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Defence Technology 11 (2015) 104–109

Defence Technology

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2D and 3D milled surface roughness of high volume fraction SiCp/Al composites

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Received 22 July 2014; revised 7 December 2014; accepted 15 January 2015
Available online 16 March 2015

Abstract

This paper presents a study on surface roughness generated by high speed milling of high volume fraction (65%) silicon carbide particle-reinforced aluminum matrix (SiCp/Al) composites. Typical 2D (R_a and R_z) and 3D (S_a and S_q) surface roughness parameters were selected to evaluate the influence of the milling parameters on the surface quality in comparison with aluminum alloy. The 3D topography of the milled surface was studied as well. The results indicate that 3D parameters (S_a and S_q) are more capable to describe the influence of the milling parameters on the surface quality, and among them S_q is preferable due to its good sensitivity. S_q decreases with milling speed and increases with feed rate. The influence of axial depth of cut (ADOC) is negligible.
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Keywords: High volume fraction; SiCp/Al; Surface roughness; 2D; 3D

1. Introduction

Particle-reinforced metal matrix composites have drawn considerable attention in aerospace, automotive, and electronic industries due to the high specific stiffness, high specific strength, and wear resistance, which make them superior to the monolithic alloys [1]. Silicon carbide particle-reinforced aluminum matrix (SiCp/Al) composites are ones of the most popular materials among them and they are taken as the potential materials which can be widely used in lightweight optical assemblies, advanced electronic packaging, thermal management. However, SiCp/Al composites usually exhibit the typical low-ductility, inhomogeneity and anisotropy due to the particular structure, which lead to poor machined surface integrity [2]. Exploring fundamental knowledge of the machined surface quality can provide a solid foundation for the widespread industrial application of SiCp/Al composites.

The investigations on the surface roughness generated by machining of SiCp/Al composites were reported in the last two decades. El-Gallab et al. [3] found that the surface roughness improved with an increase in the feed rate and the cutting speed, but slightly deteriorated with an increase in the depth of cut during machining of SiCp/Al composites. Chan et al. [4] reported that the surface roughness and surface integrity could be significantly improved by using high spindle speed and fine tool feed rate. Depth of cut did not influence the surface roughness significantly except under low spindle speed condition. Pendse et al. [5] developed an artificial neural network (ANN) based model for the prediction of surface roughness during machining of Al/SiC/30p composites. The surface roughness R_a is relatively large, almost all over 1 μm. Dabade et al. [6] studied the cutting force, surface finish, microstructure, and residual stress of the machined surfaces of Al/SiC/10p and Al/SiC/30p composites, and found that the effect of depth of cut was evident only for Al/SiC/30p composites. Feed rate was found to have influence on the

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Peer review under responsibility of China Ordnance Society.

http://dx.doi.org/10.1016/j.dt.2015.01.001
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machined surface roughness of both the composites. Ge et al. [7] carried out the ultra-precision turning tests on SiCp/2024Al and SiCp/ZL101A composites using single point diamond tools (SPDT) and polycrystalline diamond (PCD) cutters. The results indicated that a lower surface roughness value could be achieved when a positive tool cutting edge inclination angle, zero rake angle or bigger flank angle was selected. Pramanik et al. [2] investigated experimentally the effects of reinforcement particles on the machining of MMCs and found the surface roughness was mainly controlled by feed. Schubert et al. [8] utilized CVD diamond tipped indexable inserts for turning AA2124 with 25% volume proportion of SiC particles and found that the surface roughness values could be decreased by using tools with wiper geometry. Bian et al. [9] presented an exploratory study on precision milling of SiCp/Al composites with high volume fraction (65%) and large particle size (60–80 μm), and the results showed that mirror-like surface with surface roughness around 0.1 μm R_a could be achieved by precision milling with small parameters in the range of a few micros.

A summary of the above-mentioned references is listed in Table 1. As for the SiC volume fraction, the majority of the reported research have focused on SiCp/Al composites with low volume fraction (<30%), and the machining of SiCp/Al composites with high volume fraction has been rarely reported. These materials with high volume fraction are widely used in electric packaging, such as in satellites, due to its low heat expansion and high heat conductivity [10]. In terms of the machining operation, the majority of papers focus on turning operation, while according to practical production requirement, a large portion of components are supposed to be made by milling process due to the geometry features. In addition, the 2D roughness parameter is chosen by all the above reports, among which R_a is the main parameter.

