

Article

Effects of Turning Parameters and Parametric Optimization of the Cutting Forces in Machining SiCp/Al 45 wt% Composite

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Abstract: Cutting force in the machining process of SiCp/Al particle reinforced metal matrix composite is affected by several factors. Obtaining an effective mathematical model for the cutting force is challenging. In that respect, the second-order model of cutting force has been established by response surface methodology (RSM) in this study, with different cutting parameters, such as cutting speed, feed rate, and depth of cut. The optimized mathematical model has been developed to analyze the effect of actual processing conditions on the generation of cutting force for the turning process of SiCp/Al composite. The results show that the predicted parameters by the RSM are in close agreement with experimental results with minimal error percentage. Quantitative evaluation by using analysis of variance (ANOVA), main effects plot, interactive effect, residual analysis, and optimization of cutting forces using the desirability function was performed. It has been found that the higher depth of cut, followed by feed rate, increases the cutting force. Higher cutting speed shows a positive response by reducing the cutting force. The predicted and experimental results for the model of SiCp/Al components have been compared to the cutting force of SiCp/Al 45 wt%—the error has been found low showing a good agreement.

Keywords: SiCp/Al metal matrix composite; cutting force; response surface methodology; turning process; mathematical modeling

1. Introduction

Metal matrix composites (MMCs) are a kind of composite materials, which is one of the pioneers of the modern key industrial heavy-duty parts and products for nearly 30 years. The MMCs are replacing many conventional materials due to its possession of excellent mechanical properties. The MMC materials are known for such high tensile strength, wear resistance, high thermal expansion, high hardness, good dimensional stability, and higher weight ratio [1,2]. Aluminum metal matrix composite materials have wide application prospects in transportation, aviation, aerospace, medical industries, including many other important areas of different structural applications [3,4].

MMCs falls under the difficult-to-machine composite materials family. The signs that hinder the wider applications of the MMCs in the industrial sector, include serious tool wear, bad surface quality, issues related to the dimensional accuracy of component, etc. [5,6]. The researchers put more efforts in sorting out such kind of hindrances—different kinds of cutting tool material were introduced along with suitable machining operations to fulfill the gap. Such types of tools include polycrystalline diamond

(PCD), carbide tools, cemented carbide, high speed steel (HSS) cutting tools, polycrystalline cubic boron nitride (PCBN) [7,8]. The matrix phases of metal matrix composite materials consist of SiC particles, Al_2O_3 , magnesium, aluminum metal, and titanium. Although the mechanical properties of SiC-reinforced aluminum-based SiCp/Al composite materials are difficult to match with continuous fiber composites, they are the most competitive due to stable processability, efficient preparation technology. Moreover, their low cost is hugely advantageous for promotion [9,10].

Metal-based composite parts and profiles of various complex shapes, with precision controlling of dimensions, can be manufactured by relying solely on material forming technology. However, it is imperative to provide the subsequent machining in need as a secondary processing technology, in order to further promote the development and practicality of new materials for precise dimensions requirements [10–12].

The machining process of SiCp/Al is considered tough in several machining operations and techniques due to the strengthening effect of the reinforcement and the irregular distribution of the high hardness SiC particles and their volumes. The SiCp/Al composite material causes sudden breakage of the cutting tool and its rapid wear in the machining process. Such phenomena increase the processing cost and reduces the surface finish of the components [12–15].

Davim and Baptista [15] performed the processing experiments on SiCp/Al with different percentages of SiC particles (7% and 4%) to measure the relationship between cutting force and tool wear in both turning and drilling processes. The measured results from the experiment disclosed that the depth of cut and feed force were shown to be important parameters for both cutting force and tool wear. Subramanian et al. [16] also found a similar observation in the machining and optimization process of MMCs through response surface methodology. The most crucial part of the study was that the Response surface methodology (RSM) provided more convincing outcomes in understanding the behavior of machining parameters. Similarly, Jeyakumar et al. [14] measured the impact of different process parameters on cutting force, surface roughness, and wear mechanism of the cutting tool in the machining operation of Al6061/SiC materials using response surface methodology. Agarwal et al. [17] also conducted a comparative analysis of two commonly used processing performance evaluation methods namely response surface methodology and Taguchi method. The results showed that the response surface methodology had a stronger prediction ability for the interaction terms and squared terms of the machining parameter. The response surface methodology also holds the ability to establish the response model of the significant influence terms and the three-dimensional (3D) response surface, which are not possible with the Taguchi method. Kannan et al. [18] found that the plastic deformation of the matrix material had an important influence on the cutting force.

Tamang and Chandrasekaran [19] examined the tool wear and surface roughness in the machining of SiCp/Al reinforced metal matrix composites using coated carbide tools. The spindle speed, feed rate, cutting angle, volume percentage of reinforcing material, etc. were taken as research parameters. Artificial neural network (ANN) and RSM—two modeling techniques—were applied to establish a mathematical model and optimize the process parameters. The results revealed that the models had an improved performance. In some research work, it has been seen that the tool wear had a greater impact on the increasing weight percentage of SiC particles. It has been found in the wear phenomena of polycrystalline diamond tools when processing composites with 10% and 20% SiC particles reinforced metal matrix composites. As a result, the tool wear increased with the increase of the reinforcement percentage. The tool wear was found more for 20% particle reinforcement ratio compared to 10%. However, there were no signs of an abnormal rise in cutting forces with different parameters [20]. Similarly, Dabade et al. [21] validated the influence of increasing weight percentage of SiC particles on cutting force, while performing the cutting experiments of SiCp/Al composites along with different weight percentages of SiC particles. The results of the cutting experiments show that the main factors affecting cutting force depend on the

different weight percentages of the reinforcement phase of the SiCp/Al. Furthermore, the studies of the effects of cutting parameters and material parameters on the cutting force magnitude and fluctuation are systematically studied in combination with the evolution of the chip morphology of SiC. The variation of the cutting force of the SiCp/Al composite material has been related to the number of particles in the chip-to-chip contact area. As the particle size increased, the cutting force fluctuated; as the feed rate and cutting speed increased, the cutting force fluctuated [22].

In the machining process, the force needed to complete the cutting process to cut the workpiece and deform the materials to produce the chips is called the cutting force. The cutting forces have been proven to be the most effective parameter for understanding the machining process of metals. There are three kinds of forces produced in the cutting process, i.e., the feed force, tangential and radial component, when cutting tool's friction, extrusion, and shear on the component materials [23,24]. The machining angle of the cutting tool and parameters will directly influence the cutting force [25,26]. After the tool wears, the effect between the tool and the material changes, and this change is reflected in the cutting force. Therefore, the characteristics related to difficult-to-machine composite materials can be extracted by analyzing the cutting force. It rarely focusses on cutting force trends to observe the machining characteristics of high volume SiCp/Al [27].

In this paper, the RSM based box-Behnken design method has been used for the experimental planning and for developing mathematical modeling of cutting force of SiCp/Al composite materials for the turning process. The purpose of this study is to explore and investigate the impact of machining parameters on the cutting force in turning process of difficult-to-cut hard material SiCp/Al 45 wt% reinforced metal matrix composite. Individual effect evaluation using main effect plots, residual plots, and contours plots of cutting forces were developed to analyze and observe the effect of the chosen parameters of the machining process. The predicted and experimental results of the model of SiCp/Al components were compared and checked. Finally, the cutting force for SiCp/Al 45 wt% was calculated with the error percentages, which has also been analyzed and compared.

2. Materials and Methods

2.1. Experimental Conditions

An experimental study of the turning process of SiCp/Al containing 45 wt% of SiC reinforced particles has been carried out to observe the cutting force behavior with different machining parameters. To obtain the cutting force model, it is necessary to determine the experimental orthogonal relationship between the process parameters and the cutting force. In this experiment, three different responsive machining parameters such as cutting speed, feed rate and depth of cut have been employed orthogonally. The composite materials work-piece sample had a length of 98.9 mm and a diameter of 48.2 mm. The cutting force has been recorded for each cutting operation until all the number of cutting operations is completed. A total of 16 sets of cutting operations has been performed. The SiCp/Al composite has been turned by dry-cutting condition. The three-way force has been measured during the experiment. The installation method of each device has been shown in the Figure 1. The dynamometer has been mounted on a self-made T-clamp. The tool has been mounted on a dynamometer with a simple tool holder. The cutting force has been measured by a Kistler 9257B desktop dynamic strain gauge, and the maximum allowable range is 5000 N. According to ISO 3685 (ISO, 1993), an average experimental tool wear standard is $VB = 0.3$ mm [28,29]. The experimental setup for turning operation on SiCp/Al is shown in Figure 1. Table 1 shows the levels of selected cutting parameters for the turning operation.

