

Multi-Objective Optimization in CNC End Milling using Taguchi Optimization Technique

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Abstract: The present work makes an attempt to analyze various parameters of end milling in order to minimize the surface roughness and to maximize the material removal rate (MRR) of Al 2024-SiC composite. Al2024-SiC is generally used in manufacturing high strength parts of aircrafts and machinery, fuselage structural wing tension members, wing skins, engine parts subjected to high temperatures including gears and bolts and for security vans where strength is critical. The quality of the machined surface, i.e., surface finish and texture affects the function, appearance and reliability of a product. On the other hand higher production rate is possible when MRR is maximum. But higher MRR leads to lower surface finish, so a tradeoff between Surface finish and MRR is needed. In this work, the optimal selection of process parameters have been done in order to obtain optimized response output parameters namely surface roughness and MRR by using Taguchi's technique. And ANOVA analysis. In machining operations, achieving desired surface quality is a bit difficult as these quality structures are influenced by the effect of process parameters and their interactions. However, the amounts of influence of the process parameters vary for different processes. Therefore, optimization of surface roughness and MRR is a multi-factor and multi-objective optimization which is carried out successfully by the help of Taguchi optimization technique.

Keywords- Surface Roughness, Material Removal Rate, Orthogonal Array, Taguchi Technique

1. INTRODUCTION

Surface roughness is an important measure of the quality of a production and also influences the machining cost. The mechanism for achieving lower surface roughness is dynamic and process dependent.



Figure 1 Takumi CNC VMC



Figure 2 End Milling Operation on Al2024-SiC composite cast plate

So, generally machine operators use hit and trial method to achieve desired surface roughness but with lesser success rate. The Taguchi technique has been used to find a particular combination of machining parameters in end milling operation of Al2024-SiC composite under finishing condition considering input parameters namely speed, feed, depth of cut and number of flutes for assessing output responses namely surface roughness and material removal rate in order to obtain optimal parameter setting for the process. Confirmation tests were done to check the results obtained with Taguchi

technique and ANOVA analysis. Confidence interval calculations were done to check whether findings lie within the allowable range of the parameters or not.



Figure 3 ITI Surftest to measure Surface roughness

2.0 LITERATURE REVIEW

H. Basak, et al. showed that the surface roughness at the same feed rate becomes prominent with the use of a tool with small optimizing the feed rate and other geometric conditions [11]. Cutting speed affects the surface finish the most. Moheb M. Hanna et al. were of the view that material removal rate (MRR) is very critical for increasing the productivity and hence very useful for the production planners [6]. Jasmi Hashim demonstrated that material removal rate (MRR) is very crucial control factor of machining operation of production management useful for production planners [13]. U. Zuperl et al (1995) [10], investigate the characteristics parameters in milling by using PSO evaluation technique. They showed that MRR is improved by 28%, machining time reduction of up to 20% is observed.

3.0 EXPERIMENTATION: The four factors (speed, feed, depth of cut and no. of flutes) are taken as input parameter (control factors) and three levels of each factor are considered in this experiment. Taking degree of freedom of each factor as 2 and degree of freedom for interaction as 4, so for four factors and three interactions (A*B, A*C, A*D or B*C); the degree of freedom required for the experiment comes out to be 20. The degree of freedom of L27 OA is 26 (dof=27-1). As 26>20; therefore, a L27 Orthogonal Array {L27 (3X13)} is selected for the experiment. Once the experimental design is finalized and the trials are done, For the case of minimizing the performance characteristic say for the response namely surface finish; (**Smallest-is-better quality characteristic**), the following definition of the SN ratio should be calculated.

$$\frac{S}{N} = -10 \log_{10} \left(\frac{1}{n \sum y_i^2} \right)$$

For the case of maximizing the performance characteristic say for the case Material removal rate; (**Biggest-is-better quality characteristic**), the following definition of the SN ratio should be calculated:

$$\frac{S}{N} = -10 \log_{10} \left(\frac{1}{n \sum \frac{1}{y_i^2}} \right)$$

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,

The S/N ratio is associated with one of the basic goals of the Taguchi method, the reduction of variability by minimizing the effect induced by noise factors in the experiment and is given as:

$$S/N \text{ Ratio} = \mu / \sigma;$$

Where μ is the signal mean or the expected value and σ is the standard deviation of the noise. In some cases, the S/N ratio can be defined as the square of the above function.

