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Comparative study of Parametric Optimization of the End Milling of Al2024-SiC MMC on Surface Roughness using Taguchi Technique with Applied Statistical Plots

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Abstract

In today's competitive world, the industries should have production systems which are capable of versatility, high production rate, precision and ability to produce highly finished goods. Due to this the value of input machining parameters responsible for the desired surface finish & material removal rate becomes critical. Present paper presents a study on parametric optimization of the End Milling machining of Al2024-SiC metal matrix composite on quality characteristics namely surface roughness and material removal rate using Taguchi Technique. The end milling parameters selected is speed, feed, depth of cut and number of flutes. How these parameters influence the response outputs like MRR and surface roughness is analysed with the help of Taguchi Technique and ANOVA. At the same time various statistical plots are generated with the help of MiniTab software like residual plots, contour plots and surface plots. Twenty seven experimental runs based on design of experiments and L27 orthogonal array of Taguchi method are performed and data so obtained is used to subsequently applied to determine an optimal end milling parameter combination. Finally, confirmation tests carried out at optimum cutting conditions to make a comparison between the experimental results and developed model. The predicted results are found to be closer to experimental results by confirmation test. After this the results of Taguchi optimization are compared with the statistical plots found to be in close conformity with each other.

Keywords: End Milling, Taguchi Optimization, ANOVA, Surface Roughness

INTRODUCTION

The increase in demand for highly finished products has driven the manufacturing industry to continuously improve the control of the machining processes. The quality of the surface finish plays important role in various areas like tribology, wear resistant parts, fatigue life, bearing surfaces etc. End Milling is widely used machining operation in manufacturing as it is very versatile and can produce complex contours. Various end milling parameters affect response outputs like the surface texture, dimensional accuracy and MRR (material removal rate) to a greater extent.

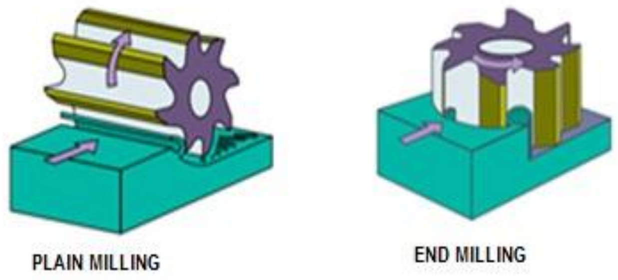

Figure 1: Difference between Plain and End Milling

Surface roughness and MRR greatly influences quality of a product and manufacturing cost. End Milling is generally applied in aerospace industry, tool and die shops and automobile sector. Slots, pockets, peripheries, and faces of machine components can be produced with this process. The machining of aluminium metal matrix composites using CNC machines is finds diverse applications in the aeronautics industry as this industry needs high quality, better surface finish and high output rate. The operation is usually performed on vertical milling machine. Quality and productivity is optimized with the help of optimization technique in such a manner that these multi-objectives could be fulfilled simultaneously up to the desired level.

LITERATURE REVIEW

Sundara Murthy et al (2010) studied provides the optimum cutting conditions for end milling of Aluminum 6063 under minimum quantity lubrication machining. The highest cutting speed, medium feed rate and medium depth of cut produces lowest surface roughness. Kromanis et al (2008), developed a technique to predict a surface roughness of part to be machined according to technological parameters & find relationships between surface roughness (Average absolute deviation of the surface) of machined workpiece and used technological parameters (cutting speed; feed ; cutting depth). They concluded that technological parameter range also plays a very important role on surface roughness. Study results can be used by technologists and other manufacturing specialists to set up cutting parameter in end-milling. Metin Kok et al(2006) studied the machinability of 2024Al/Al2O3 particle composite was investigated in terms of tool wear, tool life and surface roughness by turning specimens with TiN (K10) coated and HX uncoated carbide tools in different cutting conditions.

