The International Journal of Advanced Manufacturing Technology (2019) 105:4499–4507
https://doi.org/10.1007/s00170-018-03256-y

ORIGINAL ARTICLE

An experimental investigation on surface generation in ultraprecision machining of particle reinforced metal matrix composites

Zhichao Niu[1] · Kai Cheng[1]

Received: 10 April 2018 / Accepted: 26 December 2018 / Published online: 2 February 2019

Abstract

Ultraprecision machining of metal matrix composites (MMCs) is observed as a scientific challenge, due to their hard-to-machine property and often the poor surface finish. This paper presents an experimental investigation on surface generation in ultraprecision machining of Al/B_4C/50p MMCs. The machining trials using straight flute polycrystalline diamond (PCD) tools are conducted on a high precision micro milling machine. Side milling is adopted under varied cutting conditions. Metrology assessments on the workpiece surface roughness, topography, texture and defects/features are undertaken using a ZYGO 3D surface profiler and a scanning electron microscope (SEM). Experimental results indicate that process parameters and their contributions play essential roles in the machining process. By applying the optimal process parameters, e.g. cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm, a better surface generation with surface roughness Ra < 20 nm can be obtained in ultraprecision machining of Al/B_4C/50p particulate MMCs.

Keywords Ultraprecision machining · Micro milling · Metal matrix composites · Polycrystalline diamond tools · Surface roughness

Nomenclature

ANOM	Analysis of means
ANOVA	Analysis of variance
DOC	Depth of cut
MMCs	Metal matrix composites
PCD	Poly-crystalline diamond
S/N	Signal to noise ratio
SEM	Scanning electron microscope
Y_i	Experimental value of surface roughness in the i^{th} test
n	Number of replications

✉ Zhichao Niu
zhichao.niu@brunel.ac.uk

Kai Cheng
kai.cheng@brunel.ac.uk

[1] College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge UB8 3PH, UK

1 Introduction

In the last few decades, particle reinforced metal matrix composites (MMCs) have been increasingly developed. Incorporation of the reinforced particles enhances the physical and mechanical properties of MMCs including higher adhesive, abrasive, diffusion wear resistance, thermal stability, improved hardness and stiffness [1, 2]. With these distinctive characteristics, MMCs have been applied to replace the conventional materials in various high precision engineering areas such as armoury, nuclear, aerospace, automotive, marine, and medical engineering, etc. [3, 4]. With increasing demands on high-performance MMCs and functional products, precision machining of MMCs and its machinability assessment have become bottleneck issues and thus drawn extensive attention in engineering industries. The workpiece surface roughness, material removal rate and the tool wear and tool life are essential in machinability assessment, especially for high precision engineering applications, which are heavily dependent on the machining accuracy, surface quality, production efficiency and costs. Ultraprecision machining of particle reinforced MMCs is observed as an even higher challenge both scientifically and technologically due to their complex microstructure and hard-to-machine property. Although various non-traditional processes have been attempted on machining MMCs to even produce parts with intricate shape and profiles [5], the processes are normally inefficient and often limited. The conventional machining process is still indispensable during finish machining [6].

Substantial research has been undertaken on machining processes and surface generation in ultraprecision machining of MMCs. Karabulut et al. [7] present an experimental investigation on the surface roughness in micro milling of B_4C/Al MMCs. In this study, the best surface roughness can be observed at high milling speed, and the lowest feed rate under dry cutting conditions on Al6061 reinforced with 15 wt% B_4C. Karabulut [8] also contributes to the optimization of surface roughness in Al_2O_3 MMC milling process. The ANOVA results indicate that the most effective control factor is feed rate, followed by cutting speed and depth of cut. Moreover, Bian et al. [9] found that the surface roughness around 0.1 μm Ra, by using small parameters in the range of a few micro-meters, can be obtained in precision milling of SiC_p/Al composites. However, the high surface roughness and deterioration and defects of the machined surface significantly affect the functional performance of engineering components, which is becoming one of the major reasons limiting the widespread application of MMCs in precision engineering industries. In addition, little research is focused on ultraprecision machining or micromachining of B_4C/Al MMCs; its machinability is less understood as being progressed so far.

In this paper, a systematic experimental research is carried out to investigate the surface generation in ultraprecision machining of particle reinforced MMCs. The well-designed experimental trials on Al/B_4C/50p MMCs using polycrystalline diamond tools are performed to investigate the effects of cutting process variables, particularly for the cutting speed, depth of cut and feed rate, on the machined surface roughness, surface morphology and surface texture. Moreover, contribution percentage of these variables are analysed accompanying with adjusting process parameters so as to achieve better surface quality.

