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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Optimization of Machining Conditions for Surface Quality in Milling AA7039-Based Metal Matrix Composites

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Abstract In the present study, aluminium 7039-based 10% weight fraction of SiC and 10% B_4C_p metal matrix composites (MMCs) were produced by powder metallurgy and investigated the influential machining parameters on surface quality using an uncoated carbide tool under dry cutting environment. The experiments were performed based on Taguchi's L_{18} $(2^1 \times 3^2)$ with a mixed orthogonal array. The optimal cutting parameters for better surface finish were defined using signal-to-noise (S/N) ratio, central composite desirability function and regression analysis. Experimental results showed that the finished surface was significantly affected by the interfacial bonding effect of reinforcement particles and built-up edge formation. Better surface roughness was obtained in the milling of AA7039/B_4C-MMCs. The analysis findings indicated that the most significant cutting parameters on the finished surface were the cutting speed and feed rate. The cutting depth was not shown to have a meaningful correlation with surface quality in the milling of both MMCs. Artificial neural network was produced a low prediction error as compared to the regression modelling.

Keywords AA7039/B_4C/SiC · Metal matrix composite · Milling · Surface roughness · ANN · Regression analysis

1 Introduction

Aluminium and aluminium-based MMCs are very useful engineering materials for many engineering purposes in automotive, aerospace, armour, and aeronautical applications because of their low density in combination with their excellent wear resistance, high specific strength, hardness, and fracture toughness. However, machinability of MMCs is considered difficult in connection with hard reinforcement elements in matrix structure [1–6]. B_4C and SiC are highly hard reinforcement materials having high hardness, corrosion resistance, and good mechanical properties. These ceramics are widely preferred in numerous engineering implementations requiring high resistance such as in the nuclear industry, for tank armour, and ballistic protections. Therefore, many researchers in recent years have investigated the production and machinability requirements of aluminium-based composites reinforced with B_4C and SiC [7–10]. Karabulut [11] fabricated an aluminium 7039-based MMC reinforced with Al_2O_3. The optimal milling variables based on the Taguchi design of experiments for surface quality and milling force were investigated. The results of experiments indicated that the optimal surface measurement was achieved in milling of AA7039/Al_2O_3 composite workpiece material compared to unreinforced AA7039. The quality of finished surface was increased at lower feed rate and higher cutting speed. Kumar et al. [12] studied the influence of turning factors on surface quality in machining of Al7075/SiC and Al7075 hybrid composite using a polycrystalline diamond tool (PCD). It was found that the surface quality of the hybrid composite was lower than the Al7075 reinforced with 10 wt% SiC in all turning experiments. Venkatesan et al. [13] fabricated an aluminium alloy-based hybrid composite reinforced with different weight fractions SiC (5, 10, 15%) and B_4C (5%) and investigated the surface quality and cutting force using var-

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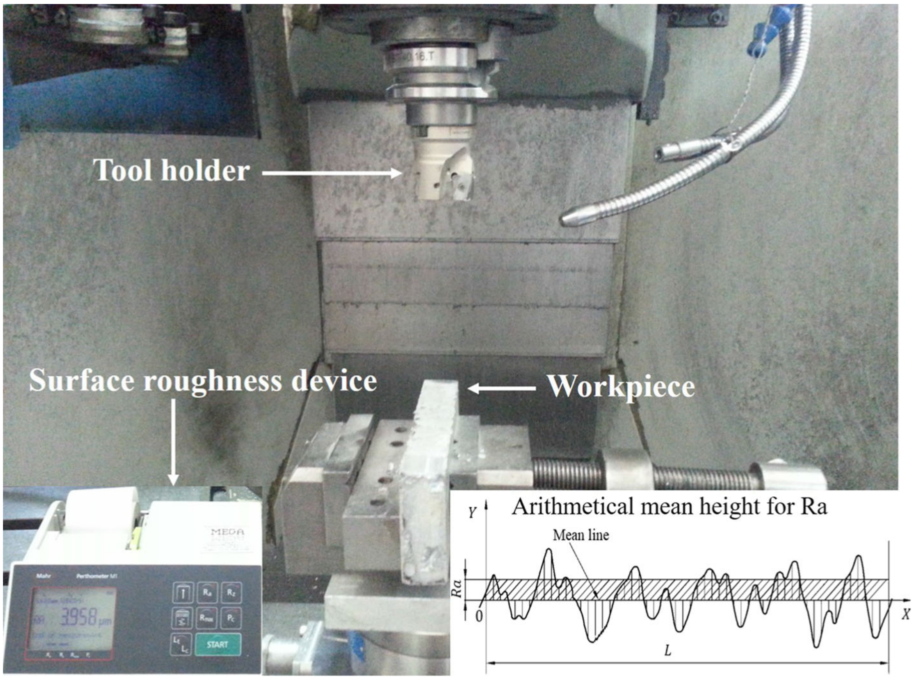


Fig. 1 Experimental set-up for surface roughness (*Ra*)

ious turning parameters. The surface quality was decreased with increasing feed rates and improved at higher cutting speed during machining. The optimal surface roughness was measured during turning with the combination of 12.5% with %5 B_4C hybrid composite material. Manna et al. [4] observed built-up edge (BUE) creation at low machining speed correlated with the increment of surface roughness and cutting forces in the machining of Al/SiC. Surface quality was improved at high machining speed, low cutting feed, and low cutting depth. Sahoo et al. [9] reported BUE formation at high and lower machining speed and at high feed rate combinations in turning Al/SiCp MMC using an uncoated tungsten cutting tool. Surface roughness was negatively affected by the BUE formation. Muthukrishnan et al. [14] experimentally investigated in turning of A356/SiC/20p using a PCD coarse grade cutting insert and modelled the experimental results to predict the surface measurement. They reported that the most influential turning factor on surface quality was the feed rate and came after by machining speed and cutting depth. Kılıçkap et al. [15,16] studied the machining characteristic of 5% SiCp aluminium MMC using TiN-coated and uncoated carbide inserts under dry turning conditions. From the experimental results, surface finish was affected with the machining speed and feed rate.

From the literature research, it is concluded that researchers have investigated the machining properties of aluminium-based MMC. In previous research, Karabulut investigated the milling of AA7039/Al_2O_3 MMC and optimized the machining parameters [11]. The machinability of AA7039/B_4C_p- and AA7039/SiC_p-reinforced composites has not been studied. The main goal of this research is to study the effect of B_4C and SiC reinforcement particles on the machining and microstructural characteristic of aluminium 7039. For this purpose, aluminium 7039-based B_4C_p and SiC_p MMCs were manufactured by powder metallurgy and consolidated with hot extrusion route for the higher mechanical properties. Then, we investigated the microstructure of the specimens to determine the particle distribution and interface bonding effect between the ceramic particles and matrix. Machining experiments were carried out to define the influence of B_4C and SiC ceramic particles on the milling and surface quality of the composites under dry cutting conditions. Machining parameters were optimized by Taguchi, response surface methods (RSM), and ANN. Furthermore, the results were analysed using ANOVA to determine the most effective parameters under study.