MATERIALS AND METHODS - EXPERIMENTAL PROCEDURE

A metal matrix composite is made up of two constituents namely matrix and reinforcement. The matrix material is generally metal and the reinforcement is generally inorganic or organic compound. Here we have used silicon carbide as reinforcement as it enhances the thermal resistance of the composite making its structure more stable for machining operation and after use. In order to get the desired properties the volume of reinforcement, shape of the reinforcement, production method etc. can be varied. The method of producing the composite with the help of stir casting is as follows:

The chosen four blade stirrer from the cold model study is connected to a 15 mm diameter hollow steel shaft. Inside the hollow shaft a rod of diameter 5 mm is concentrically placed The bottom end of the rod is attached to a tapered graphite plug. The mating hole is drilled in the crucible. Initially the shaft is placed at a level above the top surface of the crucible and the rod consisting plug closes the hole. After the Matrix material melts, the melt will be stirred at 500 rpm and then the reinforcement will be introduced in the vortex. The stirring is continued for about 3-4 min and then casting is cooled and solidified and removed from the mould.

The experimental procedure involves four stages:

(i) the selection of proper combination of composite material, necessary cutting tools, and required equipment,

(ii) data collection by conducting experiments as per the defined plan,

(iii) the establishment of a surface roughness & MRR prediction model, and

(iv) optimization of the predictive model for better results.

DESIGN OF EXPERIMENT

Experiments are designed using Taguchi method so that effect of all the parameters could be studied with minimum possible number of experiments. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. Signal to Noise (S/N) ratios are also calculated for analyzing the effect of machining parameters more accurately.

As per Taguchi’s method, the selected orthogonal array must be greater than or equal to the total degree of freedom required for the experiment. So, an L27 orthogonal array was selected for the present work. The non-linear relationship among the process parameters can be revealed when more than two levels of the parameters are considered. Hence each selected parameter was analyzed at three levels. The process parameters and their values at three levels are given in Table 1. Taguchi method is a robust optimization technique for optimizing process parameters in order to get optimum conditions with least cost and minimum number of experiments and subsequent data analysis. Due to the advantages offered by this method, researchers have used this method in the milling operations. In the present study, the Taguchi design of experiments is used to investigate the effect of the machining parameters on surface roughness (Ra) and MRR on a CNC vertical milling machine. The lower-the-better criterion for Ra and higher –the –better criterion for MRR were chosen to calculate the S/N ratio.

Quality as par Taguchi

According to Taguchi, quality of a manufactured product is loss by that product incurred to the society from the time it is shipped. Financial loss or Quality loss may be given by:

$L(y) = k(y-m)^2$, Y= objective characteristic, m = target value,

k = Cost of defective product / $(\text{Tolerance})^2 = A/\Delta^2$

Taguchi Design Approach

The Taguchi technique involves reducing the variation in a process through robust design of experiments. To achieve desired product quality, Taguchi suggested a three-stage process:

1. System Design.
2. Parameter Design
3. Tolerance Design

Analysis of Variance (ANOVA)

In addition to the Signal to Noise Ratio (S/N ratio), the results have been subjected to Analysis of Variance

(ANOVA) to evaluate the impact of control factors (process parameters) on surface roughness. In addition to the Signal to Noise Ratio (S/N ratio), the obtained results have been tested using statistical Analysis of Variance (ANOVA) to indicate the impact of process parameters on surface roughness.

$$SN_i = log\frac{\bar{y}_i^{\,2}}{s_i^{\,2}}$$

Where $y_{i,j}$ = the measurement from *group i*, *observation-index j*.

k = number of groups, n_i = number of observations in group *i*

n = total number of observations,

This ANOVA analysis was done for a significance level of 0.05 (α), i.e., for a confidence level of 95%.

