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Simultaneous optimization of wall angle and surface roughness for spif of aluminum 6063 alloy by using taguchi and gra

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Abstract:-**This paper presents optimization of performance characteristic in single point incremental forming by using Taguchi and grey relational analysis method. Performance characteristic (surface roughness and wall angle) were investigated during incremental sheet forming operation. The process parameter (tool radius, sheet thickness, step size, feed rate & lubrication) were investigated using mixed L_{18} orthogonal array on aluminum 6063 alloy. In order to optimize wall angle and Surface roughness simultaneously, grey relational analysis (GRA)is employed along with Taguchi method. Through GRA, grey relational grade is used as a performance index to determine the optimal setting of process of process parameter for multiple machining characteristics. Analysis of variance (ANOVA) shows that Lubrication spindle speed & feed rate are the most significant parameters affecting the multiple performance characteristics. Confirmatory results, proves the potential of GRA to optimize process parameters successfully for multiple–performance characteristics.**

1. I. INTRODUCTION

Incremental sheet forming is one of newer forming technologies where complicated and unsymmetrical external shapes can be formed by using single point tool to carry out progressively sheet deformation on CNC milling machine to overcome drawbacks like high cost of tooling and high set-up time in case of small batch production. Many researcher have contributed towards the process parameter optimization. For instance, Y.H. Kim and J.J.Park [2] studied the effect of process parameter on formability. J.J Park and Y.H. Kim [3] again in next year compared the formability of conventional forming and SPIF process, found SPIF process had higher formability. L.Carrino et.al[4] studied the influence of friction in the negative die less incremental forming process, found that formability and surface roughness both decreases as we go for dry run from grease through coolant supplied run. I. Cerro et al. [5] showed preliminary results obtained with experimental tests & concluded that ISF is very promising technology. Ham & Jeswiet [1] presented experiments, which formalize the forming parameters critical in SPIF and the degree to which they affect formability. The experiments shows feed rate, spindle rotation speed, step size and forming angle affect whether a part can be successfully formed. This experiment also shows depth and diameter have no effect on the likelihood of forming a part &little effect of step size on the maximum forming angle, whereas other parameters have a significant effect on maximum forming angle.

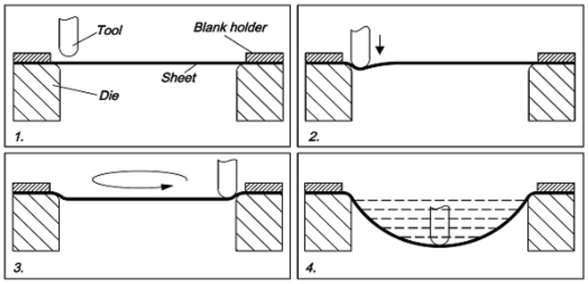


Figure 1: Principle operation of ISF [1]

G.Hussain and L.Gao[6] presented an innovative and viable method to test the thinning limits of sheet metals in Negative Incremental Forming along with verification of the Sine's law of thickness distribution. Pohlak et al. [7] predicted material and tool failure in Incremental sheet forming and strategies for determining the forming limit diagram were also pointed out. Alves et al. [8], presented the work that focused on a comprehensive experimental investigation of the geometric accuracy and surface quality of the formed parts. The experimental work led to the conclusion that the formability and surface quality of the parts are clearly influenced by: thickness of the plate; wall angle, the use of dummy sheet. Rattanachan & Chungchoo [9], studied formability in Single Point Incremental Forming of Dome Geometry. The result showed that the tool rotational speed and the feed rate affected SPIF formability of sheet metal.W.K.H. Sarraji and J.H Mohamed [10], investigated the effect of of four process parameters on thickness variation in ISF process and showed the direction of tool travel relative to rolling direction have greatest effect on the thickness variation. G.Hussain et al. [11] investigated the formability of AA-2024 sheets, in the annealed and pre-aged conditions in the SPIF process.The formability of pre-aged AA-2024 sheet decreases with the increase in the forming speed. Furthermore, the annealed sheet shows higher formability than the pre-aged sheet.S.C. Babu andC.C.Cavaleret al.[12, 13] studied roughness, Sentihiland Babu by varying the input parameter inferred that the increase in spindle speed increases the roughness values.V.Oleksik et al. [14], studied the influence of geometrical parameters, wall angle and part shape on thickness reduction of single point incremental forming. It concluded that the maximal value of the thickness reduction not reached from the beginning, but only after a critical value of the part's height reached this value depending strongly on the part's wall angle. Also depend on punch diameter and on the vertical step size.R.Crina[15] determined the formability limit, expressed as the maximum forming angle, of four materials: DC01 carbon steel, 304 stainless steel, Ti6Al4V titanium alloy and aluminum A1050, processed by SPIF. V.Gulati et al. [16] studied process parameter optimization of wall angle and surface roughness in SPIF by using Taguchi methodology to optimize single output parameter at a time.