2 Experimental Methods

2.1 Milling Experiments

The machining studies have been performed by milling of aluminium 7039-based B_4C_p/SiC_p composites using a rigid and powerful CNC milling machine (Johnford VMC550) under dry cutting conditions (Fig. 1). For milling experiments, WK10-quality uncoated carbide tool was used with an ISO designation of LNGX 130708R-L88. The machining parameters were specified according to ISO Standard 8688-1 and cutting tool manufacturer advices [17]. Three machining speeds, feed rates, and cutting depths with three levels were selected, and the experimental milling variables for surface roughness (*Ra*) and their levels are presented in Table 1.

Table 1 Milling parameters for surface roughness (*Ra*) and experimental levels

Factors	Notation	Unit	Level 1	Level 2	Level 3
A—Material	M		AA7039/B_4C	AA7039/SiC	–
B—Cutting speed	V_c	m/min	290	375	488
C—Feed rate	f_z	mm/tooth	0.1	0.13	0.17
D—Depth of cut	a_p	mm	0.8	1	1.3
Workpiece dimension		mm	90 × 50 × 24		
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		

Table 2 Chemical compositions of AA7039

Chemical composition (wt%)								
Mg	Zn	Cu	Si	Mn	Ti	Fe	Cr	Al
4.17	4.39	0.53	0.45	0.2	0.19	0.12	0.02	89.91

Table 3 Hardness of AA7039 and metal matrix composite

Hardness of AA7039 (Hv)	Hardness of AA7039/B_4C (Hv)	Hardness of AA7039/SiC (Hv)
110	129	101

Every experiment was carried out with a new carbide insert, and machined surfaces were measured at six different regions along 90 mm without removing the workpiece using a MAHR-M1 portable surface finish measurement instrument (cut of length 0.8 mm). The measurements were taken according to standard ISO 4287 [18]. The average surface roughness Ra value is defined based on the ISO 4287 standard and indicates the arithmetic average of all absolute values of the roughness profile height deviations from the mean line within the measured length as shown in Fig. 1. *Ra* is the average of all peaks and valleys on the machined surface of the roughness profile and calculated by an algorithm given in Eq. (1).

$$Ra = \frac{1}{L}\int_0^L |z(x)|\, \mathrm{d}x \qquad (1)$$

where L is the evaluation length, and z is the profile height of the function. The maximum and minimum (*Ra*) values were removed, and the mean values were computed in order to achieve the statistically meaningful result for the experiments. The microstructure of the samples and the insert used in the tests were analysed by scanning electron microscopy (SEM) using a JEOL JSM 6060 LV electron microscope.

2.2 Workpiece Materials

The milling experiments were performed using B_4C and SiC particle-reinforced aluminium AA7039 alloy composites. For producing metal matrix composites, 150 µm powders for AA7039, 10 µm B_4C, and SiC particles were used. AA7039 aluminium alloy was produced using metal powders by powder metallurgy, and the chemical compositions are given in Table 2. For this purpose, the powders in the ratios listed in Table 2 were weighed by a weighing instrument in the precision range of 10–5 g and stirred for 60 min in a three-dimensional blender in order to achieve a homogeneous mixture. Then, the resulting unreinforced aluminium 7039 alloy and B_4C and SiC powders were separately mixed uniformly for 30 min in order to obtain metal matrix composite powder mixtures. The next step, the mixed AA7039/B_4C and AA7039/SiC powders were firstly cold pressed at a pressure of 300 MPa. In the third step, the cold-pressed composites were sintered at 550 °C for 1 h and test specimens were extruded in a preheated mould of temperature 500 °C for 1 h. The AA7039/B_4C and AA7039/SiC particle-reinforced composites were heated at 470 °C for 2 h and then hardened in water. In the final phase, samples were aged at 120 °C for 24 h in a furnace. Hardness of workpiece materials was measured by using a Vickers HV_3 hardness measurement instrument by employing a 3-kg load on the composites for 5 s. The average value of hardness for each sample was determined by measuring six different zones and is represented in Table 3. To examine the machined workpiece materials and used cutting tools in the experiments utilized the SEM micrographs and energy-dispersive spectroscopy (EDS) results. The optical micrographs of the machined surface of the samples are indicated in Fig. 2a, b.

2.3 Experimental Design

The experimental design of three milling variables— cutting speed, axial cutting depth, and feed rate—was used as the cutting parameters with three levels (3^3), and specimens with two levels $\left(2^1\right)$ AA7039/B_4C and AA7039/SiC are designed by Taguchi's L_{18} $\left(3^3 \times 2^1\right)$. If the full facto-

