Modeling and Analysis of CNC Milling Process Parameters on Al3030 based Composite

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Abstract. The machining of Al3030 based composites on Computer Numerical Control (CNC) high speed milling machine have assumed importance because of their wide application in aerospace industries, marine industries and automotive industries etc. Industries mainly focus on surface irregularities; material removal rate (MRR) and tool wear rate (TWR) which usually depends on input process parameters namely cutting speed, feed in mm/min, depth of cut and step over ratio. Many researchers have carried out researches in this area but very few have taken step over ratio or radial depth of cut also as one of the input variables. In this research work, the study of characteristics of Al3030 is carried out at high speed CNC milling machine over the speed range of 3000 to 5000 r.p.m. Step over ratio, depth of cut and feed rate are other input variables taken into consideration in this research work. A total nine experiments are conducted according to Taguchi L_9 orthogonal array. The machining is carried out on high speed CNC milling machine using flat end mill of diameter 10mm. Flatness, MRR and TWR are taken as output parameters. Flatness has been measured using portable Coordinate Measuring Machine (CMM). Linear regression models have been developed using Minitab 18 software and result are validated by conducting selected additional set of experiments. Selection of input process parameters in order to get best machining outputs is the key contributions of this research work.
Keywords: CNC Milling, CompositeAl3030, Flatness, MRR, TWR, ANOVA.

1. Introduction

These variety of features can be introduced in a given component by cutting away unwanted material with precision and accuracy on CNC milling and it has transformed the manufacturing industries in a big way in the last thirty years in developing countries [1,2]. CNC milling is effective in generating flat or curved shaped components. The focus of many researchers in the past has been the area of machining of composites. However, most of them used conventional machines where spindle speed range is below 2000 r.p.m. Moreover, machining at higher speeds using CNC machine results in better surface roughness (SR), material removal rate (MRR), and tool wear rate (TWR) [3]. Hatna et al., and Smith et al., highlighted the use of flatness as one of the response variables in high speed machining using CNC [4,5]. K. Ravikumar et al. [6] deals with the analysis on mechanical properties of aluminium alloy composites reinforced with tungsten carbide particles. They used stir casting process for the fabrication of aluminium composite specimen by changing tungsten carbide constituent in 2, 4, 6, 8 and 10% by weight. Their results revealed decrease of impact strength, density and elongation of composites but increase in hardness when tungsten carbide increases; the tensile strength first increases and then decreases and hence takes a maximum value. Sheth et al. [7] discussed the effect of input parameters such as cutting speed, feed and depth of cut for face milling of wrought cast

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steel grade B (WCB). The outcome was that they could control the machining process for given values of flatness and surface roughness. Developed regression models by them could effectively predict values that are very close to experimental values.

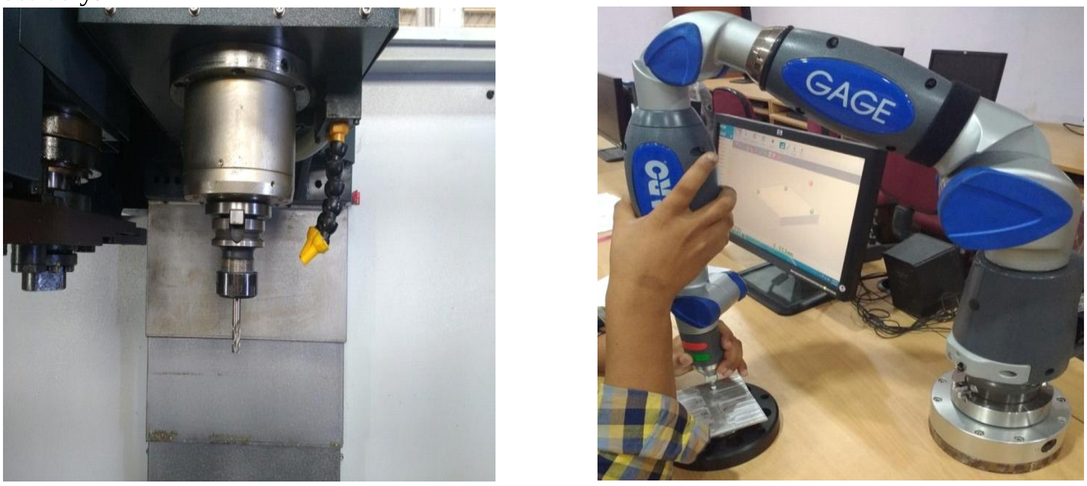
Bruce et. al. [8] improved the flatness of flat milled surface using two novel approaches; his study is based on 3-D holographic laser measurement. In the first approach, a cutting profile is generated using compensation method. It is nothing but a mirror image of the surface profile resulted from a straight cutting path. In feed rate optimization method, they could reduce the surface flatness from 32 to 7 μm using experiments with aluminium work pieces and 50.8 mm diameter face mill. With the optimized feed rate method, the flatness can be reduced by 19 μm with the same cycle time as that of the original constant feed rate. Pare et. al., [9] used Meta heuristic techniques for selection and optimization of high speed CNC end milling input process parameters. In their paper, cutting speed, feed in mm/rev, depth of cut and step over ratio are selected as independent variables and surface roughness as dependent variable. They have considered optimized control over the response parameter i.e. surface roughness.

