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Machinability Study of Aluminium 6061 Alloy on End Milling Process

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Abstract- Usage of non-ferrous materials is increasing day-by-day due to its wide variety of applications in many areas because of their properties, availability etc. Hence the study and development of these materials in many aspects is increasing. Of all the non-ferrous metals, Aluminium is one of the most widely used metal. This paper focuses on casting of Al6061 alloy by varying the composition of its alloying elements and also to study the machinability properties of Al 6061 by conducting set of experiments on Al-6061 alloy under vertical milling machine using HSS end mill cutter and finding out the output responses, Metal removal rate, Surface finish, and Cutting forces by varying process parameters speed, feed and depth of cut. Response Surface Methodology (RSM) and Full Factorial Design of Experiments were used to develop the regression equation between input parameters and output responses. Contribution of each factor (Speed, Feed and Depth of Cut) on output parameters (Metal removal rate, Surface finish, and Cutting Force) was determined using ANOVA.

Keywords: End milling, Al6061, Machinability, RSM, Full Factorial Design, ANOVA.

I. Introduction

Worldwide, most metallic components are still produced using a variety of machining techniques. However, in recent decades all these production processes have seen major changes, both advancements in technology and ever growing demands for complete process improvement. Across all industries, conflicting requirements to increase product quality, whilst reducing costs and recognizing environmental impact factors are getting ever greater. A detailed understanding of the process is essential in order to meet these new obligations. It is therefore vital to analyse the machining operation so we can better understand and control it. The forces and torques generated during machining are important indicators which help to determine what is happening to the material, and the tool, when they interact. This information can then be used to improve factors such as surface finish, metal removal rate and tool wear. Quality and productivity are the two important issues faced by any industry. In order to sustain in a competitive market, ensuring quality of the product at minimum cost is essential. Machined parts are greatly influenced by the surface quality during their useful life and productivity also plays an important role in the existence of any product in the market. In order to achieve that, the process parameters should be suitably regulated but the responses are conflicting in nature as Surface Roughness (Ra) is to be minimized and Material Removal Rate (MRR) is to be maximized. Hence machining and finding out of process parameters are very important. The main aim of this project is to conduct experiment on Al 6061 alloy on Vertical Milling machine (End Milling) by varying cutting parameters like Speed (v), Depth of cut (d) and Feed (f) and finding out optimum cutting parameters which leads to minimum Ra and maximum MRR by using DoE techniques (full-factorial approach and response surface methodology).

M. K. Pradhan, MayankMeena, ShubhamSen and Arvind Singh [1], had studied and experimented about the multi objective optimization for end milling of Al 6061 alloy and has been presented to provide better surface quality and higher Material Removal Rate (MRR). The results revealed that Taguchi based G-PCA (Principal Component Analysis) can effectively acquire the optimal combination of cutting parameters. Sivarao, FairuzDimin, T.J.S. Anand, RidzuanJamli and A.Kamely [2], had studied and investigated about the effects of varying depth of cut which could have significant effect on the surface roughness of Al 6061-T6511 work material by implementing the use of TiALN coated carbide tool using HAAS CNC milling. The outcome clearly witnessed that depth of cut made significant effect on the surface quality of end product within the range of experimental values. Mathew A. Kuttolamadom, SinaHamzehlouia and M. Laine Mears [3], had examined the achievability of surface roughness specifications of Al 6061 alloy, which is considered as a light weight automotive component and efforts were made to reduce manufacture cycle time, particularly by changing cutting feeds. Najiha M.S, M.M. Rahman and A.R. Yusoff [4], had studied and experimented to determine the optimum operating parameters for end milling process of Al6061T6 with wet cooling conditions. The adequacy of the model was tested using ANOVA at 95 % confidence level. Significant parameters were identified in terms of the cutting parameters. The obtained results showed that the most significant parameters for the machining of the mentioned alloy are feed rate and depth of cut. Prajina N V, T D John [5] , had discussed about the multiple response optimization of cutting forces in end milling operation on AlSiC metal matrix composites to get minimum forces in tangential(Fx), radial(Fy) and axial(Fz) directions using response surface methodology.