2 Experimental trials

2.1 Experimental setup

Figure 1a illustrates the schematic of the micro milling experimental setup. The experiments are conducted on a KERN HSPC 2825 micro milling machine featuring high accuracy, high precision and high dynamic performance. This enables the dynamic effects of the machine tool and cutting tool can be reduced to a minimum during the machining processes. Al/B_4C/50p MMC workpiece is performed in these experiments. Figure 1b shows the micro-structure of MMCs. The B_4C particles with 5-μm particle size are evenly distributed in the matrix materials. Due to the high volume fraction of reinforced particles and their extremely high abrasive properties, polycrystalline diamond tools are performed better than other tools consistently and widely applied in MMC machining [10, 11]. Two straight flutes PCD end mill with a diameter of 10 mm and a cutting edge radius around 1.7 μm shown in Fig. 1c are performed in the experimental work. In addition, the PCD end mill used in the experiment has a 0° rake angel and 15° clearance angle. A schematic of the machining process is shown in Fig. 1d. Properties of the MMCs used in this research are shown in Table 1. In order to monitor the machine vibration and identify the dynamic response of tool and workpiece system, a MicroSense 5810 capacitance sensor and a PCB 352C33 piezotronics accelerometer are mounted on the spindle and workpiece, respectively, during micro milling processes.

2.2 Experimental machining procedures

Since the influence of radial depth of cut on surface integrity is found to be negligible [12], three mainly machining parameters including milling speed, feed rate and axial depth of cut are chosen as independent variables that significantly affect the machined surface roughness. In order to consider the interaction effect of these three factors, the L27 (3^3) full factorial experiments based on Pareto ANOVA and Taguchi method are conducted. The process parameters used for identifying the optimum conditions are shown in Table 2 [13, 14]. In the micro milling experiments, only one of the machining parameters is varied while the others are holding constant in order to observe the effect and contribution of input parameter. Side milling with a constant radial depth of cut of 3 mm is performed in these cutting trials. In addition, cutting tool and machined surface are perpendicular. The experimental trials are conducted under dry cutting condition and only air below is applied. The machined surface roughness, surface profile and topographical features are measured and adopted by using the ZYGO New View 5000 white light interferometer and a scanning electron microscope (SEM) with excellent precision and accuracy. Measurements of surface roughness are undertaken in feed direction and the average value of machined surface roughness at five different locations under each set of milling conditions is captured for further analysis in order to reduce the measurement uncertainty and assess repeatability.

3 Experimental results, analysis and discussion

3.1 Surface roughness

The orthogonal array of cutting parameters and the machined surface roughness under different settings of cutting parameters are shown in Table 3.