Maiyaraet. al. [10] investigates optimization of machining parameters for end milling of Inconel 718 super alloy using Taguchi based grey relational analysis. They performed nine experiments based on an L9 orthogonal array in which cutting speed, feed rate in mm/min and depth of cut are the three input process parameters and surface roughness material removal rate and tool wear rate are output parameters. Most significant input parameters are identified using analysis of variance (ANOVA) method. Finally, confirmation tests were required to compare experimental results and developed models. The experimental results which are obtained, shows machining performance in the end milling process can be improved through this approach effectively.

2. Experimental Set up

2.1. Material and Processes

Aluminium is one of the very important structural materials prominently used in the aerospace industry due to its light weight properties however the low strength and low melting point of aluminium were always a big bottleneck in industries [11]. The typical alloying elements used in aluminium based composites are copper, magnesium, manganese silicon and zinc. Al3030 combined with SiO_2 (7%) extracted from rice husk is used as work material in this paper. Addition of silicon improves strength and hardness and reduces cracking tendency of Al3030 alloys. Hence, silicon is added to Al3030 in proportions of 3%, 5%, 7% and 10%. The best results are obtained for 7% addition of silicon oxide and thus the results of this combination are used for preparing required work material in this paper. The experimental setup of the work piece for end mill and Coordinate measuring instruments (CMM) which is used for flatness measurement are shown in Fig. 1(a) and 1(b) respectively.



(a) (b)

Figure 1. (a) Experimental set up for end milling operation (b) CMM for Flatness measurement

In this paper, high speed CNC milling machine is used with different process parameters and machining of AlSiO2 (25mm x 45mm x 4mm) is performed with the help of end mill cutting tool. End mill of stainless steel with M2 grade & four fluted tool and 10mm diameter (density 8138 kg/m3) is used for the machining of component. Selection of tool material for CNC milling process also plays a very important. The selection of tool material mainly depends on type of work piece and tool wear. The requirement is that the on work piece should be easily machined even for complex shaped components.

2.2. Machining Parameters

It is important to select the output parameters of interest for specific practical application. Output parameters are process dependent variables. In this paper, flatness, material removal rate (MRR), and tool wear rate (TWR) have been chosen as output variables. These variables are conflicting in nature as maximization of MRR is sought for, and optimum value of TWR is also aimed.

- Flatness: Flatness defines how much a surface on the component varies from ideal flat plane or reference plane constructed by least squares method. Coordinate measuring machines are best equipped to measure flatness.
- Material Removal Rate (MRR): Material removal rate is defined as rate of material removal per unit time. It is measured by taking the weight of part before and after machining and using the following equation.

$$MRR(mm^3/sec) = \frac{Initialweightofworkpiece - Finalweightofworkpiece}{TimingofMachiningXDensityofWorkpiece} ---- (1)$$

- Tool Wear Rate (TWR): Tool wear rate is defined as rate of tool material removal per unit time. TWR is calculated by measuring the weight of the tool before and after machining and using the following equation.

$$TWR\ (mm^3/min) = \frac{Initial\ weight\ of\ tool\ - Final\ weight\ of\ tool}{machining\ time \times Density\ of\ tool} \text{---------------------------}(2)$$

The input variables are independent of process and they are assumed to have influence on the output variables. The following input variables are selected for this research work are as follows:

- Cutting Speed (V): Cutting speed is defined as the linear speed in m/min of given tooth of a cutter will be moving while cutting operation takes place.

  $$V\ (m/min) = \pi.D.N \text{---}(3)$$

  Where ‘D’ is in ‘metre’ and ‘N’ is in ‘r.p.m’.
- Feed Rate (F): Feed rate is the relative velocity at which the cutter advances during specific movement of the work piece. The range of feed rate is taken from 200 mm/min to 300 mm/min.

- Depth of Cut (d): It is cutting depth along Z-direction. The depth of cut used for this research work is measured in mm and the range taken in this research work is from 0.4mm to 0.8mm.

- Step over Ratio (s): Step over ratio is defined as the depth of cut in radial direction. It is used to obtain better surface finish. It is measured as percentage overlap of the work piece in successive cuts. Its value is taken from 40% to 60%.

