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Surface integrity of high speed milling of Al/SiC/65p aluminum matrix composites

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Abstract

The surface quality of components produced through milling of particle reinforced aluminum matrix composites (PRAMCs) is one of the most important factors influencing their practical performance. Therefore, the increasing applications of PRAMCs necessitate an in-depth understanding of the variation law of surface integrity. This paper presents a systematic experimental research of high speed milling of Al/SiC/65p (65% volume fraction) by polycrystalline diamond tools (PCD). The influences of cutting parameters on surface roughness (Ra), surface residual stress (RS) and morphology of PRAMCs were investigated. In addition, the experiments on corresponding unreinforced matrix alloy Al 6063 were also carried out to analyze the influence of the present reinforcements on surface integrity. The results of full factorial experiment revealed that the most significant milling parameter for surface roughness was milling speed, followed by the interaction between feed rate and milling speed, then the feed rate. In terms of residual stress on the machined surface, axial depth of cut had the highest influences on surface residual stress, followed by milling speed and feed rate. The results of single-factor experiment demonstrated that surface roughness improved slightly with the decrease in the feed rate, while the effect of milling speed was negligible. Residual stress measured in feed direction by X-ray diffraction (XRD) indicated that the conditions of machined Al6063 surface were all tensile, while the conditions of Al/SiC/65p were compressive.

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Keywords: milling, residual stress, aluminum matrix composites, surface roughness

1. Introduction

Particle reinforced aluminum matrix composites (PRAMCs) made of aluminum alloy reinforced with discontinuous hard particles offer various superior material properties such as high strength, hardness, strength to weight ratio and heat-resistance which have drawn much attention among researchers. Based on special commercial and technological importance, they have been utilized in ground transportation (auto and rail), thermal management, aerospace, industrial, recreational and infrastructure industries [1].

However, due to the presence of reinforcements in the soft Al alloy matrix, PRAMCs are classified as a hard-machined material. With rapid advances in the new production techniques, most PRAMCs are manufactured by near net shape manufacturing technique, while conventional turning or milling is still indispensable during finish machine [2]. One of the major problems limiting the widespread use of PRAMCs in industry is the deterioration of the machined surface which can greatly affect the actual performance of the components.

In recent years, there has been increasing interest in different aspects of surface integrity. Turning Al/SiC/10p and Al/SiC/30p MMCs with different geometrical CBN tools, Dabade et al. [3] reported that the wiper geometry of the inserts reduces the surface damage and lowers the cutting force. Muthukrishnan and Davim [4] investigated the surface roughness of

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Al/SiC/20p MMCs by turning the composite bars using coarse grade PCD inserts under different cutting conditions. It revealed that the feed rate had the highest physical as well as statistical influence on the surface roughness, followed by depth of cut and the cutting speed. Quan and Ye [5] analysed the effect of machining on the surface of Al/SiC/15p and concluded that the surface hardness of composites reinforced by SiC particles may be lower than that of the unaffected interior material.

Due to the fact that machining on the metal matrix reinforced with a high volume fraction (over 30 vol %) of particles is seldom reported, this paper focused on PRAMCs with 65% volume fraction. The influences of three milling parameters on the surface integrity of Al/SiC/65p were investigated by analysing surface roughness, residual stress and morphology of the machined surface. The experiments on corresponding unreinforced matrix alloy (Al6063) were also carried out in order to compare the results with PRAMCs.