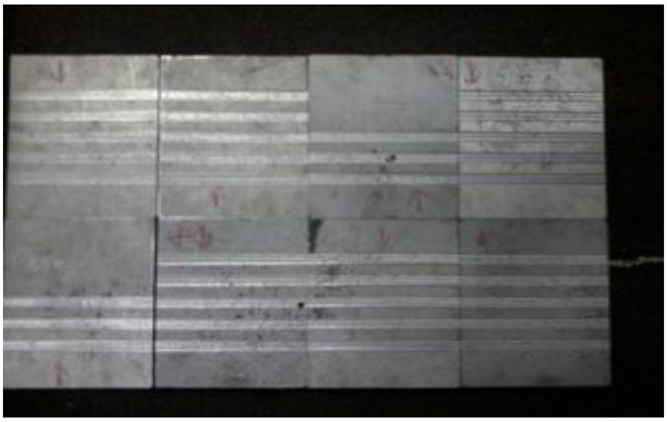

Figure 2: End Milled slots of Al 2024-SiC

Figure 3: ITI surftest to measure surface roughness

Table 1: Level of Variables used in the Experiment

Variable	***Level 1***	***Level 2***	***Level 3***	***Observed Values***
(A)Cutting Speed (RPM)	1000	2000	3000	Surface Roughness (SR) for 10 & 15 % SiC
(B)Feed (mm/min)	400	600	800	
(C)Depth of Cut (mm)	0.3	0.6	0.9	
(D)Number of Flutes	2	3	4	

Table 2: Response Table for Signal to Noise Ratios of Al 2024-10% SiC plates

Process Parameters	**Code**	**Levels for 10% SiC**			**Delta (Δ)**	**Rank**
		1	**2**	**3**	**MAX. - MIN.**	
Speed	A	-5.02	-7.354	-3.922	3.432	2
Feed	B	-2.553	-4.585	-9.158	6.605	1
Depth of Cut	C	-5.826	-4.858	-5.611	0.968	3
No. of Flutes	D	-5.405	-5.881	-5.05	0.871	4

RESULTS AND DISCUSSIONS

The microstructure of the composite material of the selected combination showed no significant difference before and after machining, thus indicating the material is stable over the selected range of speed variation.

The ANOVA analysis (see table 4.15) revealed that the feed is the most significant factor (see in the last column %contribution of Feed is 58.4154%) followed by speed (15.68%) and depth of cut (1.3199%) for obtaining optimum surface finish, i.e., minimum value of Ra. Interactions do not have much effect on the output response. Only interaction between feed and speed (A*B; see table) affects the surface roughness to some extent.

Main Effects Plots

Minitab software generates statistical results in the form of effects plots and three main effects plots based on values of response tables namely S/N ratio plots, data means plots and plots of standard deviations as shown below for Al2024-10%SiC.

Interpretation of main effect plots

S/N ratio and data means plots analysis: Figure 4 clearly indicate the level of a control factor for optimum output. For data means, we have to consider the minimum value of surface roughness while for S/N ratio we have to always consider the maximum value. From figures it is clear that a combination of speed of 3000 rpm, feed of 400 mm /min, DOC 0.6 mm and end mill having four flutes will provide better surface finish for Al 2024-10%SiC composite.

Residual plots: Residuals were scattered above and below the zero-line of the residual plot implying the adequacy of the proposed model. The residual plots for SN Ratios and Standard Deviations are shown in Fig.5.

- **Normal Probability plot of the residuals:** As is clear from residual plots (Figure no. 5) residual form a straight line distribution implying model fits the data well. As the response plot is a straight line, it indicates errors are distributed normally.
- **Residuals versus the fitted values:** If assumptions are correct then the plot should be structure less. In a good regression models, the residuals form a random and normal distribution pattern. Residuals versus fitted values hint that the variance is constant and a non-linear relationship exists. In second plot of figure nos. 5; fitted values vs. residuals the values are scattered randomly below and above zero line showing data is independent.
- **Histograms of the residuals:** Histogram show the data is not skewed and no outliers are there. The Residuals are found to be normally distributed.
- **Residuals versus the order of the data** hint that there are systematic effects in the data due to time or data collection order.

