OPTIMIZATION OF PUNCH FORCE AND THICKNESS VARIATION IN FORMING OF Al-Mg-Si ALLOYS UNDER NON-ISOTHERMAL CONDITIONS

Dhulipalla Swapna[1], Chalamalasetti Srinivasa Rao[2]

[1] Department of Mechanical Engineering, R.V.R.&J.C. College of Engineering (A), Guntur, AP 522019, India
[2] Department of Mechanical Engineering, A.U. College of Engineering, Andhra University, Visakhapatnam, AP 530003, India

Corresponding author: dswapna32@gmail.com

Abstract: The demand for Al-Mg-Si alloys, promoted the studies for understanding the formability under non-isothermal conditions. In this work, various experiments were conducted on the hydraulic deep drawing machine using Taguchi method L27 factorial orthogonal array. Determination of the forming parameters that effects the punch force and thickness variation has been done through analysis of variance (ANOVA). The selected forming parameters for experimentation are temperature, die speed, sheet thickness and type of lubricant. The analysed data indicate that the punch force and thickness variation were influenced by the temperature and sheet thickness. To predict the outcomes of the experiments, additional analyses such as linear and quadratic regression have been adopted, shows the similarity with experimentation values. Confirmation test results showed that the Taguchi method was very successful in the optimization of formability parameters for minimum punch force and minimum thickness variation in forming of Al6061-T6 alloys.
Key words: formability of Al6061-T6, non-isothermal, uniform thickness distribution, punch force, Taguchi method, regression analysis.

1. INTRODUCTION

Increasing demand of aluminium 6xxx alloy series in the manufacturing sector is due to excellent strength of the material, leading to weight fall and consequent emission reduction during vehicle life cycle (Miller et al., 2000). As mentioned by Ayres (Ayres, & Wenner, 1978), although aluminium have good strength, the application of these alloys in the specified sectors are rarely seen because of low formability at room temperature compare to steel. Flanigan et al. (Flanigan, Tedsen, & Dorn, 1946) and Li and Ghosh (Li & Ghosh, 2003) considered the Al-Mg-Si alloys behaviour at elevated temperature whose tensile elongation improved at high temperature due to increased strain rate hardening. Abedrabbo et al.(Abedrabbo, Pourboghrat, & Carsley, 2006) illustrated, that the attention towards high temperature forming when compared with cold forming, is due the drop in flow stress, enhance in ductility and improvement in toughness of the material.

Warm forming is forming performed below the recrystallization temperature (Tebbe & Kridli, 2004) of the material. Generally, forming are performed at constant blank and tool temperature , however the local softening of a blank which enable ease of deep drawing and enhanced formability are seen in gradient conditions (Li & Ghosh, 2004) . The impact of gradient forming on aluminium alloys is that the forming limit strain increases rapidly as the temperature variation improves, thus leading to more intricate geometries. The upcoming challenging task in the process is to investigate the interaction between mechanical and thermal effects on the material behaviour.

Thickness distribution is one of the quality criteria in deep drawing (Browne, 2003; Padmanabhan & Menezes, 2007). Commonly, part failures are due to thinning, uniform thickness distribution, which are the main role in the forming process. Punch force is the other major parameter that effects the uniform thickness which plays a key role in high-quality and cost-effective manufacture. Various parameters affecting punch force and thickness distribution are type of material, lubrication used in process, punch speed and geometry of the material. Based on these reasons, number of arithmetic and numerical models was generated to enhance the properties of forming parameters. Most of the authors performed experiments to optimize the punch force and uniform thickness (Ahmetoglu, et. al., 1995; Wallmeier et. al. 2015; GAO et. al., 2009), but as punch movement is replaced by die movement, the optimization of punch force has its uniqueness.