4.0 ANOVA of Surface roughness of Al 2024-10% SiC plates

The ANOVA analysis (see table 2) revealed that 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 R_a . Interactions do not have much effect on the output response. Only interaction between feed and speed (A*B; see table 2) affects the surface roughness to some extent.

Table 1 Level of Variables used in the Experiment

Variables	Level 1 (Low)	Level 2	Level 3 (High)	Response Variables
	-1	0	1	
(A) Cutting Speed (RPM)	1000	2000	3000	Surface roughness (SR) for 10 & 15 % SiC & Material removal rate (MRR) 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 ANOVA of Surface roughness of Al 2024-10% SiC plates

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 F _{0.05,2,6} = 5.14, F _{0.05,4,6} = 4.53							
** Significant factor – Feed; * Sub- significant factor – Spindle Speed							

4.2 Main effects Plots

Minitab software provides us with 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.

4.3 Interpretation of main effect plots: S/N ratio and Data Means plots analysis: Figures 4 and 5 clearly indicate the level of a control factor for optimum output. For data means and S/N ratio, we have to consider the maximum value of MRR. From figures it is clear that a combination of speed of 3000 rpm, feed of 800 mm /min, DOC of 0.9 mm and 2 flute end mill will provide better surface finish for Al 2024-10%SiC composite.

4.4 Interaction Plot: Intersecting lines indicate interaction among two factors. However, the interaction plot doesn't reveal about the statistical significance of the interaction.