In order to use 2D roughness parameter to represent the machined surface quality, it is worth pointing out an important prerequisite that the surface is characterized by a prevailing and well-determined lay in one direction and the profile is cut perpendicularly to that direction [11]. The machined surface of monolithic metal material generated by turning is assumed to comply with the above-mentioned case. However, when the milling operation is selected and the volume fraction of the reinforcement is quite high, many defects such as big cavities and crack of SiC may exist on the machined surface. Therefore, the accuracy of 2D roughness value can be influenced greatly if there are some big defects on the track of the profile, and it can even lead to larger than 50% error in some cases. It is evident that the disadvantages of the 2D roughness parameter can be eliminated if the 3D parameters are chosen.

Table 1
Summary of the above-mentioned references.

Reference	Year	SiC volume/%	SiC size/μm	Machining Operation	Roughness parameter	Roughness range/μm
[3]	1997	20	12	Turning	2D (R_{max})	2–12
[4]	2001	15	3–5	Turning	2D (R_a)	Below 0.1
[5]	2004	10 & 30	37–45	Turning	2D (R_a)	1–10
[6]	2007	10 & 30	10–12	Turning	2D (R_a)	0.4–1.0
[7]	2008	5, 10,15, 25	4 & 15	Turning	2D (R_a)	Below 0.05
[2]	2008	20	6–18	Turning	2D (R_a & R_{max})	1–2, 5–11
[8]	2011	25	2	Turning	2D (R_z)	0–12
[9]	2013	65	60–80	Milling	2D (R_a)	0.05–0.15

Based on the above analysis, the objective of the paper is to explore a more appropriate roughness parameter to evaluate the surface quality of SiCp/Al composites generated by high speed milling operation. The material is a high volume fraction (65%), small silicon carbide (nominal size 10 μm) reinforced aluminum matrix composite. Four widely utilized roughness parameters including both 2D and 3D, i.e., R_a, R_z, S_a and S_z, are used to study the influence of the milling parameters on milled surface quality. The sensitivity and effectiveness of the parameters are analyzed based on the curve graphs and milled surface morphology. In addition, the result comparison between aluminum matrix and SiCp/Al composite is presented as well.

2. Experimental design and procedure

2.1. Materials

The high-speed milling tests were conducted on high volume fraction SiCp/Al composites fabricated through vacuum infiltration method. The microstructure of the SiCp/Al composites is shown in Fig. 1. The properties of SiCp/Al composites are listed in Table 2.

2.2. Equipment setup and procedure

All the machining tests were carried on DMU80 mono BLOCK five-coordinates machining center. Work by Refs. [12] and [13] indicated that PCD was the only tool material which is capable of providing a useful tool life during machining of SiCp/Al composites due to the high abrasive character of particle reinforcement. Therefore, the end milling tools which consist of two PCD inserts brazed on the carbide

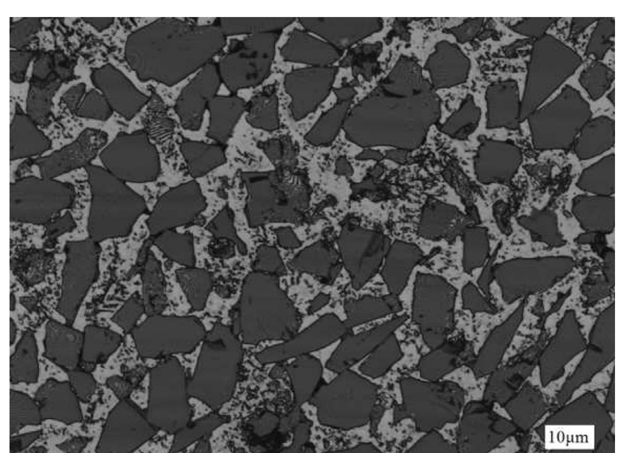


Fig. 1. Microstructure of the Al/SiC/65p composites.

Table 2
Properties of the Al/SiC/65p composites.

Properties	Value
Thermal conductivity/($W\cdot mK^{-1}$)	160–200
Coefficient of thermal expansion/(10^{-6} K)	7–9
Density/($g\cdot cm^{-3}$)	3.1
Elastic modulus/GPa	130
Passion ratio	0.3
Tensile strength/MPa	500
Average size of SiC particle/μm	10
Volume fraction of SiC/%	65

Table 3
The details of the four roughness parameters.