2. Experimental Procedures

2.1. Design of experiment

Table 1. Levels of independent variables

Factors	v_c (m/min)	f_z(mm/z)	a_p(mm)
Level -1	100	0.02	0.1
Level 1	400	0.10	0.3

Table 2. Milling parameters according to full factorial design

Test No	v_c (m/min)	f_z(mm/z)	a_p(mm)
1	100	0.02	0.1
2	400	0.02	0.1
3	100	0.10	0.1
4	400	0.10	0.1
5	100	0.02	0.3
6	400	0.02	0.3
7	100	0.10	0.3
8	400	0.10	0.3

It is known that the surface integrity during machining is influenced by a large number of factors. Since the influence of radial depth of cut on surface integrity is found to be negligible in our early work, three mainly milling parameters were chosen as independent variables influencing the surface roughness and surface residual stress, namely milling speed (v_c), feed rate (f_z) and axial depth of cut (a_p). In order to consider the interaction effect, a 2^3 full factorial experiments were carried out and each experiment was repeated twice in order to reduce the experimental error. The detailed parameter level and milling design are presented in table 1 and table 2. In addition, the change of VB value was only around 10 micro meters (from 0.070mm to 0.08mm) after the full factorial experiment so that the influence of tool wear was assumed to be negligible.

Then the effect of the feed rate and milling speed were investigated in single factor tests on surface roughness, residual stress and morphology and the change of VB value was around 20 micro meters (from 0.28mm to 0.30mm). The experiments on the corresponding unreinforced matrix alloy were also carried out.

2.2. Experimental setup and procedure

The microstructure of the PRAMCs is shown in Fig. 1. Since Kannan and Kishawy [6] reported that the application of coolant caused the loosely bonded particulates to be flushed away resulting in a higher percentage of voids and pits, all experiments in this paper were in dry conditions.

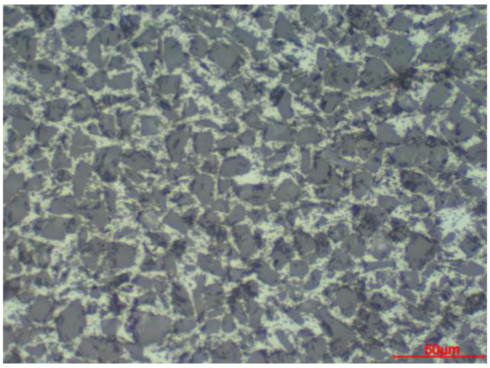


Fig. 1. Microstructure of the Al/SiC/65p

Due to the high volume fraction PRAMCs and their abrasive character, PCD inserts were recommended by researchers [7-9] who studied the machinability and tool performance of these materials. Therefore, the PCD inserts were utilized in this work. The details of the workpiece material, inserts, tool holder and machine used for experimental work are listed in table 3.

Table 3. Milling conditions

Items	Contents
Workpiece	Al/SiC/65p (mean particle size 5μm)
Insert	XOEX 090304FR-ZZ (SECO)
Insert holder	R217.69-1020.RE-09.2AN (SECO)
Machine	DMU80 mono BLOCK (DMG)

Surface roughness measurements and surface characterization capture were carried out with VK-X200

3D Laser Scanning Microscope from KEYENCE Corporation. The surface roughness measurements were taken in feed direction and the results averaged the value of five locations under each set of milling condition.

Since there is no published standard for the measurement of residual stress by X-ray diffraction (XRD) on this material, residual stress measurements were all made on the surface after machining in feed direction using X-rays by the sin2ψ technique. In addition, Al{2 2 2} reflection and CrKα radiation were chosen. The results averaged the value of three locations under each set of milling condition.