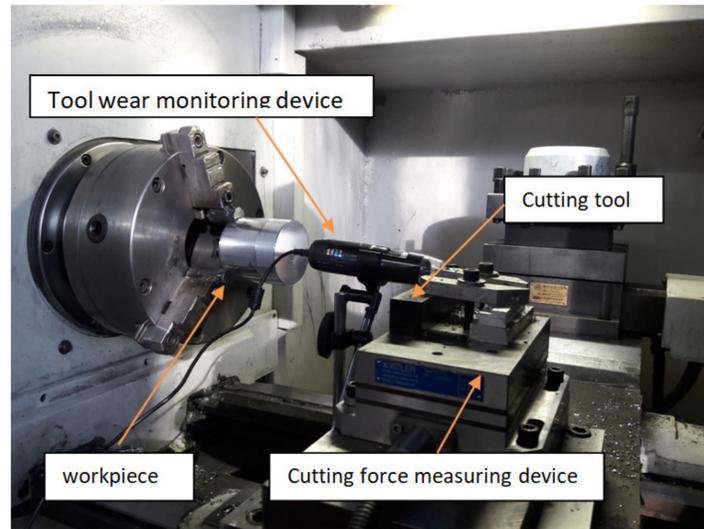


Figure 1. Experimental setup.

Table 1. Cutting Parameters for Cutting Force SiCp/Al 45 wt%.

Cutting Parameters	Levels			
	First Level	Second Level	Third Level	Fourth Level
Cutting Speed (m/min)	6.283	12.566	18.85	25.133
Feed rate (mm/rev)	0.01	0.015	0.02	0.025
Depth of cut (mm)	0.2	0.5	1	1.5

2.2. Response Surface Methodology (RSM)

RSM is based on the reasonable experimental design to analyze the experimental data sets for the required respective response. The multivariate quadratic regression equation is used to fit the functional relationship between each factor and the response result so that the optimal parameter combination is acquired from the mathematical model of response surface methodology [30,31]. The influence of turning parameters such as cutting speed, feed rate, and depth of cut on cutting force is a relatively complex nonlinear relationship, so the fitting is presented in Equation (1). The comprehensive influence of each machining parameter on cutting force was obtained as shown in the figure.

The first step for the development of the optimization model in the RSM approach and their respective design for the experimental observation is represented in Equation (1).

$$Y = F [v_c, f, a_p] \tag{1}$$

An optimization model of Y appears as the desired function, F is the response function, the other parameters v_c, f , and a_p , are the cutting speed, feed rate, depth of cut respectively. Quadratic model for Y is written as shown in Equation (2).

$$Y = a_0 + \sum a_i X_i + \sum a_{ij} X_i^2 + \sum a_{ij} X_i X_j \tag{2}$$

The number of parameters which are given in Equation (2) can be defined such as, a_0 constant, a_i, a_{ii} , and a_{ij} represent the coefficient of linear, quadratic and cross product terms respectively. X_i shows the variables which correspond to the studied machining parameters.

2.3. Desirability Function Optimization

In the composite desirability, the target set of optimizations is usually to maximize and minimize the response. It can be defined as the weighted geometric average of the individual expected values of each response. To optimize the targeted responses, the researchers use different software for optimization, in this study Minitab-17 is employed. This method is used to optimize different responses and predict the optimal combination of parameters. The optimizer searches for combinations of input variables that jointly optimize a set of responses by satisfying the requirements of each response in the set [32]. Optimization is achieved by obtaining the expected value of a single response. The desirability function is the expected value of each response scale to the 0 to 1 desirability scale. The order of each response is from the least ideal to the most ideal. The single expected value is combined to obtain the composite expected value. The obtained composite desirability value is maximized, and the optimal input variable setting is determined. This study contains three responses of cutting force that need to be minimized—the goal is achieved by simultaneously minimizing the factors. However, the mixture of one or more targets is optimized by numerical optimization, where the potential target can be, minimized, maximized target, on the range, and exact value.

The setting of each value for the optimization in desirability function optimization is given as the lower, upper and target values, which are needed to be set according to response requirements. Each response possesses the regression equation, which is used for response optimization and generates the optimization plots for respective response at some scale of the desirability in between range from 0 to 1 desirability scale.

3. Result and Discussion

3.1. Experimental Data of Cutting Forces

The existing composite machining literature shows that the research and analysis of cutting forces related to turning are mostly carried out from the aspects of cutting speed, feed rate and depth of cut. The influence of cutting force trends on cutting performance of SiCp/Al composite materials determines the necessity of analyzing the parameters in this study. Three research variables are selected which are further divided into four levels. In summary, the survey factors and their responses are shown in Tables 1 and 2. It was found that the three processing parameters of cutting speed, feed rate and depth of cut have an influence on the processing response. Therefore, to better understand the processing phenomenon, it is necessary to study the effects of these three elements on cutting force by employing RSM on experimental data for further investigation. The obtained experimental data from the turning process of SiCp/Al are given in Table 2 along with details of the cutting parameters and their effects on the cutting force.

3.2. Effects of Cutting Parameters on Cutting Forces

In the turning process of SiCp/Al, the increasing phenomena can be observed in cutting force with increasing depth of cut followed by feed rate, while cutting force reduced with increase in cutting speed—It is reported by different studies in [14–16,33–35]. In MMCs machining process, the built-up-edge (BUE) is also unwanted. BUE can be reduced with slightly increasing cutting speed, this phenomenon can provide ease of removing material in the turning process at lower cutting force. It is also seen that the more increments in feed rate along the higher cutting force is due to the increase of the contact area between workpiece and cutting tool—such a phenomenon was reported by [36].

In the conventional machining process of SiCp/Al composite material, the behavior of the cutting force mainly depends on the SiC particle size, volume, and concentration, as well as the strength of interface bond [16,37]. The increase in cutting speed leads to a decrease in cutting force. It is possible because of increments in cutting temperature in the shear plane region leads to the plastic softening of the machined

surface, which reduces the shear strength of the SiCp/Al composite material. This becomes the trend of cutting force in the cutting process, which indicates that the cutting force reduces with the increase of machining speed [14,38]. Some research work mentioned that the cutting force possesses an increasing tendency with increasing wt% of SiC particles, while decreases in SiCp wt% showed the cutting force trend to be reduced [15,39]. In all three cutting forces, the increasing evidence was found due to a higher depth of cut, it is because the contact area of component increased in cutting process, which is also higher with the material removal process. It is seen experimentally that the higher depth of cut and feed rate produce more impact, as compared to the SiCp wt% for increasing the cutting force [39,40].

Table 2. The machining parameters and experimental data of cutting force, F_x , F_y , F_z obtained in turning process of SiCp/Al 45%wt.

S: No	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	F_x Force (N)	F_y Force (N)	F_z Force (N)
1	6.283	0.01	0.2	74.13	170.01	79.98
2	6.283	0.015	0.5	134.01	249.9	138.23
3	6.283	0.02	1	261.09	295.03	199.81
4	6.283	0.025	1.5	375.29	385.11	275.12
5	12.566	0.01	0.5	143.11	250.07	126.06
6	12.566	0.015	0.2	84.33	231.96	96.11
7	12.566	0.02	1.5	409.98	319.99	289.88
8	12.566	0.025	1	290.11	315.06	221.02
9	18.85	0.01	1	274.42	317.1	171.3
10	18.85	0.015	1.5	519.8	364.89	311.05
11	18.85	0.02	0.2	69.01	214.87	86.42
12	18.85	0.025	0.5	169.04	293.15	149.79
13	25.133	0.01	1.5	529.98	355.23	278.31
14	25.133	0.015	1	327.16	361.01	207.04
15	25.133	0.02	0.5	149.97	269.96	135.61
16	25.133	0.025	0.2	89.96	256.14	104.97

As the amount of cutting speed increases along with the lower depth of cut, the built-up edge reduces as well as the cutting force reduces. It is also associated with the higher cutting temperature produced in the cutting zone during the cutting operation, which reduces the component yield strength and thickness of the manufactured chips. The lower cutting speed with increasing depth of cut fluctuated the cutting force and produced fractured chips, as well as built edge is formed. In the case of a change in feed rate, it is found that the cutting force linearly varies [33,34,41].