Contour Plot

- Provides a topographical view of the predicted process output (usually modeled through a DOE) versus two of the process inputs.
- Helps to visualize the effects of two process inputs (factors) on the process output. The contours on the graph represent values of the predicted process output at various settings of the two factors on the plot.
- Used as a graphical aid when using regression, ANOVA, or DOE.
- Enter factor levels into additional columns, one for each factor. If your model has additional factors, you must specify the levels at which to hold all other factors.
- Choose Stat > DOE > Factorial > Contour/Surface Plots or choose Stat > DOE > Response Surface > Contour/Surface Plots,

Interpretation of contour plots

- **Figure 6 - Contour Plots of DOC versus NFL:** Dark blue colour indicates lower surface roughness value (< 0.8 µm) while dark green colour indicates higher value of surface roughness (> 1.8 µm) as shown in the table given on the side of contour plot. Higher DOC (0.9 mm) and lesser number of flutes (2 fluted end mill cutters) generate smooth surface, i.e., lower value of surface roughness as indicated by dark blue colour.
- **Figure 7 - Contour Plots of DOC versus Feed:** Dark blue colour indicates lower surface roughness value (< 1.0 µm) while dark green colour indicates higher value of surface roughness (> 3.5 µm) as shown in the table given on the side of contour plot. Higher DOC (0.9 mm) and lower feed (400 mm/min) generate smooth surface, i.e., lower value of surface roughness as indicated by dark blue colour.
- **Figure 8- Contour Plots of NFL versus Feed:** Light green colour indicates lower surface roughness value (< 1.5 µm) while dark green colour indicates higher value of surface roughness (> 3.5 µm) as shown in the table given on the side of contour plot. Lesser number of flutes (2 fluted end mill cutter) and lower feed (400 mm/min) generate smooth surface, i.e., lower value of surface roughness as indicated by light green colour.
- **Figure 9- Contour Plots of NFL versus Speed:** Light green colour indicates lower surface roughness value (< 1.4 µm) while dark green colour indicates higher value of surface roughness (> 1.8 µm) as shown in the table given on the side of contour plot. Lesser number of flutes (2 fluted end mill cutter) and higher speed (3000 rpm) generate smooth surface, i.e., lower value of surface roughness as indicated by light green colour.

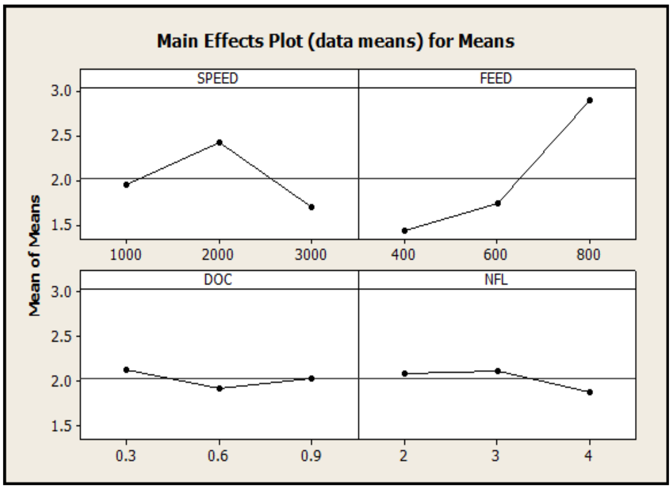

Figure 4: Main Effects plot for Data Means of Al2024-10%SiC for Ra

Figure 10- Contour Plots of DOC versus Speed: Dark blue colour indicates lower surface roughness value (< 0.8 µm) while dark green colour indicates higher value of surface roughness (> 1.3 µm) as shown in the table given on the side

of contour plot. Higher DOC (0.9 mm) and higher speed (3000 rpm) generate smooth surface, i.e., lower value of surface roughness as indicated by dark blue colour.