Since by V.Gulati [16] it is possible to optimize both output parameter individually. So need to optimize simultaneously both performance characteristic (WA and SR) by using GRA along with taguchi so that best optimal value can be obtained.

2. II. EXPERIMENTAL SET UP, DESIGN AND RESULTS

3. 2.1 EXPERIMENTAL SET UP

The experiments were carried out on a 3 axis CNC vertical milling (Bridge –Port VMC 2216). The complete clamping system composed of the static frame, fixed on the machine working table, the blank holder to hold the sheet over backing plate.Fig 2 shows the experimental set up used in SPIF. Eighteen blanks sheet metal (square shape) of same size (340mm×340mm) having different thickness (0.5 mm, 1mm and 1.5 mm) were carried out for experimental work. Two Forming HSS tools of radius 8 mm and 12 mm with hemispherical tip were designed and used for deforming of blank sheets (fig 3)..The material of sheet metal blank was used Aluminum 6063 alloy. The composition and mechanical properties are shown in Table 1 and Table 2.

Figure 2 shows the complete experimental set up used in SPIF

Figure 3. 8 mm &12 mm H.S.S tool

2.2 CAD/CAM design development

CAD model (truncated cone shape) as prescribed by Hussain and Gao, 2007 [6] was generated with the help of CATIA V5 are shown in figure 4. The generated CAD model was utilized to produce spiral tool path of same step size throughout with the help of Master CAM 9 which produces different fracture sheets at certain wall angle in SPIF are shown in figure 5. Surface roughness was measured using Mitutoya surf-testSJ-201P (Fig 6).

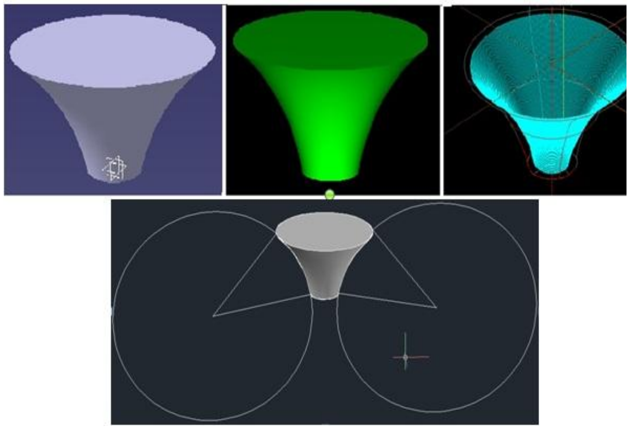


Figure 4 Development of tool path from CAD model to tool path

Figure. 5 Sheets having fracture at certain wall angle in SPIF process

Figure 6 Surfacce measurement through Mitutoya surf-test SJ-201P

2.3. Experimental Design

In present work, six process parameters namely Tool radius, sheet thickness, step size, spindle speed, feed rate, lubrication were selected as process parameter during forming of aluminum 6063 sheets with SPIF.Out of six input parameters, tool radius, which is a geometrical variable was kept at two levels while all five variables were assigned values of three levels. Table 3 depicts the value of levels of the selected process parameters.

The orthogonal array forms the basis for the experimental analysis in the Taguchi method. The selection of orthogonal array is concerned with the total degree of freedom of process parameters. Total degree of freedom (DOF) associated with six parameter is equal to 11(1×1+5×2). The degree of freedom for the orthogonal array should be greater than or at least equal to that of the process parameters [17]. Thereby, L_{18} orthogonal array having degree of freedom equal to 17 has been considered in present case. The experimental layout is shown in Table 4

2.4 Experimental results

Based on the experimental layout depicted in Table 2, the experiments were performed in random order and each specific experiment was repeated two times. Two performance characteristics namely, wall angle (WA) and surface roughness (SR) were measured. Wall angle was measured in degree by using vernier bevel protector. Surface roughness (in µm) was measured in terms of mean absolute deviation (Ra) using the digital surface tester Mitutoya 201P. Observed performance characteristics are depicted in Table 5.