Parameter	Description	Formula
R_a	Arithmetic average of the absolute values	$R_a = \frac{1}{l}\int_0^l \lvert y(x)\rvert dx$
R_z	Average of the sums of the largest valley depth to the highest peak	$R_z = \left(\sum_{i=1}^{5} y_{pi} + \sum_{i=1}^{5} y_{vi}\right)/5$
S_a	Roughness average	$S_a = \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}[z(x_k, y_l)]$
S_q	Root mean square	$S_q = \sqrt{\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}[z(x_k, y_l)]^2}$

tool shank were utilized. The tool diameter and tip corner radius of the inserts are 6 mm and 0.4 mm, respectively. Both the top and bottom surfaces of the workpiece were ground for obtaining less than 1 μm parallelism prior to the tests. The schematic diagram of the milling process is shown in Fig. 2.

Four typical surface roughness parameters including 2D and 3D, i.e., R_a, R_z, S_a and S_z, were selected to evaluate the milled surface quality of the SiCp/Al composites. The corresponding significance and formula are listed in Table 3. The measurement of both the 2D and 3D surface roughness parameters was achieved by Talysurf CCI non-contact surface profiler system. In terms of 2D, cut-off length was set to 0.8 mm and the evaluation length was ln = 4.0 mm according to ISO4288. The 2D surface roughness parameters were measured at five equally spaced locations in feed direction on each milled surface and then averaged to obtain the final value. Whereas the 3D measurement was performed in the sampling area of 1.6 mm × 1.6 mm without additional filtering and the final 3D roughness parameters were obtained by averaging the values from four locations.

3. Results and discussion

3.1. The influence of the milling speed on milled surface roughness

The influence of the milling speed on the milled surface roughness is demonstrated in Fig. 3. As for the 2D parameter,

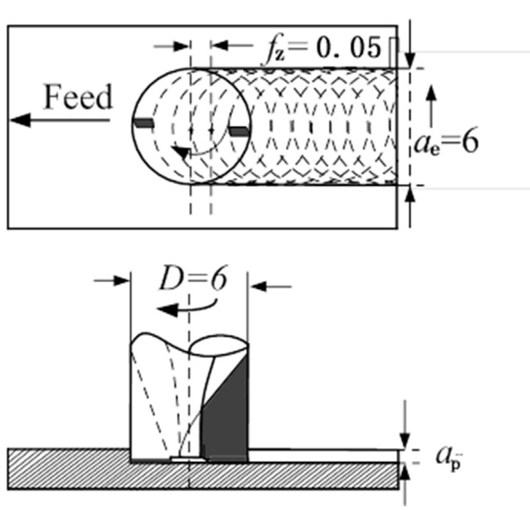


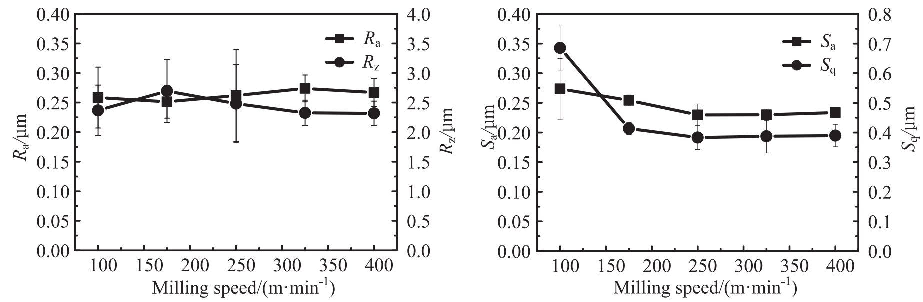
Fig. 2. The schematic diagram of the milling process.

R_a and R_z curves indicate that the influence of milling speed on the surface roughness is not obvious, although they experience some slight fluctuations, as shown in Fig. 3(a). In addition, it is worth pointing out that, when milling speed is 250 m/min, the error is relatively large, 117% for R_a and 80% for R_z. It is evident that the 2D roughness parameters are not stable in describing the milled surface quality of the SiCp/Al composites. In terms of the 3D parameters, the influence is clear, and S_a and S_q curves decrease when milling speed increases from 100 m/min to 250 m/min. After that, the two values remain steady. S_q is preferable since the trend is more obvious. In addition, it is worth mentioning that S_a is recommended to be wiped off in favor of S_q according to the research in Refs. [11], although Ramasawmy et al. [14] and Grzesik et al. [15] still took S_a as an important roughness parameter in their research.