II. Material and Methodology

Aluminium has always been popular in the world due to its ease of fabrication, strength and corrosive resistance. In Al6061 alloy, Magnesium and Silicon are the major alloy additions, making this alloy heat treatable. It is one of the least expensive and most versatile aircraft aluminium alloys available and it has good range of mechanical fatigue properties and excellent corrosion resistance for a heat treatable aircraft alloy. Typical composition of Al 6061 alloy are in table 1.

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Table 1 Chemical composition of Al6061 alloy

Component	**Amount (wt. %)**
Aluminium	95.7-98.6
Magnesium	0.8-1.2
Silicon	0.4-0.8
Iron	Max. 0.7
Copper	0.15-0.40
Zinc	Max. 0.25
Titanium	Max. 0.15
Manganese	Max. 0.15
Chromium	0.04-0.35
Others	0.05

For the above composition shown in table, the desired combination is taken by applying Taguchi L 8 array method and the desired which has highest yield strength was chosen and its composition is in table 2.

Table 2 Desired Composition of Al6061 Alloy

S.No	**Material**	**Amount (wt. %)**
1	Aluminium	98.46
2	Magnesium	0.8
3	Silicon	0.4
4	Copper	0.15
5	Zinc	0.05
6	Manganese	0.05
7	Iron	0.05
8	Chromium	0.04

2.1 Experimentation: The experiments were carried out on HMT FN2V vertical milling machine using HSS end mill cutter on Al6061 alloy and the number of trails that are required for experimentation are found out by using DoE techiniques. The forces that are generated during machining are measured by using piezoelectric dynamometer, which measures the forces in all directions and after each trail the surface finish value of the machined part is measured with the help of TALYSURF and from this the values of surface roughness are noted.

The metal removal rate (MRR) was calculated by measuring the difference between the weight of the work piece before and after each run and all these values are tabulated.

MRR = (weight of work piece before machining - weight of work piece after machining) / time

The process parameters (speed, feed and depth of cut) each are varied between two limits (lower and upper) and the number of trails are obtained from design expert full factorial method. The required number of trails from Design Expert (Full-factorial and RSM).

2.2 Design of Experiments: A two level full factorial design of experiments was adopted for calculating the main and the interaction effects of the three factors at two levels; 2^3=8 experiments are conducted to fit an equation. The design plan with high and low limits as indicated is utilized looking into practical considerations of the milling operation as in table 3.The first order model is assumed with two and three factor interactions which can be expressed as,

$$Y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{123}X_1X_2X_3$$

where 'Y' represents the response (Cutting Force, Surface Finish, MRR) X_1,X_2,X_3 represent the coded values of speed(N), feed(f) and depth of cut(d) respectively; $b_0,b_1,\ldots,b_{123}$ are the regression coefficients of polynomial to be determined.

Table 3 Process parameters and levels

Factors	**Units**	**Designation**		**Test levels**		**Avg**	**VI**
		Natural	coded	Low (-1)	High (+1)		
Speed	rpm	N	X_1	710	1120	915	205
Feed	mm/min	f	X_2	16	31.5	23.75	7.75
DoC	mm	d	X_3	0.4	1	0.7	0.3

2.3 Decoding of coded linear equation: Decoding of linear equation of Yp= $b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2 + \ldots$ is done by substituting the factors $\frac{a_1-Avg_1}{VI_1}$, $\frac{a_2-Avg_2}{VI_2}\ldots$ in place of X_1, X_2 … in the above equation. Here a_1, a_2… are natural values of factors. Avg_1, $Avg_{2)}$, (Avg – average, VI – Variation Interval) are the average values of the factors a_1, a_2… and VI_1 and VI_2 are the variation intervals.