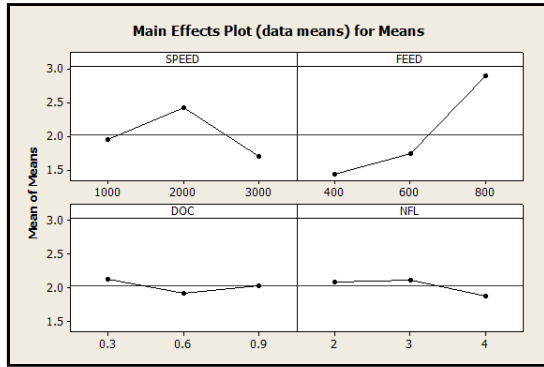


Fig 4 Main Effects plot for Means of Al2024-10%SiC

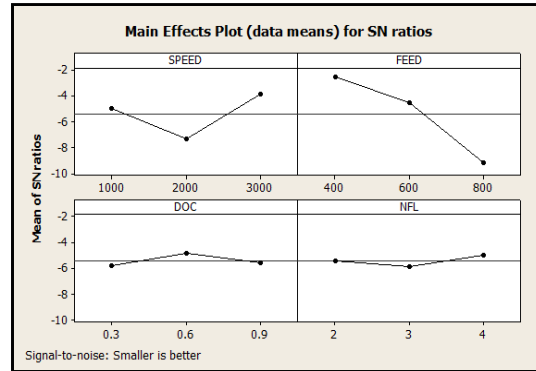


Figure 5 Main Effects plot for S/N Ratios

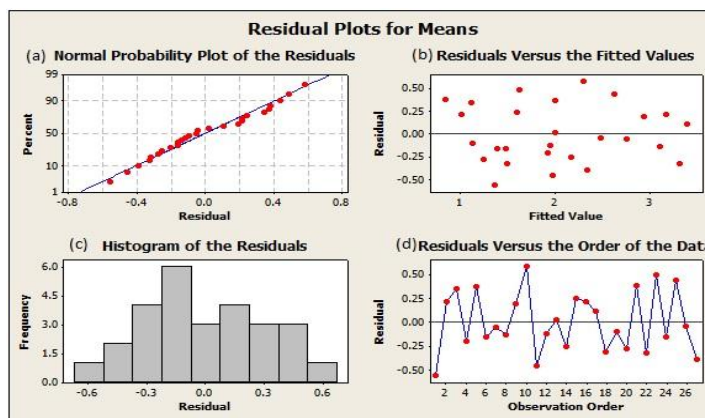


Figure 6 Residual Plots

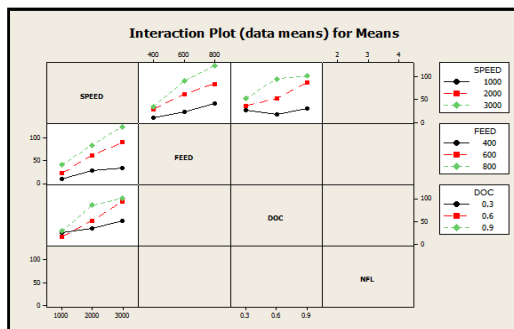


Figure 7 Interaction plot for DataMeans

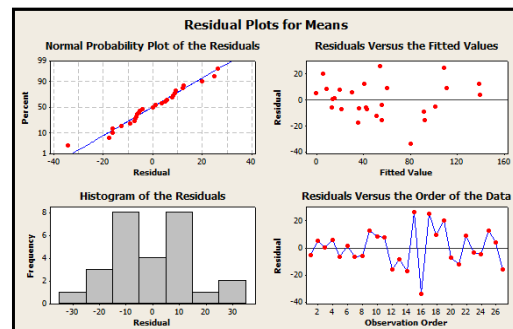


Figure 8 Interaction Plots for S/N Ratios

4.6 Interpretation of Interaction plots:

Figures 7 & 8 shows the effect of interaction among various input control factors. As one can observe that plot of factor A & C intersect each other indicating interaction of speed and DOC but plot of factor A & B intersect indicating interaction of speed and feed. But as can be seen from ANOVA table the quantum effect of interaction is not major.

4.7 Interpretation of contour plots:

Figure 9; Contour Plots of DOC versus NFL: Light green colour indicates lower MRR ($< 100 \text{ mm}^3/\text{sec}$) while dark green colour indicates higher value of MRR ($> 160 \text{ mm}^3/\text{sec}$) as shown in the table given on the side of contour plot.

Higher DOC (0.9 mm) and higher number of flutes (4 fluted end mill cutter) results in higher MRR as indicated by dark green colour.

Figure 10; Contour Plots of NFL versus Speed: Light green colour indicates lower MRR (<50 mm³/sec) while dark green colour indicates higher value of MRR (>150mm³/sec) as shown in the table given on the side of contour plot. Higher number of flutes (4 fluted end mill cutter) and higher speed (3000 rpm) results in higher MRR as indicated by dark green colour.