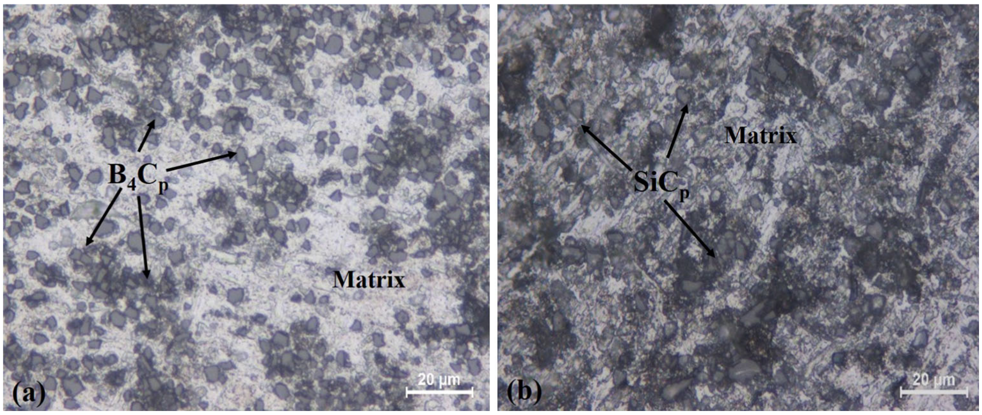


Fig. 2 Optical micrographs of **a** AA7039/B_4C; **b** AA7039/SiC

Table 4 The measurement results, S/N ratios, and desirability values for *Ra*

Exp. no.	Control factors						
	A Material (M)	B Milling speed (Vc)	C Feed rate f_z	D Axial depth of cut a_p	Surface roughness $Ra(\mu m)$	Desirability Ra(μ)m	*S*/*N* ratio for *Ra* (dB)
1	10 wt% B_4C	290	0.1	1.3	1.4	0.426	−2.927
2	10 wt% B_4C	290	0.13	0.8	1.62	0.277	−4.216
3	10 wt% B_4C	290	0.17	1	2.04	0.000	−6.191
4	10 wt% B_4C	375	0.1	1	1.08	0.643	−0.638
5	10 wt% B_4C	375	0.13	1.3	1.19	0.565	−1.535
6	10 wt% B_4C	375	0.17	0.8	1.52	0.349	−3.618
7	10 wt% B_4C	488	0.1	1.3	0.54	0.998	5.292
8	10 wt% B_4C	488	0.13	0.8	0.9	0.758	0.8840
9	10 wt% B_4C	488	0.17	1	1.06	0.655	−0.486
10	10 wt% SiC	290	0.1	1.3	5.34	0.239	−14.545
11	10 wt% SiC	290	0.13	0.8	5.3	0.255	−14.493
12	10 wt% SiC	290	0.17	1	5.79	0.000	−15.256
13	10 wt% SiC	375	0.1	1	4.42	0.722	−12.905
14	10 wt% SiC	375	0.13	1.3	5.38	0.214	−14.622
15	10 wt% SiC	375	0.17	0.8	5.52	0.144	−14.833
16	10 wt% SiC	488	0.1	1.3	3.89	0.999	−11.804
17	10 wt% SiC	488	0.13	0.8	4.26	0.806	−12.584
18	10 wt% SiC	488	0.17	1	4.85	0.492	−13.723

rial design with the machining parameters and workpiece materials was used, it would have required ($3^3 \times 2^1$) 54 experimental runs. The L_{18} $\left(3^3 \times 2^1\right)$ array requires only 18 runs in Taguchi's full factorial orthogonal arrays, which predict the influence of cutting parameters on the results and variation (Table 4). Orthogonal arrays can reduce the number of experiments and reduce the influence of machining parameters that cannot be controlled. Furthermore, it gives an efficient and systematic solutions to achieving the optimal cutting conditions during the experiments [19,20]. There are a number of external factors not considered in the experimental design affecting the results. These external factors and their effect on the results in terms of quality characteristics are named "the noise". The *S*/*N* ratio is calculated in two steps. First, mean squared deviation (MSD) between the experimental results and target results is computed by Eq. (2). Second, calculated MSD values are transformed by using Eq. (3) [21]. Then, the cutting factors are evaluated based on the *S*/*N*. There are three different *S*/*N* ratios and individual desirability functions: larger the better, nominal is best, and smaller the better. This study aims to maximize the quality of machined surface. Therefore, the smaller the better has been chosen to calculate the *S*/*N* ratios by using following formulas (Eqs. 2, 3).

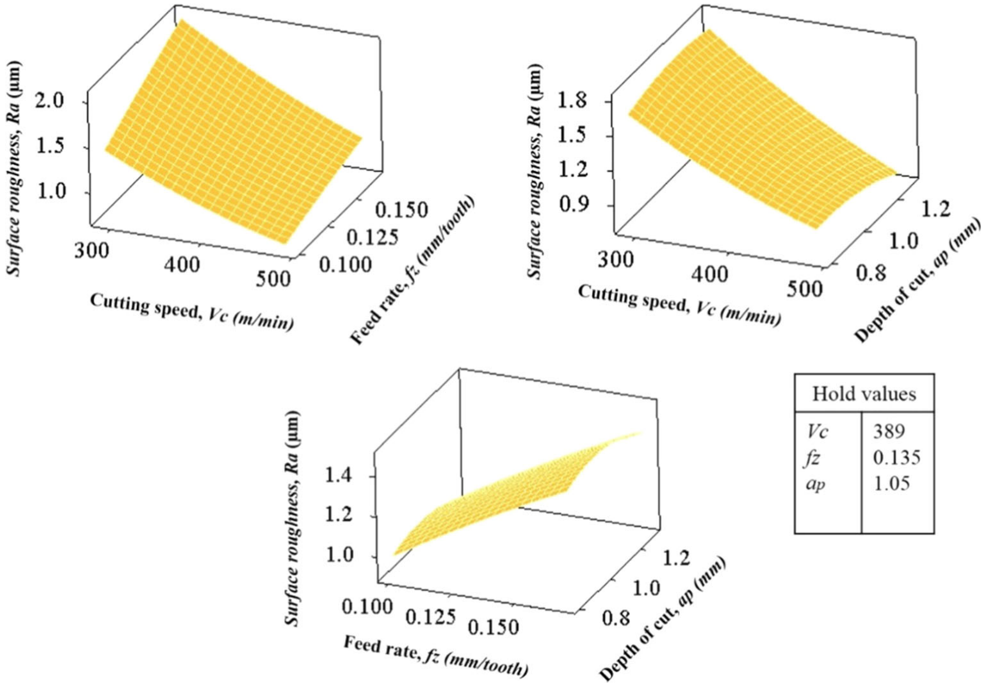


Fig. 3 The effects of milling parameters on *Ra* for AA7039/B_4C-p composite

$$\mathrm{MSD} = \left(y_1^2 + y_2^2 + y_3^2 + \cdots + y_n^2\right)/n \qquad (2)$$