4. III.Optimization of individual machining characteristics by using Taguchi method

In Taguchi method, the basic method converts the objective parameters to signal-to-noise (S/N) ratio treated as the quality characteristics evaluation index. The least variation and optimal design are obtained by means of the S/N ratio. The higher the S/N ratio, the more stable the achievable quality. Depending on the required objective characteristics, there are three types of S/N ratio, the lower-the-better, Higher-the-better and the nominal -the- better. In present work, two types of S/N ratio has been used, Higher -the-better for WA and lower-the-better for SR.

The S/N ratio with a higher –the-better characteristic that can be expressed as follows,

$$\eta_{ij}=-10\log\left\{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y\ {}_{ij}^{2}}\right\}(1)$$

The S/N ratio with a lower-the-better characteristic that can be expressed as follows,

$$\eta_{ij}=-10\log\left\{\frac{1}{n}\sum_{i=1}^{n}y_{ij}^{2}\right\}$$
(2)

Where y_{ij} is the ith experiment at the jth test and n is the total number of tests. Table 5 shows the S/N ratios of measured mean values of WA and SR.

The response table using Taguchi method is employed here to calculate the effect of each level of process parameter on machining characteristics. It is done by sorting the mean values of machining characteristics corresponding to levels of the process parameter in each column of the orthogonal array, and taking an average on those with same level. For example, the average effect on wall angle for parameters A and B at level 1 can be calculated as follows:

A_1=(55.66+64.66+76.33+64+72.33+63.33+85.33+56+63)/9 =66.74,

B_1= (55.66+64.66+76.33+65+67.66+46.66)/6 =62.66

Using same method, calculation were performed for each process parameters level and response tables were generated for wall angle and surface roughness as shown in Table 6.

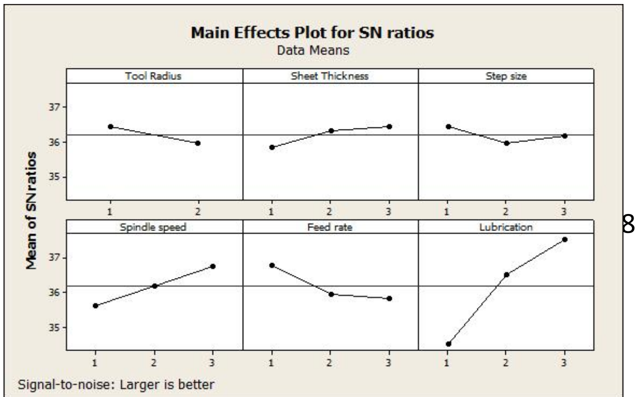


Fig. 7 and Fig.8 show the S/N ratio plot for WA and SR. the optimum parameters combination for WA and SR are $A_1B_3C_1D_3E_1F_3$ and $A_2B_1C_1D_1E_1F_3$ corresponding to the largest values of S/N ratio for all control parameters.

Figure 7 Main effect Plot for S/N Ratio for wall angle

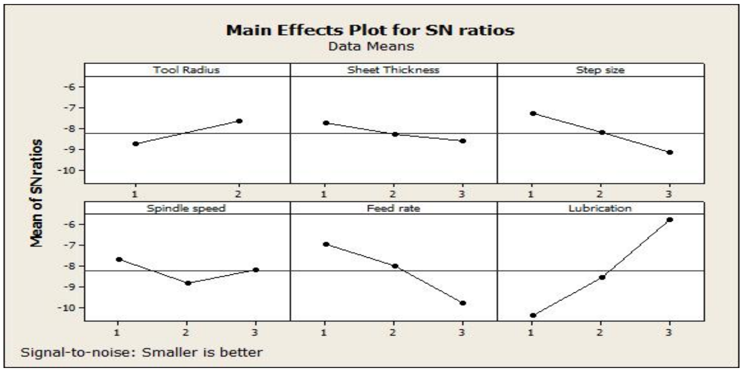


Figure 8 Main Effects Plot for S/N Ratio for Surface roughness

3.1Predicted optimal results

In order to predict the optimal values of the machining characteristics, only significant parameters are included which were found utilizing analysis of variance (ANOVA). The optimal values are predicted using the following relationship,

$$\eta_{\text{opt}}=\eta_{\text{m}}+\sum_{i=1}^{q}\quad(\eta_{\text{i}}-\eta_{\text{m}}),$$