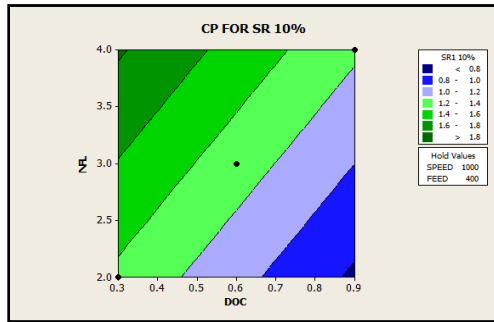


Figure 9

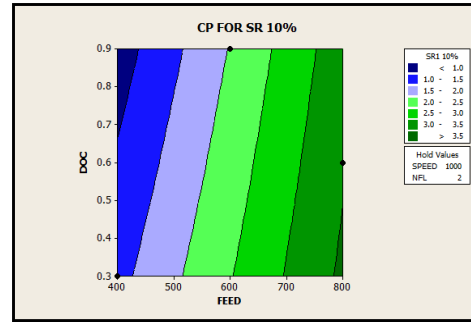


Figure 10

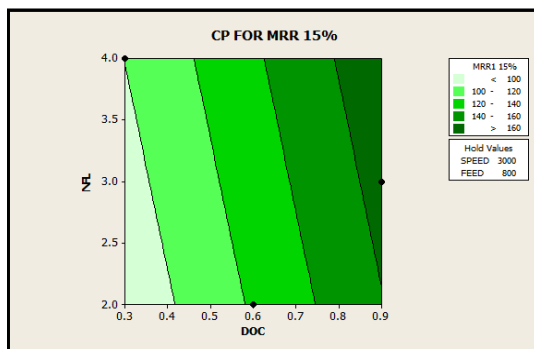


Figure 11 Contour Plots of DOC versus NFL

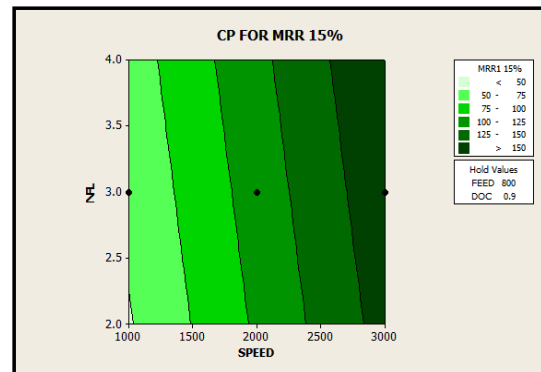


Figure 12 Contour Plots of Speed versus NFL

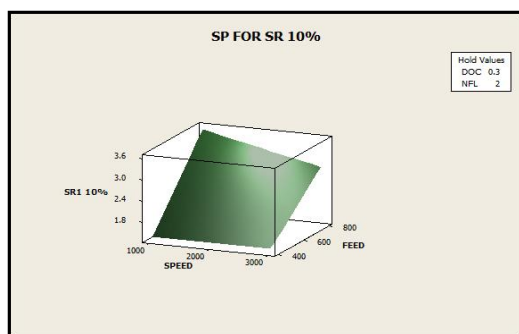


Figure 13 3-D Surface Plot -Speed versus Feed

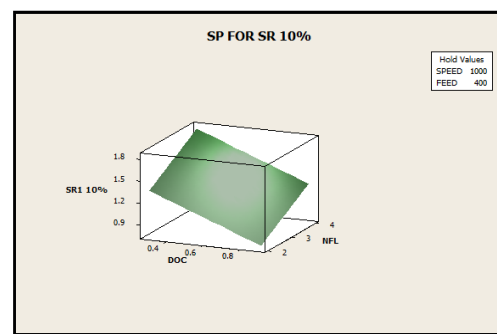


Figure 14 3-D Surface Plot-NFL versusDOC

4.8 ANOVA Analysis: The ANOVA analysis (see table 3) revealed that feed is the most significant factor (see in the last column %contribution of Feed is 44.45%) followed by speed (34.28%) and depth of cut (8.89%) for obtaining optimum material removal rate, i.e., Maximum value of MRR. Interactions do not have much effect on the output response. Only interaction between feed and speed (A*B; see table 3) affects the MRR to some extent.