2.3.Experimentation

Experiments are conducted on CNC vertical milling machine using an end mill ((10 mm diameter, 45^o helix angle with 4 flutes)) of M2 Stainless Steel. Al3030 based composite material used as work piece.

For experimental work on CNC Milling machine, CNC programmes have been developed with different levels of input parameters as per objective of research work as shown in Table 1:

Table1. Input Process Parameter and their levels

Input Parameters	Level 1	Level 2	Level 3
Cutting speed, V (m/min)	94.20	125.40	157.10
Feed, f (mm/min)	200	250	300
Depth of Cut, d (mm)	0.40	0.60	0.80
Step over Ratio, s (%)	40	50	60

For conducting the experimental work, four variables and three levels, a total of nine experiments are needed according to Taguchi Orthogonal Array which give about 95% of confidence level [9,10]. Weight of work piece and tool are taken before and after performing each experiment. Weight measurement is done using weighing balance with 0.001g accuracy. The weight before and after the machining of work piece material and tool are used to find response parameters, such as, material removal rate (MRR) and tool wear rate (TWR). Flatness of the work piece materials is measured using coordinate measuring machine (CMM).

3. Data Collection, Results and Discussion

By using the set of combination of input parameters as shown in Table-2, the weights of both tool and work piece before and after machining is obtained in order to calculate the MRR and TWR using equations 1 and 2. The flatness is measured using FARO make portable Coordinate Measuring Machine as shown in fig. 1 (b).

Table 2. Experimental Data of Composite Al3030

Exp. No.	V (m/min)	F (mm/min)	d (mm)	sr (%)	T (sec)	Flatness (µm)	MRR (mm^3/sec)	TWR (mm^3/min)
1	94.20	200	0.4	40	70	15	8.786	0.101
2	94.20	250	0.6	50	60	16	11.875	0.125
3	94.20	300	0.8	60	59	18	16.102	0.151
4	125.40	200	0.6	60	82	12	8.689	0.136
5	125.40	250	0.8	40	60	15	15.833	0.15
6	125.40	300	0.4	50	52	15	9.135	0.12
7	157.10	200	0.8	50	70	14	13.571	0.149
8	157.10	250	0.4	60	69	10	11.051	0.143
9	157.10	300	0.6	40	62	16	14.492	0.152

3.1. Regression Analysis

The prediction of output variables can be done by fitting linear or non-linear regression equations between output and input variables using the data from Table-2. MINITAB version 18 is used for fitting linear regression equation between each output variable and set of input variables. The interaction effects are taken into consideration initially but they are found to be insignificant. Hence linear regression equations are presented in the paper. The ANOVA table is given in Table-3, 4 and 5 for Flatness, MRR and TWR respectively which shows the p-value, F- value, coefficient of determination (R) and Standard Error (S) for the different input parameters.

From ANOVA table, the p-value indicates the probability of getting a test statistic at least as extreme as the one that was actually observed, considering that the null hypothesis is true. For the analysis, 0.05 has been considered as maximum value by considering 95% confidence limit [11]. Except for some of the variables, the ‘p’ value obtained is within 0.05. The coefficient of determination, R-squared value indicates how close the fitted regression line to the given data. From the ANOVA tables, the ‘R-square’ value of above 85% is considered to be acceptable and it may be conclude that model developed explains the variability of response data around its mean. The F value is the ratio of the mean regression sum of squares divided by the mean error sum of squares. The greater value of ‘F’ indicates that there is significant relationship between output variables and input variables.

Table 3. Analysis of Variance of Flatness

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Regression	4	38.293	9.573	6.46	0.049
V	1	13.460	13.460	9.08	0.039
f	1	10.667	10.667	7.20	0.055
d	1	8.167	8.167	5.51	0.079
sr	1	6.000	6.000	4.05	0.115
Error	4	5.929	1.482		
Total	8	44.222			
S= 1.21747 R-sq = 86.59% R-sq(adj) = 80.29%					

Table 4. Analysis of Variance of MRR

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Regression	4	60.848	15.2120	6.40	0.050
V	1	0.9390	0.9390	0.40	0.564
f	1	12.5657	12.5657	5.29	0.083
d	1	45.5622	45.5622	19.18	0.012
sr	1	1.7811	1.7811	0.75	0.435
Error	4	9.5039	2.3760		
Total	8	70.3519			
S= 1.54142 R-sq = 86.49% R-sq(adj) = 72.98%					

Table 5. Analysis of Variance of TWR

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Regression	4	0.002331	0.000583	14.13	0.013
V	1	0.000228	0.000749	18.15	0.013
f	1	0.000228	0.000228	5.53	0.078
d	1	0.001233	0.001233	29.89	0.005
sr	1	0.000122	0.000122	2.95	0.161
Error	4	0.000165	0.000041		
Total	8	0.002496			
S= 0.0064223 R-sq = 93.39% R-sq(adj) = 86.78%					

The above (Analysis of Variance) ANOVA table interprets the model analysis of flatness, MRR and TWR. From the above ANOVA table it is observed that P-value is approximately less than 0.05 which means the input variable is statistically significant at the 95% confidence level. It also indicates that the associated variable is an effective and efficient predictor. The value of ‘R-square’ is 85% and it indicates that the model explains approximately all the variability of the response, i.e. the better the model fits data. ‘S’, known as the Standard Error of the Estimate having smaller value which means the relationship is stronger.