In the machining process, the cutting parameter feed rate also increases with cutting force due to the occurrence of a new factor called friction. The friction factor, which is produced between the component and cutting edge of the tool, due to the increasing amount of feed rate, increases the cutting force [35,42]. While further analyzing the effect of SiCp/Al MMC materials on the cutting forces, it is mainly found in the literature that the cutting forces primarily tend to be affected by the type of matrix materials rather than reinforcement. It is mainly found that the volume, interface bond strength and reinforcement type heavily influence the cutting edge, which ultimately fluctuates the cutting forces [43,44].

3.2.1. Quantitative Evaluation Using ANOVA

As presented before, the influence of each single factor at individual response is determined by utilizing analysis of variance (ANOVA). The ANOVA functioned, based on parameters, which are F statistics, value of P and sum of squares (SS). The F statistics is achieved by dividing the MS of the factor through MS of error. The value of P signifies the statistical worth, which needs to signify the level of 0.05 at confidence interval 95%, if the value of P is lower from 0.05 the factor used is a significant factor [14,45].

Tables 3–5 display the ANOVA for cutting force responses F_x , F_y , and F_z for the turning process of SiCp/Al. Research on the basis of the above-mentioned variables divulges that the increasing variation in

cutting force is the result of increasing depth of cut trailed by cutting speed and feed rate. In the same way, the F statistics gives the similar information, the proportional significance of the depth of cut is greater, subsequently trailed by the other factors such as cutting speed and feed rate. The value of P is also asserting the significance of cutting speed and feed rate [46].

Table 3. Analysis of variance of response surface regression: F_x versus v_c, f, a_p .

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	355,838	39,538	95.08	0.000
Linear	3	121,663	40,554	97.53	0.000
v_c	1	2104	2104	5.06	0.065
f	1	684	684	1.65	0.247
a_p	1	119,441	119,441	287.24	0.000
Square	3	1674	558	1.34	0.346
$v_c \times v_c$	1	21	21	0.05	0.831
$f \times f$	1	5	5	0.01	0.913
$a_p \times a_p$	1	1648	1648	3.96	0.094
2-Way Interaction	3	6982	2327	5.60	0.036
$v_c \times a_p$	1	153	153	0.37	0.566
$v_c \times a_p$	1	5114	5114	12.30	0.013
$f \times a_p$	1	344	344	0.83	0.398
Error	6	2495	416	-	-
Total	15	358,333	-	-	-

Table 4. Analysis of variance response surface regression: F_y versus v_c, f, a_p .

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	50,355.7	5595.1	8.29	0.009
Linear	3	11,551.9	3850.6	5.71	0.034
v_c	1	1379.3	1379.3	2.04	0.203
f	1	360.2	360.2	0.53	0.493
a_p	1	10,131.1	10,131.1	15.01	0.008
Square	3	1016.6	338.9	0.50	0.695
$v_c \times v_c$	1	77.9	77.9	0.12	0.746
$f \times f$	1	73.4	73.4	0.11	0.753
$a_p \times a_p$	1	865.4	865.4	1.28	0.301
2-Way Interaction	3	805.6	268.5	0.40	0.760
$v_c \times a_p$	1	665.9	665.9	0.99	0.359
$v_c \times a_p$	1	30.5	30.5	0.05	0.839
$f \times a_p$	1	70.0	70.0	0.10	0.758
Error	6	4048.8	674.8	-	-
Total	15	54,404.5	-	-	-

The different plots were generated to analyze and understand the influence of cutting parameters on the machining behavior of SiCp/Al. This study uses the contour and main effect plots to measure and analyze the responses of cutting force such $F_x, F_y,$ and F_z . The predicted regression model of the cutting forces is found most appropriate, the equation of cutting forces are given in Equations (3)–(5).

$$F_x = 50.8 - 6.30v_c + 3317f + 110.7a_p - 0.029v_c \times v_c - 23,275f \times f + 57.8a_p \times a_p + 136v_c \times f + 9.13v_c \times a_p - 2977f \times a_p \tag{3}$$

$$F_y = 104 + 6.19v_c + 1845f + 146a_p + 0.056v_c \times v_c + 85,650f \times f - 41.9a_p \times a_p - 284v_c \times f - 0.71v_c \times a_p + 1342f \times a_p \tag{4}$$

$$F_z = 56.1 - 4.58v_c + 4334f + 79.0a_p - 0.0515v_c \times v_c - 144,000f \times f + 18.0a_p \times a_p + 224v_c \times f + 3.30v_c \times a_p + 81f \times a_p \tag{5}$$

The mathematical model accuracy is more than 95% confidence level for all responses of the cutting force in ANOVA. Therefore, the model is most suitable for the prediction of responses [45]. The ANOVA tables for the three different responses of cutting force such F_x , F_y , and F_z have been given in Tables 3–5 respectively. The value of R square and R square (adj) for F_x are obtained as R -sq 99.3% and R -sq (adj) 98.26%; for F_y they are obtained as R -sq 92.56% and R -sq (adj) 81.39%; and for F_z they are obtained such as R -sq 99.2% and R -sq (adj) 97.99%. The values of all the co-efficient of determination of R -sq and R -sq (adj) are very close to the value of 1 that fulfill the accuracy of the developed mathematical model.

R square quantity is known as a co-efficient of determination, which is utilized to observe the adequacy of the models. The more the value of R square near to 1 gives a higher fitting of the mathematical model with the obtained data. R square value indicates the acceptability of the developed model [14,47].

Table 5. Analysis of variance of response surface regression: F_z versus v_c, f, a_p .

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	89,080.0	9897.8	82.20	0.000
Linear	3	36,376.0	12,125.3	100.69	0.000
v_c	1	66.9	66.9	0.56	0.484
f	1	1283.5	1283.5	10.66	0.017
a_p	1	35,071.4	35,071.4	291.25	0.000
Square	3	433.0	144.3	1.20	0.387
$v_c \times v_c$	1	66.3	66.3	0.55	0.486
$f \times f$	1	207.4	207.4	1.72	0.237
$a_p \times a_p$	1	159.4	159.4	1.32	0.294
2-Way Interaction	3	1137.2	379.1	3.15	0.108
$v_c \times f$	1	416.3	416.3	3.46	0.112
$v_c \times a_p$	1	665.9	665.9	5.53	0.057
$f \times a_p$	1	0.3	0.3	0.00	0.965
Error	6	722.5	120.4	-	-
Total	15	89,802.5	-	-	-

3.2.2. Individual Effect Evaluation Using Main Effects Plots

The main effect diagram showing the influences of the input factors to turning of SiCp/Al 45 wt% shows the cutting forces of F_x , F_y , and F_z in Figures 2–4, respectively. Different parameters were chosen to measure the effect on the machining process such as cutting speed, feed rate and depth of cut. In the main effect plot, the horizontal line of the input parameters has little or no effect on the output response, while the vertical line has a significant effect on the response. The F_x chart shows that the depth of cut has a greater effect on the cutting force, and the feed rate has a smaller or no effect on the cutting force. Other researchers have also noticed that the cutting force increases with increasing depth of cut, followed by the feed rate [14,36]. Cutting force main effect plot for F_y shows that there is a little effect of cutting speed and feed rate however the depth of cut is significantly affecting the cutting force. In the case of F_z cutting force, it follows the feed rate to depth of cut, which affects the cutting force to follow the cutting speed to a certain extent.