(3)

Where η_{m} is the total mean of the machining characteristic under consideration η_{i} is the mean values at the optimum level (from response Tables) and q is the number of process parameters that significantly affects the machining characteristics. Table 7 and 8 depict the ANOVA for WA and SR, respectively.

The optimum value of wall angle is predicted at the optimum levels of significant variables which have already been selected first level of tool radius (A1), third level of sheet thickness (B3), first level of step size (C1), Third level of tool rotational speed (D3), first level of feed rate (E1) and Third level of lubrication F (3) provide maximum value of wall angle. (Table 6 and Figure 7).

The Estimated mean of the response characteristic (WA) can be determined as:

μ_{wa} = {(A1+B3+C1+D3+E1+F3)-5(μ)}
={(66.74+67.66+67.44+69.39+69.72+75.33)-5(65.348)}
= 89.54°

Where,
μ =overall mean of wall angle = (ΣR)/18=65.348

The 95% confidence intervals of confirmation experiments (CI_{CE}) are calculated as:

$$CI = \sqrt{f\alpha\,(1, fe)\left(\frac{1}{\eta eff} + \frac{1}{r}\right)Ve} = 2.99$$

Where, fα is found from the f table

$$\eta_{eff} = \frac{\mathrm{N}}{1+\text{total degree of freedom}}$$

Where, N= Total number of experiment, Ve= Error of Adj MS=3.96, r =be sample size for confirmation experiment, f_e =Error DOF, η_{eff} =Number of test under that conditions using participating factors

So the confidence interval is $92.53 \le \mu_{WA} \ge 86.55$

Similarly for the surface roughness the optimum value is 1.0157μm and $0.088 \le \mu_{sr} \le 1.20067$.

5. IV. MULTI-MACHINING CHARACTERISTICS OPTIMIZATION USING GREY RELATIONAL ANALYSIS

In order to optimize the WA and SR simultaneously using grey relational analysis (GRA), the following steps were followed:[18, 19]

- Convert the experimental data into S/N values.
- Normalize the S/N ratio,
- Perform the grey relational generating and calculate the grey relational coefficient,
- Calculate the grey relational grade by using the weighing factor for the performance characteristics,
- Analyze the experimental results using the grey relational grade and statistical analysis of variance(ANOVA),
- Select the optimal levels of process parameters,
- Conduct the confirmation experiment to verify the optimal process parameter settings.

4.1 Grey relational analysis

Grey data processing must be performed before calculating the grey correlation coefficients. In this study, a linear normalization of the experimental results (S/N ratios)for WA and SR were performed in the range of 0 and 1, which is also called the grey relational generating. A linear data pre-processing method for the S/N ratio can be expressed as follows,

$$\mathrm{xj(k)} = \frac{xi(k) - \min xi(k)}{\max xi(k) - \min xi(k)}$$

Where xj(k) is the value after the grey relational generation (data pre-processing).$x_i(k)$ is the original sequence of S/N ratio i=1,2,3,….,m and k =1,2,…..n with m=18 and n =2. Max $x_i(k)$ is the largest value of $x_i(k)$.Min $x_i(k)$ is the smallest value of $x_i(k)$. Table 10 shows the normalized S/N ratio for the WA and SR. Basically, larger normalized S/N ratio corresponds to the better performance and best normalized S/N ratio is equal to unity.

