ANALYTICAL MODELING OF CUTTING FORCES OF END MILLING OPERATION ON ALUMINUM SILICON CARBIDE PARTICULATE METAL MATRIX COMPOSITE MATERIAL USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

The cutting forces exerted by the cutting tool on the work piece during a machining action to be identified in order to control the tool wear and occurrence of vibration, thus to improve tool-life. Modeling of cutting force in milling is often needed in machining automation. The objective of this study is to predict the effects of cutting parameters on the variations of cutting forces during end milling operation of Al SiC metal matrix composite material. Cutting forces are measured for varies feed rates. In this study Response Surface Methodology is used by designing four factors, five level central composite rotatable design matrixes with full replication; for planning, conduction, execution and development of mathematical models. The average cutting forces are determined at different feed rates in tangential, radial, and axial directions per tooth period by keeping immersion and axial depth of cut as constant. A comparison between modeling and experiment is presented. This model and analysis are useful not only for predicting the tool wear but also for selecting optimum process parameters for achieving the stability of the end milling process.

Keywords: cutting forces, RSM, model, central composite rotatable design.

Notations and abbreviations

RSM	response surface methodology
DOC	depth of cut
Al-SiC	aluminum silicon carbide particulate composite
MMX	metal matrix
DOE	design of experiments
A	depth of cut (mm)
F	feed rate per tooth (mm/rev)
V	cutting speed (m/min)
Φ	immersion angle of cutting edge (°)
F_t	cutting force in tangential directions (N)
F_r	cutting force in radial directions (N)
F_a	cutting force in axial directions (N)
F_x, F_y, F_z	cutting force components in the dynamometer applied co-ordinate system (N)
X, Y, Z	reference linked with the workpiece

1.0. INTRODUCTION

The analysis of cutting forces generated during machining has been a main subject of research over the years and force measurements have since been shown to be an invaluable output for monitoring the cutting process. The primary objective of this modeling is to determine the model values of different parameters for milling process. This outcome facilitates the effective planning of the machining operations to achieve optimum productivity, quality and cost. A basic requirement for achieving this goal is a reliable method for predicting cutting forces for arbitrary process conditions. Many attempts were made in the past in analyzing force patterns as an indication of tool wear of the end milling process. Comprehensive reviews on cutting force modeling for the milling processes have been predicted in [1] and [2]. The analytical approach presented by Merchant [3] is based on the shear angle determination using the minimum energy principle. The different points of view [4] have led to different approaches of the cutting forces modeling. Indeed, it is necessary to consider the model used with respect to the needed accuracy. Zheng *et al.*, [5] developed an analytical model for flat end milling and expressed the cutting forces in explicit expressions. Bayoumi *et al.*, [6, 7] presented and validated an analytical cutting force model for milling operations. Hongqi Li and Yung C. Shin [8] present a comprehensive time domain model that simulates end milling processes under general cutting conditions. The model considers the variations of the dynamics along the cutting depth for both cutters and work piece. A cutting force model for a Waved-edge end milling cutter have been developed by Z. Zhang *et al.*, [9] with the analysis of the complicated cutting edge of waved-edge cutter. The present work is aimed at modeling the cutting force for four fluted flat end milling by considering also the parameter immersion angle. In the above mentioned papers, it has not been considered. K.A. Abou El. Hussein *et al.,* [10] predicted the cutting force in end milling operation of mild steel AISI P20 tool steel using the response surface methodology. S. Aykut *et al.,* [11] presented a model of cutting forces as function of cutting parameters for face milling of stellite 6. P. Palanisamy *et al.,* [12] developed a model to predict the tangential cutting force and the thrust force during the machining of AISI 1020steel. Berruti T., and Ubertali G. [13] discussed about the influence of cutting parameters on aluminum alloy components. Though the Al SiC metal matrix composite material used for vast applications in industries , the analytical approach modeling of cutting force of end milling operation with the Al SiC metal matrix composite as a work piece material has not yet been discussed. This work deals with the end milling operation on the material Al SiC metal matrix composite. With the effective cutting conditions the analytical and statistical model approach has been a simple and cost effective method. Guosong Lin *et al.,* [14] have done a computational response surface study of three dimensional Aluminium hemming process. In this study, also deals with the application of response surface methodology (RSM) in developing mathematical model and plotting graphs relating primary input variables namely the cutting speed (V) , the feed rate (F), depth of cut (A), and rotation angle (Φ) in the end milling process. The accuracy and effectiveness of an experimental program depends on careful planning and execution of the experimental procedure [15]. With a view to achieving the above mentioned aim, statistically designed experiments based on the factorial technique [16] were used to reduce the cost and time involved as well as to obtain the requires information about direct and interaction effects of process parameters on the response parameters. These developed models are very useful for the users to predict the cutting force components in all the directions for the proposed values of input variables, to select an optimum combination of input variables for the optimum cutting force condition and to automate the milling process through the development of a computer program. When the cutting forces are used to predict the vibrations of the end mill or work piece, the numerical oscillations lead to faulty simulation of vibrations. Also, an accurate prediction of force distribution along the end mill and flexible thin webs is necessary to predict the dimensional form errors left on the finish surface. In this paper, a methodology for understanding relationship between the principal factors such as cutting speed (V), feed (F), depth of cut (A) and cutting angle (Φ) and development of mathematical model for the cutting force components are presented. The adequacy of the model has been checked through F-test and plotting scatter diagram [17]. This new approach for milling force prediction is verified through comparison of the simulated and the experimental results, with good agreement.

