Arab J Sci Eng (2016) 41:1797–1812
DOI 10.1007/s13369-015-1991-4

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Experimental Investigation and Optimization of Cutting Force and Tool Wear in Milling Al7075 and Open-Cell SiC Foam Composite

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Received: 22 May 2015 / Accepted: 15 November 2015 / Published online: 9 December 2015

Abstract In the present study, aluminium alloy-based metal matrix composites were fabricated by infiltrating Al7075 into a three-dimensional open-cell silicon carbide (SiC) foam using the liquid metallurgy method. The effects of machining variables on the milling force and tool wear during milling of both Al7075 and the open-cell SiC foam metal matrix composite (MMC) using an uncoated carbide cutting tool were studied. The milling experiments were performed based on the Taguchi L_{27} full-factorial orthogonal array, and the milling variables were optimized for cutting force and tool wear. The test results showed that the cutting depth was the most significant cutting parameter affecting milling force in the milling of both workpiece materials. Cutting tool wear was directly affected by the cutting depth in the milling of MMC, and the feed rate was the most influential factor on the tool wear in the milling of Al7075. Uncoated carbide tool showed an excellent machining performance below a machining speed of 220 m/min in finish milling Al7075 workpiece material, but excessive edge chipping was observed on the cutting tool surface in the milling of MMCs. Second-order mathematical models with respect to milling parameters were created for prediction of cutting force and tool wear.

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Keywords Al7075 · Open-cell SiC foams · Cutting force · Tool wear · Taguchi method · Response surface methodology

1 Introduction

Open-cell silicon carbide (SiC) foams are suitable for a variety of specific applications, such as aerospace applications and fire protection materials. SiC foams are already commercially available and have many potential advantages because of physical properties such as high mechanical strength, good thermal conductivity and high oxidative resistance to chemical attack [1–4]. The bonding effect between the SiC particles and alloy matrix is softened at a high machining temperature, and SiC particles in composites are easily removed from the structure of the matrix in the machining process. Depending on the loss of SiC particles from the alloy matrix, wear resistance and compressive strength of MMCs can be dramatically reduced. MMCs reinforced by a three-dimensional (3D) ceramic network such as open-cell SiC foams have increased wear resistance and better high-temperature strength than traditional aluminium composites reinforced with SiC particles because of the restrictions in movement of the open-cell SiC foam network reinforcement in the matrix [5]. Subramanian et al. [6] studied optimization of the milling force in shoulder milling of Al7075-T6. Low cutting force was obtained by the combination of a high machining speed, low feed rate and low axial depth of cut. El-gallab et al. [7] stated that the cutting force decreased while the feed rate was increasing in the turning of MMCs. Increasing the depth of cut led to an increase in the flank wear, and machining speed accelerated the flank abrasion. Kannan et al. [8] observed that the cutting forces were increased as a result of increasing the particle size and cutting conditions. Zaghbani et al. [9] developed a new analytical cutting force model in the milling of aluminium alloys under dry high-speed cutting conditions. The developed model was validated by comparing the prediction for machining Al6061-T6 and Al7075-T6. The results showed that a good agreement was obtained between the experimental and predicted results for both force and temperatures. Pramanik et al. [10] investigated the turning of MMC and non-reinforced alloy. The test results showed that the turning forces were increased with the increase in feed rate. Machining speed was not significantly influenced by the forces for MMC. Manna et al. [11] investigated the machinability of SiCp composite during turning using fixed rhombic cutting tools. They observed that the tool wear was increased at low turning speed because of the high cutting forces and built-up edge (BUE) creation in machining of Al/SiC–MMCs. The feed rate had a sensitive effect on the tool wear as compared to the machining speed. Similarly, Kannan et al. stated that a high feed rate has less effect on the tool wear during machining MMCs [12]. Ciftci et al. [13] observed that the SiC reinforcement particle size and machining speed negatively influenced the tool wear. Similarly, Ozben et al. [14] investigated the machinability properties of an aluminium matrix reinforced with SiC particles and reported that the machining speed was one of the significant factors in the machining of the composite. The higher SiCp reinforcement led to higher tool wear. Joshi et al. [15] reported that the machining speed and volume of reinforcement particles had the most significant effect on the tool life in the machining of Al/SiCp composites using a carbide cutting tool. Manna and Bhattacharya [16] investigated the effect of machining speed on the cutting force during turning Al/SiC MMCs. They found that machining forces were decreased with an increase in the machining speed. Subramanian et al. [17] developed a statistical model to predict surface roughness in terms of machining parameters using response surface methodology (RSM). They also determined the significance of the machining parameters on the surface roughness by employing analysis of variance (ANOVA).

From examination of the literature, most of the research was carried out on machinability of 7075 reinforced with SiCp and investigated the cutting forces and tool wear. In this study, 3D open-cell SiC ceramic foam, which is a complex and lightweight material, was used to produce the MMCs. The open-cell SiC foam has very good thermal and electrical conductivity and can withstand very high temperatures. The machinability of reinforced open-cell SiC foam composites has not been studied. The purpose of this study is to investigate the milling force and tool wear behaviour of Al7075/MMCs in finishing and semi-finishing cutting conditions by using an uncoated carbide insert. The cutting tool wear was also observed to understand the relationship between the milling force and tool wear. A prediction model was developed based on RSM for the milling force and tool wear. Furthermore, ANOVA was applied to determine the most significant control factors based on the Taguchi L_{27} method.

2 Experimental Methods and Equipment

2.1 Workpiece Material

Al-based SiC composites were fabricated by infiltrating Al7075 into an open porous SiC ceramic foam using the liquid metallurgy method. Fabrication of the Al-based MMC, Al7075 alloy, which was obtained commercially, served as the matrix material, while open-pore ceramic foam material of dimensions 100 mm × 50 mm × 22 mm with a purity of 99 % and an average pore size of 15 pores per inch (ppi) was used as the reinforcement material. The resulting composite was composed of 40 vol% SiC ceramic. Figure 1 shows a flow chart of the production process, which employed an electric induction furnace. T6 heat treatment was applied to the specimens to increase the strength of the resulting composite material. The scanning electron microscopy (SEM) micrograph shown in Fig. 2 clearly illustrates the microstructure of the open-cell SiC foam-reinforced composite, the surface of the machined Al7075 region and the interface between the matrix structure and the open-cell SiC foam.

2.2 Milling Machine and Experimental Equipment

A Johnford VMC550 model three-axis CNC milling machine tool was used to perform the experimental study, and all experiments were performed under dry cutting conditions. A standard 40-mm tool holder with a single WK10 quality uncoated carbide insert was used in the experiments. Every surface was machined with a new tool, and the milling forces during finishing milling conditions were investigated to a depth of cut below 1.5 mm. The workpiece material, feed rates, milling speeds and depth of cut were selected as variables for the experimental tests and were chosen from the tool supplier catalogue and ISO Standard 8688-1. The milling variables used in the experiments, units and notations are shown in Table 2. A Kistler 9257B dynamometer was utilized to measure the milling forces, and the signal data were recorded to a computer using a 5017B amplifier. Before performing the experiment, the three axes of the dynamometer were calibrated using static loads. All the recorded milling force signals were transferred to a personal computer and analysed with the help of Dynaware software at the end of the experiments.

The directions of the milling forces are illustrated in Fig. 3. Milling forces were obtained during milling Al7075 and SiC foam-reinforced composite. Then, the resultant force, F_r, and normal force, F_n, were calculated with the formulae

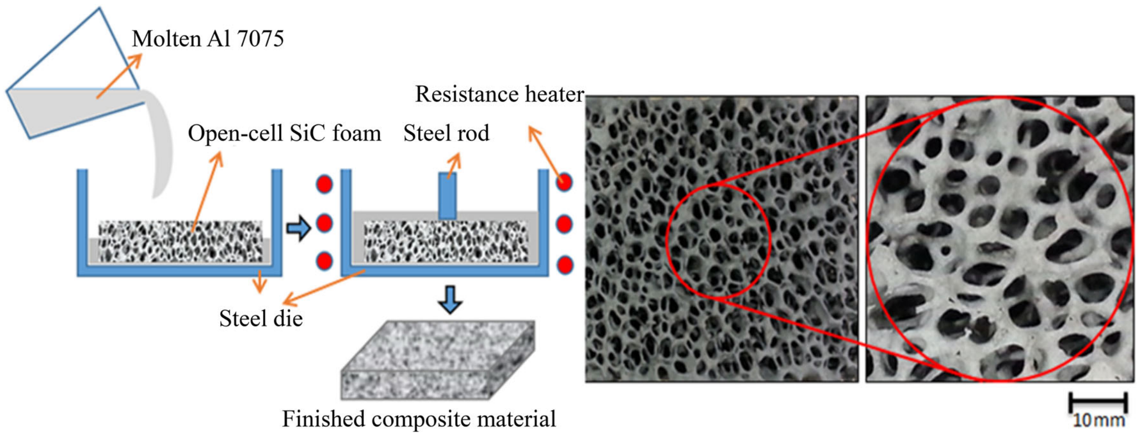


Fig. 1 Schematic diagram of the fabrication process of open-cell SiC foam composite [18]