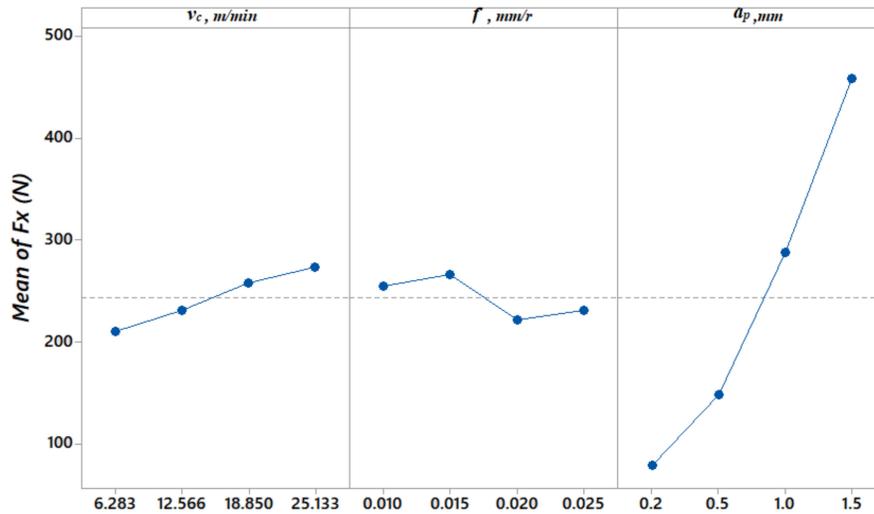


Figure 2. Main effect plots for F_x cutting force.

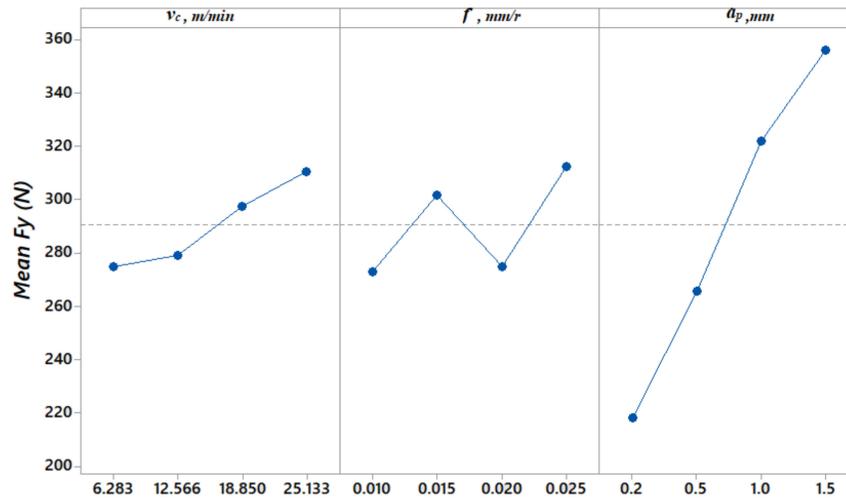


Figure 3. Main effect plots for F_y cutting force.

3.2.3. Interactive Effect Evaluation Using Contour Plots

While turning of multiphase composite materials like SiCp/Al with 45 wt% through carbide cutting tool wedge, it experienced abrasion and force variability because of the contact with brittle particles in the materials. Based on the present model of RSM which are shown in regression Equation (3), regression Equation (4), and regression Equation (5), these are made based on experimental annotations to measure the influence of nominated parameters on the cutting force. The contour plots were formed to shape the possible influence of different selected parameters. In case of depth of cut as the depth of cut rises followed by feed rate there is an accelerated increment of the cutting force, the trend is depicted in Figure 5a. However, similarly shown in [15], for the turning process of SiCp/Al solely observed, the increasing phenomena of cutting force with increasing depth of cut followed by feed rate, while cutting force reduces with an increase in cutting speed. Figure 5c divulge the clear statistics that as the cutting speed increases and the depth of cut decreases, the cutting force gives declining trending. It is due to the fact that higher amount of cutting speed create high temperature at the cutting zone; because of increasing temperature it causes thermal softening due to that it creates ease in chip formation, therefore, cutting force

reduces [22,33]. The increasing feed rate with a combination of increasing depth of cut at moderate cutting speed produces an increasing impact on movement of F_y cutting force as compared to F_x , and F_z cutting force as shown in Figure 6b. With the maximum value of 1.5 mm depth of cut as holding value in all directions of cutting force F_x, F_y, F_z , the contour plots show the same increasing phenomena as shown in Figures 5b, 6c and 7c, respectively. However, in case of holding the cutting speed to reveal the impact of cutting speed with increasing feed rate and depth of cut, it shows reducing trend in cutting force with higher cutting speed and lower depth of cut. Followed by feed rate in F_x , and F_y , the direction of cutting force in F_z there is slight addition with increasing feed rate as shown in Figures 5a, 6b and 7a. This kind of phenomenon also reported by Subramanian et al. [16] that the more increments in feed rate alone increase the cutting force due to increasing the contact area between workpiece and cutting tool.

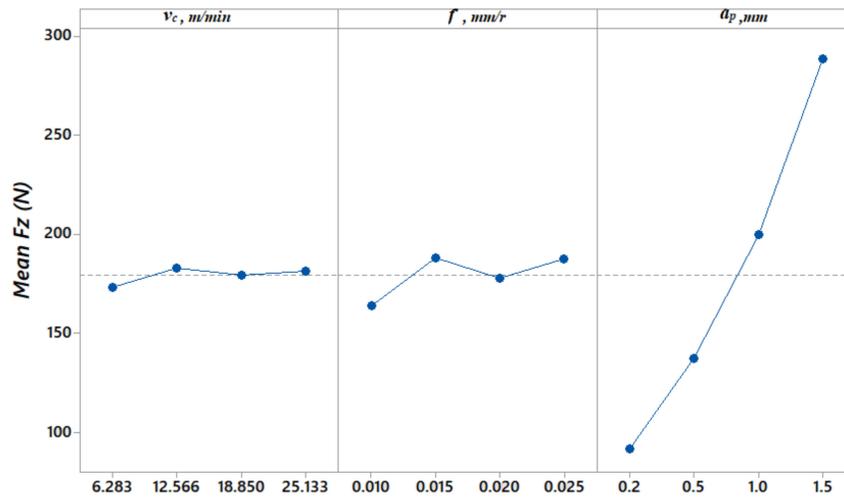
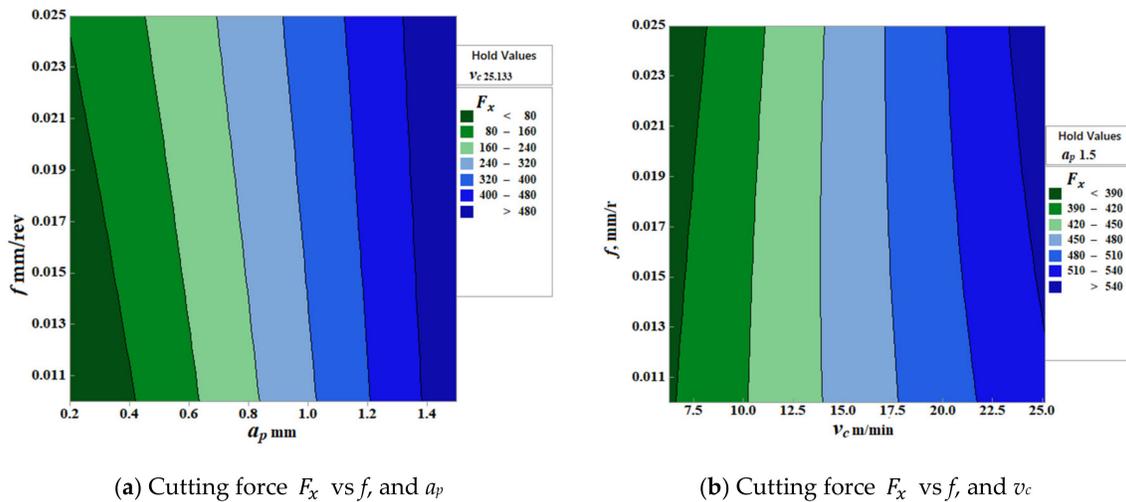


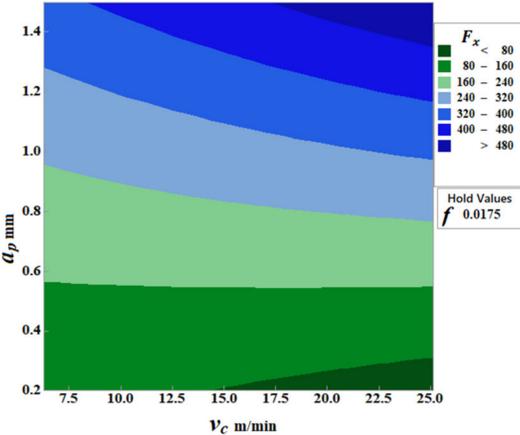
Figure 4. Main effect plots for F_z cutting force.