2.0. EXPERIMENTAL PROCEDURE

The key factor in developing a mathematical model is to obtain sufficient experimental data simulating the working environment in the laboratory. Three independently controllable factors affecting the wear performance were identified as the Depth of cut (A), Feed rate (F), Cutting speed and immersion angle (Φ). The Experiment has been conducted by milling the Al Al SiC metal matrix composite material, using HSS end mill cutter with 10mm diameter and four tooth tool in a vertical Milling machine. The cutting force components in feed, tangential, and radial directions have been measured with a Piezo-electric three-component dynamometer (Kistler, type 9257B), a multi channel charge amplifier (Kistler, Type 9403) and a data acquisition system. Before starting each experiment the gauges have been used to set the tool height. Experiments were carried out under various cutting conditions. To reduce the total number of experiments and to obtain data uniformly from all the regions of the selected working area, a factorial design procedure has been adopted. The secondary parameters that have been kept constant during the machining process are tool geometry, the tool height and hardness of the material. The experiments are planned as per the out line RSM method.

Experimental set up

Figure-1(a). Multi channels charge amplifier (Kistler, Type 9403) and a data acquisition system.

Figure-1(b). Piezo-electric three-component dynamometer (Kistler, type 9257B).

2.1. Limits of variables

Test conditions leading to various components of cutting force in Al SiC metal matrix composite were chosen. The upper limit of a factor is coded as 2 and lower

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limit as -2 and intermediate values can be calculated using the equations (1) and (2) given below:

$$X_i = \left[2\left(X - X_{min}\right)/\left(X_{max} - X_{min}\right)\right] + 1 \qquad (1)$$

Where,

$$X = \left[\left(X_i - 1\right) * \left(X_{max} - X_{min}\right)\right]/2$$

X_i is the required coded value of a variable X
X is any value of the variable from X_{max} to X_{min}.
X_{min} is the lower limit and X_{max} is the upper limit.
The limits of the process parameters are presented in Table-1.

2.2. Design matrix

A Box-Behnken design matrix shown in Table-2 consisting of 15 sets of coded conditions was selected to conduct the experiments. Box-Behnken design uses a selection of corner, face and central points to span an experimental space with fewer points than a Complete Factorial Design (CFD). It has no extended axial points, so it uses only five level factors [16].

Table-2. Box-behnken design matrix.

Run	A mm	F mm	V m/min	Φ degree	Force Components		
					F_X N	F_y	F_z
1	-1	-1	-1	-1	19.868	34.903	9.0466
2	1	-1	-1	-1	19.8683	35.075	9.245
3	-1	1	-1	-1	23.385	47.69	17.385
4	1	1	-1	-1	23.385	47.393	17.54333
5	-1	-1	1	-1	18.718	30.3916	4.7033
6	1	-1	1	-1	15.373	20.086	4.555
7	-1	1	1	-1	24.053	46.873	19.201
8	1	1	1	-1	24.271	48.075	19.806
9	-1	-1	-1	1	21.051	39.246	10.455
10	1	-1	-1	1	17.603	25.82	5.6683
11	-1	1	-1	1	24.72	49.091	22.061
12	1	1	-1	1	24.42	47.811	20.59
13	-1	-1	1	1	20.69	37.396	10.023
14	1	-1	1	1	21.14	39.456	10.513
15	-1	1	1	1	24.203	48.595	20.695
16	1	1	1	1	24.726	49.571	22.073
17	-2	0	0	0	22.013	43.656	12.503
18	2	0	0	0	22.26	44.218	12.756
19	0	-2	0	0	11.566	10.788	5.715
20	0	2	0	0	25.011	219.863	24.181
21	0	0	-2	0	22.426	44.47833	12.851
22	0	0	2	0	22.508	45.176	13.038
23	0	0	0	-2	22.506	45.408	13.168
24	0	0	0	2	21.546	42.468	12.405
25	0	0	0	0	21.645	42.63833	12.475
26	0	0	0	0	22.208	43.975	12.818
27	0	0	0	0	22.611	45.90167	13.075
28	0	0	0	0	22.711	46.388	13.258
29	0	0	0	0	22.876	46.386	13.546
30	0	0	0	0	23.271	46.386	14.895
31	0	0	0	0	23.09	46.536	14.356

2.3. Conducting the experiment and recording of responses

The process parameters such as cutting speed (V), feed F), depth of cut (A) and cutting angle (φ) of Al SiC metal matrix composite were identified as the main factors influencing the responses cutting force component in feed, tangential, and radial directions. The working range of factors was set at five levels. The selected factors and their levels are shown in Table-1. A five level four factor full factorial design matrix shown in Table-2 has been selected to conduct the experiment. The Experiment has conducted by milling the Al SiC metal matrix composite material on a vertical Milling machine.

Table-1. Factor and their levels.

Sl. No.	Parameters	Unit	Notation	Factor levels				
				-2	-1	0	+1	+2
1	Depth of cut	mm	A	0.4	0.8	1.2	1.6	2.0
2	Feed rate	mm/sec	F	0.3	0.6	0.9	1.2	1.5
3	Cutting speed	m/min	V	56	84	112	140	224
4	Immersion angle	Degree	Φ	90	120	180	270	360

3.0. DEVELOPMENT OF MATHEMATICAL MODEL

The response function representing the wear performance can be expressed as:

$$Y = f\,(A, F, V, \Phi)$$

where Y = the response or yield.

The second order polynomial (regression) equation used to represent the response surface for K factors is given by:

$$Y = b_0 + \sum_{i=1}^{k} b_i\, X_i \; + \sum_{i,j=1}^{k} b_{ij}\, X_i\, X_j + \sum_{i\neq 1}^{k} b_{ii}\, X_i^{\,2} \qquad (4)$$

Where b_0 is the free term of the regression equation, the coefficients b_1, b_2... b_k are linear terms, b_{11}, b_{22}... b_{kk} are the quadratic terms, and b_{12}, b_{13}... $b_{k-1,\,k}$ are the interaction terms. For three factors, the selected polynomial could be expressed as:

$$Y = b_0 + b_1\, a + b_2\, f + b_3\, v + b_4 \phi b_{11} a^2 \; + b_{22}\, \phi^2 + b_{33}\, v^2 + b_{44}\, \phi^2 + b_{12}\, a\, \phi + b_{13}\, av + b_{23}\, a \quad (5)$$

3.1. Calculation of coefficients of models

The values of the coefficients of the polynomial of Eq. 5 were calculated by regression method. The magnitude of the regression co-efficient is a good indication of the significance of the parameters. A statistical analysis software package QA Six Sigma DOE-PC IV was used to calculate the values of these coefficients and also to determine the significant direct and interaction effects precisely. For the required response, if all of the 31 observed values and the second order general mathematical model for the four factors are given to the software as input. These values were also checked with the values calculated using a commercial statistical package SYSTAT software. The significance of the coefficients was evaluated and insignificance coefficients are not included in the model.