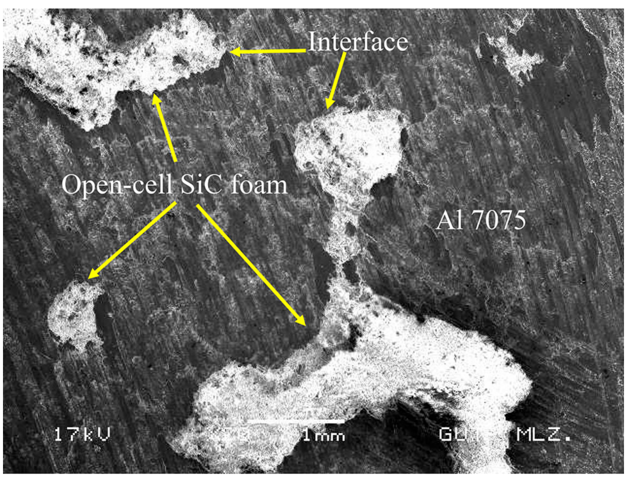


Fig. 2 Microstructure of SiC foam-reinforced composite

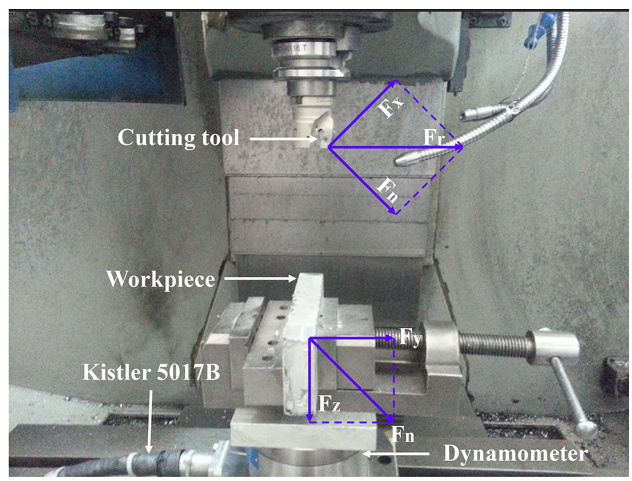


Fig. 3 Experimental set-up for milling force measurement and schematic illustration of milling forces

Table 1 Chemical composition of Al7075

Chemical composition (wt%)						
Zn	Mg	Mn	Fe	Si	Cu	Al
4.69	2.37	0.68	0.69	0.31	0.05	Bal.

$F_{\mathrm{n}} = \sqrt{F_y^2 + F_z^2}$ and $F_{\mathrm{r}} = \sqrt{F_{\mathrm{n}}^2 + F_x^2}$ where F_x is the force in the x direction, F_y is the force in the feed direction, and F_z is the radial force. In the experiments, the down-milling method was used. The trials were performed based on the

Table 2 Cutting parameters used in the experiments

Factors	Notation	Unit	Level 1	Level 2	Level 3
A—material	M		Al7075	MMC	–
B—milling speed	V_c	m/min	170	220	290
C—feed rate	f_z,	mm/tooth	0.08	0.1	0.13
D—depth of cut	a_p	mm	0.8	1	1.3
Workpiece dimension		mm	90 × 50 × 21		
Entering angle	K_r	Degree	90		
Cutting width	a_e	mm	24		
Cutting diameter	D_c	mm	40		
Number of effective tooth	z_n	pcs	1		

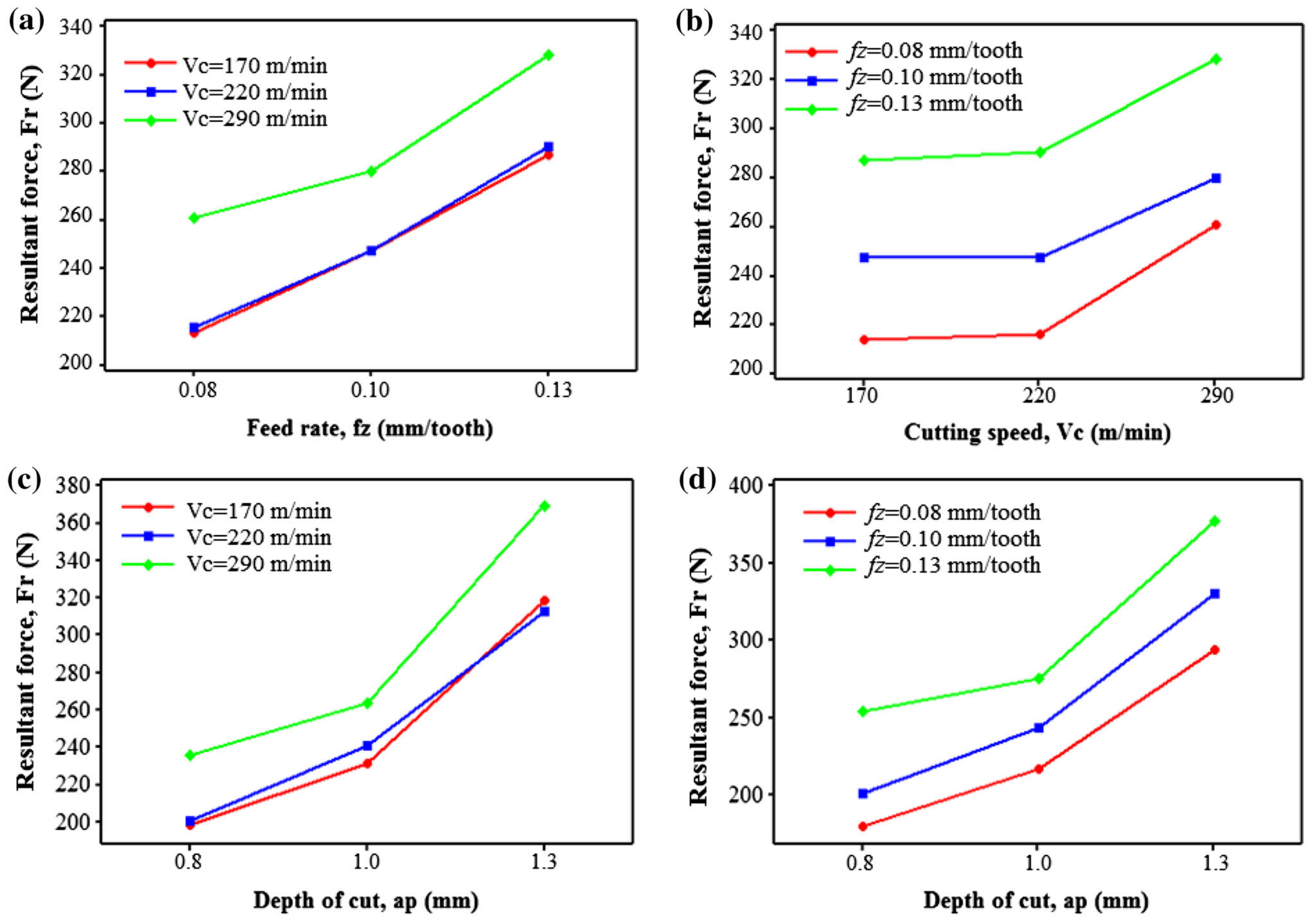


Fig. 4 Interaction effect of machining parameters on the milling force for Al7075

full-factorial experimental design, and obtained experimental results were evaluated with ANOVA. ISO 8688 Tool Life Testing in Milling—Part 1, defines a number of tool wear mechanisms in face milling operations. Tool wear experiments were performed with two passes for all of the machining parameters at a constant volume of metal removal rate. ISO 8688 was followed for measurement of flank wear, and the worn insert was analysed using an optical microscope with a precision of 0.001 mm SEM and energy-dispersive spectroscopy (EDS).