Fig. 4 shows the typical topography of the milled surface under two milling speeds. Although the cavities can be observed on both surfaces, the surface quality generated at high milling speed is superior to that generated at low milling speed in terms of the size and depth of the cavities. However, 2D value is unable to capture the phenomenon. The reason can be attributed to the fact that the increased milling speed can lead to the increase in the strain rate and the decrease in the plastic deformation of the aluminum matrix. Therefore, SiC particles are more likely to be cut through rather than pulled out during the formation of the milled surface.

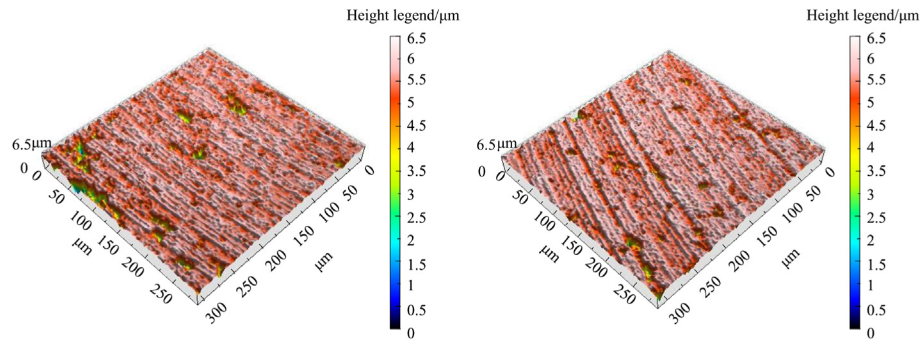
4. The influence of feed rate on surface roughness

The influence of the feed rate on the milled surface roughness is demonstrated in Fig. 5. It is evident that all the selected parameters increase with the feed rate, which complies with the conventional pattern due to the higher residual height generated at higher feed rate. Therefore, all the selected roughness parameters are capable to describe the influence of feed rate on the surface quality. Fig. 6 demonstrates the typical topographies of the milled surfaces at two feed rates. It is obvious that there are many pits and cavities on the milled surface generated at the feed rate of 0.05 mm/z, while the defects are relatively fewer when the feed rate is 0.01 mm/z. In addition, the major color in Fig. 6(a) is blue, while the corresponding color is red in Fig. 6(b), which indicates that the depths of the defects are much larger at high feed rate than that at low feed rate.



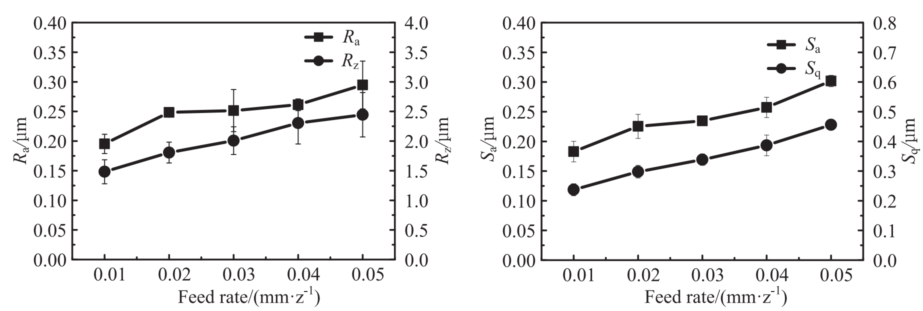
(a) 2D parameter (b) 3D parameters

Fig. 3. Influence of milling speed on surface roughness (f_z = 0.02 mm/min, a_e = 6 mm, a_p = 0.1 mm).



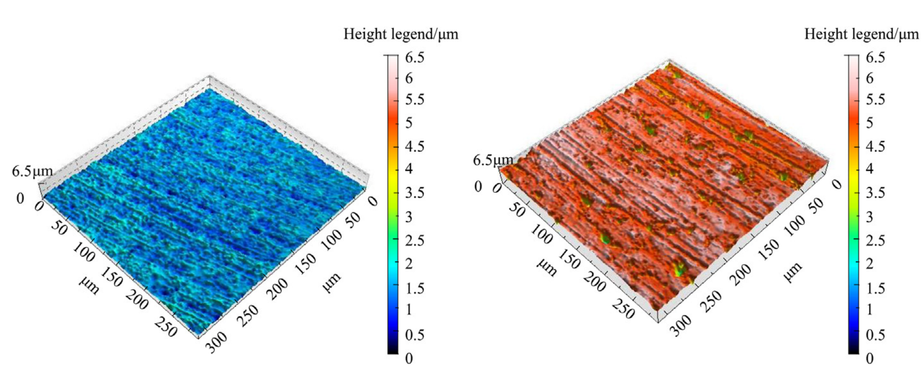
(a) v_c=100m/min (b) v_c=400m/min

Fig. 4. Typical 3D topographies at two different milling speeds (f_z = 0.02 mm/min, a_e = 6 mm, a_p = 0.1 mm).