3.2. Final developed model

The final mathematical model as determined by above analysis is given below:

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Tangential cutting force

$$F_x = 22.406 - 0.037A + 3.647F - 0.061V + 0.560\,\Phi \quad 0.064\,A*A - 0.048\Phi*\Phi - 0.043V*V - 0.218\,\Phi*\,\Phi$$
$$+ 0.183A*\Phi - 0.158A*V + 0.125A*\,\Phi + 0.380\,\Phi*V + 0.896\,\Phi*\,\Phi + 0.040V*\Phi \qquad (6)$$

Radial cutting force

$$F_y = 42.598 - 0.736A + 11.131F - 1.416V - 0.341\,\Phi + 0.468A*A - 0.878\Phi*\Phi - 0.169V*V - 0.288\,\Phi*\,\Phi$$
$$+ 1.424A*\Phi + 0.592\,A*V - 0.222A*\,\Phi - 0.571\,\Phi*V - 0.914\,\Phi*\,\Phi + 3.902V*\,\Phi \qquad (7)$$

Axial Cutting force

$$F_Z = 13.637 - 0.205A + 5.980F - 0.050V + 0.924\,\Phi - 0.057\,A*A - 0.385\Phi*\Phi - 0.126V*V$$
$$-0.004\,\Phi*\,\Phi + 0.346A*\Phi - 0.266A*V + 0.574A*\Phi + 0.799\,\Phi*V + 0.397\Phi*\Phi + 0.554V*\,\Phi \qquad (8)$$

The adequacy of the model was tested using the analysis of variance (ANOVA) technique. As per this technique, the calculated value of the F-ratio of the model developed does not exceed the standard tabulated value of F-Ratio for a desired level of confidence say 95 %. From Table-3 it is evident that the model is adequate. The scatter diagram depicted in Figure-1 clearly shows that the predictions made by the mathematical model are in good agreement with the experimental values.

Table-3. Coefficients of the models.

Specimen number	Coefficient	Tangential cutting force (Fx), N	Radial cutting force (Fy), N	Axial cutting force (Fz), N
1	b0	22.406	42.598	13.637
2	b1	-0.037	-0.736	-0.205
3	b2	3.647	11.131	5.980
4	b3	-0.061	-1.416	-0.050
5	b4	0.560	-0.341	0.924
6	b11	-0.064	0.468	-0.057
7	b22	-0.048	-0.878	0.385
8	b33	0.043	-0.169	-0.126
9	b44	-0.218	-0.288	-0.004
10	b12	0.183	1.424	0.346
11	b13	-0.158	0.592	0.266
12	b14	0.125	-0.222	-0.574
13	b23	0.380	-0.571	0.799
14	b24	0.896	-0.914	0.397
15	b34	0.040	3.902	0.554

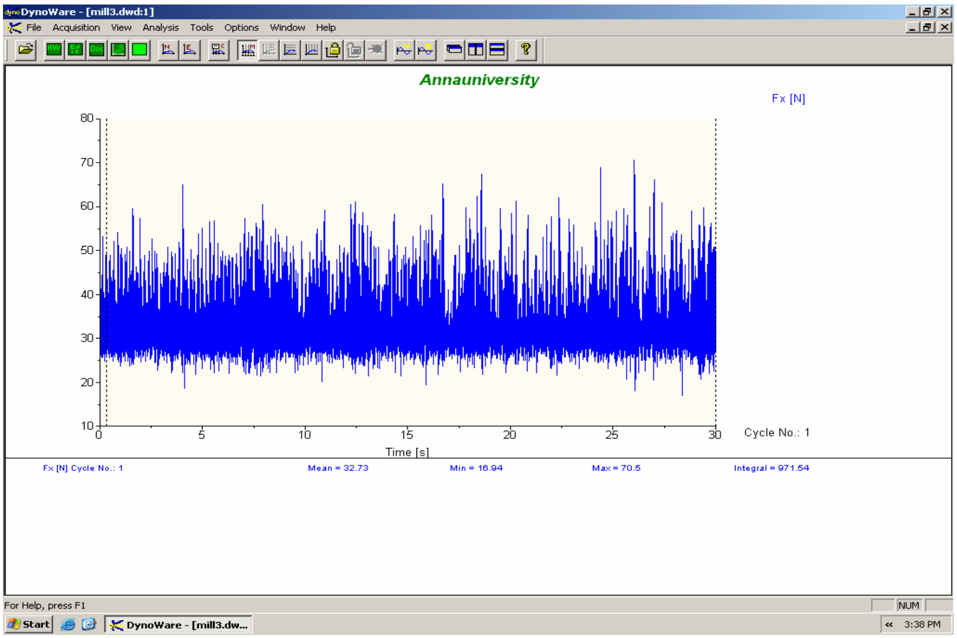
Table-4. Reregression summary for cutting force model.