The regression equations obtained from linear regression analysis using MINITAB 18, are given below

Flatness = 15.37 - 0.0476 V + 0.02667 F + 5.83 d - 0.1000 sr ……………………..…………..… (1)

MRR = -2.19 - 0.0126 V + 0.0289 f + 13.78 d - 0.0545 sr ……………………………………… (2)

TWR = -0.0046 - 0.000355 V + 0.000123 f + 0.0717 d - 0.00045 sr …..............…………………..….. (3)

The above regression equations show the relationship between the independent variable (speed, feed. Depth of cut and step over ratio) and dependent variable (Flatness, MRR and TWR). These equations can be used for predicting flatness MRR and TWR.

4. Validations of Results

In order to validate the linear regression models developed, a set of four experiments are conducted by selecting the variable combination randomly and Flatness, MRR and TWR are computed using Eqs. (1), (2) and (3). The error is the difference between the predicted and the experimental values. The error is calculated for each case. The validation results are presented in Tables 6, 7 and 8 for each of the output variable respectively. From the tables the maximum percentage of error was observed as –11.73% for flatness, -12.84% % for MRR and 11.08% for TWR. Thus it is observed that the error found between the experimental values and predicted values are within ±15% and hence the predicted models are validated.

Table 6. Validation of results for Flatness

Sr. No.	**Cutting speed V**	**Feed f**	**Depth of cut d**	**Step over ratio sr**	**Flatness (actual)** µm	**Flatness (predicted)** µm	**Error (%)**
1	94.20	200	0.4	0.5	18	18.502	-2.789
2	94.20	300	0.6	0.4	20	22.345	-11.725
3	125.40	250	0.8	0.6	22	20.672	6.034
4	157.10	200	0.6	0.5	16	16.674	-4.213

Table 7. Validation of results for MRR

Sr. No.	**Cutting Speed V**	**Feed f**	**Depth of cut d**	**Step over ratio sr**	**MRR (actual)** mm^3/sec	**MRR (Predicted)** mm^3/sec	**Error (%)**
1	94.20	200	0.4	0.5	6.990	7.888	-12.844
2	94.20	300	0.6	0.4	14.541	13.539	6.889
3	125.40	250	0.8	0.6	13.971	14.446	-3.401
4	157.10	200	0.6	0.5	10.634	9.851	7.360

Table 8. Validation of results for TWR

Sr. No.	**Cutting Speed V**	**Feed f**	**Depth of cut d**	**Step over ratio sr**	**TWR (actual)** mm^3/min	**TWR (Predicted)** mm^3/min	**Error (%)**
1	94.20	200	0.4	0.5	0.0136	0.0150	-10.397
2	94.20	300	0.6	0.4	0.0396	0.0417	-5.301
3	125.40	250	0.8	0.6	0.0429	0.0387	9.737
4	157.10	200	0.6	0.5	0.0079	0.0070	11.083

5. Conclusions

In this study, a composite material with SiO_2 extracted from rice husk is combined with Al3030, is used as work material in order to study the machining characteristics of it on high speed CNC machine. The study considered three output variables, such as, flatness, MRR and TWR and linear regression models have been developed for predicting these variables. Flatness value decreases with increase in cutting speed and increases with increase in depth of cut. Similarly it increases with increase in feed but decreases with increase in step over ratio. The effect of step over ratio is different for surface roughness as it smoothens the surface but the flatness increases which is not desirable. Hence step over ratio may not be preferred for flat surfaces.
Material removal rate (MRR) value increases drastically with increase in feed and depth of cut whereas it decreases with increase in step over ratio. Tool wear rate (TWR) value increases drastically with increase in feed and depth of cut whereas it decreases with increase in step over ratio. Hence the step over ratio may not be preferred in high speed machining of aluminium composites. For the validation of results, four additional set of experiments have been performed and the results are in agreement with predictive models within ±15% and hence the predictive models are validated and can be used for selecting input variables for required values of output variables. Further research can be done in finding the optimum values of input variables for required output variables. Work may be extended for optimizing the three output variables simultaneously.

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