2.4 Development of the model:

Design matrix for a given 2-level and 3-factor is generated and the regression coefficients are calculated. Here the number of replications for the response i.e.; y_1 and y_2 and average of these is 'y'. Regression coefficients b_0, b_1, b_2, b_{12}, b_{23} etc are calculated by using the formula.

$$b_j = \frac{[\sum_{i=1}^{N} X_{ij}Y_i]}{N}$$

Where N is the number of trails.

2.5 Fisher test for Adequacy of model (F-test for 5% significance level)

Variance of Reproducibility = $S_y^2 = \frac{2\Sigma(\Delta y)^2}{N}$

$\Delta y = (y_1-y)$

Variance of adequacy = $S_{ad}^2 = \frac{2\Sigma(y-yp)^2}{DOF}$

Where y_p= predicted response, $y_p= b_0\, x_0\, [i]+b_1x_1[i]+\ldots$

Where DOF =degree of freedom = [N-(k+1)],

N=number of trails, k=number of factors.

$F_{model}=\frac{S_{ad}^2}{S_y^2}$

For given values of f_1 and f_2, F-table value is found from Fisher table.

Here f_1= N-(k+1) and f_2=N

If F_{model}<= F-table, model is adequate in linear form from Fisher table.

2.6 Student's t-test (for 5% significance level)

When the model is adequate in linear form, then the t-test is to be conducted to the significance of each Regression Coefficient. Standard deviation of each coefficient is:

$S_{bj}=\sqrt{(S_y^2/N)}$

t-ratio = $| b_j| / (S_{bj})$

for f = N , t value is to be taken from t-table and compared with t-ratio of each regression coefficient. If t-ratio ≥ t-table corresponding regression coefficient is significant. Non-

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significant coefficients are to be eliminated from the model to arrive the final form of mathematical model in linear form as

$Y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{123}X_1X_2X_3$

2.7 Analysis of Variance (ANOVA): Analysis of variance is done to find out the percentage contribution of each factor and its relative significance.

Table 4 ANOVA Table

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio
A treatments	SS_A	a-1	$MS_A= SS_A/(a-1)$	$F_A=MS_A/MS_E$
B treatments	SS_B	b-1	$MS_B= SS_B/(b-1)$	$F_B=M_{SB}/MS_E$
Interaction	SS_{AB}	(a-1)(b-1)	$MS_{AB}= SS_{AB}/(a-1)(b-1)$	$F_{AB}=MS_{AB}/MS_E$
Error	SS_E	ab(n-1)	$MS_E= SS_E/ab(n-1)$	
Total	SS_T	abn-1		

'a' and 'b' are the levels of A and B factors

$SS_A= \{Sum [x1[i]*y_t[i]]\}^2/Nn$, $y_t = (y_1 + y_2) / 2$

$SS_T=Sum \{(y_1[i])^2+ (y_2[i])^2\}-[Sum \{(y_t[i])\}^2/Nn]$

Here N=number of trails, n = number of replications

$SS_E= (SS_T)-(SS_A)-(SS_B)$ …

Percentage contribution of factor A= $\mathbf{(SS_A/SS_T)*100}$

Coefficient of Determination, R^2= $\mathbf{(SS_{model}/SS_T)}$

Where $SS_{model}= SS_A+SS_B+SS_C+…$

III. Development of Model

Experimentation was carried out using the design matrix shown in table 5.

Table 5 Design Matrix (Full-factorial)

Trial No.	Speed (rpm)	Feed (mm/min)	Depth of Cut (mm)
1	710 (-1)	16 (-1)	0.4 (-1)
2	1120 (+1)	16 (-1)	0.4 (-1)
3	710 (-1)	31.5 (+1)	0.4 (-1)
4	1120 (+1)	31.5 (+1)	0.4 (-1)
5	710 (-1)	16 (-1)	1 (+1)
6	1120 (+1)	16 (-1)	1 (+1)
7	710 (-1)	31.5 (+1)	1 (+1)
8	1120 (+1)	31.5 (+1)	1 (+1)

3.1 Development of regression model for cutting force:

The column of each variable x_1, x_2 and x_3 are arranged in standard order. The values of regression coefficients b_0, b_1, $b_2…b_{123}$ are calculated by regression analysis.