Factor	MS Factor	DF	MS Pure Error	DF	MS Lack of Fit	DF	F-ratio	R-ratio	Coefficient of Determination
Fx	24.619	14	0.140	6	0.522	10	3.75	175.263	0.989
Fy	249.587	14	0.221	6	14.999	10	67.846	1129.005	0.954
Fz	65.055	14	0.662	6	2.456	10	3.71	98.286	0.985

Mean Square (MS) = Sum of Squares/Degrees of Freedom (DF)
F-ratio = MS Lack of fit / MS Pure error, R-ratio = MS Factors / MS Pure error
$F_{(10,6,0.05)} = 96.26$, $R_{(10,6,0.05)} = 64.51$ R-squared, adjusted = 0.982

4.0. RESULTS AND DISCUSSIONS

The results obtained through experiments have been presented in Figures 2, 3 and 4. Figure-2 shows the values of cutting force component in feed direction with respect to cutting time with the upper limit of cutting conditions as per the design matrix. In this higher cutting speed value the force in the feed direction fluctuates more through out the cutting time period by increase in feed rate and constant depth of cut. At higher cutting speed the feed force reached high. Figure-3 illustrates the frequency graph between the cutting force in the normal direction and cutting time. The cutting speed of the end milling process was more, so that the fluctuation of cutting force in the normal direction was also more. This may leave its imprints in the surface of the finished surface of the material. Figure-4 depicts the relationship between the cutting forces in axial direction and cutting time. The immersion angle of cutting tool at entry was zero and at exit, it was 180° in cycle -I. Since the Al SiC metal matrix composite has been the work piece material and it has less surface hardness and width of the chip may be very small.



MEAN Fx = 32.73N

Figure-2. Tangential force, Fx at V = 224m/min, F = 0.5mm/sec, D = 2mm t = 30 sec.

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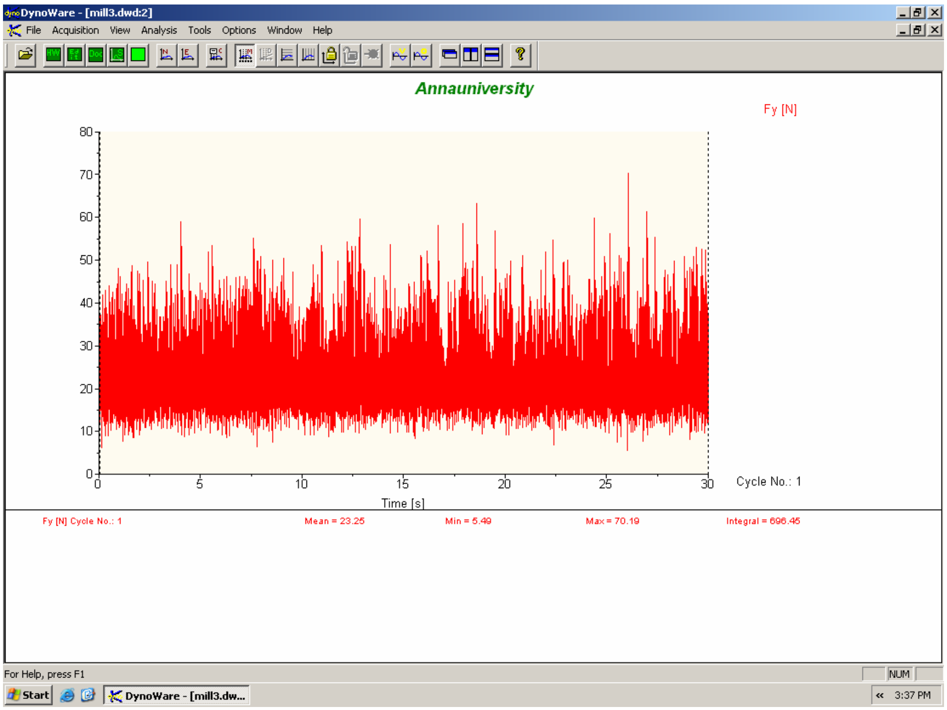
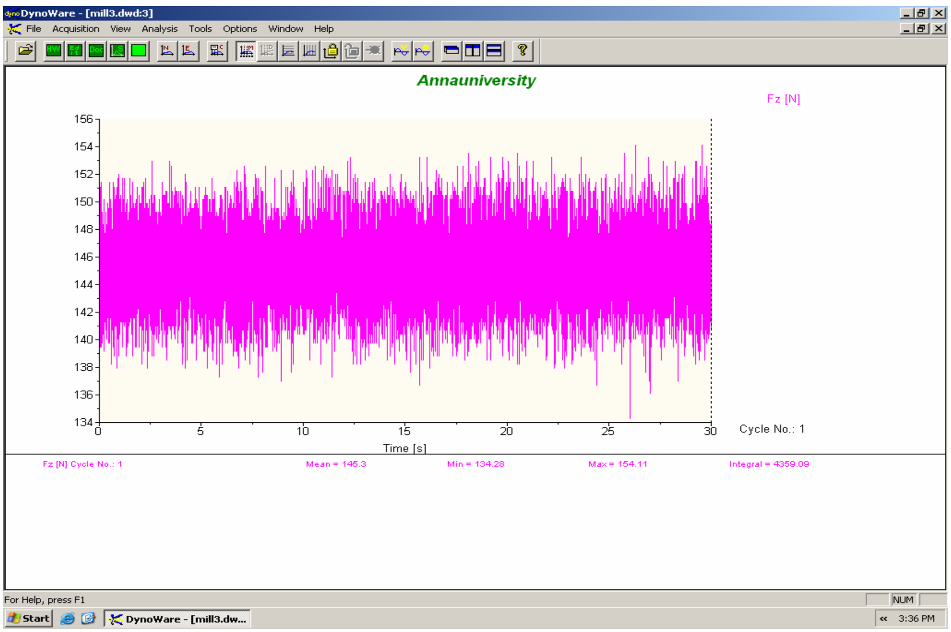


MEAN, Fy = 23.25N

Figure-3. Radial force, Fy at V = 224m/min, F = 0.5mm/tooth, D = 2mm t = 30 sec.