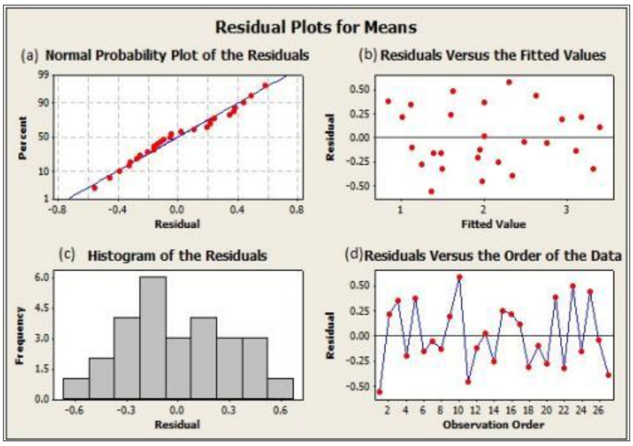

Figure 5 : Residual Plots for Means Input data analysis for surface roughness

(a) Normal Probability plot of the residuals, (b) Residuals versus the fitted values, (c) Histograms of the residuals and (d) Residuals versus the order of the data

Surface Plots

- The three-dimensional surface plot helps to visualize the effects of two process inputs (factors) on the process output. The height of the surface is the predicted process output at various settings of the two factors included in the plot.
- Used as a graphical aid in regression, ANOVA, or DOE.
- Enter factor levels into additional columns, one for each factor. if your model has additional factors, you must specify the levels at which to hold all other factors.
- Stat > DOE > Factorial > Contour/Surface Plots or Stat > DOE > Response Surface > Contour/Surface Plots.

The 3-D surface plots for the surface roughness are given in figs 11, 12, 13, 14, 15 and 16. In each of these graphs, two cutting parameters are varied while the third parameter is held as its mid value.