Table 3 ANOVA Table of S/N Ratios of MRR of Al2024-10% SiC plates

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	% SS
Speed (A)	2	562.28	562.28	281.139	41.33	0	34.28*
Feed (B)	2	729.14	729.14	364.569	53.6	0	44.45**
DOC (C)	2	145.81	145.81	72.905	10.72	0.01	8.89
NFL (D)	2	14.65	14.65	7.326	1.08	0.398	0.893
A*B	4	60.12	60.12	15.031	2.21	0.184	3.66
A*C	4	51.7	51.7	12.924	1.9	0.23	3.152
A*D	4	35.64	35.64	8.909	1.31	0.365	2.172
Residual Error	6	40.81	40.81	6.802			2.488
Total	26	1640.14					100
S = 2.608 R-Sq =97.5% R-Sq(adj) = 89.24%							
Critical F-ratio F0.05,2,6= 5.14, F0.05,4,6= 4.53							
**Significant factor – Feed; *Sub- significant factor – Spindle speed							

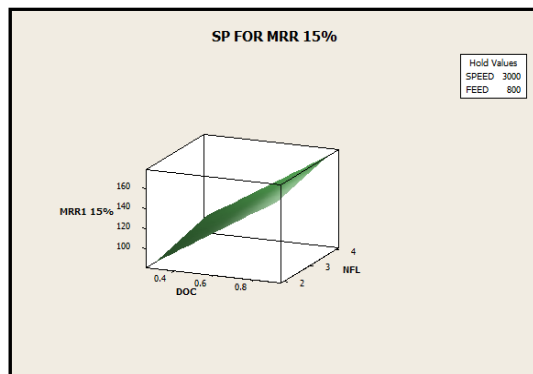


Figure 15 Surface Plot DOC versus NFL

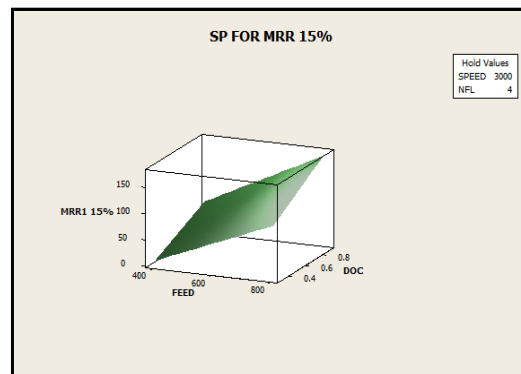


Figure 16 Surface Plot DOC versusFeed

4.9

Surface Plots

The three dimensional surface plots for surface roughness are shown in figs 13 and 14. The three dimensional surface plots for the MRR are shown in figs 15 and 16. In each of these graphs, two cutting parameters are varied while the third parameter is held as its mid value.

4.10 Discussion on Results

Predicted material removal rate = **108.17 mm³/sec**; Experimental mean MRR value for factor combination of A3-B3-C3-D1= **112.2 mm³/sec**; category of the performance characteristic, a larger S/N ratio corresponds to better performance characteristic.

5.0 Confirmation tests of optimum levels of the surface roughness:

5.1 Experimental Verification: The combination of input control factor levels, for which optimum output responses will be obtained, are 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. A minor difference between the trial value and calculated value could be assigned to the presence of random errors and different environmental parameters.

Table 4 Combination of input control factor levels for optimum output response

Expt. No.	Spindle speed	Feed	Depth of cut	No. of flutes	Surface roughness (Ra)	
					10% SiC	15% SiC
1	3000	400	0.6	4	0.987	---
2	3000	400	0.6	2	---	1.354

Table 5 Predicted Values (10% SiC)

S/N Ratio	Mean	St Dev	Log(St Dev)
-1.82224	1.30778	0.0550758	-3.97225
Factor levels for predictions			
Speed	Feed	DOC	NFL
3000 (A3)	400 (B1)	0.3 (C1)	2 (D1)

Table 6 Predicted Values (15% SiC)

S/N Ratio	Mean	St Dev	Log(St Dev)
-0.0205295	0.963333	0.015751	-4.28208
Factor levels for predictions			
Speed	Feed	DOC	NFL
3000 (A1)	400 (B1)	0.6 (C2)	4 (D3)

6.0 Confidence interval (CI): A 95% confidence interval (CI) for the predicted mean of optimum QC on a confirmation test is estimated:

$$CI = \sqrt{F(\alpha, 1, fe) * V_e * \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} \quad \text{----- (1)}$$