3 Experimental Results and Discussion

The interaction effects of milling variables on the resultant force in the milling of both Al7075 and SiC foam-reinforced composites are presented in Figs. 4 and 5, respectively. From the interaction plots, the milling force and tool wear were significantly affected depending on the increasing depth of cut because the cutting depth affects the width of the contact area in the feed and rotational directions. In addition, the length of engaging cutting insert increased and the milling force and tool wear were increased at high cutting depth. The milling forces and tool wear were more affected by the depth of cutting variations during Al7075 and MMCs milling. As shown in all interaction and 3D surface plots, the milling force and tool wear were increased, while the axial depth of cut increased from 0.8 to 1.3 mm. Figures 6 and 7 show the effect of the milling variables on the tool wear at constant volume of chip removed during milling of Al7075 and MMC. It can be seen from the 3D surface plots that the axial cutting depth has a more important effect on the tool wear during milling of MMC reinforced with open-cell SiC while having less effect on the tool wear during milling of Al7075-T6. In the experiments, the feed rate had a large influence on the milling forces and tool wear. In that case, the milling force and tool wear were greatly increased with an increase in machining feed in the milling of Al7075. The reason was that more material was removed per tooth per revolution because the feed was increased from 0.08 to 0.13 mm/tooth. It was observed that the milling force increased for machining feed at 0.1 to 0.13 mm/tooth, while the axial depth of cut increased from 1 to 1.3 mm at all machining speeds in the milling of Al7075. In contrast, it was observed that

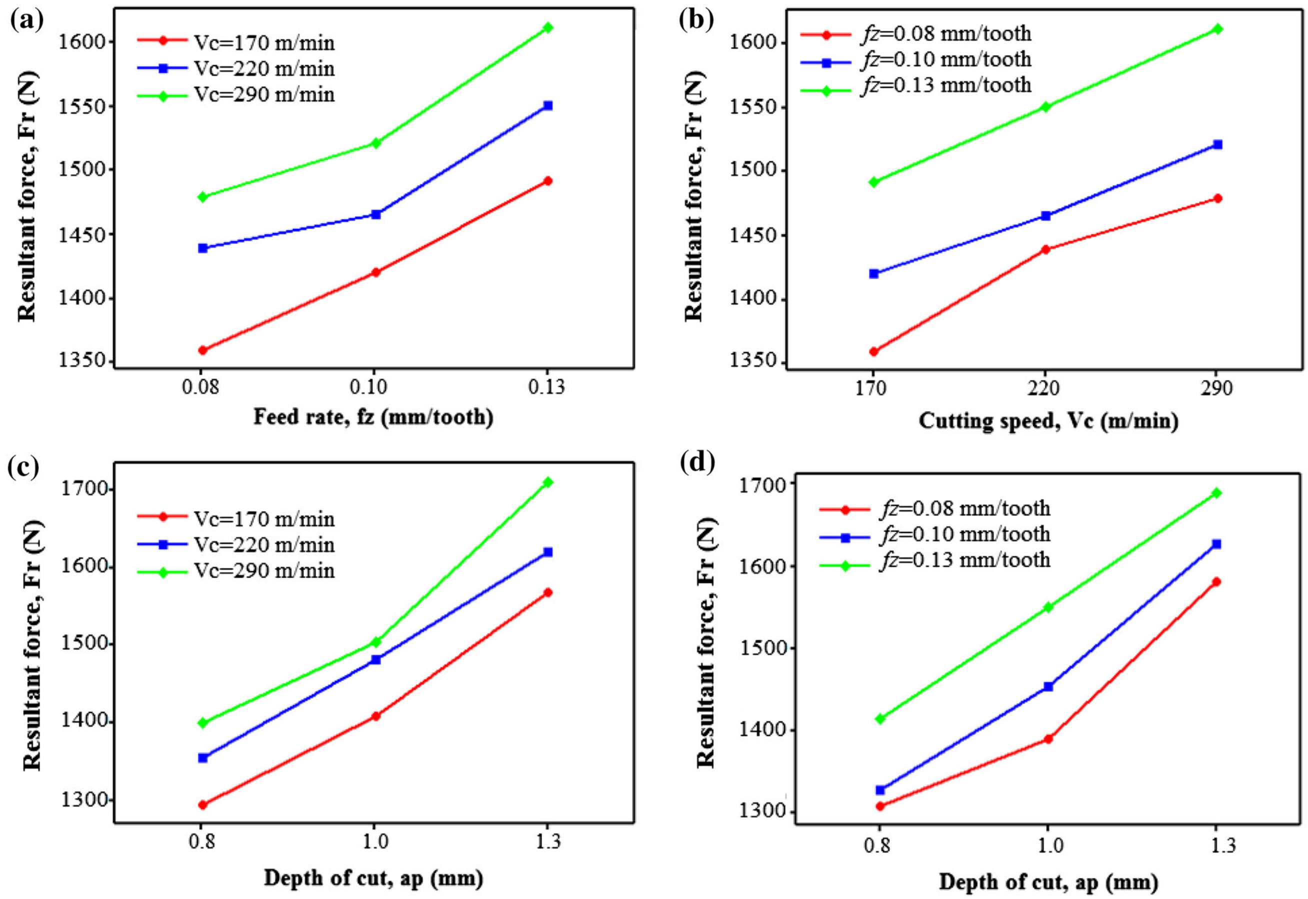


Fig. 5 Interaction effect of machining parameters on the milling force for MMCs

the tool wear decreased, while the machining feed increased from 0.1 to 0.13 mm/tooth for a constant volume of metal removed in the milling of MMCs. The feed rate showed a less positive effect on the tool wear because of the higher feed rates contributing to a minimization in contact time between the cutting insert and abrasive SiC foam in the milling of MMCs.

El-gallab et al. [8] reported similar results about the positive effect of the cutting feed on the tool wear in the machining of metal matrix composite. In most cases, increasing the machining speed caused a decrease in the cutting forces. In this experimental study, the milling force increased for a machining speed of 290 m/min while remaining almost constant for machining speeds of 170 and 220 m/min in the milling of Al7075. Normally, the cutting tool wear dramatically increases at high machining speed; the result showed that the tool wear was not affected significantly by increasing machining speed. BUE creation at low milling speed contributed to cutting tool breakage by mechanical impact during inserting and removing the cutting tool from the workpiece material in some machining conditions (Fig. 8b). As a result, the cutting tool was a failure in the milling of MMCs [16]. Uncoated carbide tool showed a good cutting performance below a machining speed of 220 m/min in finish milling Al7075 workpiece material, but it did not demonstrate the same performance in the milling of MMCs. It can be seen from the 3D surface plots that the tool life decreased dramatically with increasing machining speeds and depth of cut in all machining conditions because of the hard open-cell SiC foam in the matrix structure. As seen from the interaction effect plots in Fig. 5, the resultant milling force was dramatically increased in the milling of the open-cell SiC foam composite. This can be explained as the open-cell SiC foam content of Al7075 causing higher tool wear and cracks, as shown in Fig. 8b. Rapid tool wear was observed in the milling of metal matrix composite because of the extremely abrasive structure of the open-cell SiC foam. The hard open-cell SiC foam metallic binding in the matrix caused excessive tool wear and milling force. The microstructural studies on the machined surface and cutting tool rake face were performed using SEM to determine the deformation pattern of the workpiece material and cutting insert (Fig. 8a–c).

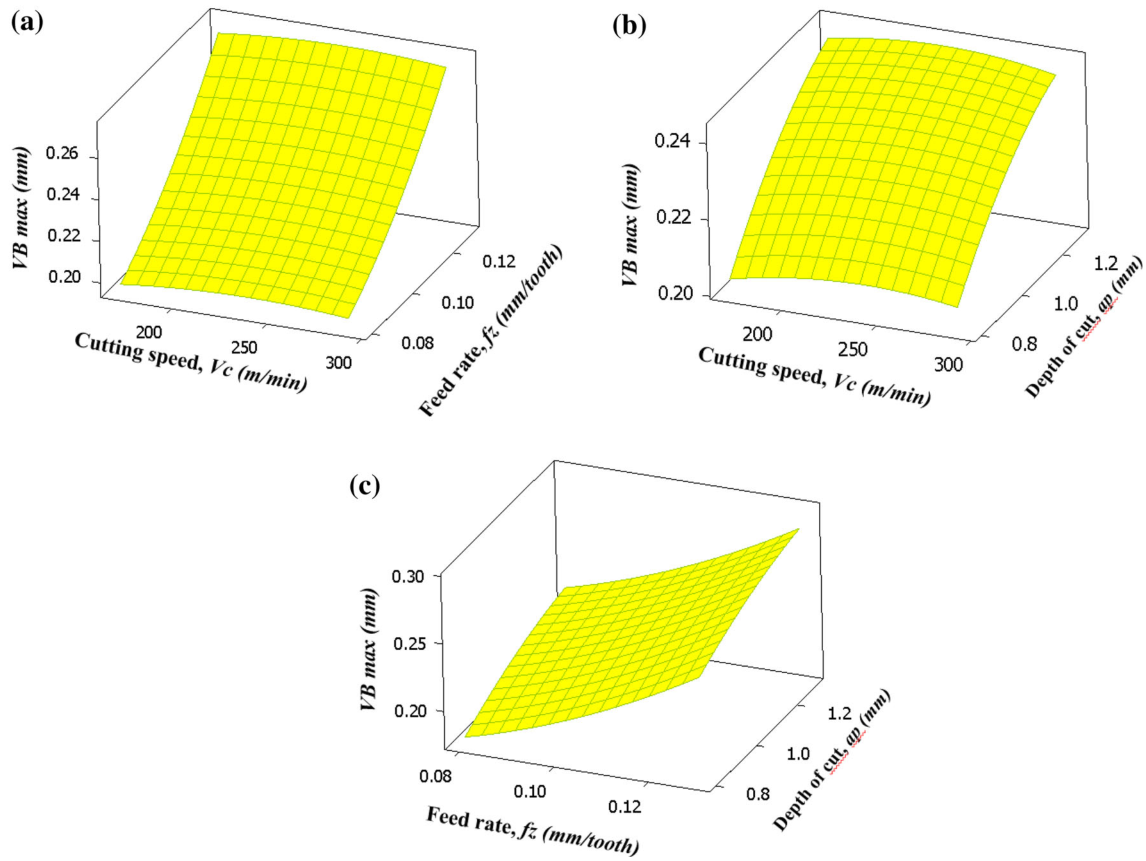


Fig. 6 Effect of **a** milling feed and speed, **b** axial cutting depth and milling speed and **c** axial cutting depth and milling feed on the tool wear for Al7075