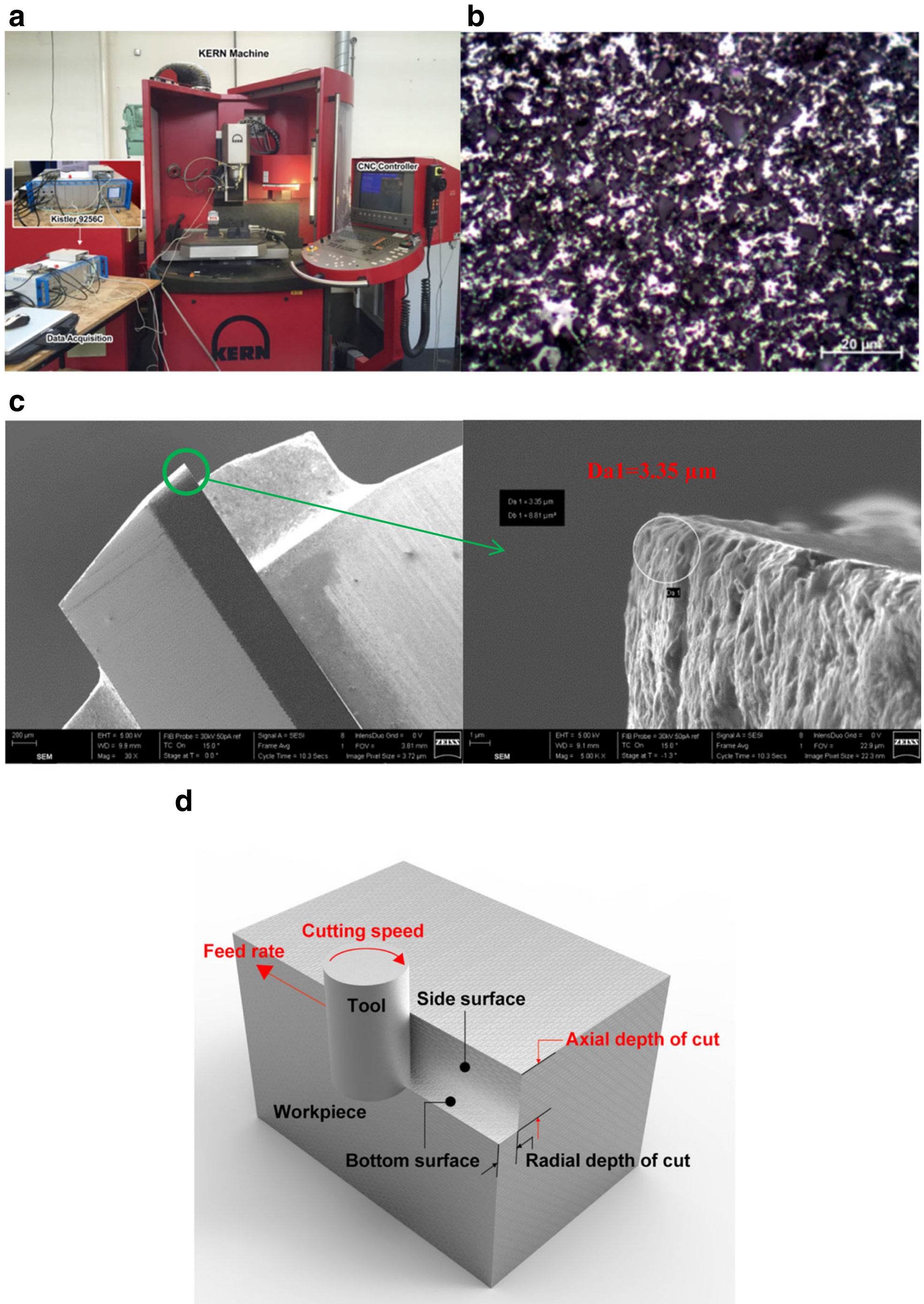


Fig. 1 Experimental ultraprecision milling set-up

Table 1 Properties of $Al/B_4C/50p$ MMCs workpiece

Material	Matrix: Al 2024	Particles: B_4C
Thermal conductivity (W/(mK))	190	42
Density (g/cm^3)	2.77	2.52
Elasticity modulus (GPa)	73	460
Poisson's ratio, ν	0.33	0.19
Specific heat (J/(kgK))	875	945

Table 2 Levels of independent process parameters

Process parameters	Levels		
	1	2	3
Cutting speed, v (m/min)	94.248	188.496	282.743
Feed rate, f (μm/rev)	5	10	20
Axial depth of cut, a_p (μm)	70	150	250

Table 3 Orthogonal array of cutting parameters and the machined surface roughness

Experimental number	Spindle speed (rpm)	Cutting speed (m/min)	Feed rate (μm/rev)	Axial depth of cut (μm)	Surface roughness (nm)	S/N ratio
1	3000	94.248	5	70	69	− 36.777
2	3000	94.248	5	150	64	− 36.1236
3	3000	94.248	5	250	52	− 34.3201
4	3000	94.248	10	70	46	− 33.2552
5	3000	94.248	10	150	28	− 28.9432
6	3000	94.248	10	250	33	− 30.3703
7	3000	94.248	20	70	75	− 37.5012
8	3000	94.248	20	150	51	− 34.1514
9	3000	94.248	20	250	60	− 35.563
10	6000	188.496	5	70	35	− 30.8814
11	6000	188.496	5	150	34	− 30.6296
12	6000	188.496	5	250	45	− 33.0643
13	6000	188.496	10	70	28	− 28.9432
14	6000	188.496	10	150	20	− 26.0206
15	6000	188.496	10	250	44	− 32.8691
16	6000	188.496	20	70	50	− 33.9794
17	6000	188.496	20	150	35	− 30.8814
18	6000	188.496	20	250	50	− 33.9794
19	9000	282.743	5	70	33	− 30.3703
20	9000	282.743	5	150	32	− 30.103
21	9000	282.743	5	250	68	− 36.6502
22	9000	282.743	10	70	72	− 37.1466
23	9000	282.743	10	150	25	− 27.9588
24	9000	282.743	10	250	43	− 32.6694
25	9000	282.743	20	70	113	− 41.0616
26	9000	282.743	20	150	71	− 37.0252
27	9000	282.743	20	250	78	− 37.8419

Workpiece material: Al/B_4C/50p MMCs; radial depth of cut: 3 mm

The arithmetic surface roughness values (Ra) of micro-milled bottom surface are shown in Fig. 2. Figure 2a presents the surface roughness as a function of cutting speed at various feed rate and axial depth of cut. It can be observed that surface roughness decreases gradually with the increase of cutting speed; with continuous increase in the cutting speed, surface roughness slightly increases in most cases. This is due to the fact that material strain rate increases with the increase of cutting speed. When machining with higher speed, the higher strain rate results in the matrix material can be removed with less deformation that occurs on the machined surface and generating a surface with smaller roughness [12]. In addition, the cracks generated on the particles have less time to transfer or further process into larger cavities due to the reduced tool-particle interaction time. As a result, particles are cut through with few defects at higher cutting speed. However, the higher cutting speed results in the increase of cutting temperature, which will lead to rapid tool wear and reduce the machined surface quality [15]. Thus, a better surface performance can be obtained when increasing the cutting speed properly.

