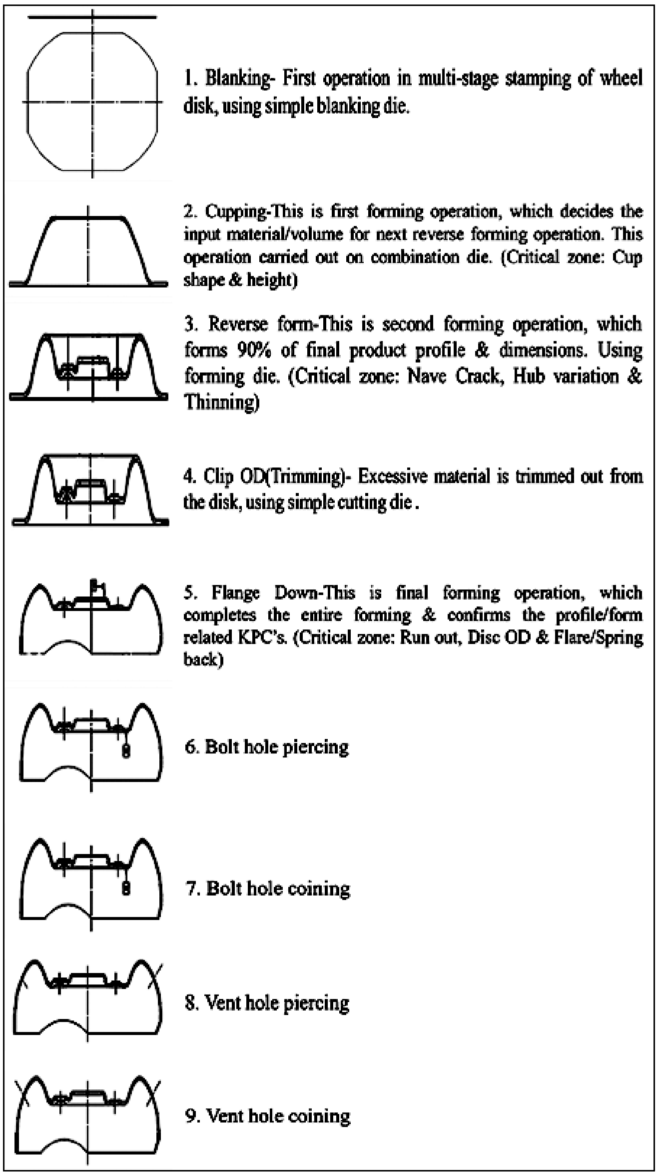

Figure 3: Multi-stage forming process of wheel disk forming

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.

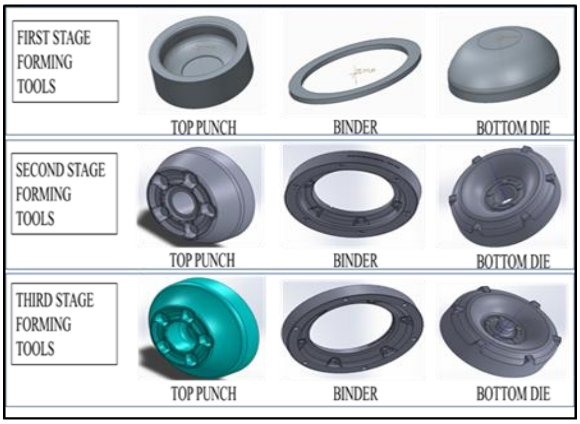

Figure 4: CAD models of forming tools for three forming stages

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.

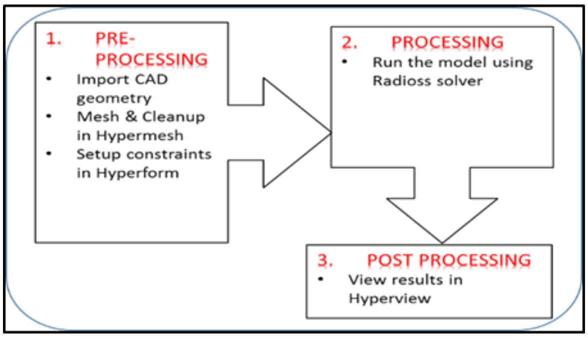

Figure 5: Steps of simulation

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.

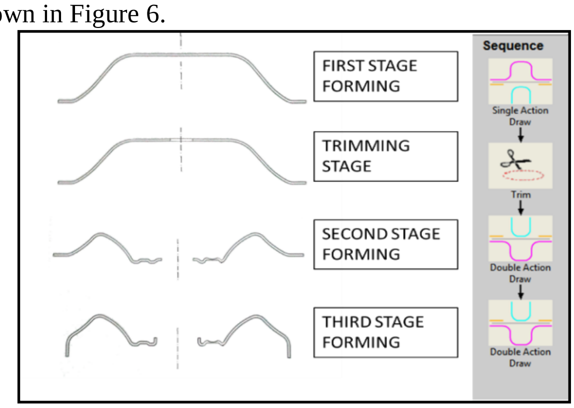

Figure 6: Conversion of actual forming process into Hyperform macros

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3.1.6 Simulation Results

After simulation of multi-stage forming process in multi-stage 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.