$$S/N = -10 * \mathrm{Log}_{10}\,(\mathrm{MSD}) \qquad (3)$$

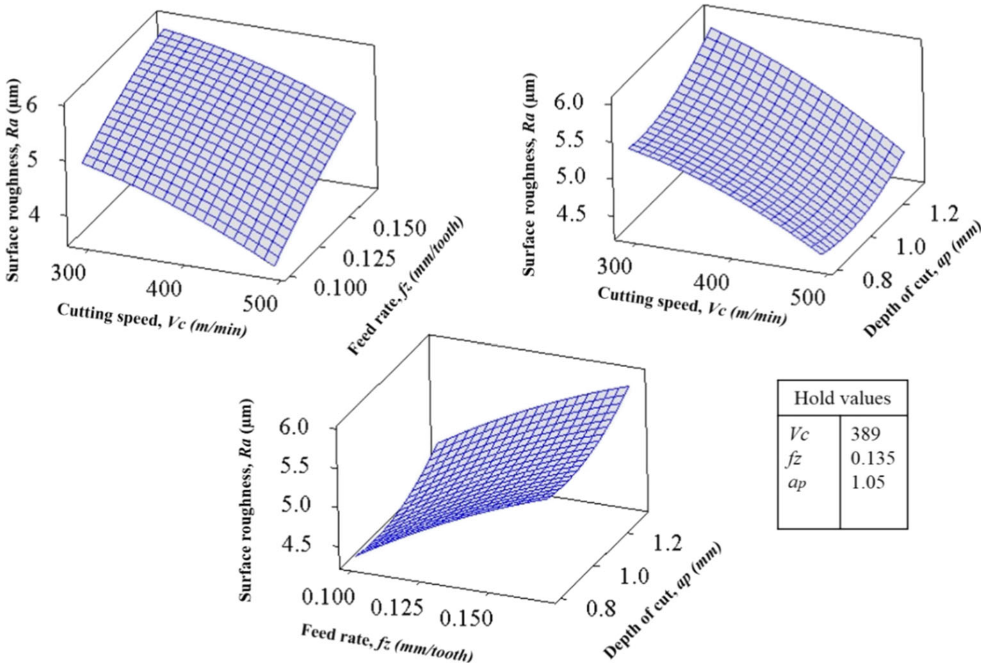
where y is the experimental (*Ra*) value and n is the number of tests in the experiments. Maximum data of *S*/*N* ratios are described as experimental parameter settings that minimized the effects of the noise factor; hence, a high *S*/*N* ratio is always chosen.

3 Experimental Results and Discussion

Aluminium 7039-based composite specimens were successfully manufactured by powder metallurgy methods and achieved a homogenous matrix structure (Fig. 2). In the milling process, quality of *Ra* is mostly affected by the machining parameters. 3D response surface plots which acquired response surface method using the developed RSM model in MINITAB 16 software were used to determine the relevance between the experimental parameters and machined surface quality.

The influences of each milling factor level on the surface quality were examined by use of the *S*/*N* ratio and a desirability function. The *S*/*N* ratios and desirability values for each experiment are computed based on the measured value as shown in Table 4. Figures 3 and 4 indicate the influence of machining speed at different feed rates on the average surface roughness during milling of both AA7039/B_4C–AA7039/SiC composites. The smallest *Ra* value was measured at high machining speed and lowest feed rate. This was ascribed to high BUE creation at low cutting speeds on the cutting insert during milling of both Al7039/B_4C–Al7039/SiC (Figs. 5, 6).

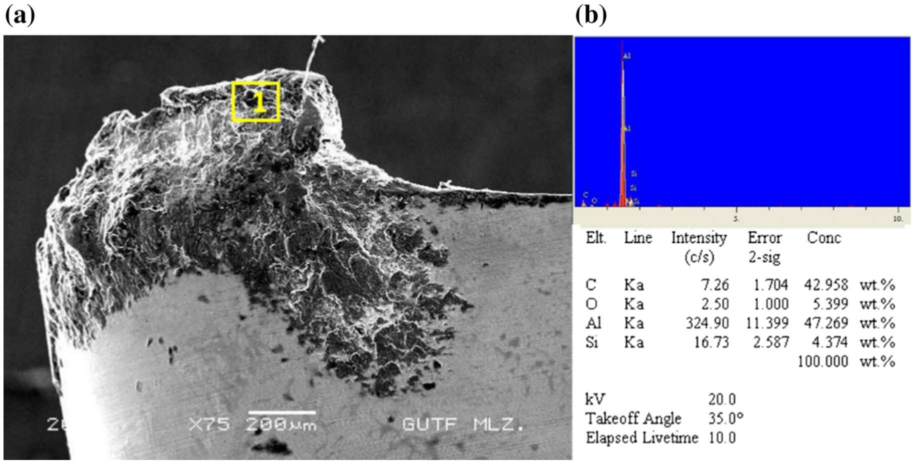
BUE constitution was observed at all milling conditions in the milling of both MMCs, but the size of the BUE was significantly reduced at higher cutting speeds. The previous and latest studies indicate that high cutting temperatures are produced at high cutting speed and feed rate [22,23]. In parallel to increasing feed rate and cutting speed, the cutting temperature increases at the machining area which carries with it the softening of the aluminium matrix and hence leads to the improved surface quality at all milling conditions. *Ra* values were almost constant at cutting depths of 0.8 and 1 mm. Surface quality was improved when cutting depth is increased from 1.0 to 1.3 mm because of the decreased BUE formation at 1.3 mm cutting depth. Higher cutting depth and higher cutting speed combination were improved the finished surface of both workpiece materials. The surface quality was decreased when the cutting feed is increased from 0.1 to 0.17 mm/tooth (Figs. 3, 4). Faster feed rates show a detrimental effect on the machined surface in the machining of both composite materials. This can be attributed to high vibration and high cutting temperatures in the machining area. The machining temperature increases at higher feed rates, and this leads to softening of the aluminium matrix in the composite structure [6,15,21]. Thus, B_4C/SiC particles are easily separated from the structure depending on the



Hold values	
Vc	389
fz	0.135
ap	1.05

Fig. 4 The effects of milling parameters on *Ra* for AA7039/SiCp composite

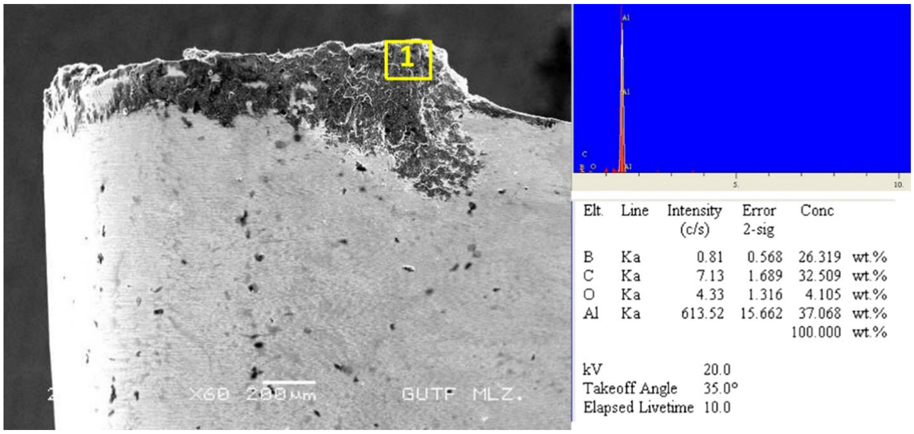
Fig. 5 **a** SEM micrograph of cutting tool in machining AA7039/SiCp MMC. **b** EDS analysis results (*1*) (Al, C, O, Si)



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	
C	Ka	7.26	1.704	42.958	wt.%
O	Ka	2.50	1.000	5.399	wt.%
Al	Ka	324.90	11.399	47.269	wt.%
Si	Ka	16.73	2.587	4.374	wt.%
				100.000	wt.%