And the effective number of replications $N_{eff} = \frac{N}{1 + T_{dof}}$ ----- (2)

In order to verify the result of the estimated surface roughness, the confidence interval (CI) is calculated as explained below:

6.1 Calculations of CI of the surface roughness from the machining data of Al 2024-10%SiC

Where Significance level; $\alpha = 0.05$

F-ratio required for 95% confidence interval $F_{0.05, 1, 6} = 5.99$ [from F-table]

DOF for error; $fe = 6$ [from ANOVA table]

Error variance, $V_e = 7.619$ [from ANOVA table]

Number of replications for confirmation experiment, $R = 3$

Total number of experiments, $N = 27 \times 2 = 54$

Total degrees of freedom: $T_{DOF} = 27 - 1 = 26$

Putting above values in equation nos. 1&2; we have

$$N_{eff} = \frac{N}{1 + T_{dof}} = \frac{54}{1 + 26} = \frac{54}{27} = 2$$

and

$$CI = \sqrt{F(\alpha, 1, fe) * V_e * \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} = \sqrt{5.99 * 7.619 * \left[\frac{1}{2} + \frac{1}{3} \right]} = \pm 6.165$$

the calculated confidence interval is $CI = \pm 6.165$.

Thus the 95% confidence interval of the predicted optimal surface roughness is obtained as:

$$[R_{a_{opt}} - CI] < R_{a_{exp}} < [R_{a_{opt}} + CI] = 0.9633 \pm 6.165 \mu m,$$

$$\text{i.e., } -5.217 \mu m < R_{a_{exp}} < 7.1283 \mu m$$

The $R_{a_{exp}} = 0.987 \mu m$, which was found experimentally is well within the confidence interval limit. Therefore, the system was successfully optimized using the Taguchi optimization technique at a significance level of 0.05 in the end milling of Al2024-10%SiC under different machining conditions.

6.2 Calculations of CI of the surface roughness from the machining data of Al 2024-15%SiC

$\alpha = 0.05$, $F_{0.05, 1, 10} = 4.97$, $f_e = 10$, $V_e = 20.365$, $N = 27 \times 2 = 54$, $T_{DOF} = 26$

$$N_{eff} = \frac{N}{1 + T_{dof}} = \frac{54}{1 + 26} = \frac{54}{27} = 2$$

and

$$CI = \sqrt{F(\alpha, 1, f_e) * V_e * \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} = \sqrt{4.97 * 20.365 * \left[\frac{1}{2} + \frac{1}{3} \right]} = \pm 9.182$$

Thus the 95% confidence interval of the predicted optimal surface roughness is obtained as:

$$[R_{a_{opt}} - CI] < R_{a_{exp}} < [R_{a_{opt}} + CI] = 1.30778 \pm 9.182 \mu m$$

i.e., $-7.87422 \mu m < R_{a_{exp}} < 10.48978 \mu m$

The $R_{a_{exp}} = 1.354 \mu m$, which was found experimentally, is well within the confidence interval limit. Therefore, the system was successfully optimized using the Taguchi optimization technique at a significance level of 0.05 in the end milling of Al2024-15%SiC under different machining conditions.

6.3 Confirmation tests of optimum levels of the MRR

Experimental Verification: The combination of input control factor levels, for which optimum output responses will be obtained, is given in Table shown below:

Table 7 Confirmation Test Results

Expt No.	Spindle speed	Feed	Depth of cut	No. of flutes	MRR (mm ³ /sec)	
					10% SiC	15% SiC
1	3000	800	0.9	2	112.2	----
2	3000	800	0.9	2	-----	133.8

The table 7 shows the results of the confirmation test with optimized input control factors for output responses namely MRR. The verification between the predicted values and experimental data for both MMCs is in good agreement for a 95% confidence level. A minor difference between the trial value and calculated value could be assigned to the presence of random errors and different environmental parameters.