Many optimization techniques have been applied in manufacturing units, but Taguchi based optimization shows its rareness, which varies from old fashioned practices (Cartwright, 2010). Kuo and Lin (Kuo & Lin, 2012) applied Taguchi method to examine the AZ31 sheets bounce back effect in bending process. Padmanabhan (Padmanabhan & Menezes, 2008) through Taguchi techniques analysed the effect of developing parameters, while maintaining the thickness distribution as objective generated using variable Blank Holder Force (BHF) and contact friction in predicting the tool aspect on stainless steel. The properties of development constraints such as speed, friction, die and punch radii was considered by Colgan and Monaghan (Colgan & Monaghan, 2003), by performing design of experiments. Taking ANOVA analysis the researcher concluded that the die entry radius is the one that improves the total thinning and decreases the drawing force. Özek and Ünal (Özek & Ünal, 2011) applied the regression analysis, signal to noise ratio and analysis of variance (ANOVA) to model the procedure and observed the effects. Raju et al (Raju et. al. 2010) studied the influence of parameters using Taguchi method and represented the best levels for aluminium sheets to attain uniform thickness distribution. Venkateswarlu (Venkateswarlu et. al. 2011) through investigations, specified that the temperature, the most influential parameter for aluminium alloys while performing deep drawing operation. Even Pourkamali Anaraki et al (Pourkamali et. al. 2012) investigated, the punch force effect and thickness variation through simulation while performing multi stage drawing.

The evaluated data, show that, several automobile units highlighted scrap rate and manufacture cost as a leading issue in generating the complex shaped part (Majeske, 2003). The feature and fabrication of the product is stimulated by many parameters such as tool materials, tool geometry, type of forming, lubricants, including forming parameters etc. The outcome of the trial and error method, adapted by most of the companies, where problems resolving done by optimization of controllable variables. Thus, not only reducing the count of tests but simultaneously minimising the fabrication cost and time loss was achieved by Taguchi method.

In this study, the influence of forming parameters on the punch force and thickness variation in the deep drawing of AL6061-T6 under gradient condition was investigated. Experiments were performed using Taguchi's L_{27} array. Additional to regression analysis, Taguchi's signal-to-noise ratio was performed for the determination of ideal forming conditions (temperature, die speed, sheet thickness and lubricating fluid) for minimum punch force and minimum thickness variation. The experimentation was carried out to check the reliability of developed models.

2. EXPERIMENTAL METHOD

Deep Drawing experiments

The deep drawing experiments were performed under gradient conditions using a hydraulic deep drawing machine of 13 tonnage prepared with a maximum pressure of 115 bars, ram stroke 150mm and power pack 10 litres per minute (LPM) max, 120 bar pressure, 2kW drive motor. The investigational system for the forming tests as in Figure 1. The AL6061-T6 material of 105mm diameter sheets of thickness 1, 1.5, 2 mm is used as work piece material and the detailed chemical composition are given in Table 1. The forming tests were performed at three different die speeds (0.4, 0.7, and 1mm/s), three temperatures (room temperature (RT), 150^{o}C and 300^{o}C) maintaining the blank holder force constant.

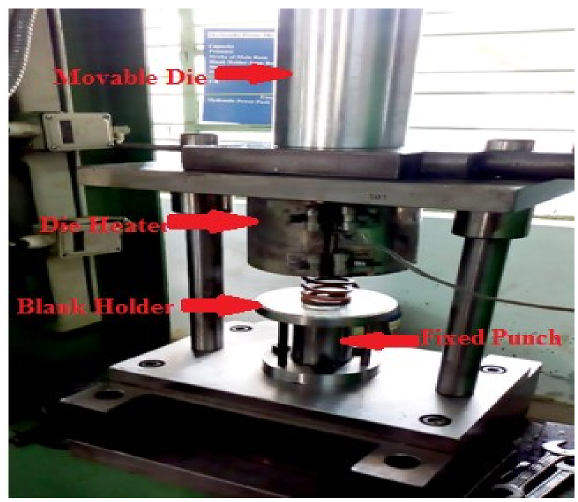

Fig. 1. Experimental setup for forming tests

Table 1. Chemical composition of Al6061-T6 (wt. %)

Sheet Thickness	Si	Cu	Fe	Zn	Mg	Mn	Cr	Al	Others
1 mm	0.570	0.181	0.279	0.048	1.199	0.067	0.179	97.300	0.170
1.5mm	0.640	0.186	0.360	0.043	1.049	0.119	0.181	97.270	0.146
2 mm	0.520	0.159	0.214	0.014	0.979	0.133	0.099	97.754	0.123

Forming tool - die design and lubrication

The forming investigations were conducted using three types of die tool inserts: D_1, D_2, D_3, are the specified dies with diameter 52.3mm, 53.3mm, 54.3mm as indicated in Table 2. Die is prepared of Inconel steel with constant punch diameter of 49.8mm diameter placed with blank holder, supported by three cushion pins. The tests were conducted at various lubrication conditions such as without lubrication (WOL), Graphite (G) and Boric

Acid (BA) are applied as solid lubricant layer over the sheets. The forming experiments were conducted by heating the die and blank at specified temperatures by maintaining the punch at constant room temperature (RT) to obtain better formability.