(a) Cutting force F_x vs f , and a_p

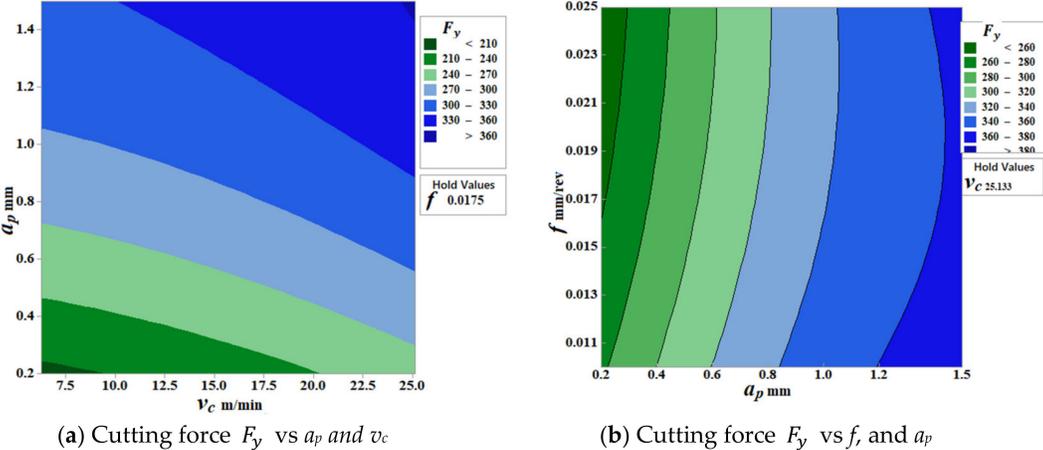
(b) Cutting force F_x vs f , and v_c

Figure 5. Cont.



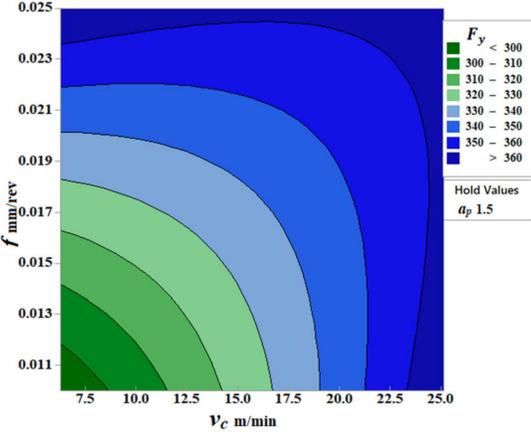
(c) Cutting force F_x vs a_p and v_c

Figure 5. (a–c) Cutting force F_x vs. v_c, f, a_p .



(a) Cutting force F_y vs a_p and v_c

(b) Cutting force F_y vs f , and a_p



(c) Cutting force F_y vs f , and v_c

Figure 6. (a–c) Cutting force F_y vs. v_c, f, a_p .

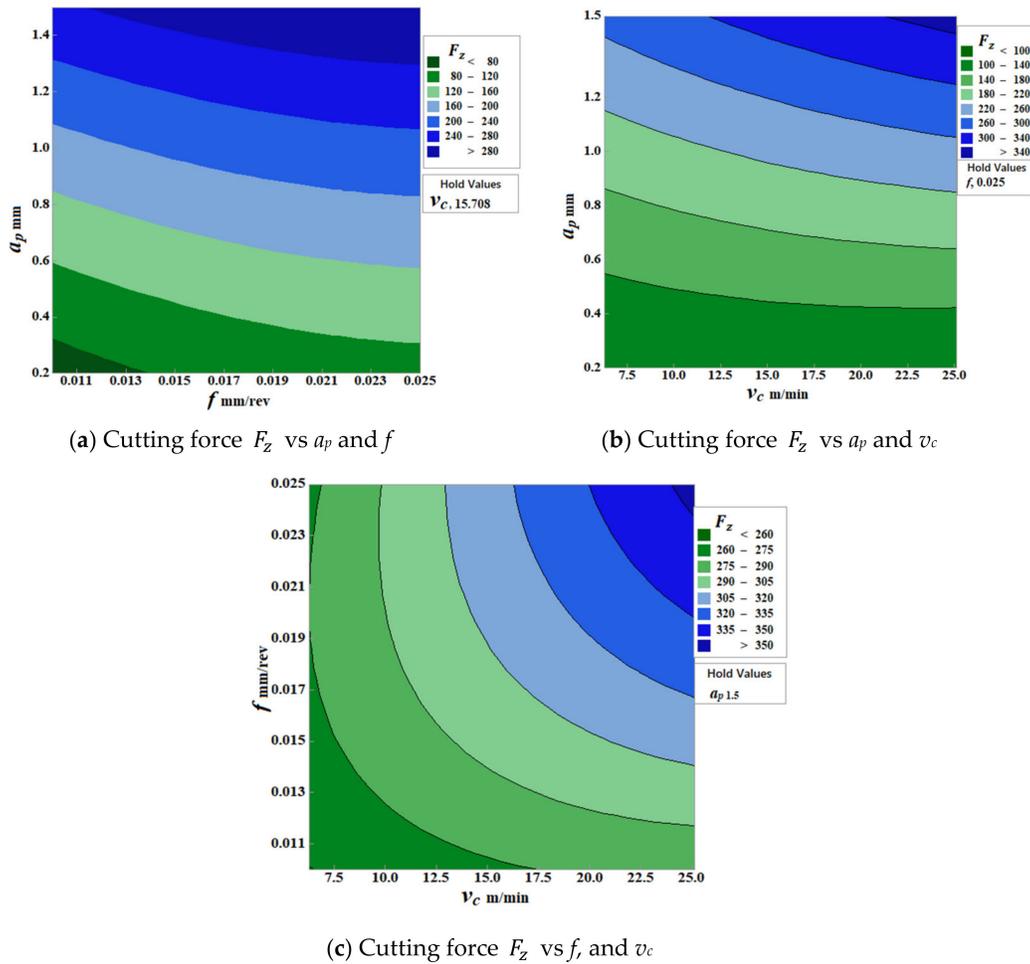


Figure 7. (a–c) Cutting force F_z vs. v_c, f, a_p .

3.3. Integrity of Models Using Residual Analysis

The residual plot is one of the important tools to evaluate the integrity of the developed model and plays a key role [30]. Figures 8–10 show the residual plot of the cutting forces $F_x, F_y,$ and F_z respectively. There are four plots of the cutting force’s arrival response, i.e., normal probability plots, residual and fit plots, residual histograms, and residual and observation sequence plots. In analyzing all four different plots seen here, in the normal probability plot, the data points reasonably approach the straight line; therefore, the normality assumption still applies [48]. Residual plots and fitted plots indicate that the data points are randomly distributed; therefore, the assumption of constant variance is accurate [49]. On the other hand, there is some distortion on the left side of the histogram. Finally, in the residual sequence chart, the first segment showed an upward trend and then fluctuated significantly. Figure 6 shows a residual curve of the cutting force F_y . The residuals of this method are normally distributed and are suitable for analysis of ordinary variance, but at the initial stage and the later stage, the distortion at the left end is small, and the correlation coefficient increases or decreases. Figure 7 shows a residual graph of the cutting force F_z . Here, the residuals are normally distributed, all three sets of data are visible, the distortion is not visible, and the trend of increase and decrease is obvious.