3. Experimental Results

3.1. Surface roughness

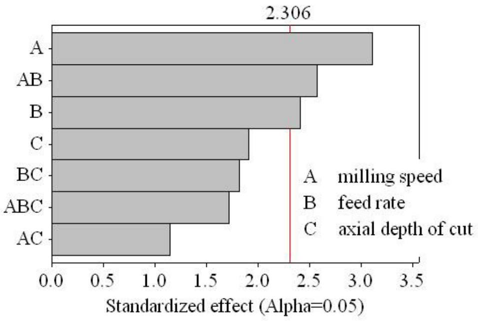


Fig. 2. Standardized Pareto chart for surface roughness

Table 4. ANOVA for surface roughness

Source	Sum squares	Df	Mean square	*F*-ratio	*P*-value
v_c	0.0049820	1	0.0049820	9.66	0.014[a]
f_z	0.0029976	1	0.0029976	5.81	0.042[a]
a_p	0.0018850	1	0.0018850	3.66	0.092
$v_c f_z$	0.0034125	1	0.0034125	6.62	0.033[a]
$v_c a_p$	0.0006803	1	0.0006803	1.32	0.284
$f_z a_p$	0.0017016	1	0.0017016	3.30	0.107
$v_c f_z a_p$	0.0015145	1	0.0015145	2.94	0.125
Error	0.0041239	8	0.0005155		
Total	0.0212974	15			

[a] Indicates statistically significant factors at 95% confidence level

The Standardized Pareto and ANOVA (analysis of variance) for surface roughness are shown in Fig. 2 and Table 4, respectively. According to the statistical results, the P value of v_c, f_z and $v_c f_z$ are smaller than 5% which indicate that they all have significant influence on surface roughness. Based on their specific value, milling speed has the highest influence on Ra, followed by interaction between milling speed and feed rate, then the feed rate. While the effect of axial depth of cut and its interaction on Ra is minimal.

Fig. 3 shows the influence of milling speed and feed rate on surface roughness when axial depth of cut keeps as 0.1mm. According to the picture, low Ra can be achieved at a lower feed rate and lower milling speed. It is interesting to find that when milling speed and feed rate both keep high, small Ra can also be achieved which provides a good developing direction for high speed and feed rate machining PRAMCs in the further.

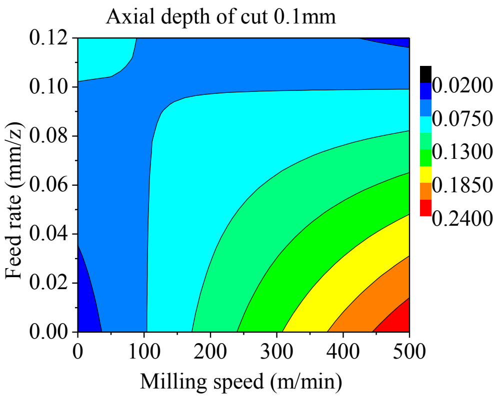


Fig. 3. Dependence of Ra on milling speed and feed rate

Based on the results of Ra measurement, a non-linear multiple regression analysis method has been employed to build the empirical equation to predict the Ra as follows:

$$
\begin{aligned}
Ra &= 2.40\times10^{-2} + 5.45\times10^{-4} v_c + 0.56 f_z + 8.87\times10^{-2} a_p \\
&-5.68\times10^{-3} v_c \times f_z - 1.41\times10^{-3} v_c \times a_p - 1.48 f \times a_p \\
&+1.62\times10^{-2} v_c \times f_z \times a_p
\end{aligned} \tag{1}
$$

Since the R^2 of the above equation is 80.64%, which is quite close to 1, it indicates that the model can achieve a good predicting accuracy.

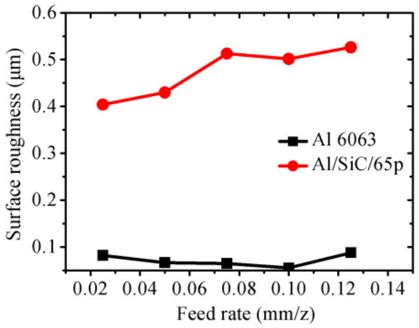


Fig. 4 Effect of feed rate on surface roughness (milling condition: v_c=300m/min, a_e=6mm and a_p=0.2mm)

The effect of the feed rate on surface roughness is illustrated in Figure 4. As for Al/SiC/65p, it is observed that the surface roughness increases gradually with the rise of the feed rate, complying with conventional knowledge. This effect of feed rate can be attributed to a change in the pitch of the profile generated due to the change in feed. In addition, with an increase of the feed rate, the amount of plastic deformation during high speed milling increases as well and it can facilitate the formation of pits and cracks. Eventually, it worsens the surface quality. Compared to Al/SiC/65p, the values of the machined surface roughness of Al6063 are quite small.