Table 6 Design Matrix for Cutting Force

Trial no	Variables							Cutting Force (N)		
	X_1	X_2	X_3	x1x2	X2x3	X3x1	x1x2x3	Y1	Y2	Avg
1	-1	-1	-1	+1	+1	+1	-1	84.44	84.49	84.46
2	+1	-1	-1	-1	+1	-1	+1	68.28	68.10	68.19
3	-1	+1	-1	-1	-1	+1	+1	77.98	77.99	77.99
4	+1	+1	-1	+1	-1	-1	-1	72.76	72.75	72.75
5	-1	-1	+1	+1	-1	-1	+1	85.33	85.41	85.37
6	+1	-1	+1	-1	-1	+1	-1	62.64	62.51	62.57
7	-1	+1	+1	-1	+1	-1	-1	99.01	100.0	99.51
8	+1	+1	+1	+1	+1	+1	+1	74.58	74.39	74.48

The values of regression coefficients b_0, b_1, $b_2…b_{123}$ are calculated for Cutting force are given below:

Regression coefficients for cutting force are

b_0=78.169 b_{12}=1.101

b_1=-8.666 b_{13}=-3.290

b_2=3.017 b_{23}= 3.496

b_3=2.318 b_{123}=-1.658

The adequacy of the model was then tested by Analysis of variance (ANOVA) As per this technique , F-ratio of the model developed does not exceed the standard tabulated value of F-ratio for a 95% confidence level. Hence, the model was adequate. The significance of the coefficients was checked by using student's t-test and only the significant coefficients were used to develop final mathematical model.

The final model in coded form for cutting force is

$Yp= 78.169-8.666x_1 + 3.017x_2 + 2.318x_3 - 3.290x_1x_3 + 3.496x_2x_3 + 1.101x_1x_2 - 1.658x_1x_2x_3$

3.2Development of regression model for Surface Roughness:

The column of each variable x_1, x_2 and x_3 are arranged in standard order. The values of regression coefficients b_0, b_1, $b_2…b_{123}$ are calculated by regression analysis.

Table 7 Design Matrix for Surface Finish

Trail no.	Variables							Surface finish(Ra) (Micrometer)		
	X1	X2	X3	X1X2	X2X3	X3X1	X1X2X3	Y1	Y2	Y (average)
1	-1	-1	-1	+1	+1	+1	-1	0.559	0.565	0.562
2	+1	-1	-1	-1	+1	-1	+1	0.800	0.789	0.795
3	-1	+1	-1	-1	-1	+1	+1	0.948	0.959	0.954
4	+1	+1	-1	+1	-1	-1	-1	0.812	0.799	0.806
5	-1	-1	+1	+1	-1	-1	+1	1.107	1.129	1.118
6	+1	-1	+1	-1	-1	+1	-1	0.899	0.779	0.839
7	-1	+1	+1	-1	+1	-1	-1	0.837	0.847	0.842
8	+1	+1	+1	+1	+1	+1	+1	0.962	0.987	0.975

The values of regression coefficients b_0, b_1, $b_2…b_{123}$ are calculated for surface roughness are given below:

b_0=0.861 b_{12}=-0.004

b_1=-0.008 b_{13}=-0.029

b_2=0.033 b_{23}= -0.068
b_3=0.082 b_{123}=0.099

The final model in coded form for Surface finish is

Yp= 0.861 - 0.008x_1 + 0.033x_2 + 0.082x_3 - 0.029x_1x_3 - 0.068x_2x_3 - 0.004x_1x_2 + 0.099$x_1x_2x_3$

3.3 Development of regressional model for MRR

The column of each variable x_1, x_2 and x_3 are arranged in standard order. The values of regression coefficients b_0, b_1, b_2…b_{123} are calculated by regression analysis.

