having lesser defects and scrap. In forming of wheel rim there is less severity of errors however in case of wheel disk the forming errors like wrinkling, thinning, disk run-out etc. are commonly observed at the very first tool tryout. In multi-stage drawing of sheet metal blank the metal is drawn over various surfaces and varying radii, this makes the prediction of defects complicated.

The Finite element simulation of sheet metal forming is increasingly applied to eliminate forming defects, predict and optimize process parameters and to predict stresses / strains in sheet metal blank to prevent blank failure.

Determination of the effect of the process parameters on the final forming quality is very difficult in sheet metal forming process because forming process experience very complicated deformation. These process parameters have to be determined for the optimum forming condition before the process design.

Conventional method to determine optimum process parameter is time consuming and costly. Throughout the years, the sheet metal forming industry experienced technological advances that allowed the production of complex parts. However, it still depends heavily on trial-anderror and the experiences of skilled workers. The quality of the final product shape is determined by the tools design, process parameters, shape and material of the blank. It is important to carefully consider all these factors prior to manufacturing otherwise a defective product could result.

Car wheel disk are formed by multi-stage forming process. Manufacturing of car wheel is done in three stages as, multistage forming of wheel disk, roll forming of wheel rim and by welding together the wheel disk and wheel rim to form complete steel wheels, refer Figure 1. In roll forming of wheel rim the occurrence of defects are very less compared to the multi-stage forming of wheel disk hence the process of multi-stage forming of wheel disk is selected for the study.





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Nimbalkar D.H. [1], describes the mathematical modelling and theoretical investigation of sheet metal forming procedure. He carried out FEM simulation for an industrial part which is to be formed by deep drawing operation. M. Firat, explained the formulations in finite element methods and their concert in manufacturing of stampings. Also examined the working of the shell element creations in the estimation of blank plastic straining, forming forces and also their computational cost.

M.J. Worswick [2], given detail information regarding how sheet metal forming operation are carried out and what are effects of different parameters such as tool geometry, friction between sheet and tool and various loads on sheet metal. Also explained latest advances related to the numerical simulation of stampings which stated methodologies for foreseeing metal formability, containing damage-based models for both the large as well as small variety. The evolution of calculating competency improving implicit as well as explicit solver algorithms has delivered the required computational rapidity to support increasing levels of practicality in mathematical representation of material performance, lubrication and tooling geometry, along with increased levels of accuracy.

Tan C. J. et al [3], explained various factors affecting the final thickness of the deep drawn sheet metal part. The small decrease in thickness is mainly because of reduction in blank thickness. Subsequently the fatigue strength of the disk abruptly reduces even for a small reduction in thickness at the inner corner, a tailored blank with local thickening at the area corresponding to the inner corner produced by stamping was used in the multistage stamping to increase the thickness at the inner corner.

A. Makinouchi [4], described different examples for simulation, in those examples defects such as, wrinkles, surface deflection are predicted and forming limit conditions are studied. So, if there is a need for obtaining valuable data within moderate time as well as cost, one has to bind the tenacity of simulation.

Sandeep Patil et al [5], used Altair's Hyperform to simulate the process of sheet metal forming and presented few case studies related to deep drawing simulation of cylindrical shells to understand sheet metal behavior. The concepts such as metal flow during drawing, severity in drawing and die requirement for deep drawing of cylindrical shells explained for education purpose with education software. He also provided methodology for simulation of metal forming process using Altair's Hyperworks package.

Sandeep Patil et al [6], analyzed trapezoidal cup forming using Hyperform. Further described the approach for predicting the effect of different factors which involve in the forming of sheet metal component and the information of post processed outcomes which is used throughout the design of product and the tool. Altair's Hyperform Radioss predictive tool is used in this study. The forming limit condition is studied for several circumstances of different factors affecting forming of component like blank holder force, coefficient of friction between metals and numerous simulation tryout sets are established and thickness changes are investigated. Major components required for simulation of sheet metal forming as die, forming punch, blank and binder are developed for simulation tryout.

R. Padmanabhan et al [7], employed Taguchi method to identify the relative influence of each process parameter. A reduced set of finite element simulations are carried out as per the Taguchi orthogonal array. Based on the predicted thickness distribution of the deep drawn circular cup and analysis of variance test, it is evident that die radius has the greatest influence on the deep drawing of stainless steel blank sheet followed by the blank holder force and the friction coefficient. Further, it is shown that a blank holder force application and local lubrication scheme improved the quality of the formed part.