MEAN = 145.3N

Figure-4. Axial force, Fz at V = 224m/min, F = 0.5mm/tooth, D = 2mm t = 30 sec.

The mathematical models furnished above can be used to predict the cutting forces in tangential, radial and axial directions by substituting the values, in coded form of the various factors. The calculated responses form these models for each set of coded process variables are represented in graphical form in Figures 5–15. The total materials removed per tooth period is constant, the average cutting forces are independent of helix angle. The main and interaction effects of the factors on the Cutting force components are obtained from mathematical model are presented in Figures 4 - 6 and are discussed below.

4.1. Direct effects of process parameters

Figures-5,6 and 7 indicates that the tangential , radial and axial cutting force components (F_x , F_y, F_z) varies by changing the range of depth of cut (A), feed rate

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(F), cutting speed (V) and immersion angle (Φ). The effect of feed rate is observed to be predominant and the cutting speed and immersion angle is having linearity effect on tangential cutting force component. From Figure-5, it is clear that the cutting force in x direction increases linearly with increase in cutting speed but the immersion angle of cutting tool with work material influences significantly in cutting force in tangential direction to the work piece. Cutting force F_x has been increased with the middle level of depth of cut, *A*. After crossing the medium level of depth of cut, the Cutting force F_x also decreases invariably with all the levels of Feed rate, F. When the feed rate increases the Cutting force F_x decreases at all levels of depth of cut. Figure-6 indicates that the cutting speed not have any influence on the cutting force in the radial direction and there was a steep increase in cutting force in radial direction with increase in Feed rate, F. Immersion angle in the entry condition has strong influence in the radial direction on the cutting force, similarly the there has been strong influence of depth of cut shown on the cutting force in the radial direction. From Figure-7, it is evident that as cutting force in axial direction has been increased with increase in depth of cut, A. Axial cutting force increases slowly by increases in Feed rate, F. Cutting force increases in entry angle and decreases in exit angle.

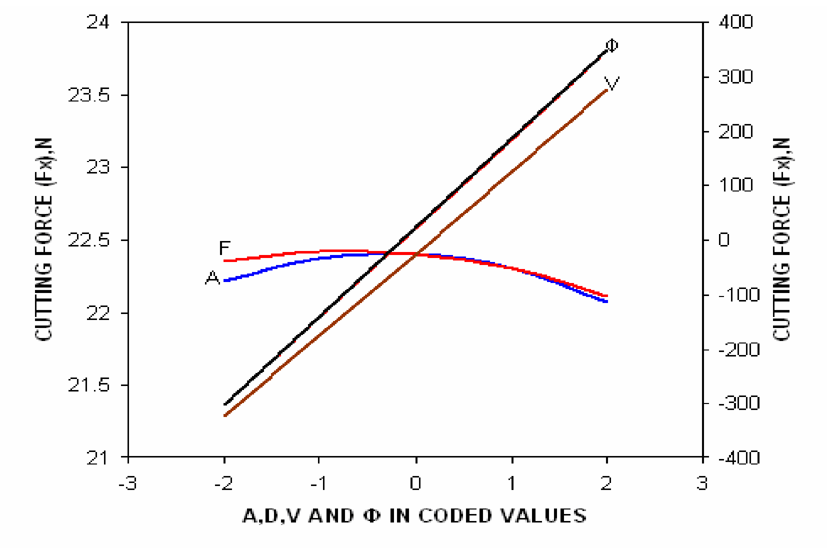
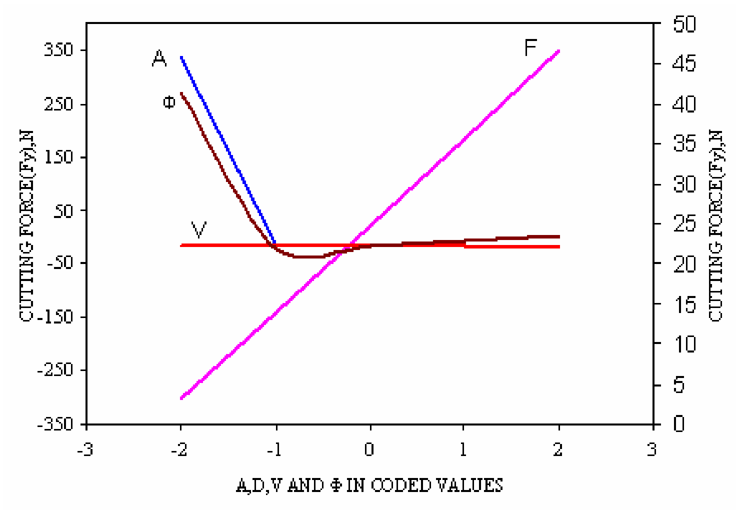


Figure-5. Direct effect of process parameters n F_x, N.



Figurte-6. Direct effect of process parameters on Fy, N.

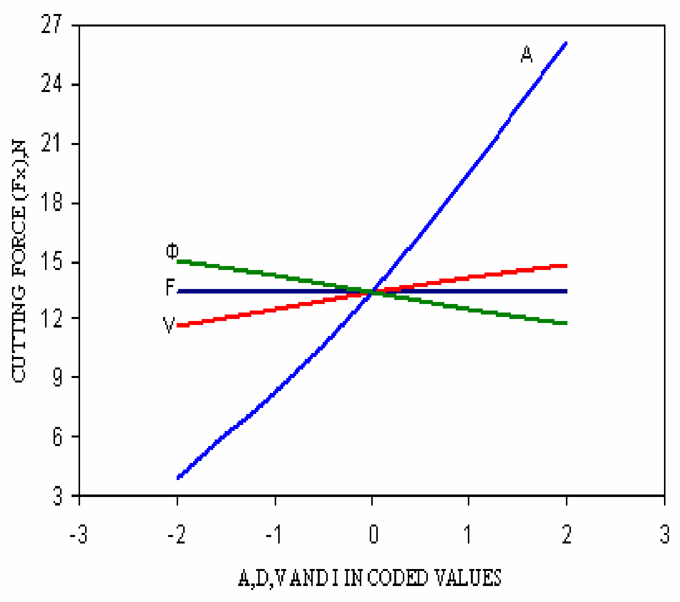


Figure-7. Direct effect of process parameters on F_z, N.