Table 2. Properties of forming die

Die	Die Diameter (min/max)	Clearance
D1	52.3/52.6 mm	2.5/2.8 mm
D2	53.5/53.6 mm	3.7/3.8 mm
D3	54.3/54.6 mm	4.5/4.8 mm

Punch force measurement

The pressure is defined as the force per cross sectional area. The average punch force (P) on the work piece was calculated by the pressure obtained from the sensors attached to the equipment, displays the values in control panel.

Thickness distribution measurement

The change in the thickness of the formed cups was measured using a digital micrometer calipers. Digital micrometers are used to calculate the thickness of the cups at different locations. Micrometer caliper instrument is used for linear measurements of dimensions such as diameters, thicknesses, of the solid bodies. It is used for exact measurements, mostly can measure up to 0.0005 inches and 0.001mm. Three times experimentation repetition is performed for accuracy in measurement.

3. EXPERIMENTAL DESIGN AND OPTIMIZATION

Taguchi method and design of experiments

Taguchi method is an influential design which not only reduces the number of tests but also minimizes the uncontrollable factors. Additionally, it directs an easy and systematic approach to make out the most favourable forming parameters in the process (Palanikumar, 2011; Asiltürk & Akkuş, 2011) .

Taguchi method depends on the signal-noise (S/N) ratio to compute the difference between the investigational and the required values (Asiltürk & Akkuş, 2011; Koksoy, 2004). Generally, S/N ratio analysis uses three kinds of excellence features, such as the lower-the-better, the higher-the-better, and the nominal-the-best (Gupta et. al. 2011) .

In each stage of the process parameters, the S/N ratio is calculated based on the S/N analysis. The objective of this learning was to reduce punch force and thickness distribution. Hence the lower-the-better feature was represented in equation (1).

$$\eta = \text{S/N ratio} = -10\ \text{Log}_{10}\left[\frac{1}{n}\sum y_i^{\ 2}\right] \qquad (1)$$

where y_i is the experimental data at the i^{th} experiment and n is the number of observations of the experiment (Mandal et. al. 2011a).

Table 3. Forming parameters and their levels

Parameters	Symbol	Level 1	Level 2	Level 3
Blank Thickness (mm)	A	1	1.5	2
Die and Blank Temperature	B	27°C	150°C	300°C
Die Speed (mm/s)	C	0.4	0.7	1
Lubrication (μ)	D	WOL	BA	G

The control factors and the level for form sheet thickness (A, temperature (B), die speed (C) and lubrication (D) were identified as given in Table 3. The most appropriate orthogonal array L_{27} was selected to conclude the most favorable forming parameters and to examine the effects of developed parameters (Badgujar & Wani, 2018).

4. ANALYSIS AND EVALUATION OF EXPERIMENTAL RESULTS

Taguchi signal-to-noise (S/N) ratio

Taguchi technique is implemented to calculate the control factors of punch force and thickness variation which are optimized through signal-to-noise ratios. The performed samples are shown in Figure 2.

As a result, the Table 5 indicates the values of S/N ratios of punch force and thickness variation calculated from the "lower-the-better" equation. As part of the forming test, the determined average values for punch force is 52.57KN and for thickness variation is 0.187mm. Accordingly, average S/N ratio values are -33.7851 and 15.2392 for punch force and thickness variation.