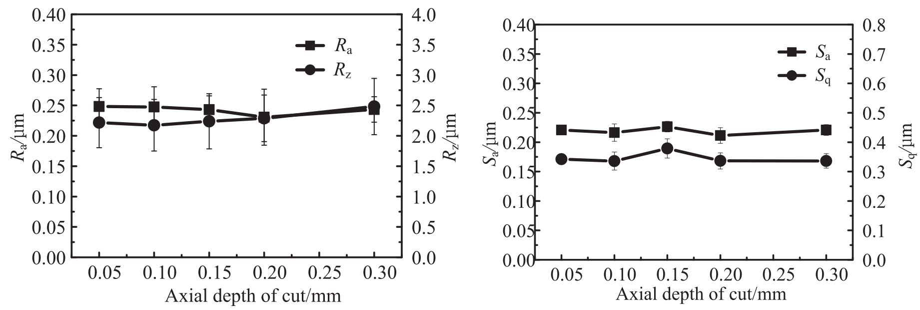
(a) 2D parameter (b) 3D parameters

Fig. 5. Influence of feed rate on surface roughness (v_c = 300 mm/min, a_e = 6 mm, a_p = 0.1 mm).



(a) f_z=0.01mm/z (b) f_z =0.05mm/z

Fig. 6. Typical 3D topographies under two feed rates (v_c = 300 mm/min, a_e = 6 mm, a_p = 0.1 mm).



(a) 2D parameter (b) 3D parameters

Fig. 7. Influence of ADOC on surface roughness (f_z = 0.02 mm/min, a_e = 6 mm, v_c = 300 mm/min).

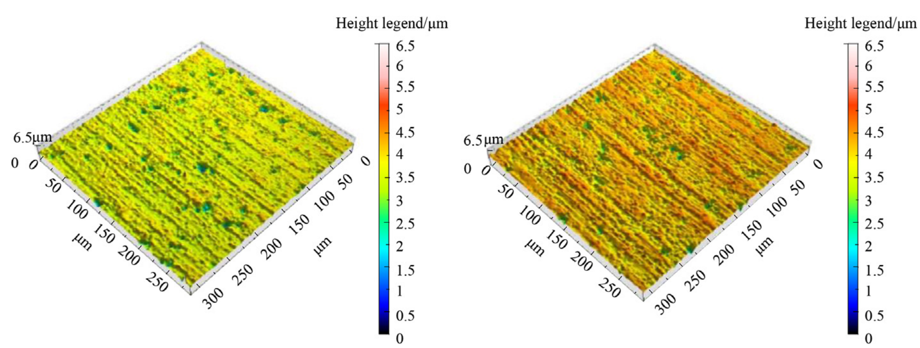
5. The influence of ADOC on surface roughness

The influence of ADOC on the milling surface roughness is demonstrated in Fig. 7. All four roughness parameter curves demonstrate that the influence of ADOC is not significant, although with tiny fluctuations. Fig. 8 demonstrates the typical topographies of the milled surfaces at two ADOCs. In terms of the depth of the cavities and pits, the difference of the two milled surfaces is not evident, which is consistent with the result reported in Ref. [4], although the R_a value is lower than 0.1 μm in their paper. Two main mechanisms have influence on the surface quality, i.e., the pull-out and cut-through of particles. Compared to the nominal size of the particles (nominal size: 10 μm), all ADOCs are large enough and their influence on the pattern of pull-out and cut-through is negligible.

6. Comparison with aluminum

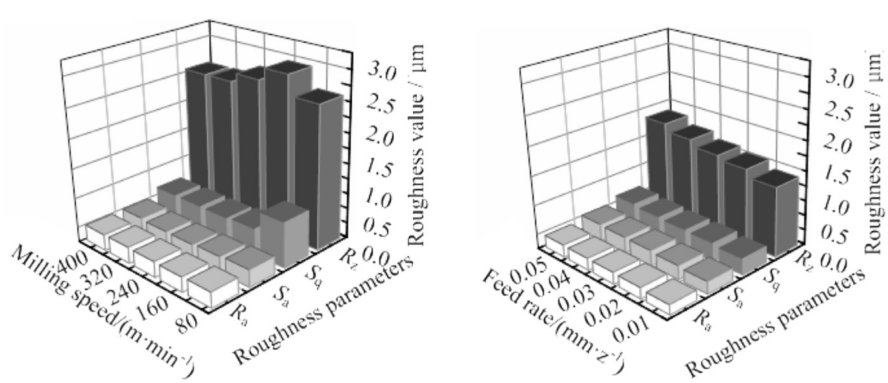
In order to reveal the influence of the SiC particles on the milled surface roughness, the high speed milling tests on the corresponding aluminum matrix were also conducted. The comparison of the surface roughness results between the SiCp/Al and aluminum matrix is shown in Fig. 9.