Figure 2b illustrates the surface roughness as a function of feed rate at various cutting speed and axial depth of cut. The experimental results indicate that the tendency is towards smaller roughness value with the increases of feed rate when feed rate is smaller than 10 μm/rev. However, when the feed rate is larger than 10 μm/rev, the roughness value increases with the increase of feed rate and the tendency rate is similar to that feed rate is smaller than 10 μm/rev. Due to the fact that milling tool has two flutes, the feed rate of each tooth is 2.5 μm/tooth, 5 μm/tooth and 10 μm/tooth, respectively, in three levels. Thus, better surface quality can be obtained when the feed rate is equal or close to the particle size, which is 5 μm. This is due to the fact that surface has been pre-machined in each cutting path; when the feed rate is equal to the particle size, most of the particles will be totally removed or perfectly cutting through along the cutting line rather than

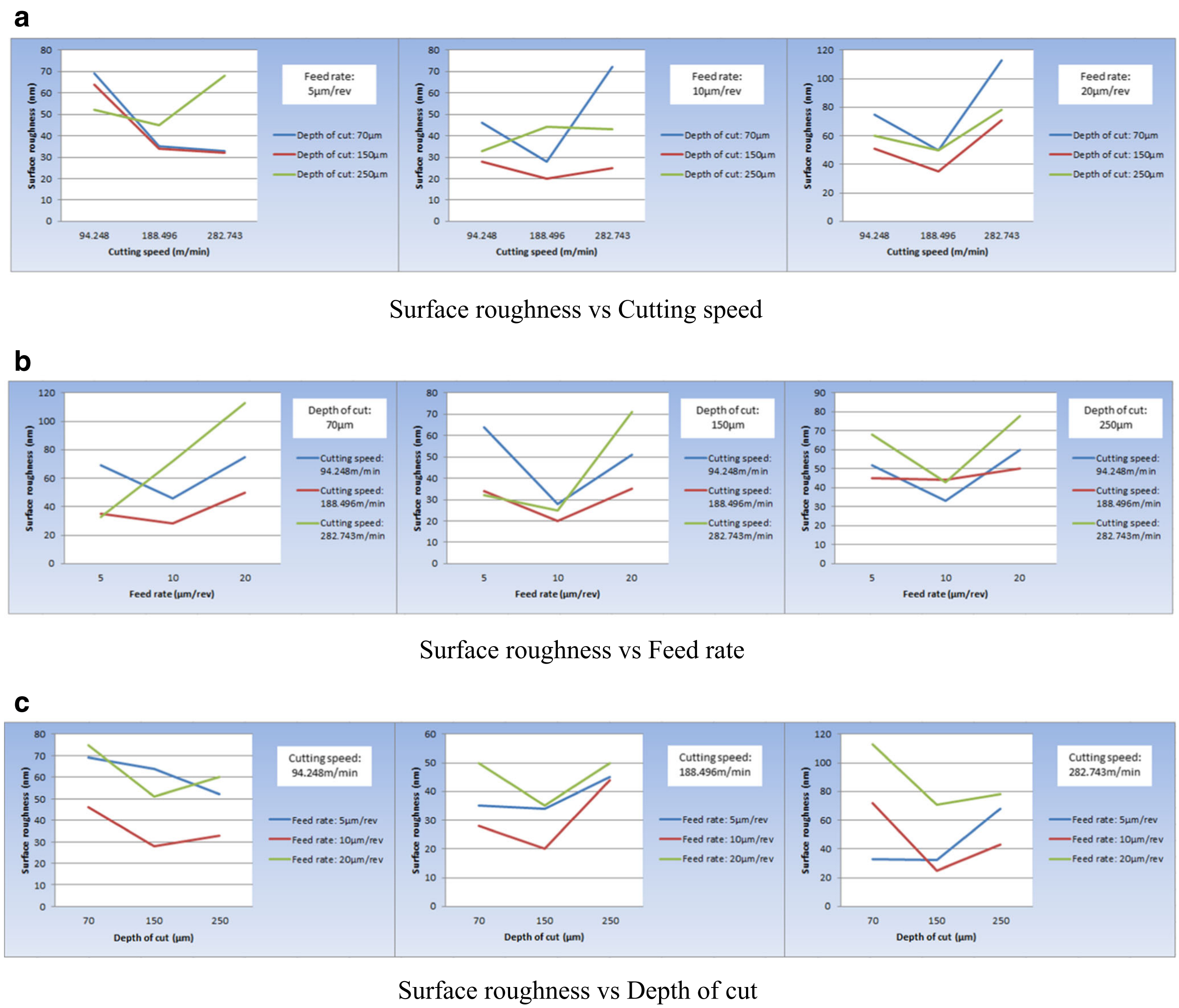


Fig. 2 Surface roughness obtained under various cutting parameters. **a** Surface roughness vs cutting speed. **b** Surface roughness vs feed rate. **c** Surface roughness vs depth of cut

badly fractured or even pulled out. In addition, the amount of plastic deformation will be increased along with the continuous increase of feed rate and this will finally facilitate the formation of large cracks on the reminded matrix material and pits on the matrix-particle bonding area.