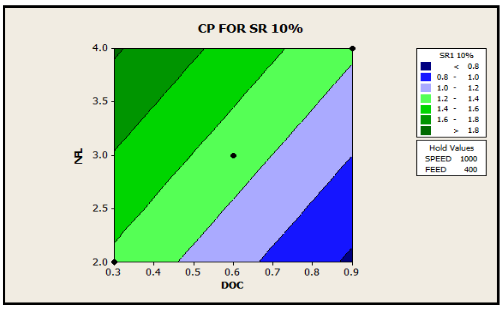

Figure 6: Contour Plots of DOC versus NFL

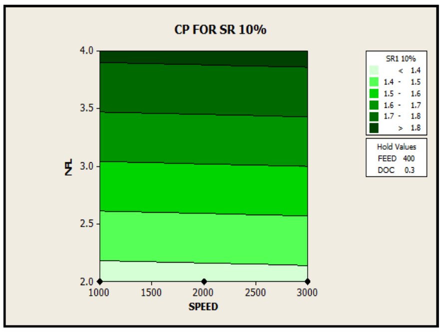

Figure 7: Contour Plots of DOC versus Feed

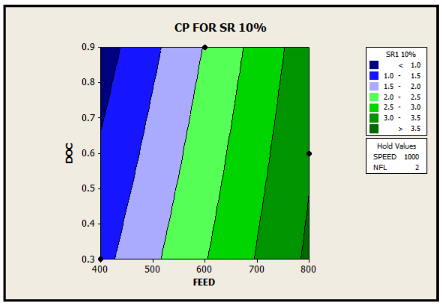

Figure 8: Contour Plots of NFL versus Feed

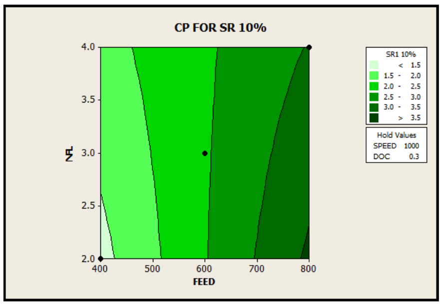

Figure 9: Contour Plots of DOC versus Speed

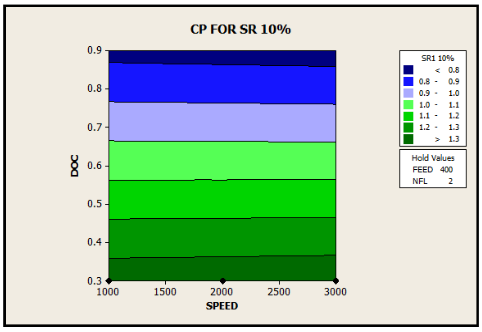

Figure 10: Contour Plots of NFL versus Speed

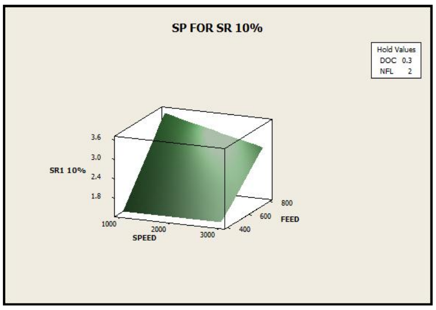

Figure 11: 3-D Surface Plot -Speed versus Feed

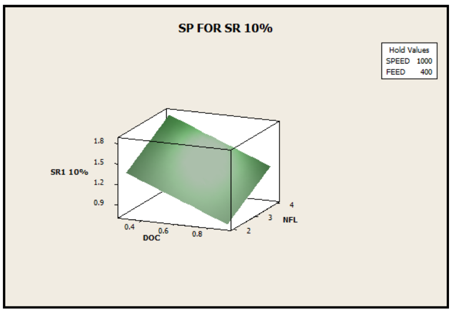

Figure 12: 3-D Surface Plot-NFL versus DOC

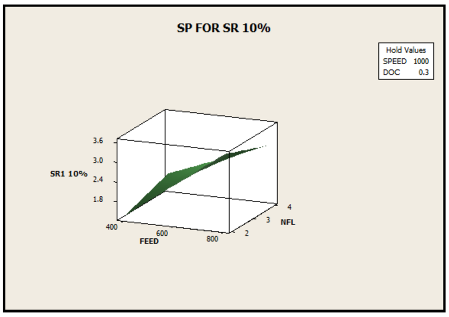

Figure 13: Surface Plot -NFL versus Feed

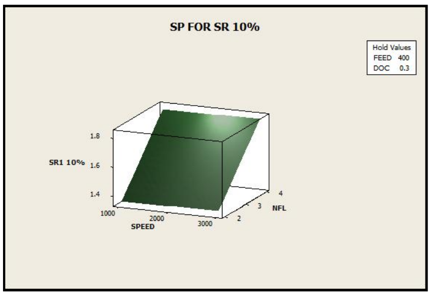

Figure 14: Surface Plot -Speed versus NFL

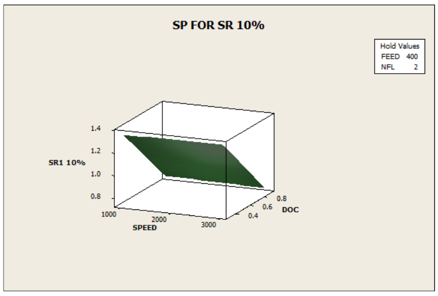

Figure 15: Surface Plot – DOC Versus Speed

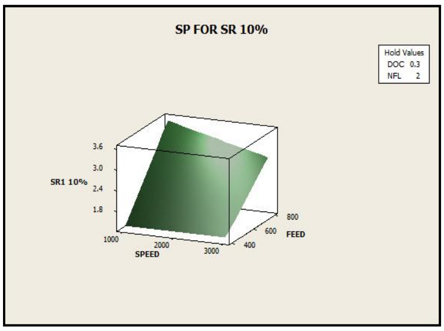

Figure 16: Surface Plot - Speed versus Feed

Table 3: ANOVA of data values of Al2024-10%SiC

Source	**DF**	**Seq. SS (sum of squares)**	**Adj. SS (Variance)**	**Adj. MS (Variance ratio)**	**F**	**P**	**% SS (% contribution)**
Speed (A)	2	55.291	55.291	27.6455	3.63	0.093	15.68 ✵
Feed (B)	2	205.986	205.986	102.993	13.52	0.006	58.4154 ✵✵
DOC (C)	2	4.654	4.654	2.327	0.31	0.748	1.3199
NFL (D)	2	3.423	3.423	1.7115	0.22	0.805	0.9708
A*B	4	17.429	17.429	4.35725	0.57	0.694	4.9427
A*C	4	4.346	17.429	1.086	0.14	0.96	1.2325
A*D	4	15.779	4.346	3.945	0.52	0.727	4.4748
Residual Error	6	45.716	45.716	7.619			12.9646
Total	26	352.623=SS_T					100
S = 2.760 R-Sq = 87.0% R-Sq(adj) = 43.8%							
Critical F-ratio F0.05,2,6= 5.14, F0.05,4,6= 4.53							
✵✵Significant factor – Feed; ✵Sub- significant factor – Spindle Speed							

Interpretation of interaction effects of surface plots

- **From fig. 11; 3-D Surface Plot --Speed versus Feed (DOC & NFL – Hold):** It is observed that best surface finish was obtained for low feed value and speed does not have much effect on surface finish but at higher speeds; surface roughness attains lower value to some extent.

  From figure 12; 3-D Surface Plot-- NFL versus DOC (Feed & Speed – Hold): It is observed that best surface finish originated due to the combination of higher depth of cut and lower number of flutes of the end mill cutter. The surface roughness shows a poor surface finish for a lower depth of cut and this may be attributed to the plugging action of the end mill on the surface of MMC which also give rise to raised temperature and hence poor finish.

  The slope of the plot also shows the non-linear relationship of the output response parameter surface roughness with depth of cut.