Table 8 Design Matrix for MRR

Trail no.	Variables							Metal Removal Rate (gm/ hr.)		
	X1	X2	X3	X1X2	X2X3	X3X1	X1X2X3	Y1	Y2	Y (average)
1	-1	-1	-1	+1	+1	+1	-1	14.400	14.590	14.495
2	+1	-1	-1	-1	+1	-1	+1	18.000	17.997	17.999
3	-1	+1	-1	-1	-1	+1	+1	28.800	28.831	28.816
4	+1	+1	-1	+1	-1	-1	-1	32.400	32.321	32.361
5	-1	-1	+1	+1	-1	-1	+1	28.800	28.859	28.830
6	+1	-1	+1	-1	-1	+1	-1	28.800	28.775	28.788
7	-1	+1	+1	-1	+1	-1	-1	72.000	72.099	72.050
8	+1	+1	+1	+1	+1	+1	+1	72.000	69.994	70.997

The values of regression coefficients b_0, b_1, b_2…b_{123} are calculated for MRR are given below

b_0=36.792 b_{12}=-0.121
b_1=0.744 b_{13}=-1.018
b_2=14.264 b_{23}= 7.093
b_3=13.374 b_{123}=-0.131

The final model in coded form for Material Removal Rate is

Yp= 36.792 + 0.744x_1 + 14.264x_2 + 13.374x_3 -1.018x_1x_3 + 7.093x_2x_3 - 0.121x_1x_2 - 0.131$x_1x_2x_3$

3.4 Optimization of output values by RSM:

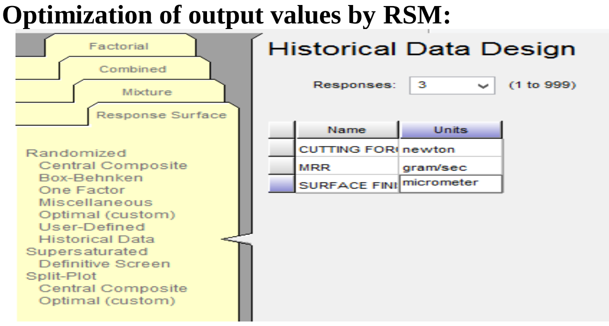


Figure 1 Design Expert - RSM

The input parameters and output responses after experimentation are tabulated in RSM historical data option and the optimization values are found.

The procedure for finding optimum values are as follows:

Step: 1

In this step the number of input parameters with their units are to be given and the number of rows to be selected are 11. Here the input parameters are considered as factors. They are

Factor 1: Speed (rpm)
Factor 2: Feed (mm/min)
Factor 3: Depth of Cut (mm)

After giving input factors, the output responses with their units are given.

Response 1: Cutting force (Newton)
Response 2: Metal Removal Rate (gram/sec)
Response 3: Surface Finish (micrometer)

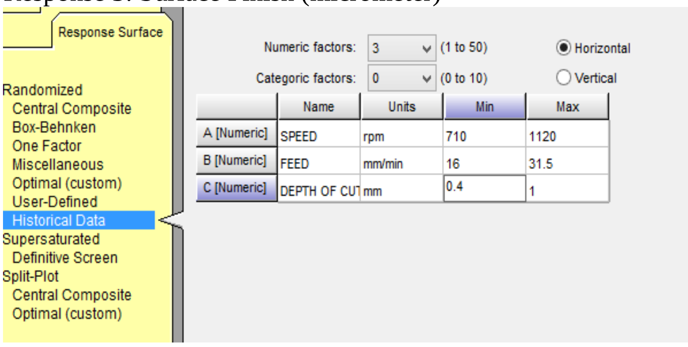
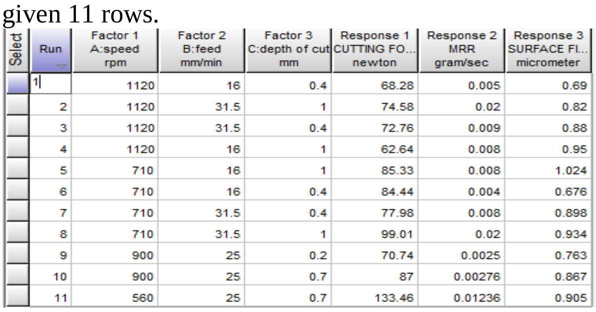