In this paper study the wheel disk is observed to be having an error thinning at the inner corner of wheel disk. This error is being minimized at the plant by optimizing the forming process parameters by making use of experience of skilled designers and the factors which are affecting the process for thinning are determined by optimization of influencing process parameters in Minitab software using Taguchi method is done. Hence cost of experimentation, cost of die rework and time of experimentation are trial and error method. Virtualization of this process by taking trials in a computer software i.e. Altair's Hyperform and saved.

# 3. Methodology

#### 3.1 Simulation

#### 3.1.1 Modeling of Wheel Disk

Modelling of wheel disk was done in CATIA V5R19 as shown in fig as per component specification and IGS provided by R&D department of the industry. Figure 2 shows isometric view of wheel disk.

#### 3.1.2 Specification of Disk

Material – Mild steel (Hot rolled) Yield strength (YS) – 450 MPa Ultimate tensile strength (UTS) – 550 MPa Thickness – 3.7 mm Developed Blank diameter- 419 mm



Figure 2: CAD model of wheel disk

#### 3.1.3 Complete Wheel Disk Forming Process

The complete wheel disk is formed in 9 stages as shown in Figure 3.

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Figure 3: Multi-stage forming process of wheel disk forming

In first stage blank is prepared from raw material and then after 8 subsequent stages forming of wheel disk is completed. Cupping (stage-2), reverse form (stage-3) and flange down (stage-4) are the only forming stages.

After that remaining operations are only shearing operations like punching center hole, some piercing and coining operations are done in which no shape change of wheel disk occurs. So in our study we will analyze only stages 2, 3 and 5 as first forming stage, second forming stage and third forming stage respectively.

#### 3.1.4 Modeling of Forming Tools

The tools required for multi-stage forming of wheel disk are designed as per above process and wheel shape, and modelling of tools is done in Solidworks 2013 software (CAD software). The tools modelled for three forming stages are shown in Figure 4.



Figure 4: CAD models of forming tools for three forming stages

### 3.1.5 Simulation of Drawing Operation

The general procedure as mentioned in the Figure 5 below is followed and multi-stage simulation is carried out using Altair's Hyperform software.



Figure 5: Steps of simulation

The actual process of wheel disk forming as shown in Figure are to be transferred into the simulation software, hence the data for simulation are collected. The values of required press tonnages, blankholder loads and contact friction coefficients are calculated. This data is to be used to simulate the process in software. Simulation steps are explained in Figure

An inbuilt macro named multi-stage manager is used to simulate the process in Hyperform and the whole problem is solved in Hyperwork's inbuilt Incremental Radioss solver. The similar macros are selected suitable for our processes as shown in Figure 6.



Figure 6: Conversion of actual forming process into Hyperform macros

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#### 3.1.6 Simulation Results

After simulation of multi-stage forming process in multistage manager of Hyperform using Incremental Radioss as solver. The results of simulation are viewed in Hyperview and the results for %thinning after third forming stage are shown in Figure 7.

By the time simulation is carried out simultaneously experimental run for same design of tools is done and the profile of final wheel disk is checked over Co-ordinate measuring machine (CMM) and thickness at various points are measured, as in Figure The maximum %thinning observed on the final wheel disk is observed 27%, which is not a desirable result. Next the %thinning is to be reduced by optimizing the process parameters.



**Figure 7:** Simulation results of third forming stage The results of simulation process and actual experiment for thickness variation are compared and shown in Figure 8

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Simul	ation results v/s A	ctual resu
Points	3rd forming	
	Simulation results	Actual results
1	4.386	4.09
2	3.961	4.05
3	3.961	3.85
4	3.961	4.21
5	3.961	4.11
6	3.961	3.85
7	3.961	3.84
8	2.685	2.87
9	3.12	3.04
10	3.535	3.6
11	3.111	3.27
12	3.32	3.2
13	3.32	2.95
14	3.961	3.14

Figure 8: Comparison between simulation and experimental results

From the comparison of results, refer Figure 15, we get that simulation results are in good agreement with the actual results ( $\pm$  6 % error).

Hence we can replace the actual process by simulation for the future trials required for the optimization of forming process parameters by using Taguchi method to get %thinning below the permissible limits, i.e. below 10%.

# 3.2 Design of Experiments Using Taguchi's Orthogonal Arrays

We will use Design of Experiments (DOE) using Taguchi's design for optimization of these factors by designing the experiments rather than carrying out random experiments.