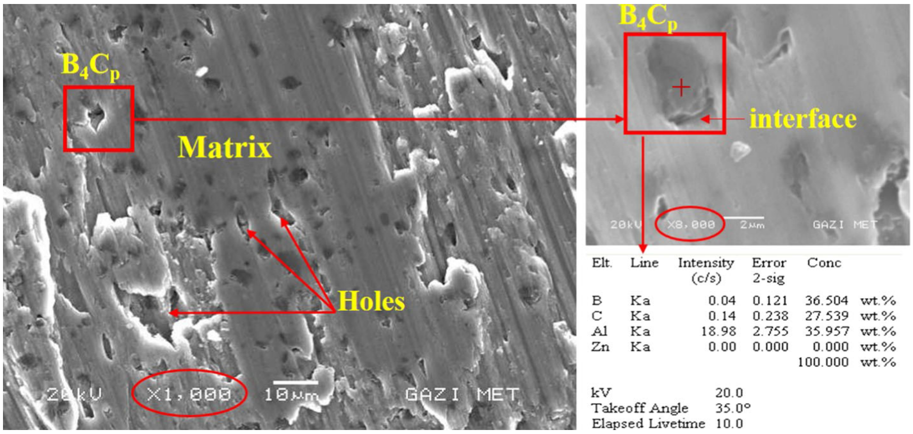
kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 10.0

Fig. 6 SEM micrograph of cutting tool in machining AA7039/B_4C-p and EDS analysis results (*1*) (Al, C, B, O)



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	
B	Ka	0.81	0.568	26.319	wt.%
C	Ka	7.13	1.689	32.509	wt.%
O	Ka	4.33	1.316	4.105	wt.%
Al	Ka	613.52	15.662	37.068	wt.%
				100.000	wt.%

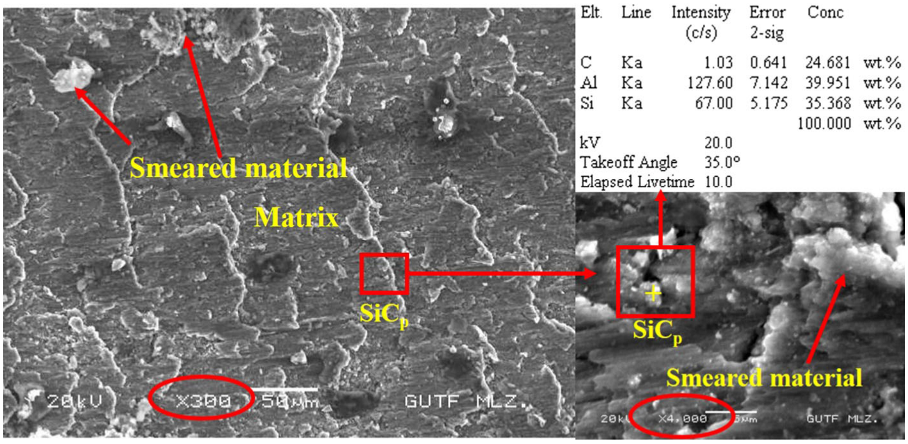
kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 10.0



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	
B	Ka	0.04	0.121	36.504	wt.%
C	Ka	0.14	0.238	27.539	wt.%
Al	Ka	18.98	2.755	35.957	wt.%
Zn	Ka	0.00	0.000	0.000	wt.%
				100.000	wt.%

kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 10.0

Fig. 7 Machined surface of AA7039/B_4C-p and EDS analysis results



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	
C	Ka	1.03	0.641	24.681	wt.%
Al	Ka	127.60	7.142	39.951	wt.%
Si	Ka	67.00	5.175	35.368	wt.%
				100.000	wt.%

kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 10.0

Fig. 8 Machined surface of AA7039/SiCp and EDS analysis results

loosening effects between the reinforcement elements and AA7039.

This study indicated that lower surface quality measurements were obtained in the machining of AA7039/SiC sample compared to AA7039/B_4C sample. These SiC/B_4C reinforcement materials are extremely hard, and the machinability of metal matrix composites also depends on the interfacial bond between the reinforcement particles and aluminium alloy. The interfacial bonding between the reinforcement element and matrix significantly affects the quality of the machined surface. A strong interfacial bond depends on the aluminium matrix structure and the nature of reinforcement particles. As shown in optical micrographs in Fig. 2a, b, B_4C and SiC particles are homogeneously dispersed in the matrix. SiC particles exhibited a good bonding at interfaces in the matrix, but there are voids around the B_4C particles and matrix. This indicates that the bonding between the B_4C and matrix weakens. Increasing machining temperatures depending on the higher cutting speeds and feed rates leads to softening of the aluminium matrix in the milling process [24]. Thus, B_4C particles were easily pulled out from the matrix by the cutting insert due to the reduced interface bonding between B_4C and matrix. This caused tiny holes in the machined surface of the composite material. These tiny holes and weak interfacial bonds are shown in Fig. 7. In the milling of SiC reinforcement composite, surface quality was decreased because SiC particles and matrix were removed together because of the strong bonding between SiC and matrix [20]. Therefore, this led to big holes in the machined surface in the milling of AA7039/SiC compared to AA7039/B_4C. During the machining process, it was also observed that smeared material remaining on the machined surface caused a poor surface quality in the milling of AA7039/SiC composites (Fig. 8). Some part of the softened matrix material was swept and moved across the machined surface instead of being cut, and the another part of the softened workpiece material was adhered to the cutting insert as a formation of BUE. Hence, better surface quality was obtained in the milling of AA7039/B_4C composite. As shown in the SEM micrographs in Figs. 5 and 6, the appearance of adhered workpiece material on the cutting edge as a formation of BUE was remarkably advanced in the machining of AA7039/SiC because of strong interfacial bonding between the SiC particles and aluminium alloy 7039. This BUE formation has also indicated a negative influence on the finished surface. The results of the experiment are in agreement with the previously published literature [4,9].