Figure 2 Process Parameters

Step: 2

In this step all the input and output data is tabulated in RSM in the given 11 rows.



Run	Factor 1 A:speed rpm	Factor 2 B:feed mm/min	Factor 3 C:depth of cut mm	Response 1 CUTTING FO... newton	Response 2 MRR gram/sec	Response 3 SURFACE FI... micrometer
1	1120	16	0.4	68.28	0.005	0.69
2	1120	31.5	1	74.58	0.02	0.82
3	1120	31.5	0.4	72.76	0.009	0.88
4	1120	16	1	62.64	0.008	0.95
5	710	16	1	85.33	0.008	1.024
6	710	16	0.4	84.44	0.004	0.676
7	710	31.5	0.4	77.98	0.008	0.898
8	710	31.5	1	99.01	0.02	0.934
9	900	25	0.2	70.74	0.0025	0.763
10	900	25	0.7	87	0.00276	0.867
11	560	25	0.7	133.46	0.01236	0.905

Figure 3 Input and Output values

Step: 3

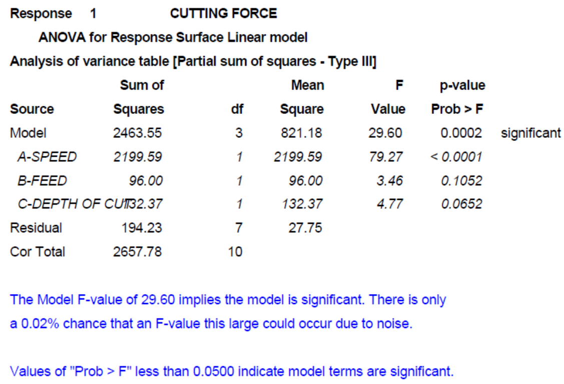
In this step, for each output response by using process parameters the equation is developed.

3.5 ANOVA: Analysis of Variance

ANOVA is done to find out the percentage contribution of each factor and their relative significance of each factor.

By using the experimented values the equation values for cutting force is found by using process model as Linear (suggested) and the equation as follows:

CUTTING FORCE in terms of coded factors = 81.23 - (14.35 * A) + (3.45 * B) + (3.55 * C)



Response 1 CUTTING FORCE
ANOVA for Response Surface Linear model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2463.55	3	821.18	29.60	0.0002	significant
A-SPEED	2199.59	1	2199.59	79.27	< 0.0001	
B-FEED	96.00	1	96.00	3.46	0.1052	
C-DEPTH OF CUT	132.37	1	132.37	4.77	0.0652	
Residual	194.23	7	27.75			
Cor Total	2657.78	10				

The Model F-value of 29.60 implies the model is significant. There is only a 0.02% chance that an F-value this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.