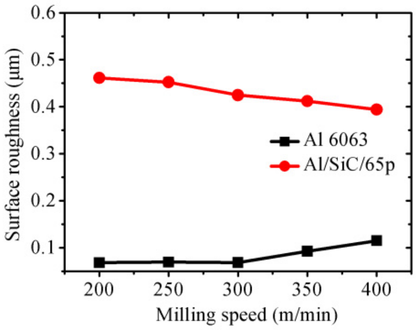


Fig. 5. Effect of milling speed on surface roughness (milling condition: f_z=0.075m/min, a_e=6mm and a_p=0.2mm).

Figure 5 demonstrates the influence of the milling speed on surface roughness. As for Al/SiC/65p, surface roughness decreases slightly with the increase in milling speed, from around 0.46μm at 200m/min to 0.40μm at 400m/min. There may be two factors contributing to the decrease in surface roughness. One factor is that the milling force will reduce because of the high temperature in high speed milling, resulting in increased flowability of the aluminum matrix. The other factor is that the strain rate increases with the increase of the milling speed which makes deformation of the matrix material more difficult to deform. Consequently the SiC particles are more likely to be cut though rather than to be pulled out, reducing the number of pits and voids. In this way, a better surface quality can be achieved. Given the excellent thermal conductivity of PCD tools and the aluminum matrix along with the short contact time, a considerable rise in temperature of machined surface may not occur in the cut-ting process. Therefore, it is reasonable to expect that the influence of the latter factor is predominant.

However, the influence on the surface of Al6063 experiences a converse trend, which probably indicates that the influence of the side flow of the workpiece on surface roughness outweighs the influence by reduced milling force in high temperatures.

3.2. Surface residual stress

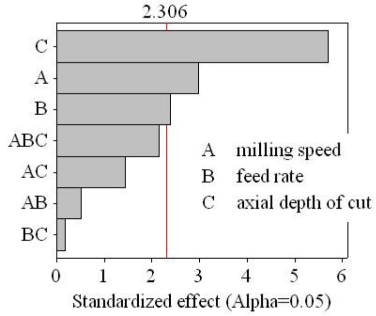


Fig. 6. Standardized Pareto chart for surface residual stress

Table 5. ANOVA for surface residual stress

Source	Sum squares	Df	Mean square	*F*-ratio	*P*-value
v_c	2525.1	1	2525.06	8.82	0.018[a]
f_z	1640.3	1	1640.25	5.73	0.044[a]
a_p	9312.3	1	9312.25	32.53	0.000[a]
$v_c f_z$	76.6	1	76.56	0.27	0.619
$v_c a_p$	588.1	1	588.06	2.05	0.190
$f_z a_p$	9.0	1	9.00	0.03	0.864
$v_c f_z a_p$	1314.1	1	1314.06	4.59	0.065
Error	2290.0	8	286.25		
Total	17755.3	15			

[a] Indicates statistically significant factors at 95% confidence level

The Standardized Pareto and ANOVA (analysis of variance) for surface residual stress are shown in Fig. 6 and Table 5, respectively. According to the statistical results, the P value of v_c, f_z and a_p are smaller than 5% which indicate that they have significant influence on surface residual stress. Among all the factors, axial depth of cut has the highest influences on surface residual stress, followed by milling speed and feed rate.