The basic steps associated with Design of experiments (DOE) using Taguchi are:

- i. Experiments for selected influential factors
- ii. The statistical analysis of the data
- iii. Evaluate most influential factors
- iv. Predict the optimized setting from Taguchi analysis.
- v. Carry out experiments
- vi. The conclusions reached and recommendations made as a result of the experiment.

#### 3.2.1 Collection Of Different Factors In Each Stage For Screening Experiments

The thinning error has been analyzed for influence of factors and it is observed that punch corner radius, die corner radius, blankholder load and friction between contact surfaces are the factors that affect the thinning in deep drawing processes. In first and second forming stages the part is shaped to its 90% of form and in third forming only the outer flange is rolled down and some shape corrections are carried out hence the third stage factors are not considered as influential for thinning error and influential factors selected from first and second forming stages are as shown in Figure 9.



Figure 9: Factors selected for Taguchi analysis

In the present system seven operating parameters, each at three levels, are selected to evaluate change in % thinning in wheel disk. The factors to be studied are mentioned in Figure 10.

For stage - I								
Factors influencing % thinning		Levels						
	Level 1	Level 2	Level 3					
Die radius (R1) in mm	10	15	20					
Binder load (BL1) in Tons	35	25	20					
Contact friction coefficient (F1)	0.125	0.100	0.075					
For stage – II								
Factors influencing % thinning		Levels						
	Level 1	Level 2	Level 3					
Die radius (R2) in mm	14.3	16.3	18.3					

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Binder load (BL2) in Tons	65	60	55
Punch radius (R3) in mm	4.5	5.5	6.5
Contact friction coefficient (F2)	0.125	0.100	0.075

Figure 10: Selected factors and their levels

Based on Taguchi method, the L27-OA was constructed. The reason for using L27-OA is to evaluate the significance of interaction terms. Virtual simulation experimentation are carried out using Altair's Hyperform software. Results in terms of %thinning at the end of third forming stage are shown in the Figure 11.

Figure 11: Simulation experiments and results

Expts.	<b>R1</b>	BL1	F1	R2	BL2	R3	F2	%	S/N ratios
1								THINNING	
1	10	35	0.125	14.3	65	4.5	0.125	27.419	-28.76103223
2	10	35	0.125	14.3	60	5.5	0.1	22.894	-27.19443357
3	10	35	0.125	14.3	55	6.5	0.075	18.369	-25.28171028
4	10	25	0.1	16.3	65	4.5	0.125	20.1765	-26.09691663
5	10	25	0.1	16.3	60	5.5	0.1	17.6515	-24.93563234
6	10	25	0.1	16.3	55	6.5	0.075	14.1265	-23.00069148
7	10	20	0.075	18.3	65	4.5	0.125	20.269	-26.13664645
8	10	20	0.075	18.3	60	5.5	0.1	15.744	-23.94230162
9	10	20	0.075	18.3	55	6.5	0.075	11.219	-20.99908296
10	15	35	0.1	18.3	65	5.5	0.075	18.0615	-25.13507631
11	15	35	0.1	18.3	60	6.5	0.125	18.5365	-25.36055471
12	15	35	0.1	18.3	55	4.5	0.1	19.2315	-25.68026318
13	15	25	0.075	14.3	65	5.5	0.075	24.689	-27.85006999
14	15	25	0.075	14.3	60	6.5	0.125	18.164	-25.18422986
15	15	25	0.075	14.3	55	4.5	0.1	16.859	-24.53663621
16	15	20	0.125	16.3	65	5.5	0.075	15.629	-23.87862382
17	15	20	0.125	16.3	60	6.5	0.125	13.104	-22.34807769
18	15	20	0.125	16.3	55	4.5	0.1	12.799	-22.14352078
19	20	35	0.075	16.3	65	6.5	0.1	23.574	-27.44866558
20	20	35	0.075	16.3	60	4.5	0.075	22.269	-26.95401431
21	20	35	0.075	16.3	55	5.5	0.125	19.744	-25.90870285
22	20	25	0.125	18.3	65	6.5	0.1	14.179	-23.03291205
23	20	25	0.125	18.3	60	4.5	0.075	12.874	-22.1942701
24	20	25	0.125	18.3	55	5.5	0.125	11.349	-21.09915192
25	20	20	0.1	14.3	65	6.5	0.1	16.1415	-24.15887781
26	20	20	0.1	14.3	60	4.5	0.075	15.9365	-24.04785894
27	20	20	0.1	14.3	55	5.5	0.125	15.3115	-23.70035477

#### 3.2.2 Analysis of Data

After conducting the experiment, the results were converted into S/N ratio values. The final L27-OA displaying response values and their corresponding S/N ratio values for % thinning error are shown in Figure 11. For these experimentation and analysis using Taguchi results are-

#### Main Effects Plot

Main effects plot for the main effect terms viz. factors R1, BL1, F1, R2, BL2, R3 and F3 are shown in Figure 12. From the main effect plots, it has been observed that % thinning decreases with increase in punch and die radius at stage two i.e. for R2 and R3, where it increases with increase in die radius at stage one i.e. R1 and increase in blankholder loads.