By using the experimented values the equation values for metal removal rate is found by using process model as Linear (suggested) and the equation as follows:

MRR = $(9.465*10^{-3})$ - $(1.201*10^{-4}$ * A) + $(3.873*10^{-3}$ * B) + $(3.959*10^{-3}$* C)

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Response 2 MRR

ANOVA for Response Surface Linear model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.803E-004	3	9.344E-005	6.67	0.0184	significant
A-SPEED	*1.540E-007*	*1*	*1.540E-007*	*0.011*	*0.9195*	
B-FEED	*1.208E-004*	*1*	*1.208E-004*	*8.62*	*0.0219*	
C-DEPTH OF CUT	*1.648E-004*	*1*	*1.648E-004*	*11.76*	*0.0110*	
Residual	9.811E-005	7	1.402E-005			
Cor Total	3.784E-004	10				

The Model F-value of 6.67 implies the model is significant. There is only a 1.84% chance that an F-value this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.

By using the experimented values the equation values for surface finish is found by using process model as 2FI (suggested) and the equation as follows:

$$\textbf{SURFACE FINISH} = 0.86 - (0.024 * A) + (0.024 * B) + (0.073 * C) - (8.949 \times 10^{-3} * AB) - (0.023 * AC) - (0.079 * BC)$$

Response 3 SURFACE FINISH

ANOVA for Response Surface 2FI model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.12	6	0.020	4541.56	< 0.0001	significant
A-SPEED	*5.979E-003*	*1*	*5.979E-003*	*1382.06*	*< 0.0001*	
B-FEED	*4.647E-003*	*1*	*4.647E-003*	*1074.30*	*< 0.0001*	
C-DEPTH OF CUT	*0.056*	*1*	*0.056*	*12853.60*	*< 0.0001*	
AB	*6.449E-004*	*1*	*6.449E-004*	*149.08*	*0.0003*	
AC	*4.232E-003*	*1*	*4.232E-003*	*978.23*	*< 0.0001*	
BC	*0.050*	*1*	*0.050*	*11622.69*	*< 0.0001*	
Residual	1.730E-005	4	4.326E-006			
Cor Total	0.12	10				

The Model F-value of 4541.56 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.

Optimum Solutions and Graphs

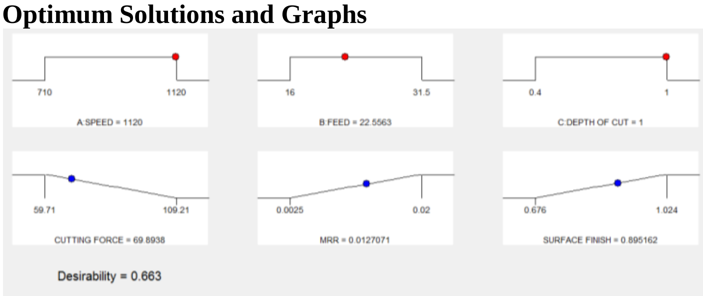

Figure 4 Optimum Solutions in Ramp form

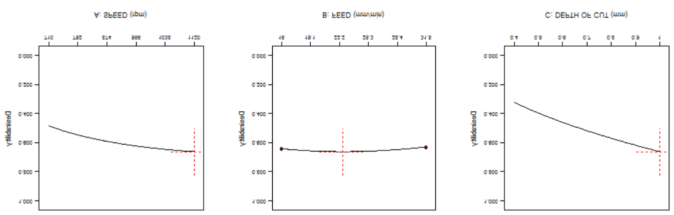

Figure 5 Graphs of Speed vsDesirability, Feed vs Desirability, Depth of Cut vs Desirability

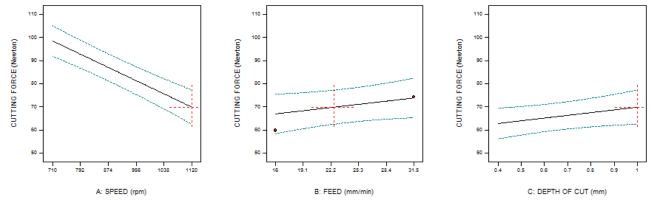

Figure 6 Graphs of Speed vsCutting force, Feed vs Cutting force, Depth of Cut vs Cutting Force