During the milling process of the composite material, the removal of hard SiC foam generated some small gaps and microcracks on the finished surface of the workpiece, as shown in Fig. 9. Cracking and rupturing of the 3D SiC network structure caused significant damage on the machined surface and directly affected the tool performance and milling force. When the cutting tool encountered hard SiC foam in the matrix structure, it was suddenly released from the hard cutting area and passed into the soft Al matrix. As a result of this cutting phenomenon, the cutting tool ran into a sudden high-stress level and sudden relaxation because of the high stiffness of the insert. With the rise of feed rate, the cutting temperature increased, which led to weakening of the bonding between the SiC foam and alloy matrix [19]. Consequently, the cutting insert tended to break them rather than cutting the SiC foam in the matrix structure. Therefore, the open-cell SiC foam generated small gaps, microcracks and scratches on the finished surface of the workpiece when the tool edge came in contact with hard and brittle reinforcement material. These small gaps, microcracks and hard SiC foam particles caused high milling force and cutting tool failure in the milling of SiC foam composite [20].

3.1 S/N Ratio and RSM-Based Modelling for Milling Force and Tool Wear

RSM and signal-to noise ratio (S/N) were performed for modelling to determine the relationship between the milling parameters and responses. Several researchers have benefitted from the Taguchi and RSM method to determine the influence of machining parameters in their experimental results [21–24]. Response surface design is a set of advanced design of experiments techniques that gives better analysis and optimizes the experimental responses. A central composite design, which is a widely used response surface in designed experiments, was employed for optimizing the experimental results. The experimental results and the effect of the milling parameters on the milling force and the tool wear were analysed using MINITAB 16 software. Second-degree equations have been developed based on RSM in order to predict the influence of the machining factors. The S/N ratio was also utilized to identify the effect of control factors and the deviation between the experimental values and the desired values by minimizing the effects of uncontrollable noise factors in the Taguchi design. There are three types of quality

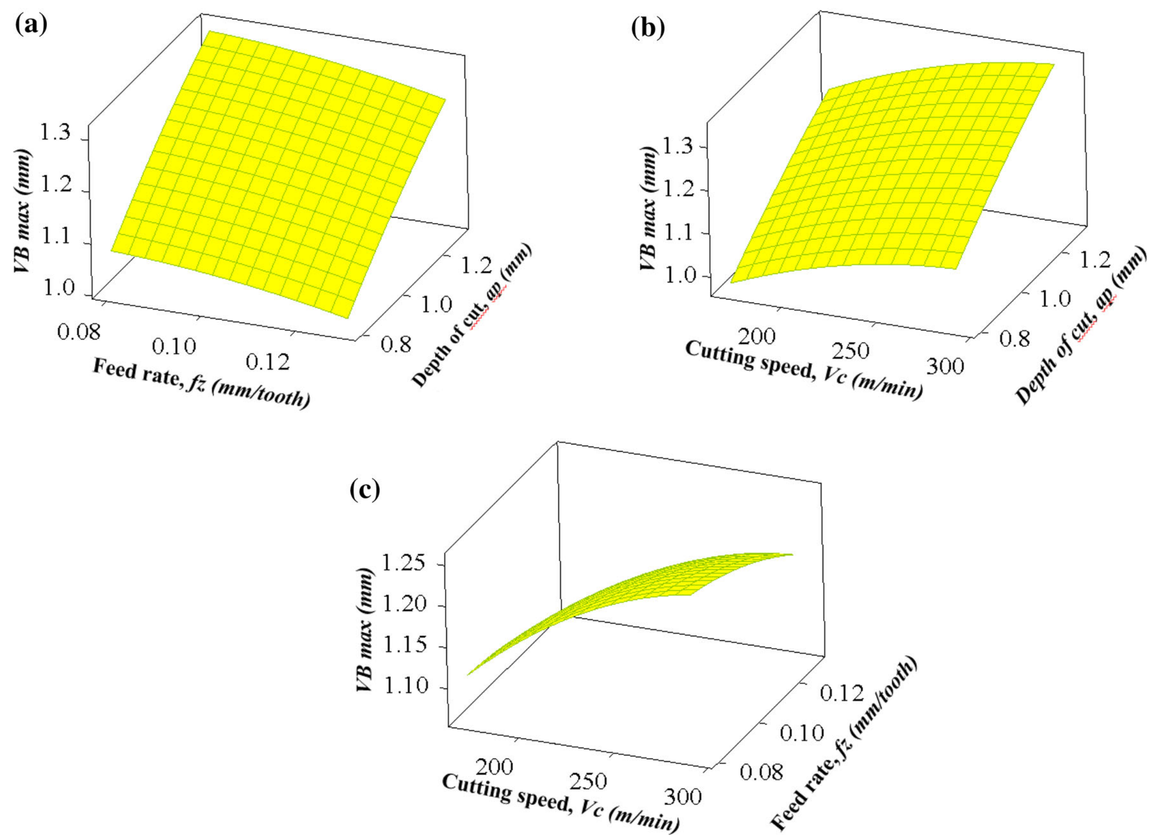


Fig. 7 Effect of **a** milling feed and speed, **b** axial cutting depth and milling speed and **c** axial cutting depth and milling feed on the tool wear for SiC foam composite

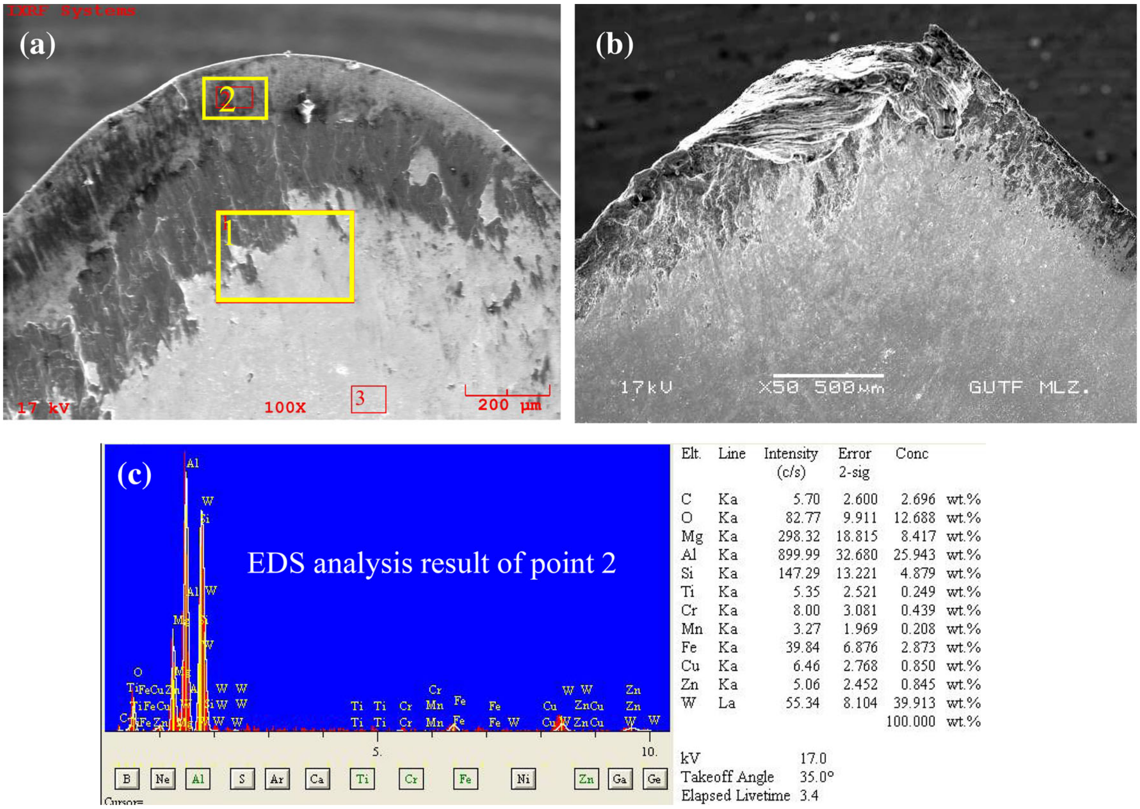
features in the analysis of the S/N ratio: Larger is better, nominal is best, and smaller is better. The smaller is better characteristic (in dB) has been taken to compute the signal-to-noise ratio and some of the minimum composite desirability functions.

$$S/N_{\mathrm{LB}} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} R_i^2\right) \quad (1)$$

The measured experimental values and mean S/N ratios for milling force and tool wear are illustrated in Tables 3 and 6, respectively. The main effects of milling parameters are shown in Figs. 10 and 11.