- **From figure 13; 3-D Surface Plot -- NFL versus Feed (DOC & Speed – Hold):**It is observed that best surface finish was obtained from the combination of lower feed value and lower number of flutes of the end mill cutter. The slope of the plot also shows the non-linear relationship of the output response parameter surface roughness with combination of feed and number of flutes.
- **From figure 14; 3-D Surface Plot -- Speed versus NFL (DOC & Feed – Hold):**It is observed that lowest surface roughness was obtained for lesser number of flutes and speed does not have much appreciable effect on surface roughness but at higher speeds; surface roughness attains lower value to some extent.
- **From figure 15; 3-D Surface Plot -- DOC versus Speed (NFL & Feed – Hold):** It is observed that best surface finish was produced by the combination of higher depth of cut and higher RPM. The speed has less effect on the surface roughness.
- **From figure 16; 3-D Surface Plot -- Speed versus Feed (NFL & DOC – Hold):** Best surface finish was produced by the combination of lower feed and higher feed. The curvature of the plot also shows the non-linear relationship of the output response parameter surface roughness with the combination of feed and speed.

CONFIRMATION EXPERIMENT

The combination of input control factor levels, for which optimum output responses will be obtained, is given in Table 4 which shows the results of the confirmation test with optimized input control factors for output responses namely surface roughness. The verification between the predicted values and experimental data for both MMCs is in good agreement for a 95% confidence level.

Table 4: Confirmation Test Results

Expt. No.	Spindle speed	Feed	Depth of cut	No. of flutes	Surface roughness (Ra)	
1	3000	400	0.6	4	0.987	---
2	3000	400	0.6	2	---	1.354

A minor discrepancy between the experimental results and calculations could be inferred due to the presence of random errors and uncontrollable errors of the machining process, as well as environmental effects.

CONCLUSIONS

The optimization has been done to reduce surface roughness. From this study it can be concluded that:

1. ANOVA and S/N plots reveals that the speed is dominant parameter followed by depth of cut and feed.
2. Contour and surface plots also revealed that the feed rate and spindle speed are by far the most dominant factor than the depth of cut for surface finish.
3. Applied statistical plots do not provide exact numerical values of response output as provided by the ANOVA method.
4. In end milling, use of high spindle speed (3000 rpm), low feed rate (400 mm/min.) and low depth of cut (0.3 mm) and 4 fluted end mill tools are optimized parameters to obtained better surface finish for the specific test range in an Al2024-10% SiC composite.

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