Table 5 Signal-to-noise ratios for B$_4$C and SiC (smaller is better)

Level	*Vc*	*fz*	*ap*	Level	*Vc*	*fz*	*ap*
1	−4.445	0.575	−2.317	1	−14.8	−13.1	−14
2	−1.930	−1.622	−2.438	2	−14.1	−13.9	−14
3	1.897	−3.432	0.2767	3	−12.7	−14.6	−13.7
Delta	6.3412	4.007	2.7148	Delta	2.06	1.52	0.31
Rank	1	2	3	Rank	1	2	3

Table 6 Optimal milling parameters based on RSM for *Ra*

Responses	Goal	Optimum milling parameters			Lower level	Upper level	Optimized response	Desirability
		Vc (m/min)	*fz* (mm/tooth)	*ap* (mm)				
*Ra*_B$_4$C	Minimum	488	0.1	1.3	0.54	1.62	0.543	0.99750
*Ra*_SiC	Minimum	488	0.1	0.95	3.89	5.79	3.552	1.00000

The *S*/*N* ratios and RSM were employed in order to define the optimal machining parameters in the milling of MMCs. The RSM is an optimization method using mathematical and statistical tools to determine the relationship between dependent variables and independent variables in the experimental procedure. The interaction effects of experimental variables on the output parameter can be determined by using this method and achieved the best set of factor levels [20,25]. The milling parameters, measured average surface roughness results, desirability values, and the *S*/*N* ratios are presented in Table 4.

The optimal milling variables and their levels were defined based on the *S*/*N* ratios (Table 5) and RSM (Table 6). The higher *S*/*N* ratios and composite desirability values indicate the optimum machining parameters and better quality of surface roughness. The value of desirability has a range between 0 and 1. If the desirability value is equal or close to 1, then this represents the ideal machining parameters. If the desirability value equals or approaches 0, then this means that responses are outside their acceptable machining parameters. The optimal machining parameters were defined as factor A (Level 3, $S/N = 1.897$), factor B (Level 1, $S/N = 0.575$), and factor C (Level 3, $S/N = 0.276$) based on the S/N ratios in the milling of AA7039/B$_4$C. The ideal milling variables for a better surface were obtained as factor A (Level 3, $S/N = 12.7$), factor B (Level 1, $S/N = 13.1$), and factor C (Level 3, $S/N = 13.7$), depending on the S/N ratios in the milling of AA7039/SiC. RSM was also used to identify the optimal milling parameters and compared with S/N ratios to maximize the quality of machined surfaces. Optimization values for AA7039/B$_4$C and AA7039/SiC are indicated in Table 6 obtained from the response surface method. Optimum milling parameters are achieved cutting feed of 0.1 mm/tooth, machining speed of 488 m/min, and an axial cutting depth of 1.3 mm in the machining of AA7039/B$_4$C. The predicted surface roughness value is Ra = 0.543 μm, and desirability value is 0.9975. In the milling of AA7039/SiC, the optimal machining parameters are specified as a feed rate of 0.1 mm/tooth, cutting speed of 488 m/min, and cutting depth of 0.95 mm; the optimized value for surface roughness is Ra = 3.552 μm and the desirability value is 1.0000.

3.1 Analysis of Variance (ANOVA)

The test results and significance level of milling variables on the quality of machined surface were analysed using ANOVA and main effect plots. The statistical contribution levels were evaluated by the machining parameter's *P* and *F* values at the 95% confidence level. If the *P* results are smaller than 0.05, the experimental factors are considered at a meaningful level of 95%. The milling factors, *P* values, and their significance rates for measurements are given in Table 7. From the result of ANOVA, the most effective parameter on the finished surface is a cutting speed with a 70.22% contribution of total variation. The next influential machining parameter is feed rate with a percentage contribution of 27.48% for AA7039/B$_4$C composite. The ANOVA results show that cutting speed and the feed rate influence the surface finish by factors of 59.52 and 30.91% for AA7039/SiC composite, respectively. The finished surface of workpiece was considerably affected by cutting speed with a percentage contribution of 70.2 and 59.52 % in the cutting of both AA7039/B$_4$C and AA7039/SiC. The least influential milling factor on the quality of machined surface was axial depth of cut with a percentage contribution of 3.96 and 4.07% in the cutting of both composite workpiece materials, respectively.

As shown in mean effect plots in Figs. 9 and 10, surface quality was improved with increasing cutting depth from 1.0 mm to 1.3 mm. Surface quality was remarkably worsened during milling of the AA7039/SiC metal matrix composite compared to AA7039/B$_4$C (Fig. 9). Better surface quality can be achieved for a higher machining speed and lower feed

Table 7 The outcomes of ANOVA for *Ra*

Source	Degree of freedom (*df*)	Sum of squares (SS)	Mean of squares (MS)	*F* ratio	*P* value	Significance rate (%)
Surface roughness (*Ra*) for B_4C MMCs						
Vc	1	108.558	108.558	185.595	0.000038	70.22
fz	1	0.42492	0.27161	46.435	0.001037	27.48
a_p	1	0.00613	0.00613	1.049	0.352782	3.96
Error	5	0.02925	0.00585			1.89
Total	8	154.588				
Surface roughness (*Ra*) for SiC MMCs						
Vc	1	201.021	201.021	542.619	0.000724	59.52
fz	1	104.421	114.137	308.091	0.002608	30.91
a_p	1	0.13758	0.13758	37.138	0.111903	4.07
Error	5	0.18523	0.03705			5.4
Total	8	337.723				