Fig. 2. Experimentation Samples

Table 5. The results of experiments and S/N ratios values

Experiment No.	Control factors				Punch Force, P (KN)	S/N ratio for P (dB)	Thickness Variation, Th (mm)	S/N ratio for Th (dB)
	A Sheet Thickness (mm)	B Die and Blank Temperature (°C)	C Die Speed (mm/s)	D Lubrication (μ)				
1	1.5	300	0.7	G	39.4797	-31.9275	0.2125	13.4528
2	2	150	1	BA	66.6358	-36.4742	0.233521	12.6335
3	1.5	27	0.4	G	70.0294	-36.9056	0.117376	18.6084
4	2	300	1	G	73.7564	-37.3560	0.2786	11.1004
5	1	27	0.7	BA	50.2945	-34.0304	0.101652	19.8577
6	1	300	0.4	G	26.8453	-28.5774	0.145989	16.7136
7	1	300	0.7	WOL	25.9053	-28.2678	0.172466	15.2659
8	1.5	150	0.4	WOL	42.0087	-32.4668	0.175747	15.1022
9	1	27	0.4	WOL	54.2636	-34.6902	0.094252	20.5142
10	2	300	0.7	BA	44.8966	-33.0443	0.26804	11.436
11	2	27	0.7	G	92.4663	-39.3197	0.192625	14.3057
12	1.5	300	0.4	BA	21.8005	-26.7693	0.201206	13.9272
13	1	27	1	G	70.4265	-36.9547	0.110914	19.1003
14	1.5	150	0.7	BA	37.6288	-31.5104	0.203428	13.8318
15	1	150	1	WOL	32.2885	-30.1810	0.157349	16.0627
16	1	300	1	BA	32.8800	-30.3386	0.148733	16.5519
17	2	150	0.4	G	66.2397	-36.4224	0.2248	12.9641
18	1.5	27	0.7	WOL	55.5013	-34.8861	0.13448	17.4268
19	1.5	300	1	WOL	33.8566	-30.5929	0.24308	12.285
20	2	300	0.4	WOL	46.5978	-33.3673	0.274061	11.2431
21	1	150	0.7	G	48.7557	-33.7605	0.140068	17.0732
22	2	150	0.7	WOL	64.3460	-36.1704	0.236012	12.5413
23	1.5	150	1	G	67.7087	-36.6129	0.191699	14.3476
24	2	27	0.4	BA	84.4921	-38.5363	0.182839	14.7586
25	2	27	1	WOL	78.1531	-37.8589	0.178275	14.9782
26	1.5	27	1	BA	62.1216	-35.8649	0.133806	17.4705
27	1	150	0.4	BA	30.1380	-29.5823	0.127271	17.9054

T_P (Punch Force total mean value) = 52.5746KN.
$T_{P\text{–}S/N}$ (Punch Force S/N ratio total mean value)=-33.7951.
T_{Th} (Thickness variation total mean value) =0.1807mm.
$T_{Thb\text{–}S/N}$ (Thickness Variation S/N ratio total mean value) =15.2392.
The Table 6 representing the level values of control factors for P and Th are given in graph forms shown in Figures 3 and 4 through which most favorable forming parameters for minimizing the punch force and thickness variation are determined. The maximum S/N ratio values for control factor of each level to represent the finest value for punch force is $A_1B_3C_1D_2$ and for thickness variation is $A_1B_1C_1D_2$.

Table 6. S/N response table for P and Th factor

Levels	Control factors							
	Punch Force (P)				Thickness Variation (Th)			
	A	B	C	D	A	B	C	D
Level 1	**-31.82**	-36.56	**-33.04**	-33.16	**17.67**	**17.45**	**15.75**	15.05
Level 2	-33.06	-33.69	-33.66	**-32.91**	15.16	14.72	15.02	**15.37**
Level 3	-36.51	**-31.14**	-34.69	-35.32	12.88	13.55	14.95	15.30
Delta	4.69	5.42	1.66	2.41	4.79	3.89	0.80	0.33
Rank	2	1	4	3	1	2	3	4

Evaluation of experimental results

The means response for Punch Force and thickness variation given in Table 7 shows the optimum level for each control factor was identified according to the lowest Means ratio among the levels of that control factor.

Table 7. Mean response table for P and Th factor

Levels	Control factors							
	Punch Force (P)				Thickness Variation (Th)			
	A	B	C	D	A	B	C	D
Level 1	41.31	68.64	49.16	48.10	0.1332	0.1385	0.1715	0.1851
Level 2	47.79	50.64	51.03	47.88	0.1793	0.1878	0.1846	0.1778
Level 3	68.62	38.45	57.54	61.75	0.2299	0.2161	0.1862	0.1794
Delta	27.31	30.19	8.38	13.87	0.0967	0.0776	0.0147	0.0072
Rank	2	1	4	3	1	2	3	4

Depending on this, the levels $A_1B_3C_1D_2$ gives the best P value. Similarly, the levels and Mean response for the factors giving the best Th were specified as $A_1B_1C_1D_2$. According to the difference of the die speed, there was not much change in the punch force values. In thickness distribution, the starting speed displays an advantage compare to higher speeds, resulted due to rapid deformation of the tool edge.