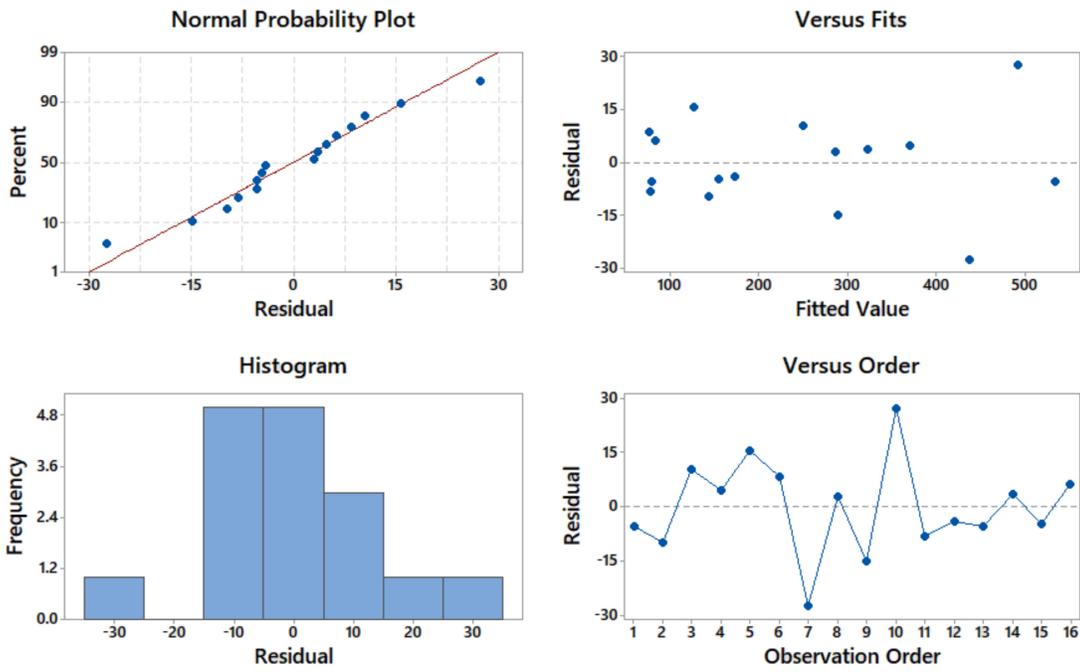


Figure 8. Residual plot of the cutting force F_x .

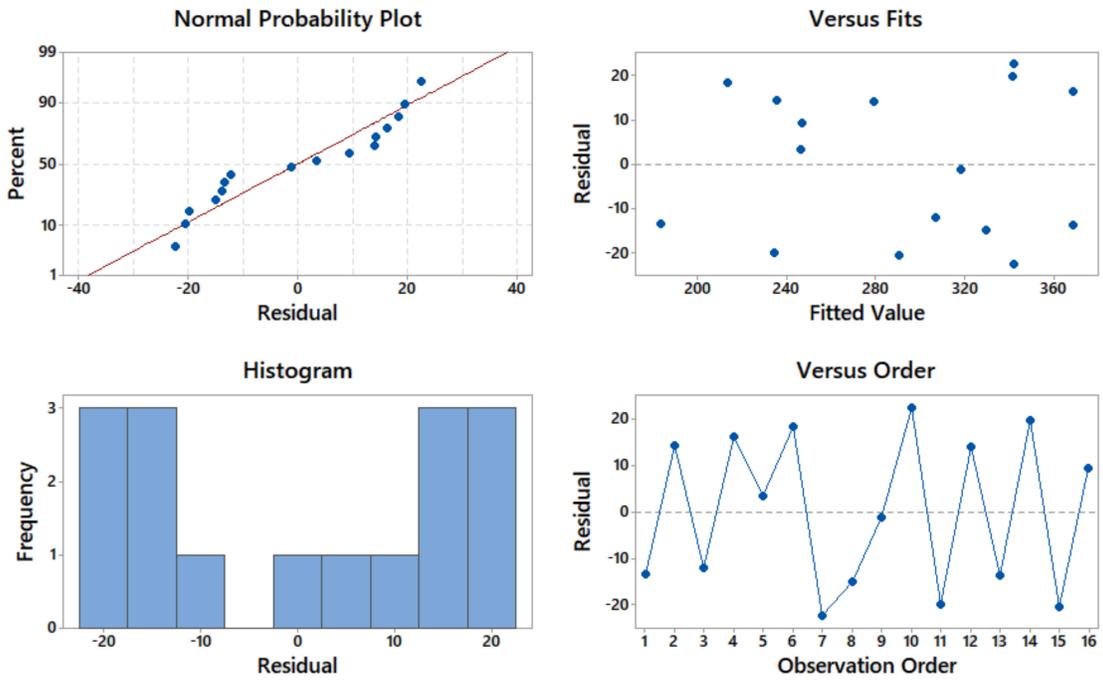


Figure 9. Residual plot of the cutting force F_y .

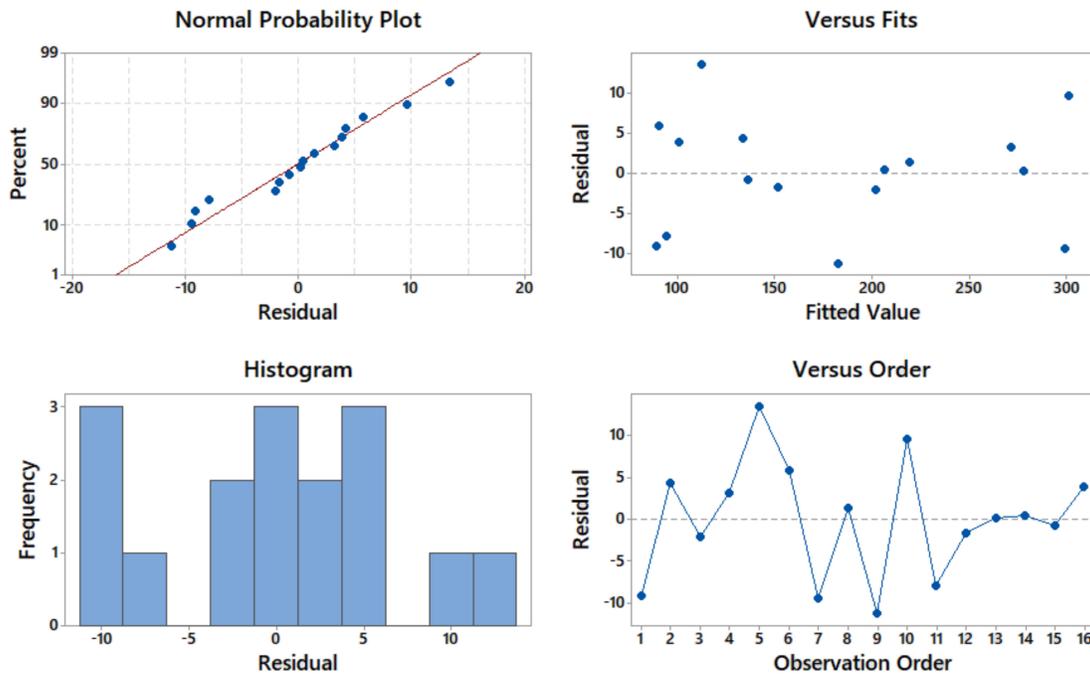


Figure 10. Residual plot of the cutting force F_z .

3.4. Optimization of Cutting Forces Using Desirability Function

The cutting force trend in the turning process of SiCp/Al material has a significant theoretical and practical consequence. The cutting forces were observed as major impacting factors in the machining process. On a different combination of cutting parameters and weight percentage of SiC particles in SiCp/Al material, the cutting forces significance was found accordingly. Evidence shows that the cutting force varies with the change in cutting parameters. The type, hardness and content, shape, size, and distribution of the reinforcement in SiCp/Al influence the cutting force. In the turning process, due to the extrusion, shearing, and friction between the tool and the workpiece, the cutting layer of the workpiece undergoes strong elastic and plastic deformation. The root cause of these deformations is the effect of cutting forces. Hence, the cutting force is one of the most basic physical phenomena in material cutting [40,41,50].

Cutting force optimization plot for F_x , F_y , and F_z SiCp/Al 45 wt% has been given in Figure 11. The purpose is to minimize the cutting force. For F_x , F_y , and F_z the setting of values for the optimization plot is given as the lower, and the target values are 69.01, 170.01 and 79.98 N respectively and upper values are 529.98, 385.11 and 311.05 N for F_x , F_y , and F_z respectively. The optimization plot for minimization of cutting force suggests that the cutting parameters are cutting speed (v_c) of 6.283 m/min, feed rate (f) of 0.01 mm/rev and depth of cut (a_p) of 0.2 mm. The value of desirability (d) of optimization is noted at 0.9576. The projected response for the cutting force F_x , F_y , and F_z SiCp/Al 45 wt% are 79.5160, 183.3829 and 89.1095 N respectively. Similarly, the cutting force maximization was plotted to find the parameters which increases the cutting force with similar settings, such as lower value targeted and the upper value in Figure 12. However, in Figure 12 targeted value and upper value are similar. The projected response for identifying the maximized cutting force F_x , F_y , and F_z SiCp/Al 45 wt% are 557.0966, 364.9312 and 89.1095 N respectively. The desirability is 0.9584. The regression equation used for response optimizer plots for F_x , F_y , and F_z SiCp/Al 45 wt% is given in Equations (6)–(8).