4.2. Interaction effect of process parameters

The interaction effect of depth of cut (A) and feed rate (F) on cutting force in tangential direction has been shown in Figure-8.

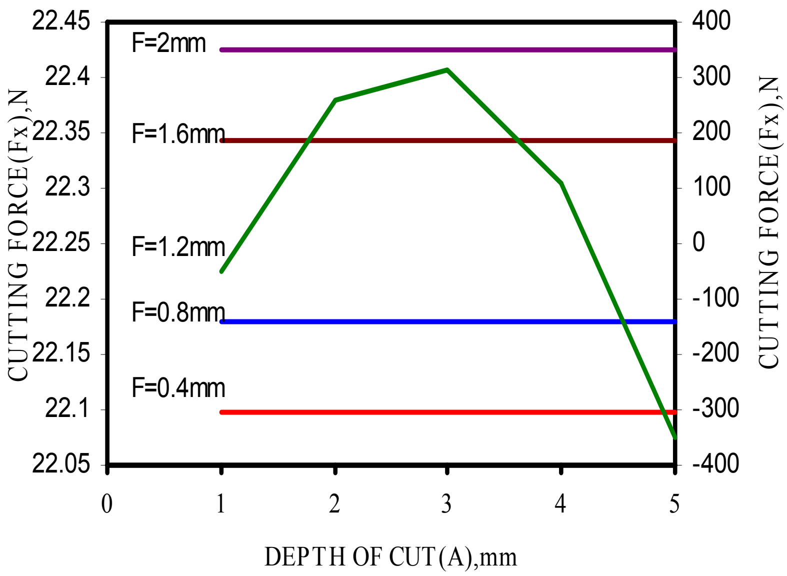


Figure-8. Effects of depth of cut and Feed rate on tangential cutting force (F_x).

It is clearly conveys that the feed is at the middle level (F = 1.2mm), the cutting force in X-direction were increases at all levels of depth of cut. This trend shows that the feed rate in the tangential direction has not been the influencing parameter in the four fluted end milling tool, when the immersion angle 180° and it decreases the cutting force at that moment of entry in the case of axial rotation of end milling process. The immersion angle at exit of cutting tool was not being an influencing factor on the tangential cutting force. As an interaction effect of the feed rate with immersion angle on tangential cutting force in X- direction could not be the influencing factor. This trend might be understood from Figure-9.

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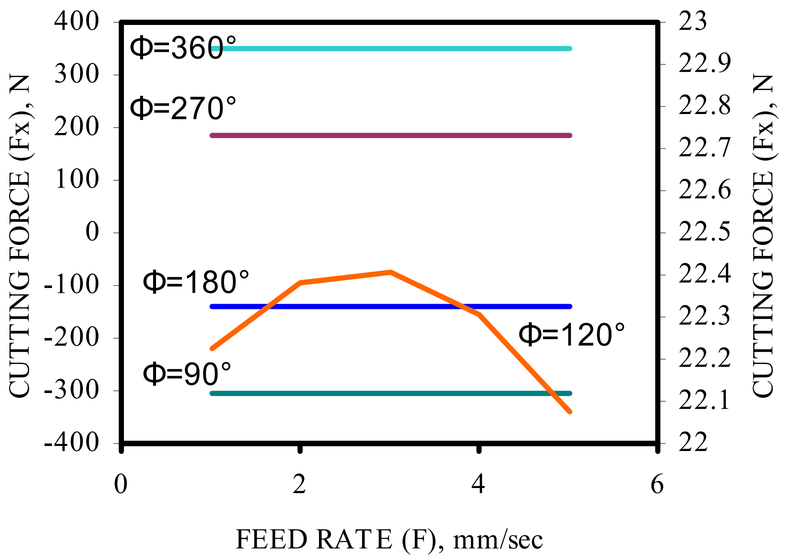

Figure-9. Effects of feed rate and immersion angle on tangential cutting force (F_x).

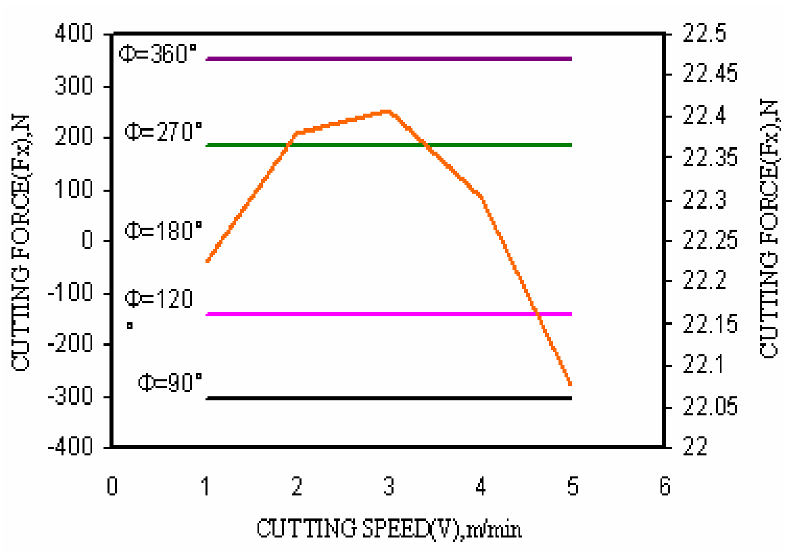

Figure-10. Effect of cutting speed and Immersion angle on cutting force (F_x).