The punch force values exhibited a decreasing tendency with rise in temperature, as work hardening decreases at elevated temperature. As sheet thickness plays a role, lower thickness can be easily deformed, so lower punch force is preferable. Lubrication would reduce the co-efficient of friction and enhance the generation of smooth cups. Boric Acid the best lubrication for the formability of the materials. The punch force requirement can be reduced automatically but the effect on the thickness distribution won't be changed due to lubrication. Thus on observation, the results, convey that for Punch force the sequence of the parameter effect are temperature, sheet thickness, lubrication and die speed. Similarly for thickness variation, the sequences of the parameter effect are sheet thickness, temperature, die speed and lubrication. The Figures 3 and 4 shown graphically represent the results of the effects of control factors on P and Th which are obtained from Taguchi Method. The Figures 5,6 represents the residual plots for means of punch force and thickness.

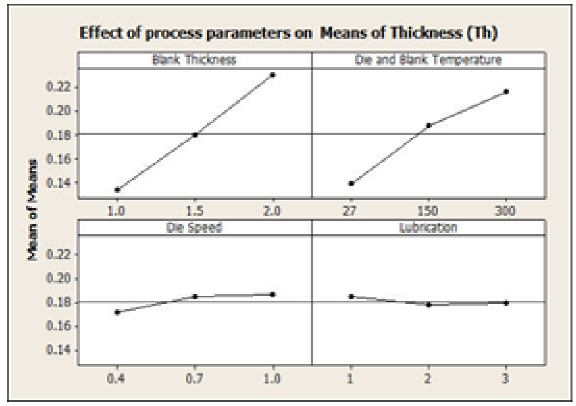

Fig 4. Effect of process parameters on Means of Thickness (Th)

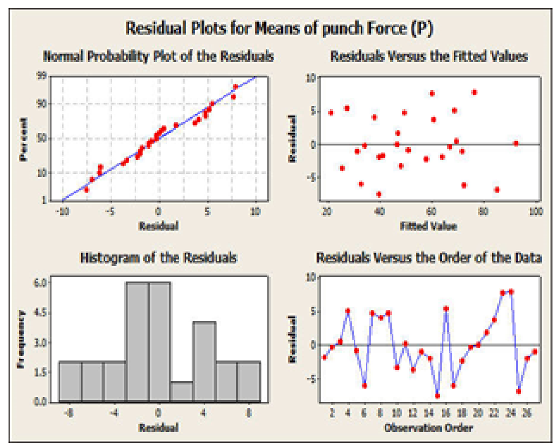

Fig 5. Residual Plots for Means of Punch Force (P)

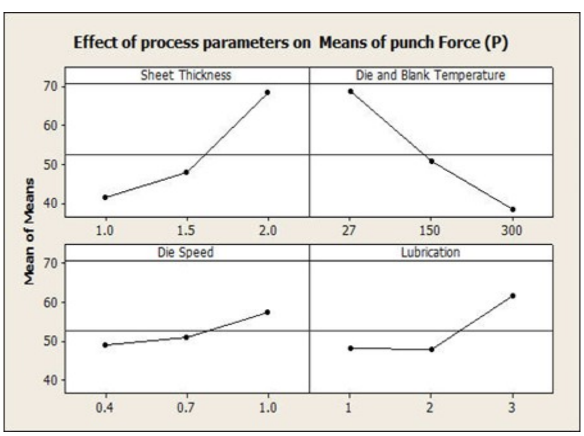

Fig 3. Effect of process parameters on Means of Punch force (P)

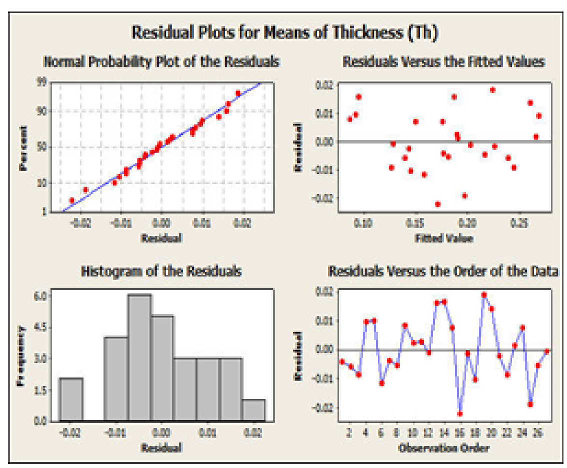

Fig 6. Residual Plots for Means of Thickness (Th)

ANOVA method

Determination of the individual interactions on the control factors are done through statistical method, ANOVA in Minitab, is used to analyze the effect of process parameters on punch force and thickness variation shown in Table 8. F values of each control factor are used to identify the importance of control factors in ANOVA. Degree of influence on the process performance was discussed as the percentage value.