Figure 2c demonstrates the surface roughness Ra as a function of axial depth of cut (DOC) at various cutting speed and feed rate. The experimental results present that surface roughness decreases with the increase of DOC when DOC is smaller than 150 μm, while the roughness value increases when the DOC is over 150 μm. This can be attributed to the chatter stability of cutting tool is low and cutting process vibrations are high during milling operation. Damping, as the main factor in MMC micro milling due to the existing high volume particles, is able to stable end milling operations by raising the critical axial depth of cut and the damping is more effective at higher DOC [16–18]. While, due to the cutting force increases with the continue increase of DOC, the cutting process vibrations increase and significantly reduce the surface quality. However, in most cases, the influence of DOC on surface roughness is smaller compared to cutting speed and feed rate, a proper larger DOC will contribute to the efficiency in micro machining of MMCs.

According to the experimental results, cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm are visualised as the optimal cutting condition to obtain the best surface quality with surface roughness Ra < 20 nm in MMC micro milling processes.

(1) Analysis of means (ANOM)

The effects of cutting parameters on surface roughness values are further evaluated through Taguchi method. The

S/N ratios, which are known as the signal-to-noise ratios, are shown in Table 3. As the aim of this research is to make the machined surface roughness response as small as possible, "smaller the better" characteristic is applied to predict the S/N ratio against each level of initial parameters and can be expressed by

$$\frac{S}{N_{smaller}} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} {Y_i}^2\right] \quad (1)$$

where Y_i is the experimental value of surface roughness in the i^{th} test and n is the number of replications.

The variations of response due to the change of cutting parameters are shown in Table 4 and Table 5 as below. These tables illustrate that feed rate has the most influence on the surface roughness, followed by cutting speed and the effect of depth of cut is minimal. This will be further validated through analysis of variance (ANOVA).

The response parameters are presented by the S/N ratio and the main effects are plotted from the mean value of Ra and S/N ratio. Figure 3a, b below indicates that the level of these three cutting parameters increases; significant response can be observed on surface roughness and S/N ratios. According to the Taguchi method, the lower surface roughness due to the smaller-the-better characteristic and higher S/N ratio, which means that the signal level is much higher than the noise level and further leads to an optimal machined surface, is applied. As a result, a level of factor with the lowest mean value of Ra and the highest mean value of S/N ratio is observed as the optimal cutting parameter. Thus, the optimal cutting conditions in this MMCs micro milling process, i.e. cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm, are adopted to achieve the lowest surface roughness. This shows a good agreement with the presented analytical results of machined surface roughness.

(2) Analysis of variance (ANOVA)

Figure 3a, b implies that these three cutting parameters have similar effects on the surface roughness; however, their contribution on the machined surface is contrast and can be achieved through analysis of variance (ANOVA). ANOVA, as a confirmation test used with the identified optimum levels of all the parameters, is conducted in Matlab. This method is applied to identify the factor significance on response and influence of each factor on the resultant surface roughness. The approach is carried out for a confidence level of 95%, which means that the factors with a P value less than 0.05 are considered to have significant influence on resultant surface roughness. In addition, the contribution percentages of cutting parameters are presented to find the most effective factor.

Table 4 Response for S/N ratios

Level	v	f	a_p
1	53.11111	48	57.88889
2	37.88889	37.66667	40
3	59.44444	64.77778	49
Delta	21.55556	27.11111	17.88889
Rank	2	1	3

Table 5 Response for surface roughness

Level	v	f	a_p
1	−34.1117	−33.2133	−34.4351
2	−31.2498	−30.9085	−31.3152
3	−34.5363	−35.776	−34.1475
Delta	3.2865	4.867579	3.119901
Rank	2	1	3