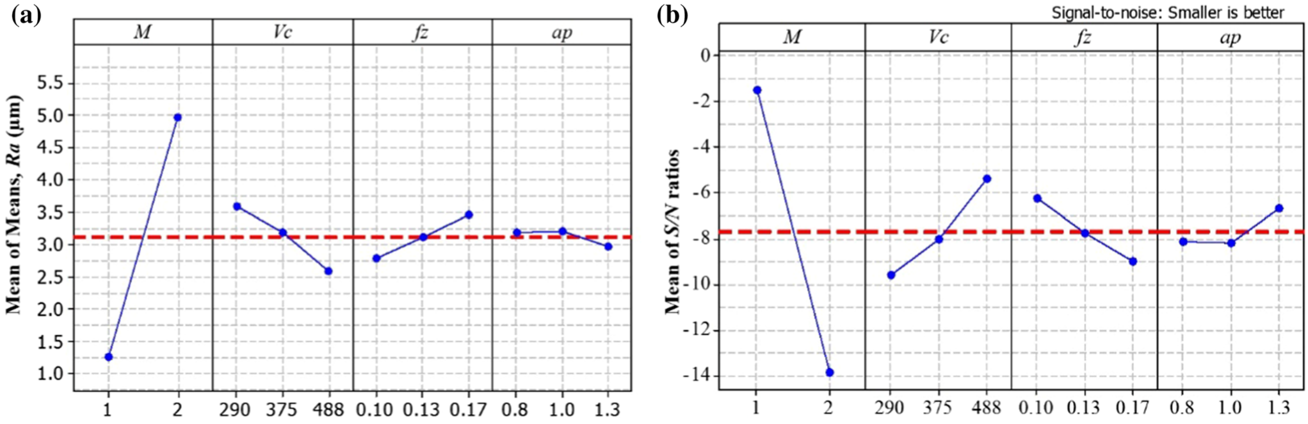


Fig. 9 The mean effects of milling variables on average S/N ratio for *Ra*

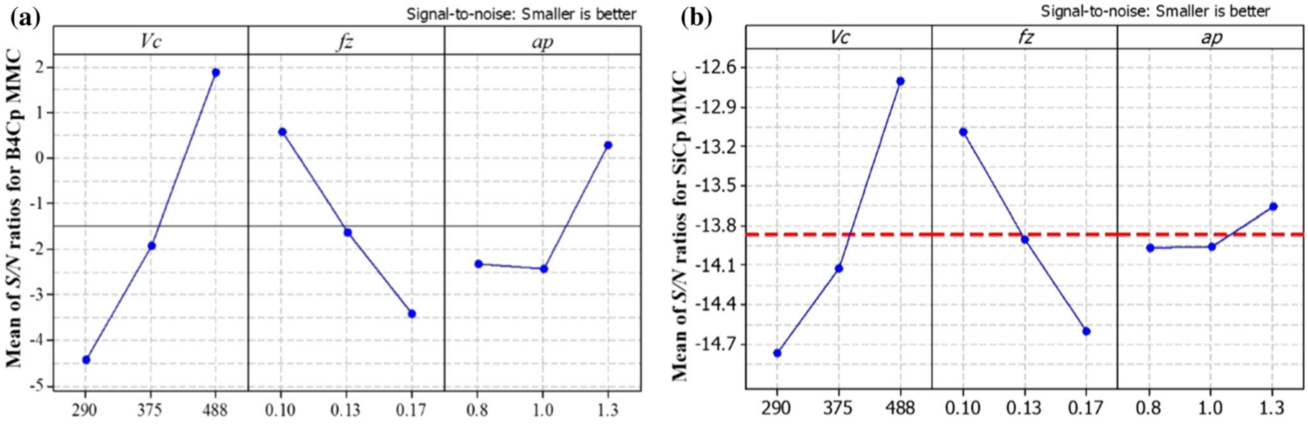


Fig. 10 The mean effects of milling variables on average S/N ratio for *Ra* **a** AA7039/B_4Cp MMC. **b** AA7039/SiCp MMC

rates. The increasing machining speed improved the quality of the machined surface, and increasing feed rate reduced the quality of surface in the milling of both MMC workpiece materials.

3.2 Artificial Neural Network

Artificial neural networks (ANNs) are a computational learning algorithm approach inspired by biological neural

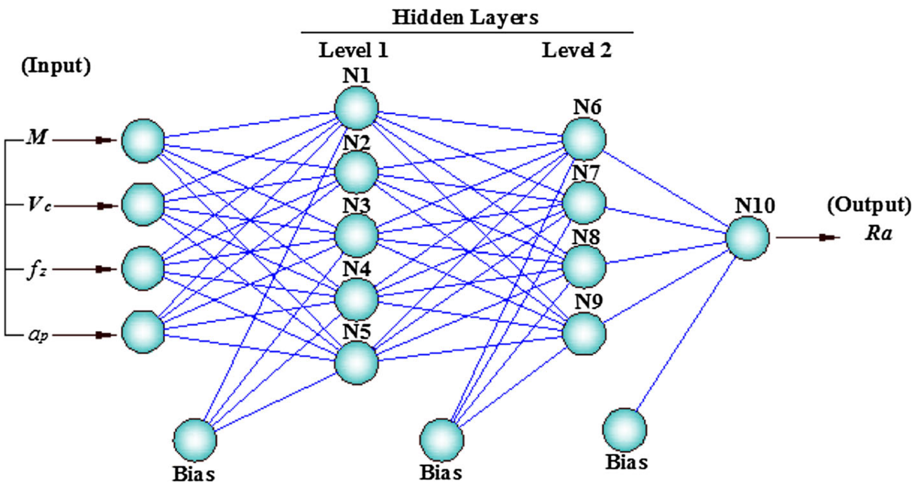


Fig. 11 ANN network in the LM algorithm with ten neurons

networks and are performed to generate a solution for engineering problems [21,22]. In this study, we used a multilayer ANN model to estimate the *Ra* value developing mathematical model depends on inputs in the milling of AA7039/B$_4$Cp and AA7039/SiCp. Two different workpiece materials, cutting speed, feed rate, and axial cutting depth were used as the input parameters, and the estimated output parameter was the *Ra* value. The ANN was constructed with four layers 3-5-4-1 for the *Ra* in order to predict the optimal output data in the propagation phase. The Pythia software was used to train the experimental values, and the experimental sets are normalized in the range −1,1 previous to processed by the neural network. After determined the network, the weight values in the neurons were transferred into the Excel software. As a result, a prediction model was achieved using these weight values in order to predict the *Ra* for AA7039/B$_4$Cp and AA7039/SiCp MMC. The weight values of the neuron are multiplied to calculate each input data in the network. The weighted input values are added linearly to obtain the output values. Consequently, the target value N10, thus achieved, was computed as input values for other neurons, as depicted in Fig. 11. Equation (7) was developed utilizing the weight values in the network and can be used for estimating the *Ra* in the milling of AA7039/B$_4$Cp and AA7039/SiCp MMC.

The following Fermi transfer function is used in the ANN software and can be expressed as Eq. (4).

$$N_{(z)} = \frac{1}{1 + e^{-4(z-0.5)}} \tag{4}$$

The Ei value was computed by Eqs. (5) and (6) for the neurons from N1 to N5 and N6 to N9. Here i indicates the number of neurons, and the weight values obtained from neurons are presented in Table 8.

$$E_i = M{*}w_{1i} + V_c{*}w_{2i} + f_z{*}w_{3i} + a_p{*}\, w_{4i} \tag{5}$$

$$E_i = w_{1i}{*}N_1{+}w_{2i}{*}N_2{+}w_{3i}{*}N_3{+}w_{4i}{*}N_4{+}w_{5i}{*}N_5 \tag{6}$$

$$aN_{10}(Ra)$$

$$a = \frac{1}{1 + e^{-4(-0.997511*N_6+0.601480*N_7+0.736669*N_8+1.309857*N_9-0,5)}} \tag{7}$$

3.3 Confirmation Experiments

The measured experimental results were optimized utilizing a Taguchi method and a response surface method in order to estimate and specify the ideal milling factors. The following regression analysis equation for *Ra* was used for both AA7039/B$_4$C and AA7039/SiC metal matrix composite.