In Table 8, the percent contributions of the A, B, C and D factors on the punch force were found to be 34.53%, 43.13%,, 4.11% and 10.25% respectively. Thus, the dominating factor affecting the punch force was temperature (factor B, 43.13%). The ANOVA results indicate the percent contributions of the A, B, C and D factors on thickness variation as 56.77%, 37.45%, 1.58% and 0.35% respectively. The sheet thickness (factor A, 56.77%) is considered as the effective parameter on thickness variation. Thus the percent error is 7.98% for P and 3.86% for Th.

Table 8. Results of ANOVA for Punch Force and Thickness Variation

Variance source	Degree of freedom (DoF)	Sum of squares (SS)	Mean square (MS)	F ratio	Contribution rate (%)
P					
A	2	106.08	53.041	38.92	34.53
B	2	132.49	66.246	48.61	43.13
C	2	12.62	6.309	4.63	4.11
D	2	31.49	15.747	11.56	10.25
Error	18	24.53	1.363	–	7.98
Total	26	307.21	–	–	100
Th					
A	2	0.042088	0.021044	132.48	56.77
B	2	0.027763	0.013882	87.39	37.45
C	2	0.001171	0.000585	3.69	1.58
D	2	0.000262	0.000131	0.82	0.35
Error	18	0.002859	0.000159	–	3.86
Total	26	0.074143	–	–	100

Regression analysis of punch force and thickness variation

The variables that show the relation between dependent variable and independent variables was analyzed by regression analyses using excel software (Cetin et.al., 2011). In this study, the dependent variables are punch force (P) and thickness variation (Th), whereas the independent variables are sheet thickness (A), temperature (B), die speed (C) and lubrication (D). The linear and quadratic regression models were used to generate predictive equations for punch force and thickness variation as shown below.

$$P_1 = 5.6078 + 27.3096A - 0.1095B + 13.9652C + 6.82148D \quad (2)$$

$$R - Sq = 87.34\% \qquad \text{R - Sq(adj)} = 85.04\%$$

$$Th_l = -0.02037 + 0.09667A + 0.00028B + 0.02452\text{C} - 0.002841\text{D} \quad (3)$$

$$\text{R - Sq} = 94.02\% \qquad \text{R - Sq(adj)} = 92.93\%$$

The comparisons of predictive equations P_l (equation (2)) and Th_l (equation (3)) with actual test results shown in Figure 7 are generated by linear regression model. The obtained R^2 values from linear regression model are 87.34% for P and 94.02% for Th. The predictive equations for the quadratic regression of punch force and sheet thickness are given below, equations (4) and (5):

$$P_q = 121.93742 - 48.62591A - 0.184589B - 76.75241C - 28.57795\text{D} + 28.6912\text{A}^2 - 0.039855AB + 1.95705AC - 2.58555\text{AD} + 0.000238\text{B}^2 + 0.103006BC - 0.008125BD + 25.73697\text{C}^2 + 17.6861CD + 7.0473D^2 \quad (4)$$

$$\text{R - Sq} = 99.49\% \qquad \text{R - Sq(adj)} = 98.89\%$$

$$\text{Th}_q = 0.00669 + 0.0417525\text{A} + 0.0004164\text{B} + 0.11773\text{C} - 0.02391\text{D} + 0.009071\text{A}^2 + 0.000128\text{AB} - 0.00552\text{AC} + 0.00555\text{AD} - 7.76798\text{e}^{-7} + 5.92496\text{e}^{-6} - 3.7669\text{e}^{-5} - 0.06359\text{V}^2 + 0.001582\text{CD} + 0.00440\text{D}^2 \quad (5)$$

$$\text{R - Sq} = 98.11\% \qquad \text{R - Sq(adj)} = 95.91\%$$

The comparisons of predictive equations P_q and Th_q with actual test results shown in Figure 8 are generated by the quadratic regression model. The obtained R^2 values from the quadratic regression model are 99.49% for P and 98.11% for Th.