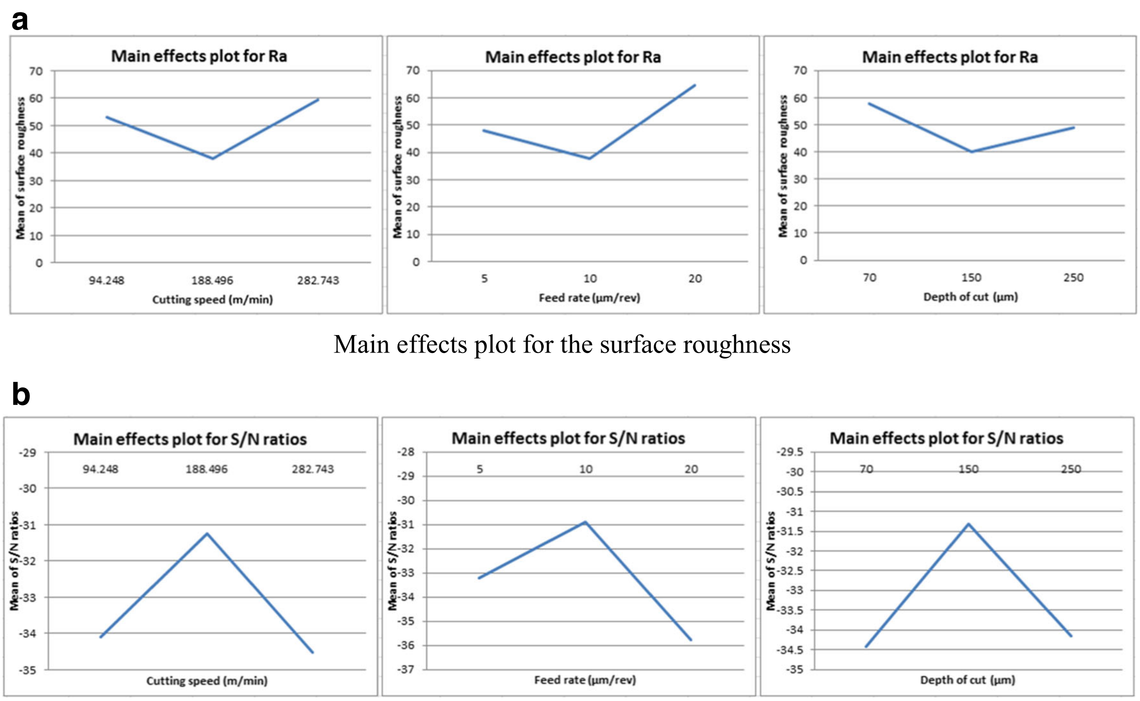
According to the statistical results shown in Table 6, cutting speed, feed rate and axial depth of cut are observed to have a P value less than 0.05. This indicates that cutting speed, feed rate and axial depth of cut have significant contribution to the machined surface performance. Based on the specific value, feed rate has the highest influence on machined surface roughness, followed by cutting speed, interaction of cutting speed and feed rate, and axial depth of cut, whereas the effects of interaction of these factors, particularly for axial depth of cut, on surface roughness are minimal.

According to the statistical results shown in Table 6, cutting speed, feed rate and axial depth of cut are observed to have a P value less than 0.05. This indicates that cutting speed, feed rate and axial depth of cut have significant contribution to the machined surface performance. Based on the specific value, feed rate has the highest influence on machined surface roughness, followed by cutting speed, interaction of cutting speed and feed rate and axial depth of cut, whereas the effects of interaction of these factors, particularly for axial depth of cut, on surface roughness are minimal.

3.2 Surface morphology

The surface roughness chart indicates that surface quality deteriorates dramatically due to the distinct micro-structure of MMCs. As the Ra value cannot exactly depict the characteristics of machined surface, the surface profile and surface defects are further measured by 3D profiler and SEM.

Figure 4 shows the machined surface morphology. As can be observed from the images, the feed marks are noticeable which means most of particles are perfectly cut through rather than badly fractured or pulled out. Significant burrs can be seen on the machined surface particularly along the tool paths shown in Fig. 4b, d. Small pits are visible on the machined surface and the size of these pits is approximately 5 μm as



Main effects plot for the surface roughness

Main effects plot for the S/N ratio

Fig. 3 Main effects plotted from the mean value of Ra and S/N ratio. **a** Main effect plot for the surface roughness. **b** Main effect plot for the S/N ratio

shown in Fig. 4a, c. This may be formed by the particles pulled out from Al matrix.

Figures 5a, b demonstrates the micro-structures and surface profiles of the un-machined and machined surfaces by using the optimal cutting conditions, i.e. cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm, respectively, through SEM images. From the images, it is found that the reinforced B_4C particles can be distinguished from the Al matrix by different colour scale. It can be observed that particles are fractured into small pieces while Al matrix still bonded to the particles and machined surface quality enhanced. This implies that the plastically deformed aluminium fills the gaps of small particles which formed during machining. In addition, the cracks and pits formed on the fractured particles are also covered by the deformed aluminium. Thus, the machined surface areas are smoother.

Table 6 ANOVA values for different factors

Analysis of variance

Source	Sum Sq.	*df*	Mean Sq.	*F* ratio	*P* value	Contribution
v	2209.4	2	1104.7	8.12	0.0119	19.2%
f	3369.9	2	1684.93	12.38	0.0036	29.3%
a_p	1518.3	2	759.15	5.58	0.0304	13.2%
$v*f$	1816.1	4	454.04	3.34	0.0691	15.8%
$v* a_p$	776.4	4	194.09	1.43	0.3094	6.7%
$f* a_p$	736.6	4	184.15	1.35	0.3309	6.4%
Error	1088.7	8	136.09			9.4%
Total	11,515.4	26				100%

Indicates statistically full significant factors at 95% confidence level

4 Conclusions

Ultraprecision machining of particle reinforced MMCs with PCD end mill is performed to experimentally investigate the surface generation and the best surface roughness to be achieved against the process conditions. A series of ultraprecision milling experiments are conducted based on the L27 orthogonal array and the optimal cutting parameters are identified towards lower surface roughness and better surface morphology. The following conclusions can be drawn from the experimental results and analysis:

(1) Cutting speed, feed rate and axial depth of cut are observed as the most influencing factors for the machined surface roughness and surface quality.
(2) According to the experimental results, the optimal cutting conditions, i.e. cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm, lead to the smallest value of surface roughness Ra < 20 nm.
(3) Analysis of means (ANOM) results reveal that these three cutting parameters have similar effects on the

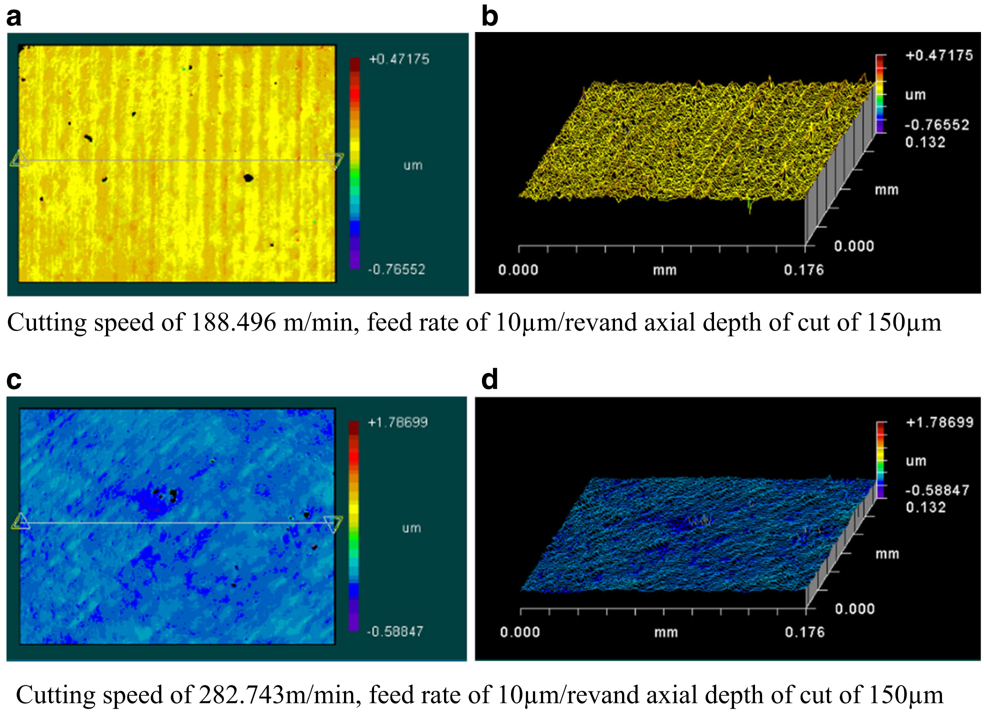


Fig. 4 Surface morphology of the machined Al/B_4C/50p MMCs workpiece. Cutting speed of 188.496 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm. Cutting speed of 282.743 m/min, feed rate of 10 μm/rev and axial depth of cut of 150 μm

surface roughness and the optimal cutting conditions via roughness analysis are confirmed by ANOM.

(4) Analysis of variance (ANOVA) results indicate that contribution percentages of these parameters on the machined surface are contrast. Feed rate, as the dominate factor, has the highest influence on the responses, followed by cutting speed and depth of cut. Interaction of these factors has the minimal effects on the machined surface roughness.

(5) For the surface morphology, feed marks, burrs and pits are noticeable. Some of the reinforced particles are pulled out during the machining, while most are perfectly cut through. Plastically deformed aluminium fills the gaps and covers the cracks and pits generated on the