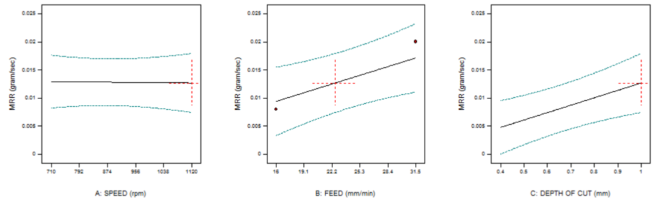

Figure 7 Graphs of Speed vs MRR, Feed vs MRR, Depth of cut vs MRR

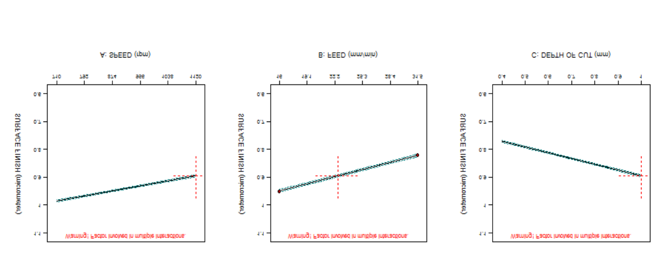

Figure 8 Graphs of Speed vs Surface Finish, Feed vs Surface Finish, Depth of cut vs Surface Finish

IV.Results and Conclusion

Contribution of Factors from Design of Experiments:

Percentage contribution of the Factors and their Interactions for Cutting force:

Table9 Percentage contribution of the Factors and their Interactions for Cutting force

Factor	X1	X2	X3	X1X2	X2X3	X1X3	X1X2X3
Contribution (%)	64.4	7.8	4.6	1.03	10.47	9.28	2.35

Percentage contribution of the Factors and their Interactions for Surface Finish:

Table 10 Percentage contribution of the Factors and their Interactions for Surface Finish

Factor	X1	X2	X3	X1X2	X2X3	X1X3	X1X2X3
Contribution (%)	0.25	4.53	28.59	0.06	19.47	3.52	41.43

Percentage contribution of the Factors and their Interactions for MRR:

Table 11 Percentage contribution of the Factors and their Interactions for MRR

Factor	X1	X2	X3	X1X2	X2X3	X1X3	X1X2X3
Contribution (%)	0.12	46.83	41.17	0.00	11.58	0.23	0.004

The suggested or optimized values i.e the values with maximum desirability is selected. For all the trails conducted, the maximum desirability trail contributes 66.3% out of 100% which is more desirable value. The process parameters for this desirability are as follows:

Speed = 1119.999 rpm

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Feed = 22.556 mm/min
Depth of cut = 1.00 mm
For the above desired inputs the desired outputs are:
Cutting force = 69.894 N (minimum)
Metal removal rate = 0.013 gram/sec (maximum)(46.8 g/h)
Surface finish = 0.895 micrometer (maximum)
From the above results it is clear that the desirability is 0.663 (66.3%) which is satisfactory result, which gives the optimum values for speed, feed and depth of cut.
From table 9, it is clear that, the percentage contribution of cutting force given by parameter 'X1', i.e., the speed contributes 64.4%, feed ('X2') contributes 7.8%, depth of cut ('X3') contributes 4.6% of the resultant cutting force and remaining percent of force is contributed by interaction of cutting parameters. From table 10, it is clear that, the percentage contribution of surface finish given by parameter 'X1', i.e., the speed contributes 0.25%, feed ('X2') contributes 4.5%, depth of cut ('X3') contributes 28.5% of the resultant surface finish and remaining percent of surface finish is contributed by interaction of cutting parameters. From table 11, it is clear that, the percentage contribution of metal removal rate given by parameter 'X1', i.e., the speed contributes 0.12%, feed ('X2') contributes 46.8%, depth of cut ('X3') contributes 41.1% of the resultant metal removal rate and remaining percent of metal removal rate is contributed by interaction of cutting parameters.

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