7.0 Confidence interval (CI): A 95% confidence interval (CI) for the predicted mean of optimum QC on a confirmation test is estimated.

7.1 Calculations of CI of the MRR from the machining data of Al 2024-10%SiC

$\alpha = 0.05$, $F_{0.05, 1, 6} = 5.99$, $f_e = 6$, $V_e = 40.81/26 = 1.569$, $N = 27 \times 2 = 54$, $T_{DOF} = 26$

Putting above values in equation nos. 1&2; we have

$$N_{eff} = \frac{N}{1 + T_{dof}} = \frac{54}{1 + 26} = \frac{54}{27} = 2$$

and

$$CI = \sqrt{F(\alpha, 1, f_e) * V_e * \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} = \sqrt{5.99 * 6.802 * \left[\frac{1}{2} + \frac{1}{3} \right]} = \pm 5.826$$

the calculated confidence interval is $CI = \pm 5.826$

Thus the 95% confidence interval of the predicted optimal MRR is obtained as:

$$[MRR_{opt} - CI] < MRR_{exp} < [MRR_{opt} + CI] = 108.170 \pm 5.826 \text{ mm}^3/\text{sec}$$

i.e. $102.344 \text{ mm}^3/\text{sec} < MRR_{exp} < 113.996 \text{ mm}^3/\text{sec}$

The $MRR_{exp} = 112.2 \text{ mm}^3/\text{sec}$, which was found experimentally is well within the confidence interval limit. Therefore, the system was successfully optimized using the Taguchi optimization technique at a significance level of 0.05 in the end milling of Al2024-10%SiC under different machining conditions.

7.2 Calculations of CI of the MRR from the machining data of Al 2024-15%SiC

$\alpha = 0.05$, $F_{0.05, 1, 6} = 5.99$, $f_e = 6$, $V_e = 8.5333$, $N = 27 \times 2 = 54$, $T_{DOF} = 26$

$$N_{eff} = \frac{N}{1 + T_{dof}} = \frac{54}{1 + 26} = \frac{54}{27} = 2$$

$$CI = \sqrt{F(\alpha, 1, fe) * V_e * \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} = \sqrt{5.99 * 8.5333 * \left[\frac{1}{2} + \frac{1}{3} \right]} = \pm 6.5252$$

the calculated confidence interval is $CI = \pm 5.826$. Thus the 95% CI is calculated below:

$$[MRR_{opt} - CI] < MRR_{exp} < [MRR_{opt} + CI] = 130.389 \pm 6.5252 \text{ mm}^3/\text{sec}$$

i.e. $123.3638 \text{ mm}^3/\text{sec} < MMR (\text{mm}^3/\text{sec}) < 136.9142 \text{ mm}^3/\text{sec}$

$$(MRR)_{exp} = 133.8 \text{ mm}^3/\text{sec}$$

The $MRR_{exp} = 133.8 \text{ mm}^3/\text{sec}$, which was found experimentally is well within the confidence interval limit. Therefore, the system was successfully optimized using the Taguchi optimization technique at a significance level of 0.05 in the end milling of Al2024-15%SiC under different machining conditions.

8.0 Conclusion

The analysis of the result of the surface roughness shows that the optimal combination higher spindle speed, low feed rate, lower depth of cut (DOC) and for number of flutes it's a mixed one. But as the content of SiC increases in the metal matrix composite an end mill with lesser flutes generates better surface finish. The following conclusions were drawn from the analysis:

1. In end milling, increase in spindle speed, decrease in feed rate and decrease in depth of cut and less flutes will decrease the surface roughness within specified test range.
2. 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 tool are optimized parameters to obtain better surface finish for the specific test range in a Al2024-10% SiC composite while the values of same control factors for Al 2024-15%SiC are (3000 rpm), low feed rate (400 mm/min.) and low depth of cut (0.3 mm) and 2 fluted end mill tool.

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