Figure-10 indicates that the cutting forces were increases in the in each level of immersion angle. The cutting force in X direction remains constant when the cutting speed was being continuously increasing. Figure-11 depicts that if feed rate increase then the cutting force in radial direction, F_y also increases with the increase in depth of cut value with the constant machining time. In the lower limit values of depth of cut, the radial cutting force has been decreases even though the feed rate increases.

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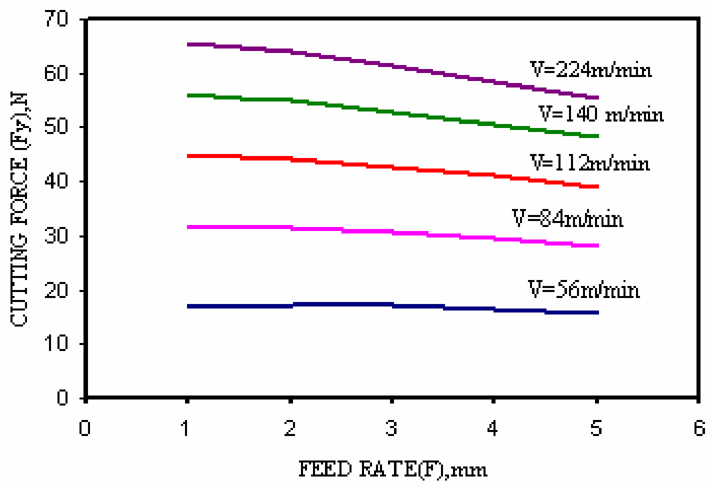

Figure-11. Effect of feed rate and depth of cut on Radial cutting force (F_y).

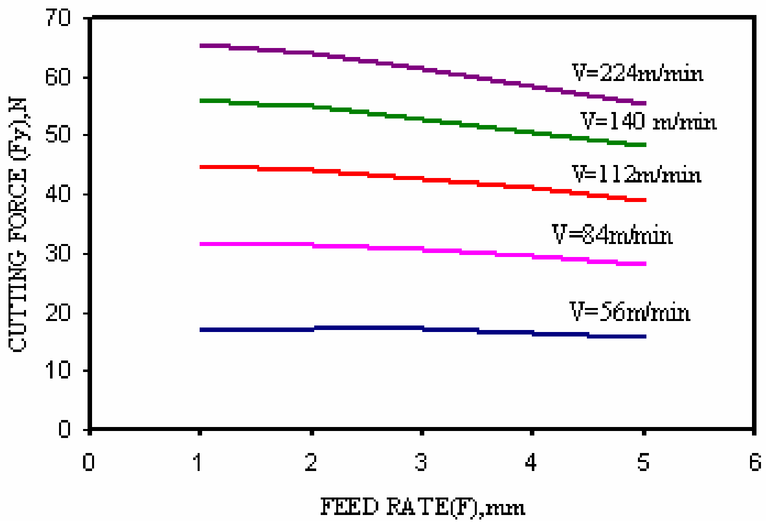

Figure-12. Effect of Feed rate and cutting speed on cutting force in radial direction (F_y).

It is clear from the Figure-12 that the cutting force in radial direction is proportional to the cutting speed but the force is declining with the increased feed rate even in the high cutting speed. Predominantly the machined material (Al SiC metal matrix composite) property tends to reduce the force at the higher level of cutting speed. Figure-13 indicates that the cutting force in the radial direction increase in the immersion angle higher than the 180 degrees of angle, that is nothing but the exit angle of end milling geometry and with the gradual increase of the cutting speed. In the mid value of the angle, the cutting forces have been constant value. The starting point of the entry angle improves with the cutting force and decreases with increase in cutting speed.

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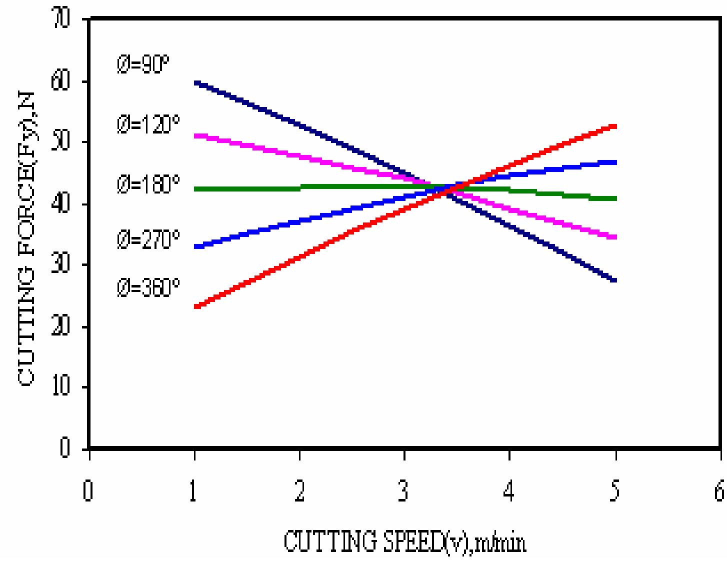

Figure-13. Effect of Cutting speed on radial cutting force (F_y)

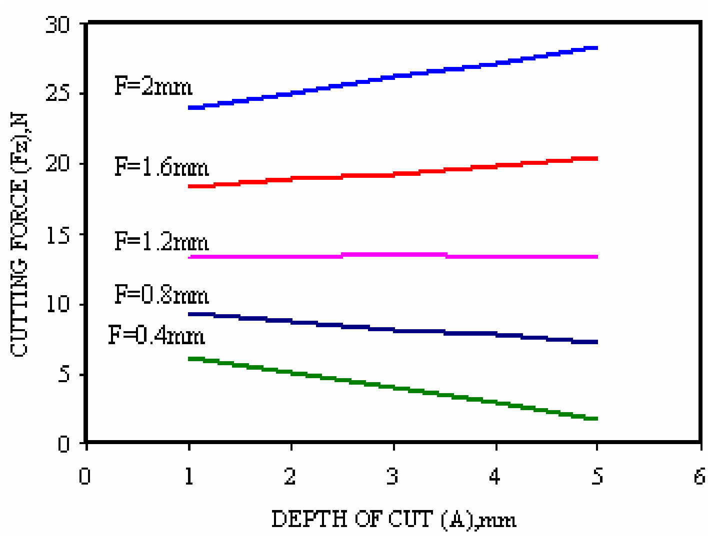

Figure-14. Effect of Depth of cut and feed rate on axial cutting force(Fz).