Next, grey relational coefficient was calculated to express the relationship between the best (reference) and the actual normalized S/N ratio. The grey relational coefficient is expressed as follows,

$$\xi(\mathrm{k}) = \frac{\Delta min - \zeta\Delta max}{\Delta i(k) - \zeta\Delta max} \quad \ldots \qquad (5)$$

Where,

$\xi_i(k)$ is grey relational coefficient, $\Delta_i(k)$is the deviation sequence of the reference sequence $x_0(k)$ and the comparability sequence $x_i(k)$ shown in Table 11 by using equation 4.10.

$$\Delta i(k) = |xj(\,k\,) - \,xi\,(k)| \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.10)$$

Δ_{max} =highest value of $\Delta_i(k)$

Δ_{min}=smallest value of $\Delta_i(k)$

Where,ζ is distinguishing or identification coefficient :ζ Ω [0,1].ζ=0.5 is generally used

After obtaining the grey relational coefficient, we normally take the average of the grey relational coefficient as the grey relational grade .The grey relational grade is defined as follows

$$\Upsilon\mathrm{i} = \frac{1}{n}\sum_{k=1}^{n}\xi(k) \quad \ldots\ldots\ldots\ldots\ldots\ (4.11)$$

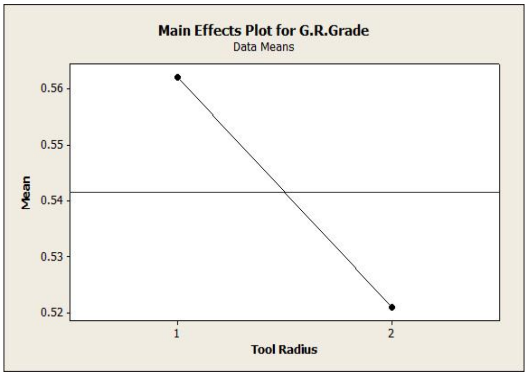
Where γ_i =Grey relational grade for particular experiment number.

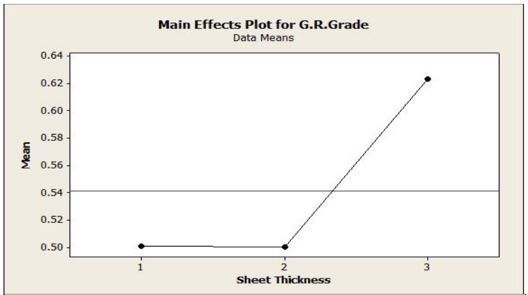
k = number of response

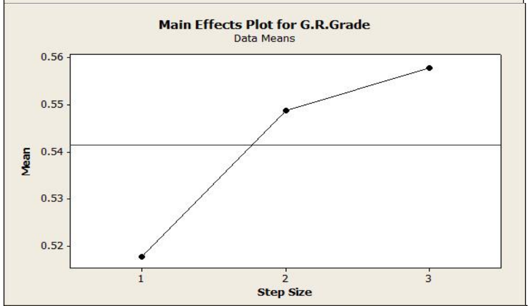
The grey relational grade is a weighing-sum of the grey relational coefficients. The overall evaluation of multiple performance characteristics is based on the grey relational grade which is shown in Table 12.

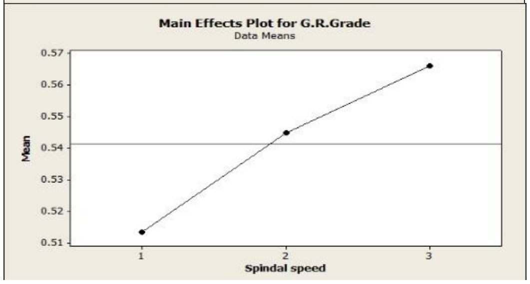
4.2 Optimal level of process parameters

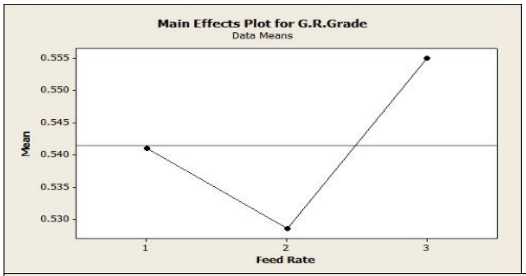
Optimization of the multiple performance characteristics can be converted into optimization of single grey relational grade. It is clearly observed from Table 12 for grey relational grade, the process parameters setting of experiment No.7 has the highest grey relational grade. Thus, the seventh experiment gives the best multiple performance characteristics among the 18 experiments using GRA. To separate out the effect of each process variable on the grey relational grade at different levels, response graph for grey relational grade at different levels, response graph for grey relational grade is constructed using the Taguchi methodology as shown in fig 8.