High S/N ratios are always preferred to define the ideal machining conditions. The optimum milling parameters could be seen from the mean effect plots in Figs. 10 and 11. The mean S/N ratio for every level of experiment is computed based on the measured experimental value, as listed in Tables 3 and 5. Residual plots were also used to examine the goodness of fit in regression and the proficiency of the models. Residual error shows the difference between a measured value and its corresponding fitted value. A normal probability plot of residuals indicated that the residuals are regularly distributed and approximately followed a straight line, as shown in Figs. 12a, c and 13a, c. Residuals versus fits plots were employed to validate the assumption that the residuals have a constant variance. The residuals were randomly distributed on both sides of the 0 line, and non-random patterns could be seen from the residuals versus fits plots, as shown in Figs. 12b, d and 13b, d.

The optimal milling parameter combinations for milling force and tool wear based on the S/N results in the milling of both workpiece materials are listed in Table 7. These optimal milling parameters and predicted values were inferred from responses for the S/N ratios in Tables 4 and 6. The optimal milling force and tool wear were measured at low milling speed, feed rates and axial cutting depth for both types of specimens. Milling force and tool wear were harmfully increased when machining the open-cell SiC foam-reinforced composite in the same cutting conditions. Thus, it could be concluded that a machining speed of 170 m/min, machining feed of 0.08 mm/tooth and axial depth of cut of 0.8 mm would give minimum milling force and tool wear from the optimization results of the milling experiments. Table 8 shows the optimum milling parameters and their desirability values based on the response surface optimizer. The desirability value has a range of zero to one. A higher desirability



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	
C	Ka	5.70	2.600	2.696	wt.%
O	Ka	82.77	9.911	12.688	wt.%
Mg	Ka	298.32	18.815	8.417	wt.%
Al	Ka	899.99	32.680	25.943	wt.%
Si	Ka	147.29	13.221	4.879	wt.%
Ti	Ka	5.35	2.521	0.249	wt.%
Cr	Ka	8.00	3.081	0.439	wt.%
Mn	Ka	3.27	1.969	0.208	wt.%
Fe	Ka	39.84	6.876	2.873	wt.%
Cu	Ka	6.46	2.768	0.850	wt.%
Zn	Ka	5.06	2.452	0.845	wt.%
W	La	55.34	8.104	39.913	wt.%
				100.000	wt.%

Fig. 8 SEM micrographs of the cutting tool surface for **a** Al7075, **b** MMCs and **c** EDS analysis result at point 2

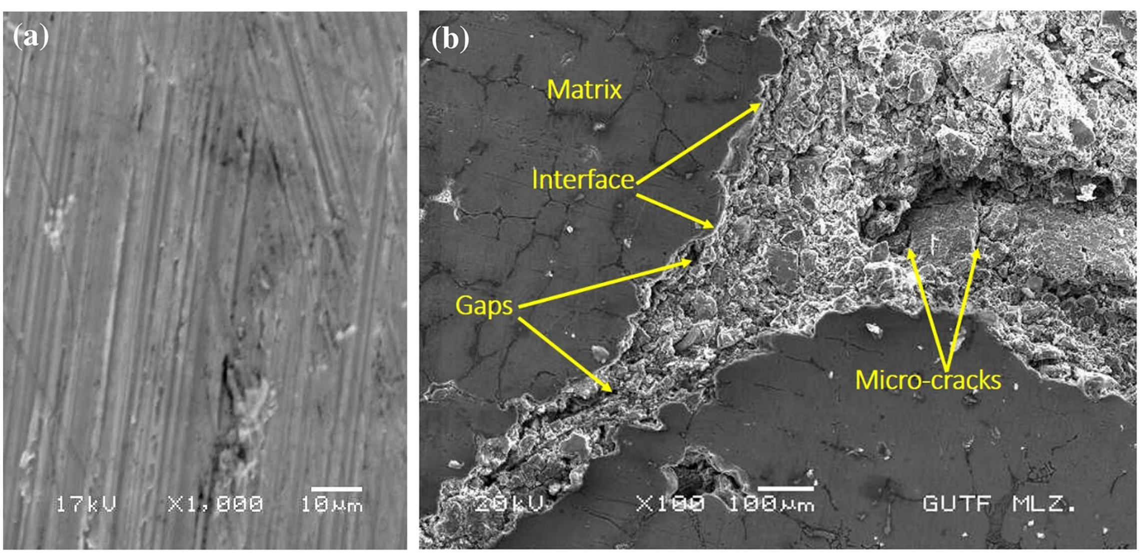


Fig. 9 SEM pictures of machined matrix (**a**) and composite (**b**) workpiece material

value indicates optimal milling parameters, and a lower value shows that one or more machining parameters are outside the acceptable limits. Because of the aim of this study, the goal column was adjusted as a minimum to achieve higher individual desirability. Lower and upper values are indicated by the experimentally measured minimum and maximum values. The optimum milling parameters, predicted responses and desirability values were calculated using the optimization plot based on the RSM method (Table 8). The response surface optimizer suggested a machining speed of 195.45 m/min,

Table 3 The test results and S/N ratio values for Al7075

Parameters			Milling forces						Tool wear		
Vc	*fz*	*ap*	*Fx*	*Fy*	*Fz*	Measured *Fr*	Predicted *Fr*	Error %	Measured V_B	Predicted *VB*	Error %
170	0.08	0.8	90.1	111.5	81.4	164.8	168.8	2.4	0.18	0.17	3.2
170	0.08	1	131.8	139.1	91.1	212.3	197.6	6.9	0.19	0.19	1.9
170	0.08	1.3	161.1	173.3	117.2	264.1	278.8	5.6	0.21	0.21	0.5
170	0.1	0.8	92.7	139.7	84.6	187.8	195.8	4.3	0.19	0.20	3.4
170	0.1	1	143.2	155.4	90.2	229.8	226.2	1.6	0.22	0.22	1.9
170	0.1	1.3	196.9	228.7	117.1	324.3	309.9	4.5	0.23	0.23	1.4
170	0.13	0.8	133.5	181.5	88.0	241.8	238.2	1.5	0.24	0.25	2.8
170	0.13	1	150.2	175.8	97.7	251.0	271.0	8.0	0.27	0.27	1.5
170	0.13	1.3	219.7	262.7	136.7	368.7	358.3	2.8	0.29	0.28	2.4
220	0.08	0.8	96.0	118.8	81.4	173.1	168.4	2.7	0.18	0.18	1.1
220	0.08	1	118.0	135.9	88.0	200.3	200.0	0.2	0.2	0.20	1.5
220	0.08	1.3	173.7	178.2	116.0	274.6	285.4	3.9	0.21	0.21	1.8
220	0.1	0.8	111.5	139.2	81.0	195.9	194.7	0.6	0.2	0.20	0.1
220	0.1	1	145.7	164.4	94.3	239.0	227.8	4.7	0.22	0.22	0.3
220	0.1	1.3	181.5	214.8	123.8	307.3	315.6	2.7	0.24	0.24	1.7
220	0.13	0.8	130.3	173.1	84.7	232.6	235.8	1.4	0.26	0.25	3.7
220	0.13	1	158.7	210.7	101.0	282.4	271.4	3.9	0.26	0.27	3.6
220	0.13	1.3	215.7	256.3	122.7	356.7	362.8	1.7	0.28	0.29	2.1
290	0.08	0.8	105.0	126.0	117.0	201.5	203.6	1.1	0.17	0.18	3.7
290	0.08	1	129.3	150.7	129.7	237.2	239.1	0.8	0.2	0.19	2.6
290	0.08	1.3	203.3	215.0	175.7	344.1	330.3	4.0	0.21	0.21	0.5
290	0.1	0.8	130.7	133.0	113.7	218.4	228.7	4.7	0.2	0.20	0.7
290	0.1	1	159.7	162.0	130.0	262.0	265.7	1.4	0.21	0.22	3.4
290	0.1	1.3	215.3	230.3	172.7	359.5	359.4	0.0	0.24	0.23	2.9
290	0.13	0.8	158.7	205.7	120.3	286.3	268.1	6.4	0.25	0.25	0.5
290	0.13	1	174.0	193.3	133.7	292.4	307.5	5.2	0.27	0.27	1.1
290	0.13	1.3	231.7	284.0	174.3	405.9	404.8	0.3	0.28	0.28	1.1