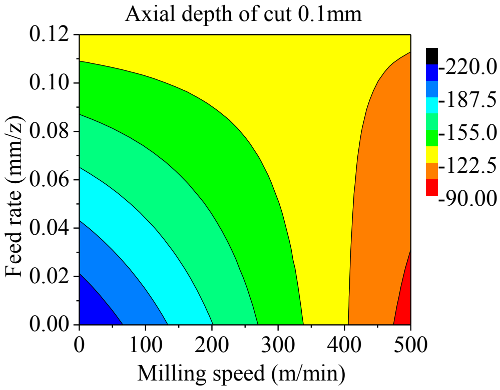


Fig. 7. Dependence of surface RS on milling speed and feed rate

Fig. 7 shows the influence of milling speed and feed rate on surface residual stress when axial depth of cut keeps as 0.1mm. According to the picture, the largest compressive residual stress can be achieved at a lower feed rate and lower milling speed.

An empirical equation to predict the surface residual stress is also built based on the results of RS measurement as follows:

$$\sigma = -277.49 + 0.37v_c + 1136.98f_z + 580.10a_p \\ -3.39v_c \times f_z - 1.31v_c \times a_p - 3963.54f_z \times a_p \\ +15.10v_c \times f_z \times a_p \qquad (2)$$

Since the R^2 of the above equation is 87.10%, which is quite close to 1, it indicates that the model can also achieve a good predicting accuracy.

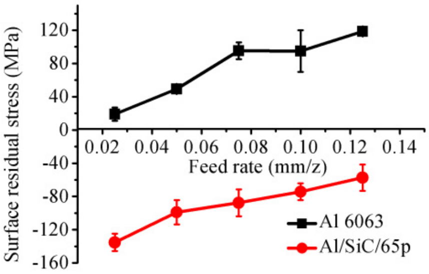


Fig. 8. Effect of feed rate on residual stress (milling condition: v_c=300m/min, a_e=6mm and a_p=0.2mm)

Fig. 8 shows the effect of the feed rate on the residual stress on machined surface of Al/SiC/65p and unreinforced matrix material Al6063. According to the figure, residual stresses Al6063 surface are tensile throughout the whole spectrum of the investigated feed rate, while they are compressive for Al/SiC/65p. The pattern is similar with the results reported by Pramanik et al. [10]. The curves of residual stress for the two materials both witness an upward trend with the increase in feed rate. This can be mainly attributed to the fact that when other parameters are fixed, the higher feed rates can lead to larger removal rate, resulting in higher temperatures. Then the residual stress is expected to become more tensile stress.

Fig. 9 indicates that the residual stresses are tensile (20-80MPa) in all milling speeds for machined surface of Al6063 while they are all compressive for Al/SiC/65p, similar to the results in Fig. 8. The curves of Al/SiC/65p and Al6063 both witness a slight fluctuation over the five speeds. Generally, the influence of speed is relatively not as significant as feed rate which consists with the results of ANOVA. It can mainly be attributed to the excellent thermal conductivity of PCD tools and the aluminum matrix, although the high speed in milling can bring out a higher temperature.

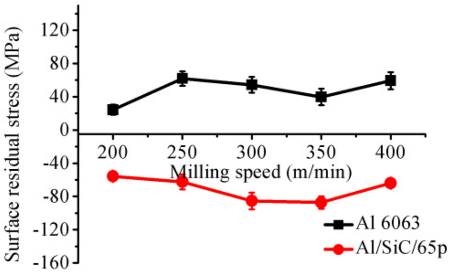


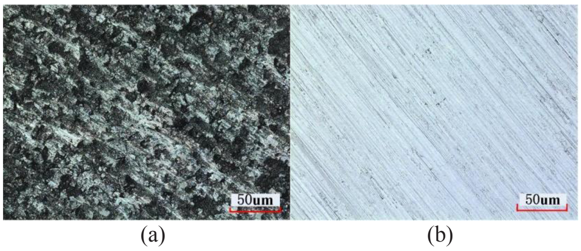
Fig. 9. Effect of milling speed on residual stress (milling condition: f_z=0.075m/min, a_e=6mm and a_p=0.2mm)

It is worth mentioning that, according to Quan and Ye [5], the measurement accuracy of residual stress by means of X-ray diffraction should be considered. In general, when the measured stress is lower than 100 MPa, the results may have notable error. Therefore, the results should be regarded as a qualitative analysis.