Figure 12: Main effects plots for % thinning

Analysis of Variance for Means (ANOVA)

The Analysis of variances (ANOVA) is carried out for the experiments and results of ANOVA are shown in Figure 13.

Analysis of Var	rianc	e for Mea	ns			
					_	_
Source	DF	Seq SS	Adj SS	Adj MS	F	Р
R1	2	15.588	15.588	7.794	3.34	0.070
BL1	2	174.300	174.300	87.150	37.37	0.000
F1	2	33.934	33.934	16.967	7.28	0.009
R2	2	65.452	65.452	32.726	14.03	0.001
BL2	2	94.409	94.409	47.204	20.24	0.000
R3	2	24.047	24.047	12.024	5.16	0.024
F2	2	6.616	6.616	3.308	1.42	0.280
Residual Error	12	27.982	27.982	2.332		
Total	26	442.327				
1						

Figure 13: Results of ANOVA

Response table for mean (Smaller is better)

Response Table for Means									
Level	R1	BL1	F1	R2	BL2	R3	F2		
1	18.65	15.13	19.17	19.53	15.45	18.65	17.02		
2	17.45	16.67	17.24	17.67	17.46	17.90	17.67		
3	16.82	21.12	16.51	15.72	20.02	16.38	18.23		
Delta	1.83	5.99	2.66	3.81	4.57	2.27	1.21		
Rank	6	1	4	3	2	5	7		

Figure 14: Response table for means

Taguchi's predictions for optimum %thinning results are collected as shown in Figure 15.

Taguchi Analysis: %THINNING versus R1, BL1, F1, R2, BL2, R3, F2 Predicted values S/N Ratio Mean -20.6039 9.66178 Factor levels for predictions R1 BL1 F1 R2 BL2 R3 F2 55 20 0.125 18.3 6.5 0.1 10



By doing Taguchi analysis and analysis of variances (ANOVA), we got the factors which influence more on %

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thinning are selected.

# 4. Results and discussion

The optimum values for influential factors for thinning % less than 10% i.e. 9.66178% are obtained from Taguchi's prediction.

- i. Die radius for first stage (R1) = 10 mm
- ii. Blankholder load in first stage (BL1) = 20 Tons
- iii. Contact friction coefficient in first stage (F1) = 0.125
- iv. Die radius for second stage (R2) = 18.3 mm
- v. Blankholder load in second stage (BL2) = 55 Tons
- vi. Punch radius for second stage (R3) = 6.5 mm
- vii. Contact friction coefficient in second stage (F2) = 0.1Now the simulation the whole process with these predicted optimized settings is carried out, and the results of this simulation for %thinning at the final third forming stage are shown in Figure 16.



Figure 16: Simulation results for optimized parameters

The maximum % thinning observed in this process is 9.1786%, which proves the optimization was successful till the simulation is concerned. Now, this virtual simulation experiments and the optimization results are to be validated with actual experimental run at industry. Hence, we manufactured the tooling and one experiment is carried out over actual metal sheet in industry and the part is analyzed for thinning error and the %thinning observed on the final part is 9.5458%.

# 5. Conclusion

In wheel disk forming process blank holder load in first and second stage forming and the die corner radius in the second stage are observed to have most influence on the % thinning error and thus contributed to improving the process's reliability. This study has shown the application of Simulation and Taguchi method on the optimization of forming process parameters to eliminate the thinning error. The level of importance of the process parameters is determined by using ANOVA. The simulation experiment was successful in terms of achieving the objective of experiment. Hence by using the simulation tool (Altair's Hyperform) and optimization of forming process parameters using Taguchi, the error of thinning in wheel disk is eliminated.

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# **Author Profile**

**Rohit S. Birajdar** is currently student of M. Tech (CAD-CAM) at YCCE, Nagpur. He is completed his graduation in Mechanical Engineering in 2011from SRTMU Nanded, Maharashtra, India.

Prashant D. Kamble is an Assistant Professor in Y.C.C.E., Nagpur.