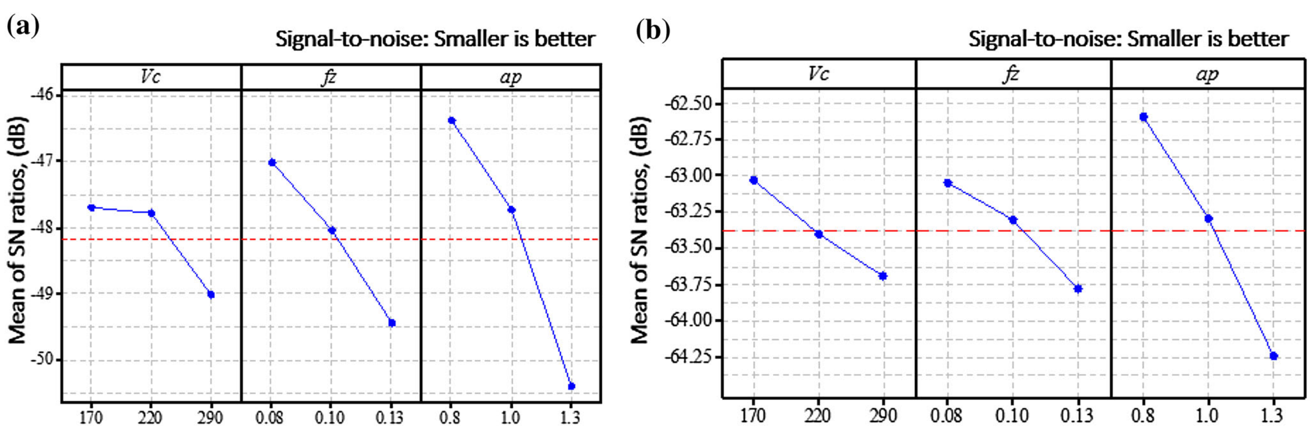


Fig. 10 Mean effect plots for the milling force for **a** Al7075 and **b** MMCs

machining feed of 0.08 mm/tooth and axial depth of cut of 0.8 mm for the milling force during milling the Al7075 in contrast to the S/N ratios results. From evaluation of the RSM results, the composite desirability values (from 0.98814 to 1) are close to or equal to 1, which indicates the optimal cutting conditions for all responses.

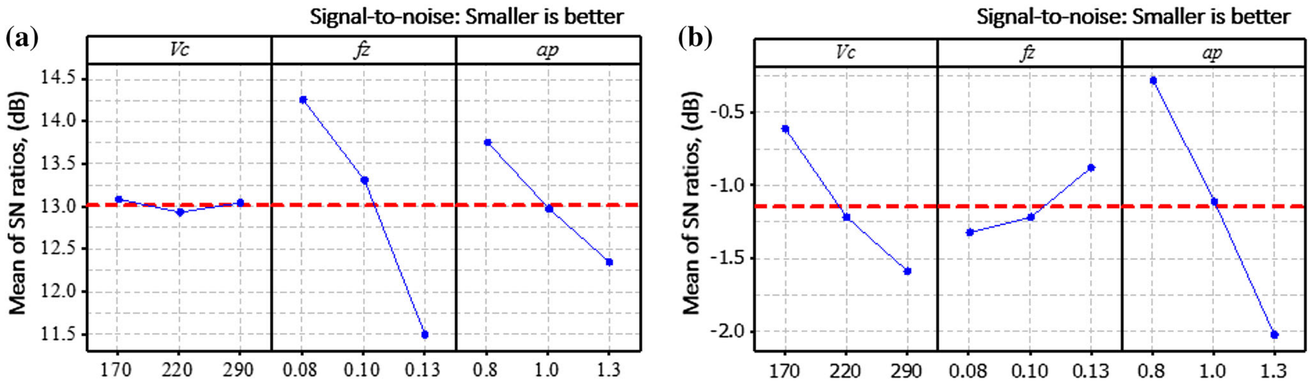


Fig. 11 Mean effect plots for the tool wear with **a** Al7075 and **b** MMCs

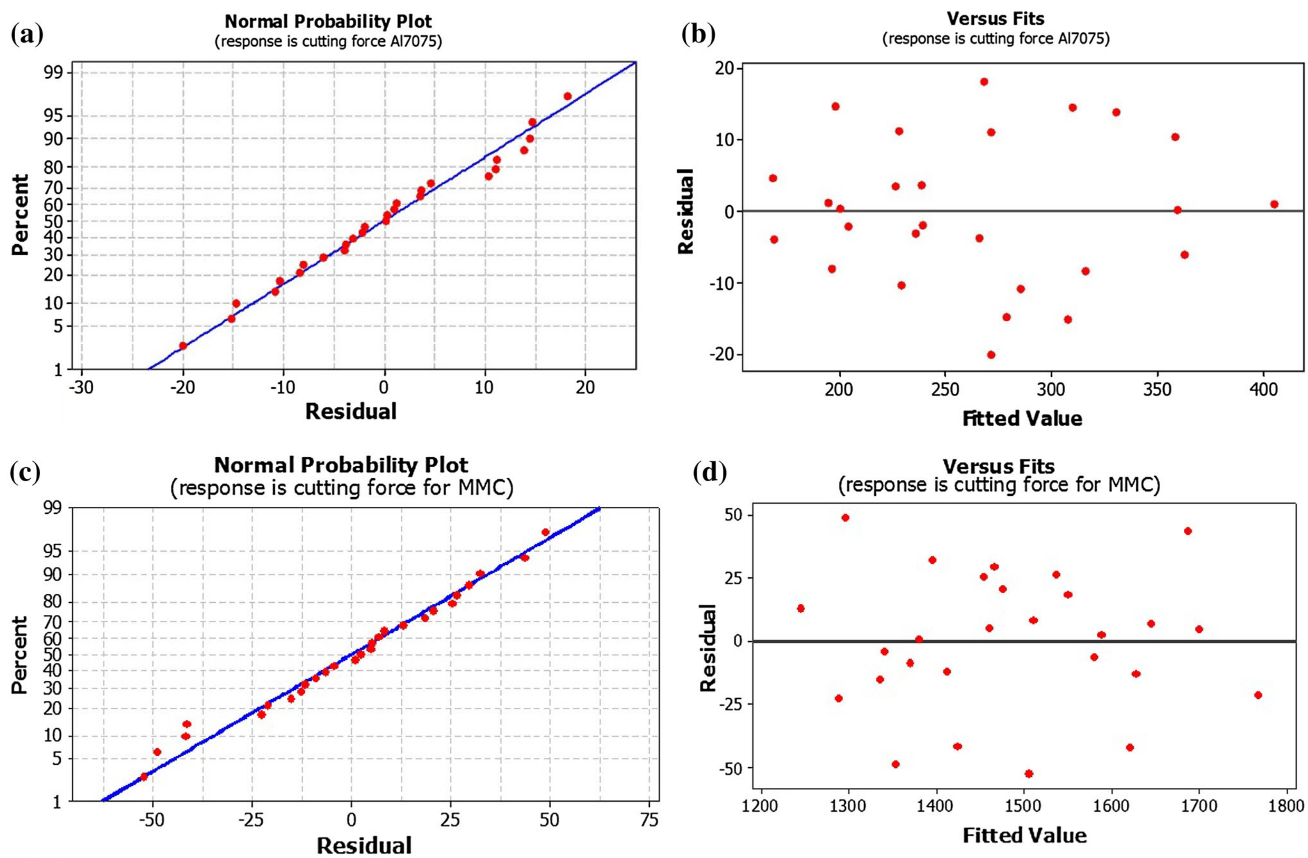


Fig. 12 Residuals plots for milling force **a** normal plot of residuals, **b** residuals versus predicted for Al7075 and **c** normal plot of residuals and residuals versus predicted for MMC

3.2 Analysis of Variance (ANOVA)

ANOVA was used to understand the effect of important coefficients of the cutting parameters on the quality of milling force and tool wear based on their *P* value and *F* value at the 95 % confidence level. The important coefficients of machining variables on the milling force and tool wear are presented in Tables 7 and 8, respectively. The effect rate column indicates that the milling speed, feed and axial cutting depth have a significant effect on the milling force. In conclusion from the ANOVA, the milling speed, feed and axial cutting depth affected the milling force 8.61, 23.23 and 65.51 %, respectively, for Al7075-T6 and 11.26, 14.22 and 70.48 %, respectively, for Al7075 reinforced with open-cell SiC foam composite. It is concluded that the axial cutting depth is the most influential factor for milling force in the milling of both experimental workpiece materials. The ANOVA analysis showed that the machining speed has minimal correlation