$$\begin{aligned} R_a &= -2.222282 + 3.71109 * M - 0.0050548 * Vc \\ &\quad +10.7344 * fz + 0.275752 * ap \\ R - S_q &= 99.32\% \end{aligned} \tag{8}$$

A second-order mathematical model as shown in Eq. (9) was developed using the response surface methodology to determine the interaction effect of the milling parameters on the *Ra*.

$$\begin{aligned} Ra &= -1.4915 + 2.4445 * M + 0.0019 * Vc \\ &\quad +9.6847 * fz - 1.8249 * ap - 39.5848 * fz^2 \\ &\quad +0.8778 * ap^2 - 0.0015 * M * Vc + 7.3907 \\ &\quad *M * fz + 0.8467 * M * ap + 0.0031 * Vc * fz \\ &\quad -0.0025 * Vc * ap \\ R - S_q &= 99.78\% \end{aligned} \tag{9}$$

In order to validate the estimation ratio of the artificial neural network, RSM, and regression analysis, eight confirmation tests for both composite materials were executed at random levels of predetermined milling conditions. The observed *Ra* values for both AA7039/B$_4$C and AA7039/SiC metal matrix composites were compared for the accuracy of the predicted

Table 8 Neuron weight values used in Eqs. (4) and (5) from neurons 1–9

i	w_{1i}	w_{2i}	w_{3i}	w_{4i}
N1–N5 neuron weight values for Ra				
1.1	−0.955715	0.388072	−0.049962	0.301441
1.2	1.415495	0.836915	−0.292737	0.558510
1.3	−0.806561	−0.378130	0.911495	0.380340
1.4	−0.848057	−0.783057	0.727854	0.166155
1.5	−0.164195	−0.768809	0.807027	0.366141

i	w_{1i}	w_{2i}	w_{3i}	w_{4i}	W_{5i}
N6−N9 neuron weight values for Ra					
2.6	0.729026	0.281545	−0.432519	0.585919	−0.362143
2.7	−0.955185	0.670994	0.221985	−0.678506	0.134531
2.8	−0.681443	0.429739	−0.353969	−0.320033	0.782470
2.9	−1.047865	0.207501	−0.449365	−0.060292	0.807154

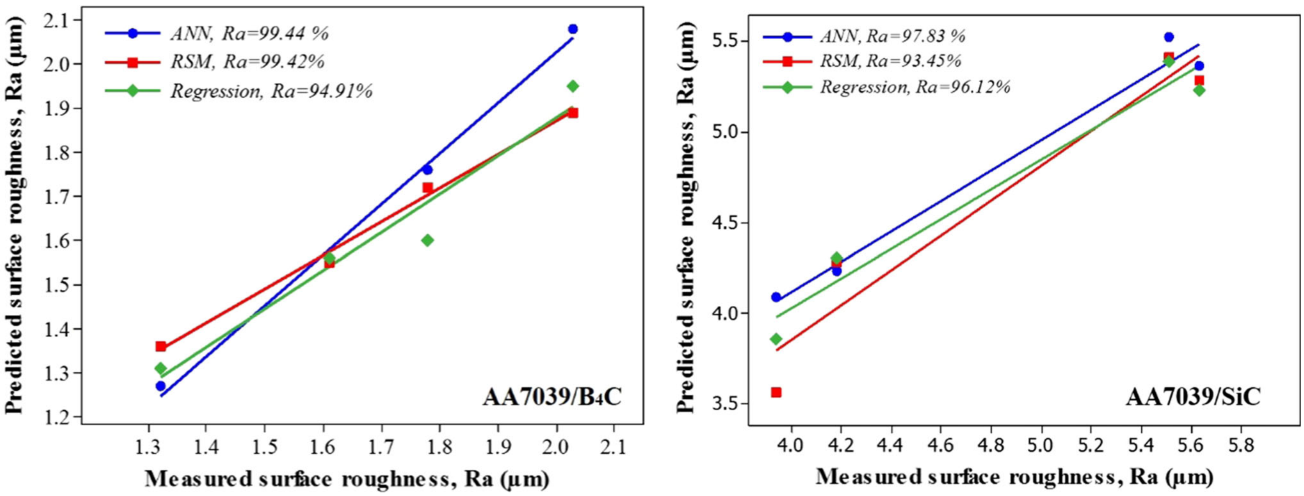


Fig. 12 Prediction performance of models for surface roughness (*Ra*)

values obtained from prediction models. Experimental values and estimated values with the percentage of prediction are presented in Fig. 12. The estimated values based on the RSM, Taguchi method, and regression models with the least residual errors are very coherent to the real test results. During the validation experiments, ANN was estimated with the average prediction errors 0.56 and 2.17% for AA7039/B_4C and AA7039/SiC, respectively. RSM's average prediction error rate was accomplished with the percentage of 0.58 and 6.55%. Average errors for the performance of mathematical model developed by regression analysis for AA7039/B_4C and AA7039/SiC were 8.09 and 3.88%, respectively. The comparison of the measured experimental results, ANN, RSM, and regression model was made based on the confirmation test. Acceptable prediction performance was achieved between the actual measurement value and estimated value for *Ra* during the milling of both composite materials. Therefore, the optimization methods used in the experiments and analytical models can be successfully utilized to estimate the milling parameters within the limits of the experimental investigation.

4 Conclusions

In this work, aluminium 7039-based MMCs reinforced with B_4C and SiC particles were successfully fabricated by a powder metallurgy method and investigated the optimal milling parameters for surface roughness using uncoated carbide insert. The experimental findings can be summarized as follows:

- The reinforced ceramic particles were homogeneously dispersed in the matrix structure. SiC particles presented a good bonding interface in the matrix; in contrast, there were observed clear contours between the interface of the B_4C particles and matrix.

- Better surface quality was obtained during milling of AA7039/B_4C compared with AA7039/SiC because of the bonding effect of reinforcement particles.
- The optimal milling parametric combinations were specified at highest value of cutting speed (488 m/min), lowest feed rate (0.1 mm/tooth), and the largest depth of cut (1.3 mm) for both workpiece materials.
- From the result of ANOVA, the machining speed was the most influential machining parameter for surface finish with a percentage contribution of 70.22% followed by the cutting feed with percentage contribution of 27.48% during milling AA7039/B_4C. In the milling of AA7039/SiC, the cutting speed and feed rate were the most effective cutting parameters on finished surface by factors of 59.52 and 30.91%, respectively.
- The axial cutting depth was not shown to have a meaningful correlation with surface quality in the machining of both MMCs.
- ANN model was produced a low prediction error as compared to the RSM and regression modelling.
- The findings of this experimental study and optimization models can be useful for aerospace industries in the face milling of aluminium 7039 composites reinforced with B_4C and SiC.

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