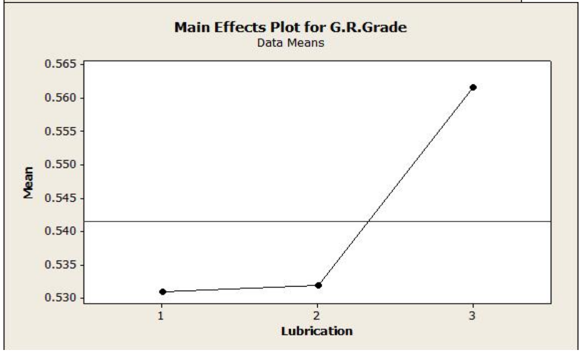












6. Fig. 8. Response graph for mean grey relational grade

Basically, the larger the grey relational grade, the better is the multiple performance characteristics. The combination of $A_1B_3C_1D_2E_2F_3$ shows larger value of the grey relational grade for the factors A,B,C,D,E,F respectively. Therefore Tool radius (8mm), sheet thickness (1.5mm), step size (0.5mm), spindle speed (250 rpm), feed rate (1000 mm/min) and lubrication (grease) respectively is the optimal parameter combination for multi-machining characteristics.

4.3 predicted optimal results

The optimal value of the machining characteristics has been predicted using the same procedure as discussed in previous section. ANOVA results given in table 13 depict that the Corresponding optimal setting values of process parameter using GRA.

V. Conclusions

In present work, Single point incremental (SPIF) for Al 6063 alloy has been studied. Grey relational analysis (GRA), along with Taguchi method were used to optimize the WA and SR, simultaneously. Based on the results and discussions, the following conclusions are made:

- The output parameter surface roughness has great influenced by the six process parameter. When tool radius increases, the surface roughness also increases. But on decreasing feed rate, sheet thickness, step size, and tool rotational speed causes surface roughness decreases. While surface roughness is dependent on the lubrication factors, it decreases in sequence as we go from dry, coolant to grease.

- The optimum value of surface roughness is predicted at the optimum levels of significant variables which have been selected as Tool radius (12mm), first level of sheet thickness (0.5mm),second level of step size (1mm), third level of tool rotational speed (500 r.p.m) , first level of Feed rate (1000 mm/min) and third level of lubrication (grease).
- Percentage contribution of process parameter for surface roughness are 57.44% of lubrication, 22.03% of feed rate, and 9.76% of step size. There are less contribution of other parameters.

- The predicted optimal values for the wall angle and surface roughness are found to be 89.54° and1.0157 µm.
- The confirmation experiment were conducted to verify the optimal machining parameters. The value of formability (wall angle) and surface roughness was found to be85.33^o and1.15µm.
- The grey relational analysis is done to find out optimum parameter levels of multi-characteristics. After grey relational analysis, it is found that optimum parameter levels are Tool radius (8mm), sheet thickness (1.5mm), step size (0.5mm), spindle speed (250 rpm), feed rate (1000 mm/min) and lubrication (grease) respectively.
- The result of optimum parameters are wall angle of 85.33^o and surface roughness of 1.776µm.

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TABLE 1: THE COMPOSITION OF AL 6063

Component	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Weight %	97.5	0.1	0.1	0.35	0.45 - 0.9	0.1	0.2 - 0.6	0.1	0.1	0.15

TABLE 2: MECHANICAL PROPERTIES OF AL 6063

Properties	Metric Units
Density	2.70 gram/cc
Hardness No., Brinell	60
Ultimate Tensile Strength	186 MPa
Tensile Yield Strength	145 MPa
Modulus of elasticity	68.9 GPa
Poisson’s Ratio	0.33
Fatigue Strength	68.9 MPa

TABLE 3: PROCESS PARAMETERS AND THEIR LEVELS

Factors	Machining parameters	Levels		
		L1	L2	L3
A	Tool Radius(mm)	8	12	-
B	Sheet Thickness(mm)	0.5	0.9	1.5
C	Step size(mm)	0.5	1	1.5
D	Spindle Speed(rpm)	0	250	500
E	Feed rate(mm/min)	1000	2000	2500
F	Lubrication	Dry	Coolant	Grease