From Figure-14, it is apparent that the axial cutting force F_z increases with increase in upper limit of feed rate, F and decrease in the lower level of feed rate, f value with increasing depth of cut , A. This is because both F and A have positive effects on Fz. Hence increasing trend of F_z, from this graph it is noted that F_z is maximum when F is at its +2 level whilst A is between -1 and +2 level but decreases further with further increase in depth of cut. From Figure-15, it is apparent that the axial cutting force F_z, increases with increase in the cutting speed,V, but it decreases with increase in the feed rate, F. These effects are due to that V having a positive effect but F having a negative effect on F_z. Thus the increasing trend of F_z with increase in V decreases with an increase in F. The graph also shows the same trend in which maximum value of F_z is obtained when V is at its +2 level with F is at its -2 level.

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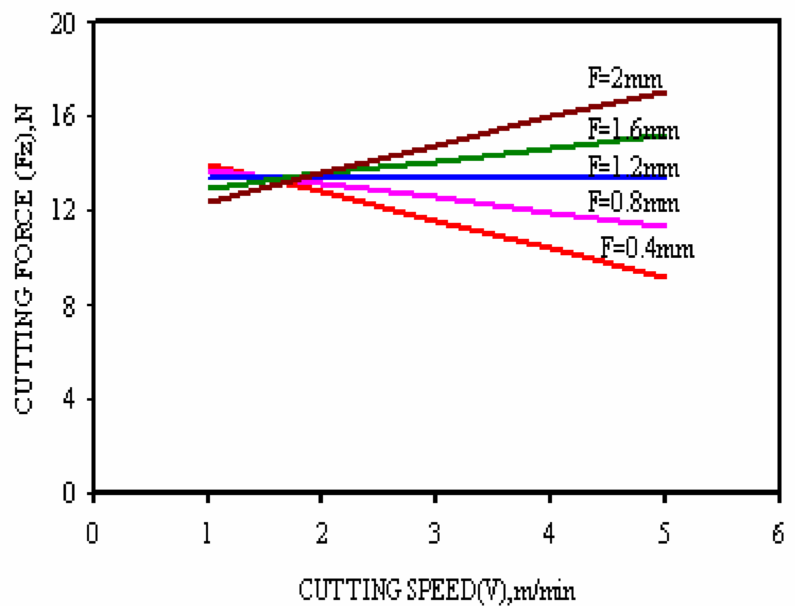

Figure-15. Effect of Cutting speed and feed rate on axial cutting force (Fz).

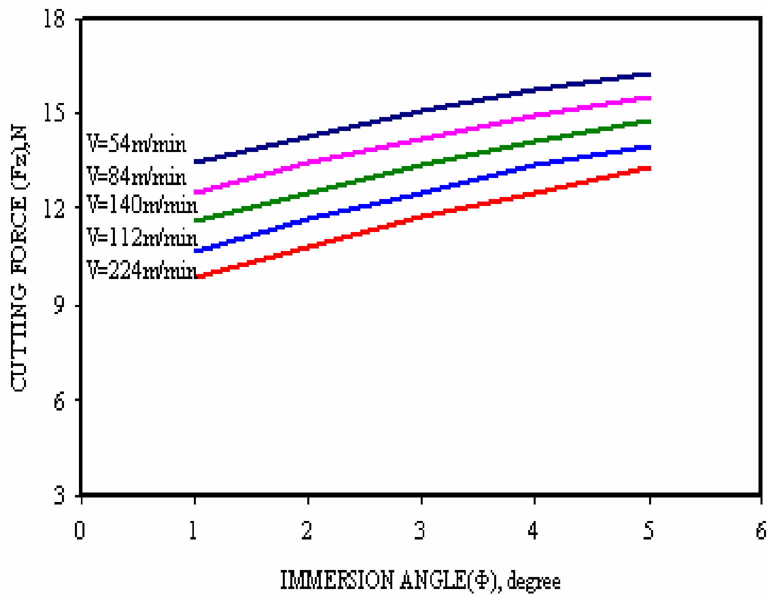

Figure-16. Effect of Immersion angle and cutting speed on axial cutting force (Fz).

Figure-16 indicates that the axial cutting force, Fz, generally increase in the cutting speed, V. It also increases with an increase in immersion angle, Φ. The positive effects of both V and Φ are the reasons for the above effects on Fz.

5.0 CONCLUSIONS

The following conclusions were derived from the results of the present investigation:

- A Five-level factorial technique can be employed easily for developing mathematical model for predicting cutting Forces in tangential, radial and axial directions with in the workable region of control parameters in the end milling of Al SiC metal matrix composite material surface.
- Cutting force in tangential direction increases when the depth of cut increases.
- The rate of increase in Force components with the increase in higher speed is predominant.
- The cutting forces are found to be low in radial and axial directions, when all the four factor values are in between levels 1 and 2.
- The cutting force components are more sensitive in the high speed and full immersion condition.

- The responses can be effectively controlled by substituting appropriate values of the process variables in to the mathematical model developed.
- RSM can be used effectively in analyzing the cause and effect of process parameters on response.
- An optimal solution could also be obtained by formulating the above as a linear programming model.

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