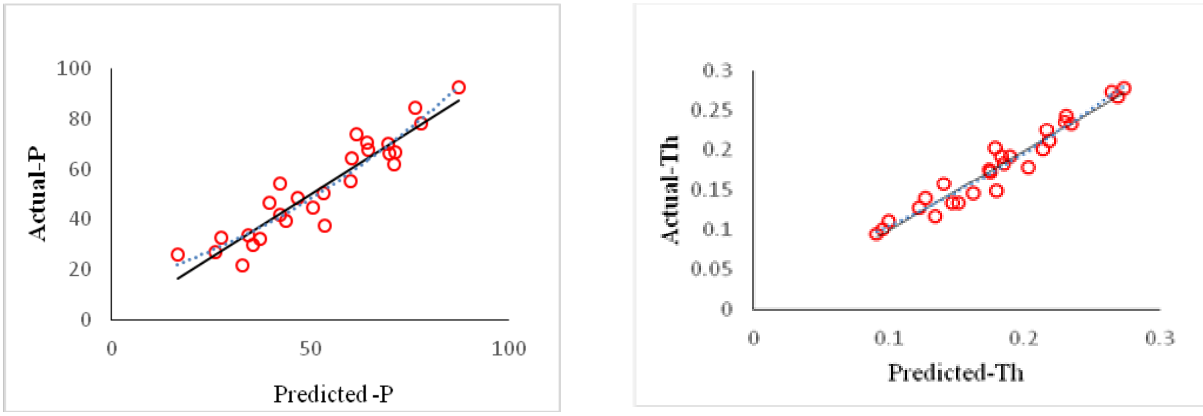

Fig. 7. Comparison of the linear regression model with experimental results for P and Th.

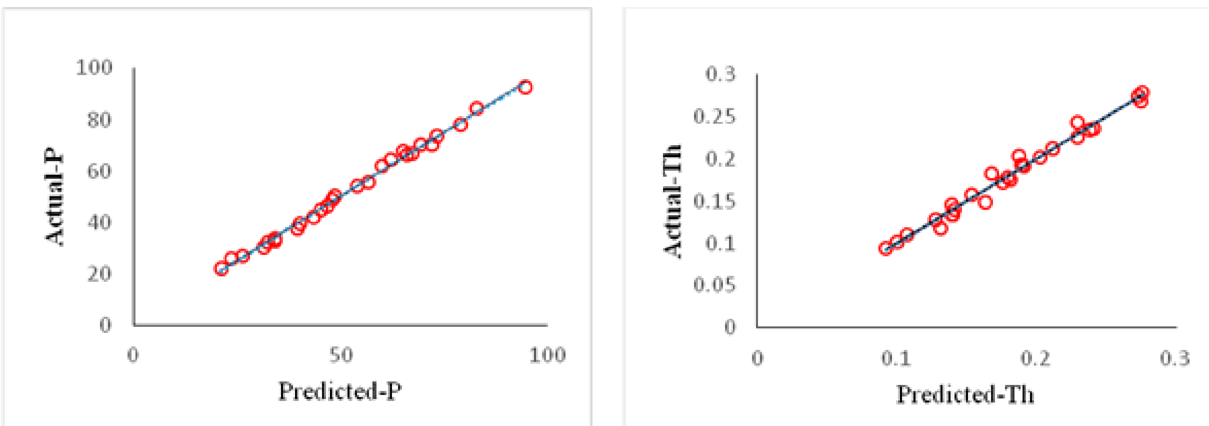

Fig. 8. Comparison of the quadratic regression model with experimental results for P and Th

Evaluation of optimum punch force and thickness variation

Verification test was needed for Taguchi optimization technique to validate the optimized results (Mandal et. al., 2011b) . In the estimation of optimum punch force and thickness variation, equations (6) and (7) were used respectively.

$$P_{opt} = (A_1 - T_p) + (B_3 - T_p) + \\ + (C_1 - T_p) + (D_2 - T_p) + T_p \tag{6}$$

$$Th_{opt} = (A_1 - T_{Th}) + (B_1 - T_{Th}) + \\ + (C_1 - T_{Th}) + (D_2 - T_p) + T_{Th} \tag{7}$$

Here, (A_1, B_3, C_1, D_2) and (A_1, B_1, C_1, D_2) represent the optimum level average values of punch force (P_{opt}) and thickness variation (Th_{opt}) respectively. T_P and T_{Th} state the average of all of the P and Th values obtained from the experimental study (Table 5). As a result of the calculations, it was estimated that P_{opt} = 19.07594KN and Th_{opt} = 0.07869mm.