3.3. Surface morphology

Due to the distinct structure of PRAMCs, surface quality deteriorates gravely especially when the fraction volume is high (65%). Since the effect of feed rate and milling speed on machined surface image is not evident, two typical images of machined surface morphology for PRAMCs and Al6063 are shown in Fig. 10.

As can be seen from the picture, the feed marks are not noticeable on the machined PRAMCs surfaces, and surface texture is quite irregular due to the presence of the high fraction volume of reinforcements. On the other hand, there are very evident feed marks on the corresponding unreinforced matrix alloy Al6063. Since the feed rate is relatively low compared to the traditional milling feed, no burr formations are visible on the Al6063 surface.



(a) (b)

Fig. 10. 2D microscopic images of machined surface morphology: (a) PRAMCs; (b) Al6063. (milling condition: v_c=300m/min, f_z=0.075m/min, a_e=6mm and a_p=0.2mm)

In order to further investigate the defects on the machined surface of PRAMCs, a 3D laser microscopic image of the machined surface is illustrated in Fig. 11. A vast number of small pits exist on the machined surface. Since the diameter of them is approximately 5-20μm, which are almost the same size as the mean particle diameters (5μm), they are probably formed by abrasives pulled out from the matrix material. In the meantime, dislocation may pile up in the matrix material which surrounds the rigid reinforcements, they may cause decohesion between the particles and matrix aluminum. Consequently, SiC particles are easily pulled out from the surface during milling, resulting in big cavities.

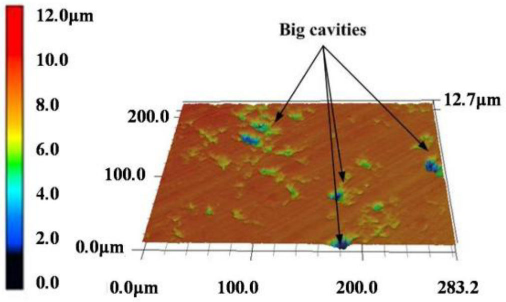


Fig. 11. 3D microscopic images of the machined surface of PRAMC (milling condition: v_c=300m/min, f_z=0.075m/min, a_e=6mm and a_p=0.2mm)

4. Conclusions

This experimental work focused on high speed milling of high fraction volume Al/SiC/65p. There are three main milling parameters (i. e. milling speed, feed rate and axial depth of cut) investigated to provide deep understanding of their effect on the machined surface integrity, including surface roughness, residual stress and morphology. Both full factorial and single factors experiment design were included. In addition, the experiments were also carried on unreinforced aluminum material Al6063 in order to compare to Al/SiC/65p. Some conclusions can be drawn as follows:

- Milling speed has the highest influence on *Ra*, followed by interaction between milling speed and feed rate, then the feed rate. While the effect of axial depth of cut and its interaction on Ra is minimal.
- The surface roughness of Al/SiC/65p increases gradually with the rise of the feed rate. As for Al6063, compared to Al/SiC/65p, surface roughness is quite small. When milling speed varies, the change of surface roughness is marginal with a slight reduction.
- Axial depth of cut has the highest influences on surface residual stress, followed by milling speed and feed rate. While the influence of interaction between the independent factors is marginal.
- The surface residual stress of both Al6063 and Al/SiC/65p experiences a potential trend to increase tensile stress with the increase of the feed rate, while the trend is not evident when speed varies. Residual stresses on Al6063 surface are tensile throughout the whole spectrum of investigated feed rate, while they are compressive for Al/SiC/65p.
- As for surface morphology, the feed marks are not noticeable on machined PRAMCs surfaces and surface texture is quite irregular due to the presence of the high fraction volume of reinforcements. There are many defects on the machined surface of Al/SiC/65p, such as pits and big cavities.

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