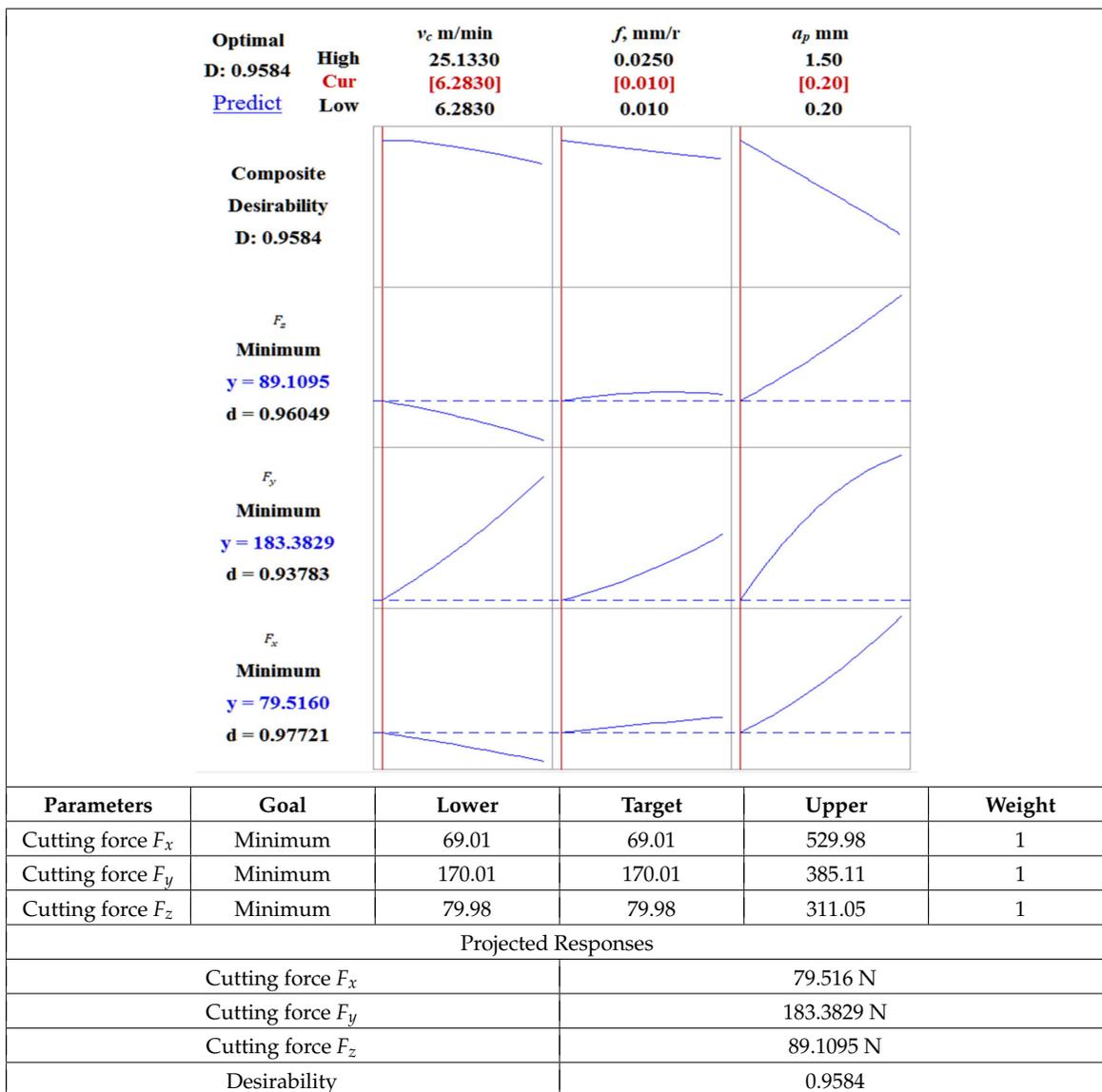


Figure 11. Optimization Plot for Minimum Cutting Force of F_x, F_y, F_z SiCp/Al.

Regression Equation for F_x, F_y , and F_z SiCp/Al 45%wt.

$$F_x = v_c + f + a_p - v_c \times v_c - f \times f + a_p \times a_p + v_c \times f + v_c \times a_p - f \times a_p \tag{6}$$

$$F_y = v_c + f + a_p + v_c \times v_c + f \times f - a_p \times a_p - v_c \times f - v_c \times a_p + f \times a_p \tag{7}$$

$$F_z = v_c + f + a_p - v_c \times v_c - f \times f + a_p \times a_p + v_c \times f + v_c \times a_p + f \times a_p \tag{8}$$

A comparison of the experimental cutting force values Table 2 and predicted cutting force values is shown in Table 6. This is not the validation of the model but a table to show the differences found for the cutting force values. The RSM predicted model was compared with the experimental values and found in good agreement as shown in Figure 13. The error (difference) percentages between model predicted and experimental values are compared in Figure 14—majority of the error percentages are under 10%

except for the few values which are up to 16%. Few error percentages are above 10%—it can be due to some tool’s measurement calculation error and machine vibration during cutting process of SiCp/Al composite materials.

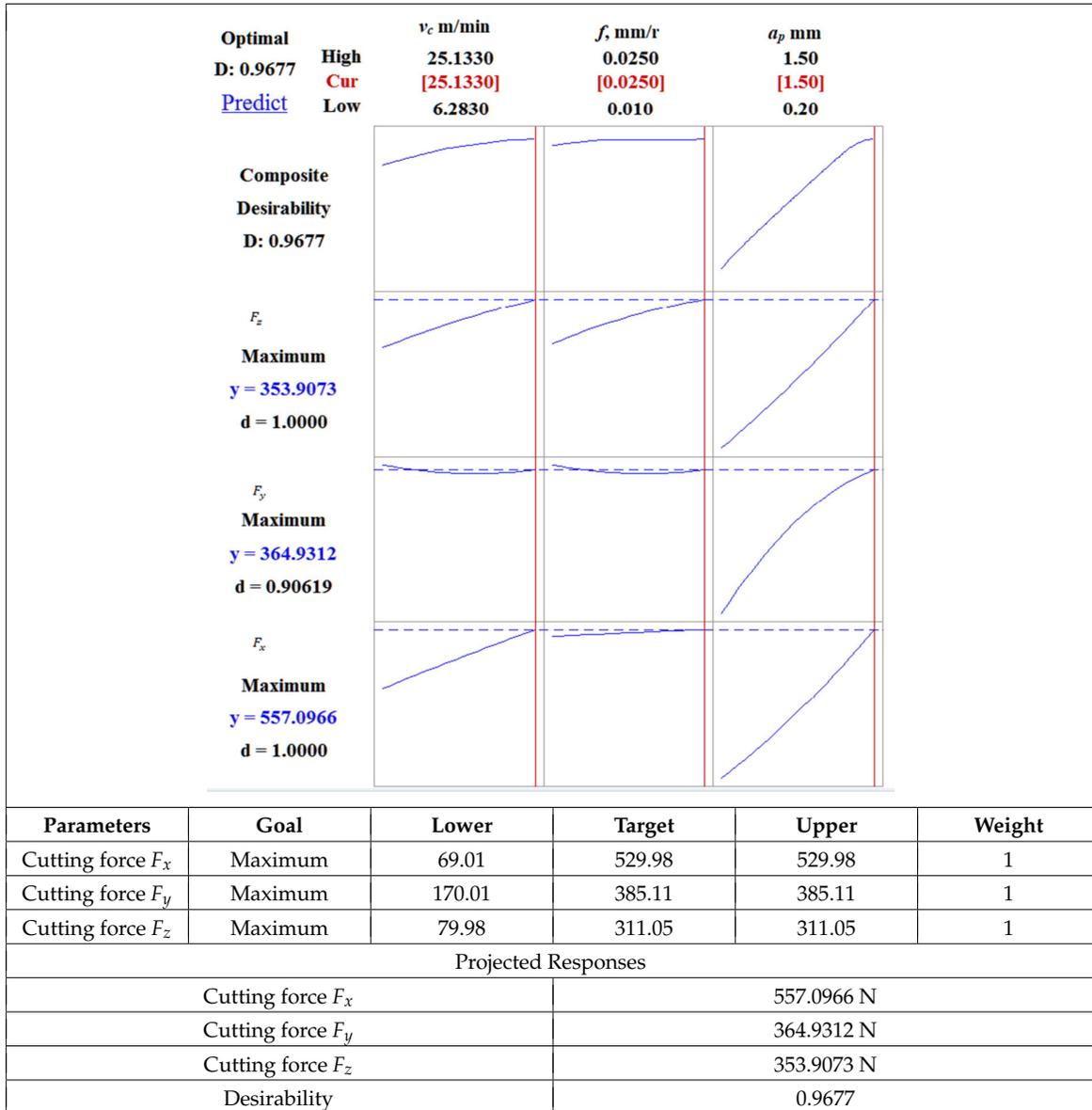


Figure 12. Optimization Plot for Maximum Cutting Force of F_x, F_y, F_z SiCp/Al.