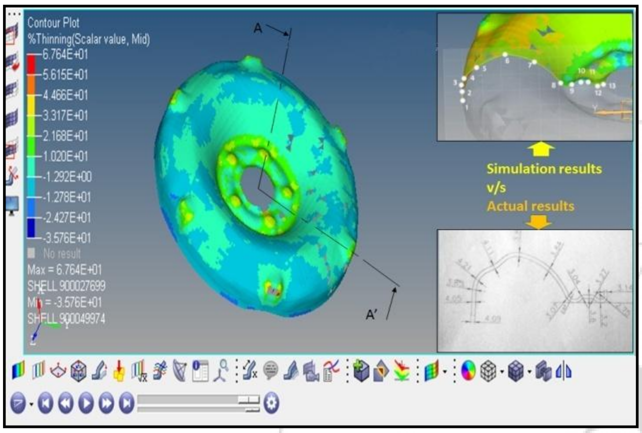

Figure 7: Simulation results of third forming stage

The results of simulation process and actual experiment for thickness variation are compared and shown in Figure 8

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DISC NO. 0973 REPORT		
THICKNESS VARIATION CHECK		
Simulation results v/s Actual results		
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 (± 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.

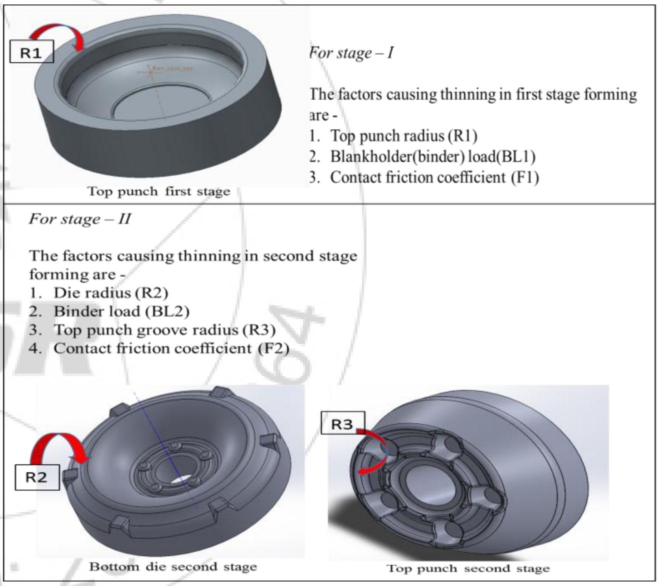

Figure 9: Factors selected for Taguchi analysis

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

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.	R1	BL1	F1	R2	BL2	R3	F2	% THINNING	S/N ratios
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.

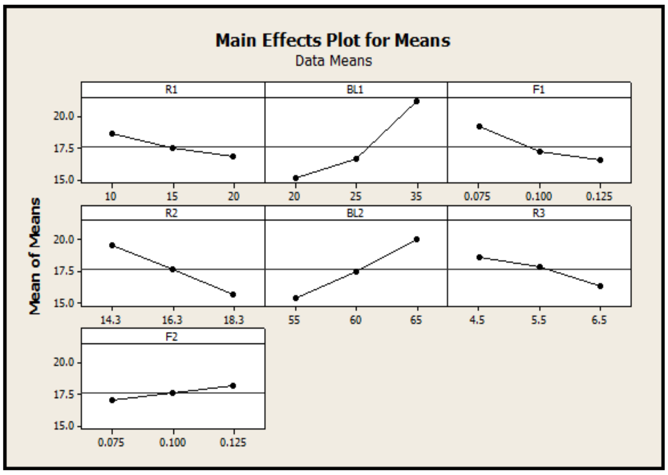

Figure 12: Main effects plots for % thinning

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 Variance for Means

Source          DF   Seq SS   Adj SS   Adj MS      F      P
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
```

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
10   20  0.125  18.3   55  6.5  0.1
```

Figure 15: Taguchi analysis predictions

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

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) = 0.1

Now 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.

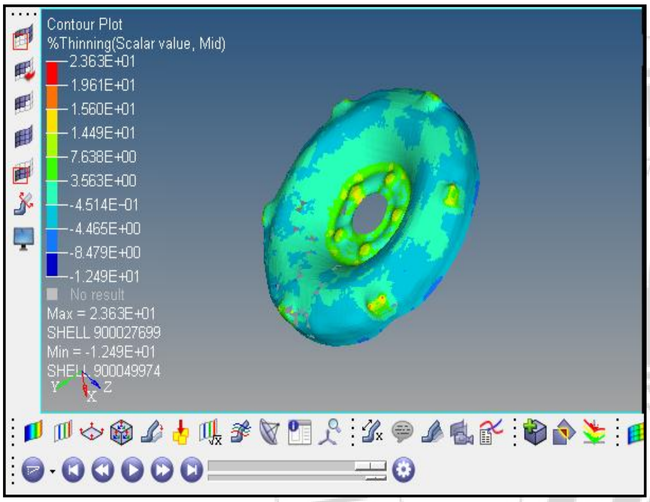

Figure 16: Simulation results for optimized parameters

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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