Confidence interval (CI) equations are used for the evaluation of optimization accuracy for punch force and thickness variation (Dvivedi & Kumar, 2007):

$$CI_{Ra,Vb} = \sqrt{F_{\alpha,1,F_e} V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \tag{8}$$

and

$$\eta_{eff} = N / (1 + T_{dof}) \tag{9}$$

Here V_e is error variance, the useful number of replication is η_{eff} , the error of DOF is f_e , R is the experimental replications, $F_{\alpha,1,fe}$ is the F ratio at a 95% confidence are the terms in equation (8). N is the number of experimentation and the total DOF is T_{dof} given in equation (9). $F_{0.5,2,18}$ = 3.5546 (from F test table), V_{eP} = 1.363 and V_{eTh} = 0.000159 (Table

5), R=3 (equation (8)). N = 27, T_{dof} = 8 and n_{eff} = 3 (equation (9)).

By using the equations (8) and (9) the confidence intervals were calculated as CI_P = ± 1.7972 and CI_{Th}=± 0.0194. The expected average optimal punch force and thickness variation with the confidence interval at 95% confidence is:

$[P_{opt} - CI_P] < P_{exp} < [P_{opt} + CI_P]$, i.e.,
=[19.07594-1.797205] < 18.2 < [19.07594+1.797205]
= 17.27874< 18.2 <20.87315

$[Th_{opt} - CI_P] < Th_{exp} < [Th_{opt} + CI_P]$, i.e.,
= [0.07869 -0.019411] < 0.0832 < [0.07869 +0.019411]
= 0.059279 < 0.0832 <0.098101

The P_{exp} and Th_{exp} values, obtained from the experimental study stayed within the confidence interval limits. Thus, the system optimization for punch force and thickness variation with a significance level of 0.05 was achieved using the Taguchi method.
By means of Taguchi method, the significance level of 0.05 while optimizing the punch force and thickness variation was obtained, indicating P_{exp} and Th_{exp} experimental values lying within the confidence interval limits.

Confirmation tests
Confirmation tests of the control factors were conducted both for optimum and random levels by using Taguchi method and regression linear - quadratic equations.

Table 9. Predicted values and confirmation test results by Taguchi method and regression equations

Level	For Taguchi method			For linear regression equations			For quadratic regression equations		
	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
P (KN)									
$A_1B_3C_1$ D_2 (Optimum)	18.20	19.0759	4.78	18.20	19.2857	6.00	18.20	17.8131	2.17
$A_2B_2C_1$ D_2 (Random)	39.50	37.7459	4.44	39.50	41.7279	5.6404	39.50	38.0194	3.748
Th (mm)									
$A_1B_1C_1$ D_2 (Optimum)	0.0832	0.0786	5.42	0.0832	0.0880	5.78	0.0832	0.0865	3.91
$A_2B_3C_1$ D_2 (Random)	0.2151	0.2023	6.00	0.2151	0.2130	1.00	0.2151	0.2021	6.00

Table 9 indicates, the comparison of experimental and the predicted values obtained from equations (equations (2)-(5)), are almost similar to each other. M.H. Cetin, suggested that, the error values must be below 20% for a reliable statistical analyses (Cetin et al., 2011). Even though the calculated error percentages are higher in few conditions, the results within acceptable limit, made the confirmation test as successful optimization.

5. CONCLUSIONS

In this study, the effect of forming parameters and the optimal condition while drawing of Al6061-T6 under gradient conditions was determined through Taguchi method. ANOVA is used to evaluate the experimentation results. For minimizing the punch force and thickness variation, the optimum levels of the control factors using S/N rates were determined. The most favorable conditions for punch force is $A_1B_3C_1D_2$ (i.e., sheet thickness = 1mm, temperature = 300°C, die speed = 0.4mm/s and lubrication = graphite) and for thickness variation at $A_1B_1C_1D_2$ (i.e., sheet thickness = 1mm, temperature = RT, die speed = 0.4mm/s and lubrication = boric acid) were observed. It has been further identified that the temperature and sheet thickness are the main parameters that foretell the better formability of Al6061-T6 with major contirbutions. Quadratic regression models with R^2 values more than 95% were developed to estimate the values of punch force and thickness variation. Therefore, this paper succesffuly reported the minimization of forming cost and time in non-isothermal deep drawing of Al6061-T6 alloy through Taguchi method which can be multipurpose for both academic and industrial applications. In future, studies could consider other factors such as the depth of cup, forming tool geometry, drawing tool materials, wrinkle generation, die entry radius, punch nose radius and lubricants, all of which affect the punch force and thickness variation.

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