TABLE 4: TAGUCHI’S L18 ORTHOGONAL ARRAY WITH RESPONSE AND S/N RATIO

Trial No.	A	B	C	D	E	F	Response(Raw Data)			
							R1	R2	R3	S/N ratio (dB)
1	1	1	1	1	1	1	-	-	-	S/N(1)
2	1	1	2	2	2	2	-	-	-	-
3	1	1	3	3	3	3	-	-	-	-
4	1	2	1	1	2	2	-	-	-	-
5	1	2	2	2	3	3	-	-	-	-
6	1	2	3	3	1	1	-	-	-	-
7	1	3	1	2	1	3	-	-	-	-
8	1	3	2	3	2	1	-	-	-	-
9	1	3	3	1	3	2	-	-	-	-
10	2	1	1	3	3	2	-	-	-	-
11	2	1	2	1	1	3	-	-	-	-

12	2	1	3	2	2	1	-	-	-	-
13	2	2	1	2	3	1	-	-	-	-
14	2	2	2	3	1	2	-	-	-	-
15	2	2	3	1	2	3	-	-	-	-
16	2	3	1	3	2	3	-	-	-	-
17	2	3	2	1	3	1	-	-	-	-
18	2	3	3	2	1	2	-	-	-	-

TABLE 5: EXPERIMENTAL RESULTS OF MACHINING RATE AND SURFACE ROUGHNESS

Trial No	Wall angle(degrees)			Mean	S/N Ratio	Surface Roughness (µm)			Mean	S/N Ratio
	W1	W2	W3			R1	R2	R3		
1	57	54	56	55.66	34.9109	2.57	2.51	2.56	2.546	-8.1172
2	66	64	64	64.66	36.2127	2.83	2.84	2.83	2.833	-9.0449
3	76	77	76	76.33	37.6539	2.81	2.82	2.81	2.813	-8.9834
4	64	63	65	64	36.1236	2.41	2.44	2.38	2.41	-7.6403
5	71	72	74	72.33	37.1864	2.62	2.66	2.69	2.656	-8.4846
6	63	62	65	63.33	36.0322	3.21	3.19	3.25	3.216	-10.1463
7	86	85	85	85.33	38.6220	1.79	1.75	1.79	1.776	-4.9889
8	57	56	55	56	34.9638	3.49	3.52	3.50	3.5	-10.8814
9	64	62	63	63	35.9868	3.42	3.32	3.47	3.403	-10.6372
10	64	65	66	65	36.2583	2.44	2.46	2.45	2.45	-7.7833
11	69	68	66	67.66	36.6066	1.44	1.20	1.20	1.28	-2.1442
12	49	45	46	46.66	33.3789	3.31	3.24	3.34	3.296	-10.3597
13	54	51	53	52.66	34.4296	3.48	3.51	3.55	3.513	-10.9136
14	71	76	74	73.66	37.3446	2.22	2.26	2.22	2.233	-6.9778
15	70	67	68	68.33	36.6922	1.93	1.98	1.90	1.936	-5.7381
16	81	82	83	82	38.2763	1.84	1.86	1.87	1.638	-4.2863
17	46	47	48	47	33.4420	3.88	3.84	3.88	3.866	-11.7452
18	74	72	72	72.66	37.2259	2.4	2.5	2.26	2.86	-9.1273
MEAN				65.348					2.6792	

TABLE 6: RESPONSE FOR MEAN WALL ANGLE AND SURFACE ROUGHNESS

Mean wall angle							Mean surface roughness						
Level	A	B	C	D	E	F	Level	A	B	C	D	E	F
1	66.74	62.66	67.44	60.94	69.72	53.55	1	2.795	2.536	2.389	2.574	2.319	3.323
2	63.96	65.72	63.55	65.72	63.61	67.16	2	2.564	2.661	2.728	2.822	2.602	2.698
3	-	67.66	65.05	69.39	62.72	75.33	3	-	2.841	2.921	2.642	3.117	2.017

Table 7: Analysis of Variance for mean (ANOVA), using Adjusted SS for Tests (WA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
A	1	34.75	34.75	34.75	8.78	0.025	3.42
B	2	76.33	76.33	38.17	9.65	0.013	3.75
C	2	46.19	46.19	23.09	5.84	0.039	2.27
D	2	215.18	215.18	107.59	27.19	0.001*	10.58
E	2	174.11	174.11	87.05	22.00	0.002*	8.56
F	2	1452.54	1452.54	726.27	183.55	0.000*	71.41
Error	6	23.74	23.74	3.96			
Total	17	2022.83	34.75				