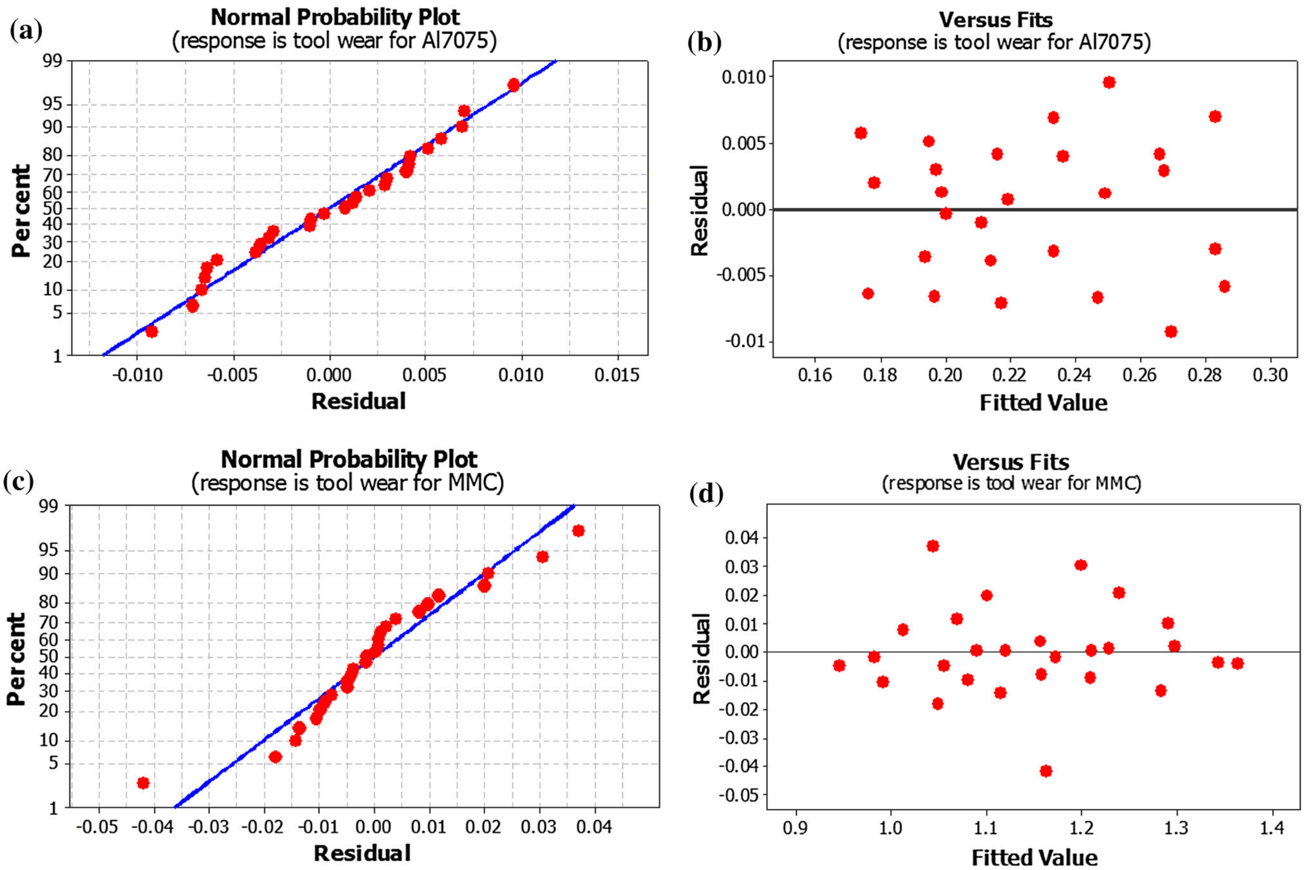


Fig. 13 Residuals plots for tool wear **a** normal plot of residuals, **b** residuals versus predicted for Al7075 and **c** normal plot of residuals and residuals versus predicted for MMC

Table 4 Response table for S/N ratios for Al7075 (smaller is better)

Level	S/N ratios for Milling force			S/N ratios for tool wear		
	Vc	*fz*	a_p	*Vc*	*fz*	a_p
1	**−47.69**	**−47.02**	**−46.38**	**13.08**	**14.25**	**13.74**
2	−47.79	−48.04	−47.73	12.93	13.31	12.97
3	−49.02	−49.45	−50.40	13.04	11.49	12.34
Delta	1.33	2.42	4.02	0.15	2.75	1.40
Rank	3	2	1	3	1	2

with the cutting tool wear, while the feed rate is the most significant machining parameter in the milling of Al7075 [25]. It seems obvious that the feed rate and axial cutting depth influenced the tool wear 79.31 and 18.34 % for the Al7075-T6. On the other hand, the milling speed, cutting feed and axial cutting depth affected the tool wear 21.35, 4.85 and 70.23 %, respectively, in the milling of Al7075 reinforced with open-cell SiC foam composite. Cutting tool wear was directly affected by depth of cut in the milling of MMC [16]. It was observed that the axial cutting depth has a stronger effect on the tool wear as compared to milling speed and milling feed.

In order to predict the optimized conditions for the milling forces and cutting tool wear, second-degree polynomial models have been developed using RSM in the milling of both Al7075 and MMC. Response surface quadratic equations were utilized to understand the relationship between the responses and independent milling parameters and their squared terms in a central composite design. A quadratic polynomial function with three milling variables x, y and z can be stated using the following Eq. (2):

$$\eta = \beta_0 + \beta_1 \times x + \beta_2 \times y + \beta_3 \times z + \beta_4 \times x^2 + \beta_5 \times y^2 + \beta_6 \times z^2 + \beta_7 \times x \times y + \beta_8 \times x \times z + \beta_9 \times y \times z \quad (2)$$

where η is the predicted response (milling force and tool wear), β_0 is constant, and β_1–β_9 are the coefficients of the second-degree model. Second-degree polynomial models can be expressed as a function of the milling parameters such as machining speed (x), feed rate (y) and axial depth of cut (z). Second-degree analytical models have been developed for estimation of the milling force using experimentally measured values by RSM methodology and expressed as follows:

Table 5 Experimental results and S/N ratio values for Al7075–MMC

Parameters			Milling forces						Tool wear		
Vc	*fz*	*ap*	*Fx*	*Fy*	*Fz*	Measured *Fr*	Predicted *Fr*	Error %	Measured *VB (mm)*	Predicted *VB (mm)*	Error %
170	0.08	0.8	746.0	478.7	891.7	1257.3	1235.5	1.73	0.98	0.99	1.07
170	0.08	1	809.3	568.0	849.7	1303.7	1350.4	3.58	1.09	1.09	0.06
170	0.08	1.3	1087.7	633.0	849.7	1518.4	1518.0	0.03	1.21	1.21	0.05
170	0.1	0.8	753.3	451.3	911.0	1265.4	1278.4	1.03	0.98	0.98	0.14
170	0.1	1	907.0	563.7	947.0	1427.3	1393.3	2.38	1.07	1.08	0.93
170	0.1	1.3	1063.7	703.0	914.3	1568.9	1560.9	0.51	1.23	1.20	2.48
170	0.13	0.8	774.7	524.3	989.3	1361.5	1360.2	0.10	0.94	0.94	0.53
170	0.13	1	929.0	650.3	976.0	1496.2	1475.0	1.41	1.08	1.04	3.42
170	0.13	1.3	1043.0	771.0	963.3	1615.6	1642.6	1.67	1.12	1.16	3.73
220	0.08	0.8	821.0	493.7	943.7	1344.7	1296.4	3.59	1.08	1.07	1.07
220	0.08	1	908.0	587.3	888.7	1399.7	1411.3	0.83	1.17	1.17	0.13
220	0.08	1.3	1082.7	693.7	906.7	1573.3	1578.9	0.35	1.3	1.30	0.16
220	0.1	0.8	733.0	521.3	987.7	1335.9	1339.3	0.26	1.05	1.05	0.47
220	0.1	1	960.7	575.3	967.3	1479.7	1454.2	1.73	1.15	1.16	0.68
220	0.1	1.3	1071.3	733.7	898.3	1578.9	1621.8	2.71	1.27	1.28	1.08
220	0.13	0.8	811.0	524.3	989.3	1382.5	1421.0	2.78	1.02	1.01	0.79
220	0.13	1	984.0	675.7	1008.7	1562.8	1535.9	1.72	1.1	1.11	1.30
220	0.13	1.3	1159.3	772.0	983.0	1704.8	1703.5	0.07	1.26	1.24	1.63
290	0.08	0.8	794.3	477.3	940.0	1320.0	1348.7	2.17	1.12	1.12	0.02
290	0.08	1	926.7	616.7	953.7	1465.8	1463.6	0.15	1.23	1.23	0.09
290	0.08	1.3	1118.0	741.0	962.7	1651.0	1631.1	1.20	1.36	1.36	0.31
290	0.1	0.8	831.0	516.3	975.3	1381.5	1391.5	0.73	1.12	1.10	1.77
290	0.1	1	896.3	586.0	981.3	1452.5	1506.4	3.71	1.2	1.21	0.74
290	0.1	1.3	1152.0	792.0	1018.7	1729.8	1674.0	3.22	1.34	1.34	0.28
290	0.13	0.8	829.7	628.3	1074.0	1495.5	1473.3	1.49	1.03	1.05	1.74
290	0.13	1	949.7	728.7	1047.7	1590.7	1588.2	0.16	1.16	1.16	0.33
290	0.13	1.3	1175.7	797.3	1015.0	1745.9	1755.8	0.57	1.3	1.29	0.75

Table 6 Response table for S/N ratios for MMCs (smaller is better)

Level	S/N ratios for milling force			S/N ratios for tool wear		
	Vc	*fz*	a_p	*Vc*	*fz*	a_p
1	**−63.03**	**−63.05**	**−62.59**	**−0.6172**	−1.3326	**−0.2890**
2	−63.40	−63.30	−63.30	−1.2258	−1.2260	−1.1201
3	−63.70	−63.78	−64.24	−1.5987	**−0.8830**	−2.0325
Delta	0.66	0.73	1.65	0.9815	0.4495	1.7434
Rank	3	2	1	2	3	1

Table 7 Optimal milling parameters based on S/N for F_r and tool wear (VB)