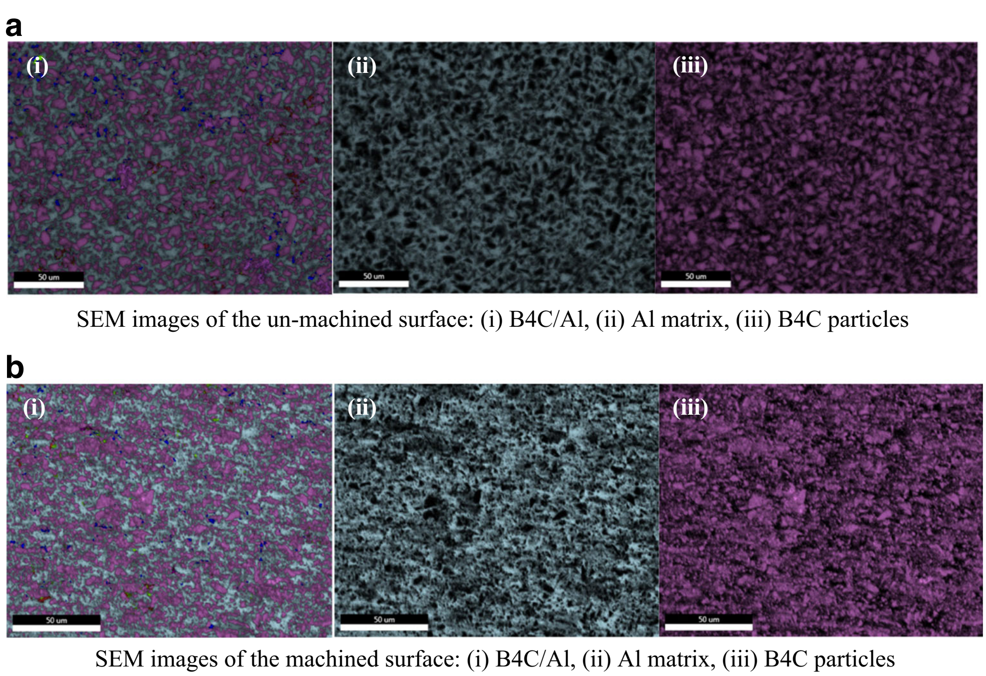


Fig. 5 SEM images of the un-machined and machined MMC workpiece surfaces. **a** SEM images of the un-machined surface: (i) B_4C/Al, (ii) Al matrix, (iii) B_4C particles. **b** SEM images of the machined surface: (i) B_4C/Al, (ii) Al matrix, (iii) B_4C particles

fractured particles, which helps result in a smooth surface roughness and better surface quality to some extent.

Acknowledgements The authors thank Professor G.H. Wu and his team at Harbin Institute of Technology in providing the MMC materials, and the interesting and helpful discussion on the MMC materials design and fabrication.

References

1. Teti R (2002) Machining of composite materials. CIRP Ann 51(2): 611–634
2. Bains PS, Sidhu SS, Payal HS (2016) Fabrication and machining of metal matrix composites: a review. Mater Manuf Process 31:553–573
3. Dabade UA, Jadhav MR (2016) Experimental study of surface integrity of Al/SiC particulate metal–matrix composites in hot machining. Procedia CIRP 41:914–919
4. Muthukrishnan N, Murugan M, Rao KP (2008) An investigation on the machinability of Al-SiC metal matrix composites using pcd inserts. Int J Adv Manuf Technol 38(5–6):447–454
5. Pramanik A (2014) Developments in the non-traditional machining of particle reinforced metal matrix composites. Int J Mach Tools Manuf 86:44–61
6. Nicholls CJ, Boswell B, Davies IJ, Islam MN (2017) Review of machining metal matrix composites. Int J Adv Manuf Technol 90: 2429–2441
7. Karabulut Ş, Karakoç H, Çıtak R (2016) Influence of B_4C particle reinforcement on mechanical and machining properties of Al6061/B_4C composites. Compos Part B 101:87–98
8. Karabulut Ş (2015) Optimization of surface roughness and cutting force during AA7039/Al2O3 metal matrix composites milling using neural networks and Taguchi method. Measurement 66: 139–149
9. Bian R, He N, Li L, Zhan ZB, Wu Q, Shi ZY (2014) Precision milling of high volume fraction SiCp/Al composites with monocrystalline diamond end mill. Int J Adv Manuf Technol 71:411–419
10. Davim JP, Antonio CAC (2001) Optimization of cutting conditions in machining of aluminium matrix composites using a numerical and experimental model. J Mater Process Technol 112:78–82
11. Ding X, Liew WYH, Liu XD (2005) Evaluation of machining performance of MMC with PCBN and PCD tools. Wear 259:1225–1234
12. Wang T, Xie LJ, Wang XB, Jiao L, Shen JW, Xu H, Nie FM (2013) Surface integrity of high speed milling of Al/SiC/65p aluminum matrix composites. Procedia CIRP 8:475–480
13. Niu ZC, Cheng K (2016) Multiphysics based modelling and analysis of micro milling metal matrix composites (MMCs) against the effects of key process variables. The euspen's 16th International Conference, Nottingham, UK
14. Niu ZC (2018) Investigation on the multiscale multiphysics based approach to modelling and analysis of precision machining of metal matrix composites (MMCs) and its application perspectives. PhD thesis, Brunel University London
15. Teng X, Huo D, Wong E, Meenashisundaram G, Gupta M (2016) Micro-machinability of nanoparticle-reinforced mg-based MMCs: an experimental investigation. Int J Adv Manuf Technol 87:2165–2178
16. Ahmed GMS, Reddy PR, Seetharamaiah N (2012) Experimental evaluation of critical axial depth of cut with magneto rheological damping in end milling process. Int J Sci Res Publ 2(8):1–11
17. Cheng K, Huo D (2013) Micro cutting: fundamentals and applications. John Wiley & Sons, Chichester
18. Liu J, Cheng K, Ding H, Chen S, Zhao L (2018) An investigation of the influence of phases' removal ways on surface quality in micro milling SiCp/Al composites. Procedia CIRP 71:59–64