It can be seen from Fig. 9 that there are several distinctions between the pattern of aluminum matrix and SiCp/Al composes. Specifically, in terms of the varying trend, the influence of milling speed on milled surface of aluminum matrix is not significant and all the four roughness parameters experience some fluctuation when milling speed increases, while the influence of milling speed is evident for the SiCp/Al composites that the roughness parameters decline with the increases in milling speed, especially



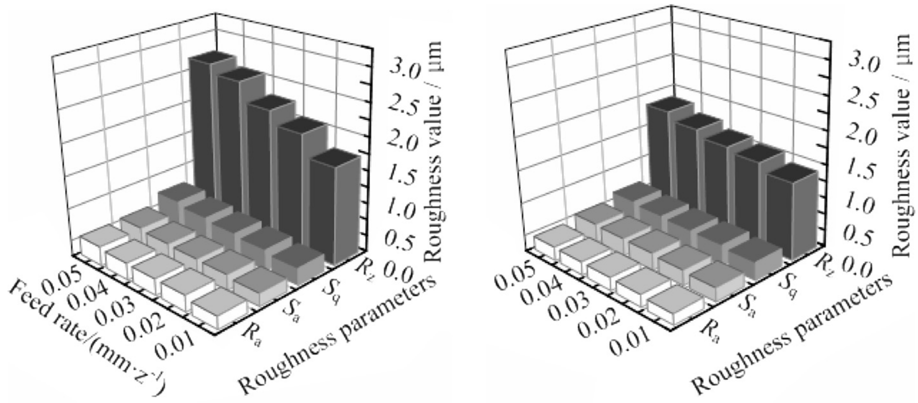
(a) a_p=0.05mm (b) a_p=0.30mm

Fig. 8. Typical 3D topographies at different ADOCs (f_z = 0.02 mm/min, a_e = 6 mm, v_c = 300 mm/min).



(a) SiC/Al composites (b) Aluminum matrix

Fig. 9. The comparison between two materials at different milling speeds (f_z = 0.02 mm/z, a_e = 6 mm, a_p = 0.1 mm).



(a) SiC/Al composites (b) Aluminum matrix

Fig. 10. The comparison between two materials at different feed rates (v_c = 300 mm/min, a_e = 6 mm, a_p = 0.1 mm).

for S_q and S_a. This can be attributed to the fact that the SiC particles are more likely to be cut through rather than pulled out when milling speed is high, thereby reducing the surface roughness, as mentioned before. However the mechanism is eliminated when aluminum matrix is milled due to the lack of SiC reinforcements. In terms of the amplitude, it is expectable that all the roughness parameters for aluminum matrix are smaller than those of SiCp/Al composite, which can be attributed to the absence of the defects, e. g., cavities and pits, on the milled surfaces of aluminum matrix. The phenomenon can be observed in Fig. 10 as well when the influence of feed rate is concerned.

7. Conclusions

1) Compared to 2D parameters (R_a and R_z), 3D parameters (S_a and S_q) are more accurate to describe the surface quality. As for the error bar, the standard error of 3D is smaller than that of 2D.
2) Milled surface roughness of SiCp/Al composites decreases gradually when milling speed increases from 100 m/min to 250 m/min, and then the values remain stable. However, the trend is not evident when aluminum matrix is studied.
3) The influence of feed rate on the surface qualities of both SiCp/Al composites and aluminum matrix is consistent, and all the roughness parameters increase with feed rate. All the roughness amplitudes of aluminum matrix are lower than those of SiCp/Al composites.
4) The influence of ADOC on the surface quality is negligible. All ADOCs are large enough compared to the nominal size of the particle, and their influence on the pattern of pull-out and cut-through is not significant.

Acknowledgment

This work was supported by the National Key Projects of Science and Technology of China (Item No.: 2012ZX04003051-3).

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