	S/N ratios results for milling force				S/N ratios results for tool wear			
Material	*Vc* (m/min)	*fz* (mm/tooth)	*ap* (mm)	Predicted *Fr*	*Vc* (m/min)	*fz* (mm/tooth)	*ap* (mm)	Predicted *VB*, mm
Al7075	170	0.08	0.8	164	170	0.08	0.8	0.17
MMCs	170	0.08	0.8	1235.5	170	0.13	0.8	0.93

Table 8 Optimal milling parameters based on RSM for F_r and VB

Responses	Goal	Optimum milling parameters			Lower level	Upper level	Predicted response	Desirability
		Vc (m/min)	*fz* (mm/tooth)	*ap* (mm)				
Fr_Al7075	Minimum	195.45	0.08	0.8	164	406	165.96	0.99189
Fr_MMC	Minimum	170	0.08	0.8	1257	1746	1244.3	1.000
VB_Al7075	Minimum	170	0.08	0.8	0.17	0.29	0.1742	0.96479
VB_MMC	Minimum	170	0.13	0.8	0.94	1.36	0.9450	0.98814

Table 9 Milling force results of ANOVA for S/N ratios in the milling of Al 7075–MMC

Source	DF	SS	MS	F	P	Effect rate (%)
Milling force for Al7075						
Vc	2	9.888	4.9439	32.61	0.000	8.61
fz	2	26.670	13.334	987.95	0.000	23.23
a_p	2	75.205	37.602	4247.99	0.000	65.51
Residual error	20	3.033	0.1516			2.64
Total	26	114.795				
Milling force for MMC						
Vc	2	1.9766	0.98830	27.92	0.000	11.26
fz	2	2.4959	1.24794	35.25	0.000	14.22
a_p	2	12.3693	6.18466	174.69	0.000	70.48
Residual error	20	0.7081	0.03540			4.03
Total	26	17.5499				

Table 10 Tool wear results of ANOVA for S/N ratios in the milling of MMC

Source	DF	SS	MS	F	P	Effect rate (%)
Tool wear for Al7075						
Vc	2	0.000052	0.000026	0.77	0.477	%
fz	2	0.024630	0.012315	365.38	0.000	79.31%
a_p	2	0.005696	0.002848	84.51	0.000	18.34%
Residual error	20	0.000674	0.000034			2.17%
Total	26	0.031052				
Tool wear for MMC						
Vc	1	0.072377	0.072377	138.111	0.000000	21.35%
fz	1	0.016464	0.016464	31.417	0.0000105	4.85%

Table 11 Comparison of experimental and predicted values by RSM models for F_r

Test no.	*Vc* (m/min)	*fz* (mm/tooth)	*ap* (mm)	Experimental results, Fr (N)	Predicted results, Fr (N)	Desirability	Error (%)
Al7075							
1	180	0.08	0.9	189	179	0.93737	5.29
2	190	0.1	1.2	260	276	0.53669	6.15
3	210	0.12	1	273	255	0.62491	6.59
4	240	0.09	0.8	178	187	0.90464	5.06
MMC							
1	180	0.08	0.9	1325	1311	0.88852	1.05
2	190	0.1	1.2	1548	1528	0.44416	1.29
3	210	0.12	1	1432	1496	0.51002	4.47
4	240	0.09	0.8	1348	1332	0.84598	1.19

Table 12 Comparison of experimental and predicted values by RSM models for VB

Test No.	*Vc* (m/min)	*fz* (mm/tooth)	*ap* (mm)	Experimental results, Fr (N)	Predicted results, Fr (N)	Desirability	Error (%)
Al7075							
1	180	0.08	0.9	0.190	0.185	0.86882	2.63
2	190	0.1	1.2	0.240	0.230	0.49457	4.17
3	210	0.12	1	0.260	0.250	0.33314	3.85
4	240	0.09	0.8	0.200	0.188	0.84675	6.00
MMC							
1	180	0.08	0.9	1.14	1.060	0.71289	7.02
2	190	0.1	1.2	1.30	1.200	0.38006	7.69
3	210	0.12	1	1.08	1.119	0.57171	3.61
4	240	0.09	0.8	1.02	1.083	0.65746	6.18

$$F_{\mathrm{rAl7075}} = 370.2 - 1.82 \times Vc + 955.8 \times fz - 392 \times ap + 0.004 \times Vc^2 + 1186.6 \times fz^2 + 253.5 \times ap^2 - 0.82 \times Vc \times fz + 0.28 \times Vc \times ap + 404.8 \times fz \times ap. \quad (3)$$

$R^2 = 97.5\,\%$

$$F_{\mathrm{rMMC}} = 471.7 - 1.92 \times Vc + 199.7 \times fz + 501.3 \times ap - 0.004 \times Vc^2 + 11607.8 \times fz^2 - 31.65 \times ap^2 + 0.82 \times Vc \times fz + 0.72 \times Vc \times ap - 320 \times fz \times ap. \quad (4)$$

$R^2 = 96.3\,\%$

The quadratic polynomial model can be stated as a function of the milling parameters for tool wear (VB) using RSM methodology with uncoded cutting levels. The prediction models obtained from experimental results for VB are represented with Eqs. (5) and (6).

$$\mathrm{VB}_{\mathrm{Al7075}} = -0.016 + 0.0004 \times Vc - 0.87 \times fz + 0.24 \times ap - 0.00000082 \times Vc^2 + 11.11 \times fz^2 - 0.077 \times ap^2 - 0.000004 \times Vc \times fz - 0.000036 \times Vc \times fz - 0.018 \times fz \times ap. \quad (5)$$

$R^2 = 97.8\,\%$

$$\mathrm{VB}_{\mathrm{MMC}} = -0.17 + 0.0004 \times Vc + 3.09 \times fz + 0.77 \times ap - 0.0000069 \times Vc^2 - 15.18 \times fz^2 - 0.19 \times ap^2 - 0.0044 \times Vc \times fz + 0.00043 \times Vc \times fz - 0.083 \times fz \times ap. \quad (6)$$

$R^2 = 98.1\,\%$

3.3 Confirmation Experiments

In order to verify the prediction performance of the developed RSM model, four confirmation experiments for each response parameter were carried out. The milling parameters for the validation experiments were selected within the limits of predetermined and applied experimental conditions. The measured experimental milling force and tool wear for both Al7075 and MMC were compared with the predicted values (Tables 11 and 12). The results indicate that the percentage error between experimental data and the estimated results for milling force and tool wear are within the acceptable limits. Milling forces and tool wear estimated by the analytical model are in concordance with experimentally measured values.

4 Conclusions

Al7075-based MMCs reinforced with 3D open-cell SiC foam were successfully produced using the liquid metallurgy technique, and the effects of the milling parameters on the milling force and tool wear were investigated. From the results of this experimental investigation, conclusions may be drawn as follows:

- The resultant milling force increased for a machining speed of 290 m/min while remaining almost constant for machining speeds of 170 and 220 m/min in the milling of Al7075 and MMC.
- The milling force and tool wear increased, while the axial cutting depth increased from 0.8 to 1.3 mm.
- From the ANOVA, milling speed, feed and axial cutting depth affected the milling force with percentage contributions of 8.61, 23.23 and 65.51 %, respectively, for Al7075 and 11.26, 14.22 and 70.48 %, respectively, for SiC foam composite. The most effective milling para-

meters for milling force were the axial cutting depth for both workpiece materials.

- It was observed that milling speed, feed and axial cutting depth influenced the tool wear with percentage contributions of 21.35, 4.85 and 70.23 %, respectively, in the milling of MMCs. Tool wear was directly affected by the axial cutting depth in the milling of MMC.
- The cutting feed was the most significant effect, with percentage contributions of 79.31 % followed by the axial depth of cut at 18.34 % on the tool wear in the milling of Al7075.
- From the ANOVA results, a meaningful correlation was not observed between the machining speed and tool wear in the milling of Al7075.
- The optimum levels of the control factor for minimizing the resultant milling force and tool wear were obtained at a machining speed of 170 m/min, at feed per tooth of 0.08 mm/tooth and at an axial depth of cut of 0.8 mm in the milling of both workpiece materials.
- Confirmation experiments were carried out to determine the prediction performance of the mathematical models. The percentage errors between measured data and estimated data were between 1.05 and 6.59 % for milling forces. Tool wear was predicted with a percentage error between 2.63 and 7.69 %.
- Uncoated carbide tool showed a good machining performance below a machining speed of 220 m/min in finish milling Al7075 workpiece material, but it was not efficient in the milling of MMCs. It was observed that the machining parameters for milling forces and tool wear were not suitable for the milling of MMCs. A milling speed below 170 m/min and axial cutting depth under 1 mm can be suggested for the milling of reinforced SiC foam composites using an uncoated carbide tool.

These experimental results and prediction models are expected to provide useful guidelines for automotive and aerospace applications in the face milling of aluminium composites reinforced with open-cell SiC foam.

Acknowledgments The authors wish to thank the Hacettepe University Scientific Research Projects Coordination Unit for the financial support to this work through the Scientific Research Projects Grant Funding No. 1743.

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