Table 6. The machining parameters and comparison of experimental cutting force F_x, F_y, F_z vs. measured cutting force F_x, F_y, F_z .

S: No	F_x			F_y			F_z		
	Exp. Force (N)	Pred. Force (N)	Error %	Exp. Force (N)	Pred. Force (N)	Error %	Exp. Force (N)	Pred. Force (N)	Error %
1	74.13	79.39	7.09	170.01	180.91	6.41	79.98	88.41	10.5
2	134.01	143.19	6.85	249.9	235.64	5.7	138.23	132.12	4.42
3	261.09	250.51	4.05	295.03	307.05	4.07	199.81	183.87	7.97
4	375.29	370.3	1.32	385.11	368.5	4.31	275.12	231.42	16
5	143.11	127.26	11.06	250.07	246.72	1.32	126.06	108.14	14.2
6	84.33	71.6	15.09	231.96	213.8	7.82	96.11	89.58	6.79
7	409.98	445.4	8.53	319.99	338.24	5.7	289.88	258.92	10.6
8	290.11	286.26	1.32	315.06	329.83	4.68	221.02	201.62	8.77
9	274.42	289	5.31	317.1	318.19	0.34	171.3	182.64	6.62
10	519.8	479.16	7.81	364.89	342.06	6.25	311.05	307.19	1.24
11	69.01	77	11.57	214.87	234.88	9.3	86.42	100.82	15.7
12	169.04	172.49	2.04	293.15	268.2	8.51	149.79	160.91	7.4
13	529.98	534.27	0.8	355.23	368	3.59	278.31	277.87	0.15
14	327.16	306.6	6.28	361.01	341.21	5.48	207.04	206.67	0.17
15	149.97	153.94	2.64	269.96	271.92	0.72	135.61	136.41	0.58
16	89.96	83.43	7.25	256.14	250.17	2.33	104.97	101.06	3.7

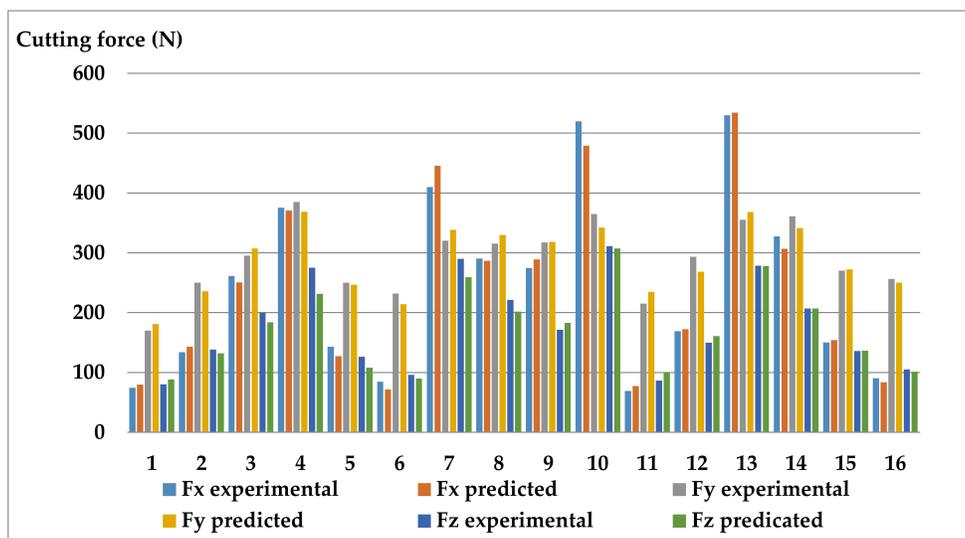


Figure 13. Cutting force comparisons between experimental and RSM predicted values of F_x, F_y, F_z .

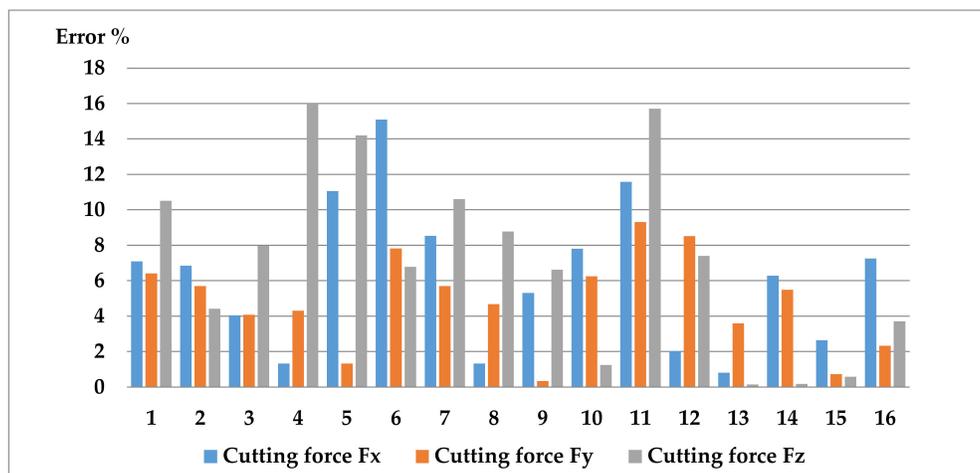


Figure 14. Cutting force error percentage comparison between experimental and RSM predicted values.

4. Conclusions

The experimental research work of this paper investigates the influence of machining parameters on the cutting force in turning process of difficult-to-cut hard material SiCp/Al reinforced metal matrix composites. The desirability function has been used for the optimization of the responses. The considered machining parameters were taken as cutting speed, feed rate, and depth of cutting. It was evaluated the impact of SiCp/Al materials on the cutting force. The box-Behnken based mathematical predictive model was developed with RSM for measuring the impact of different input parameters such as cutting speed, feed rate, and depth of cut and SiC particles on cutting force.

- In machining SiCp/Al materials, the machining behavior acted like for the machining of metals/alloys—the depth of cut produced more effect on the cutting force, followed by feed rate. However, the cutting forces (for F_x and, F_z mostly) show decreasing trend with higher cutting speeds.
- The cutting forces were increasing with the increase in the feed rate which can be accredited to a higher contact area due to increased feed. Also, the content of SiC particles resulted in an increase in the cutting force.
- The increase in cutting speed leads to a decrease in cutting force. It is possible because of the increments in cutting temperature in the shear plane region which leads to the plastic softening of the machined surface. This reduces the shear strength of the SiCp/Al composite material.
- Mathematical models (RSM) showed very competent comparable values of the cutting forces. Here, these equations can be used to predict SiCp/Al 45 wt% reinforced metal matrix composite cutting forces when turning. RSM generated mathematical models were found accurate and their predicted values were very close to the experimental data points with overall minimal error percentages.
- The composite desirability for optimization, i.e., minimization of cutting forces, which suggest that the optimum cutting parameters are cutting speed (v_c) of 6.283 m/min, feed rate (f) of 0.01 mm/rev and depth of cut (a_p) 0.2 mm and the value of (d) desirability of optimization is noted at 0.9576. The projected response for the cutting force F_x , F_y , and F_z and SiCp/Al 45wt% are 79.5160 (N), 183.3829 (N), and 89.1095 (N), respectively.

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