Table 8: Analysis of Variance for mean (ANOVA), using Adjusted SS for Tests (SR)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
A	1	0.24059	0.24059	0.24059	12.16	0.013	5.40
B	2	0.28063	0.28063	0.14032	7.09	0.026	3.15
C	2	0.87000	0.87000	0.43500	21.98	0.0020	9.76
D	2	0.19841	0.19841	0.09921	5.01	0.052	2.26
E	2	1.96537	1.96537	0.98268	49.66	0.000*	22.03
F	2	5.12277	5.12277	2.56138	129.43	0.000*	57.44
Error	6	0.11874	0.11874	0.01979			
Total	17	8.79651					

Table 9 Predicted and confirmative results for wall angle and surface roughness

Response	Optimal Set of Parameters	Predicted Optimal Value	Predicted Confidence Intervals at 95% Confidence Level	(average of three confirmation experiments)
Wall Angle	A1, B3, C1, D3, E1 & F3	89.54°	85 ≤ WA ≤ 90	85.33°
Surface Roughness	A2,B1,C1,D1,E1&F3	1.0157µm	0.088 ≤ µsr ≤ 1.20067	1.15µm

Table: 10 Normalization of experimental results

Experiment no.	Wall angle (in degree)	Surface roughness (µm)
1	0.2327	0.4896
2	0.4655	0.6005

3	0.7673	0.5928
4	0.4484	0.4370
5	0.6638	0.5321
6	0.4311	0.7486
7	1.0000	0.1918
8	0.2415	0.8585
9	0.4225	0.8210
10	0.4743	0.4524
11	0.5431	0.0000
12	0.0000	0.7796
13	0.1552	0.3585
14	0.6982	0.3685
15	0.5604	0.2537
16	0.9139	0.1384
17	0.0088	1.0000
18	0.6724	0.6110

TABLE: 11 DEVIATION SEQUENCES OF NORMALIZED RESPONSES

Deviation sequence	**Δi(1)**	**Δi (2)**
1	0.7673	0.5104
2	0.5345	0.3995
3	0.2327	0.4072
4	0.5516	0.5630
5	0.3362	0.4679
6	0.5689	0.2514
7	0.0000	0.8082
8	0.7585	0.1415
9	0.5775	0.1790
10	0.5257	0.5476
11	0.4569	1.0000
12	1.0000	0.2204
13	0.8448	0.6415
14	0.3018	0.6315
15	0.4396	0.7463
16	0.0861	0.8616
17	0.9912	0.0000
18	0.3276	0.3890

TABLE: 12 CALCULATION OF GREY RELATIONAL COEFFICIENT & GREY RELATIONAL GRADE

Experiment no	Grey relational coefficient	Grey relational grade	Orders

	Wall angle (degree)	Surface roughness (µm)		
1	0.3945	0.4949	0.4447	16
2	0.4833	0.5559	0.5196	11
3	0.6824	0.5511	0.6168	3
4	0.4755	0.4704	0.4730	14
5	0.5979	0.5166	0.5573	9
6	0.4678	0.6654	0.5666	8
7	1.0000	0.3822	0.6911	1
8	0.3973	0.7794	0.5884	6
9	0.4640	0.7364	0.6002	5
10	0.4875	0.4773	0.4824	13
11	0.5225	0.3333	0.4279	17
12	0.3333	0.6941	0.5137	12
13	0.3718	0.4380	0.4049	18
14	0.6236	0.4419	0.5328	10
15	0.5321	0.4012	0.4667	16
16	0.8531	0.3672	0.6102	4
17	0.3353	1.0000	0.6677	2
18	0.6042	0.5624	0.5833	7

TABLE: 13 RESPONSE TABLE FOR GREY RELATIONAL GRADE

Process Parameters	Average Grey Relational Grade by Factor Level		
	Level 1	Level 2	Level 3
Tool Radius	0.561967*	0.521011	_
Sheet Thickness	0.5007667	0.5002167	0.623483*
Step Size	0.517717*	0.548867	0.557883
Spindle Speed	0.513283	0.544983*	0.5662

Feed Rate	0.540983*	0.5286	0.565183
Lubrication	0.531	0.531883	0.561583*