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# Effect of Milling Parameters on the Surface Roughness of SiCp/Al Materials

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**The presence of reinforcing particles SiCp seriously affects the cutting surface quality of SiCp/Al materials.In this study, different machining parameters were tested to obtain good surface quality, and the surface quality of SiCp/Al alloy material under different milling parameters was studied by using the surface profilometer and scanning electron microscope to explore the effect of cutting parameters on surface quality. The results showed that the Surface roughness value increased with the increase of feed rate and milling speed, and milling speed was the dominant factor in the microstructure evolution of the machined surface. In addition, an exponential model related to feed rate and milling speed was constructed.**

**Keywords:** SiCp/Al, Cutting Parameters, Surface Roughness, Parameter Optimization

## 1 Introduction

Aluminum-based silicon carbide (SiCp/Al) is an alloy material with aluminum as the matrix, reinforced by silicon carbide particles. This material has low density, high specific strength and specific stiffness, low coefficient of thermal expansion, wear and high temperature resistance, good fatigue resistance and fracture toughness, and is widely used in aerospace, automotive industry and optical engineering. Although the addition of silicon carbide particles effectively improves the material properties, the high hardness and very low plasticity of silicon carbide particles lead to the plastic deformation phase of the Al matrix during the cutting process, while the SiCp particles hardly deform plastically and turn and detach, resulting in poor surface quality. Particle-reinforced Al matrix composites are similar to metal-based grinding wheels for tool grinding. Therefore, the unreasonable cutting parameters will lead to rapid tool wear, making the machining efficiency extremely low, making it difficult to realize mass production and restricting the popularization of SiCp/Al composites.

Previous authors have proposed some solutions to the above problems.Liu, Lin et al [1-4] proposed analytical models related to reinforcing particles, thermal coupling and tool wear to predict the depth of subsurface damage in SiCp/Al composites during cutting.Duan et al [5] revealed the formation mechanism of surface defects in SiCp/Al composites and established a dual-tree complex wavelet based transformation-based roughness extraction method. Kundrák J[6] predicted the milling roughness based on the model.Huang et al. [7] investigated tool wear resistance and wear morphology of PCD cutters in milling of SiCp/Al composites. Zhao, C. [8] predicted the surface roughness of Hard State Cutting.

The previous people mainly used to build models to simulate the cutting process or used polycrystalline diamond material (PCD) tools. However, PCD tools are expensive and not conducive to corporate production. Therefore, this paper studies the effect of carbide coated tools on the surface roughness and surface morphology of SiCp/Al composites under different milling parameters, aiming to provide some process and experimental support for the cutting machining of SiCp/Al composites.

## 2 Experimental model

The difficulty in obtaining surface quality for finishing SiCp/Al materials is due in large part to the presence of SiC-reinforced particles within the material, which can disengage and rupture during the machining process. The process of debonding of the reinforced particles near the cutting edge of the tool along the cutting direction is shown in Fig. 1, as the tool tells the rotary cutting motion, in the case that the cutting force of the tool on the SiC reinforced particles is not enough to cause the rupture of the reinforced particles[9], it will result in the failure of the interfacial layer, and the reinforced particles will lose the bonding force with the interfacial layer to detach from the metal matrix, the particles will be pulled out of the work piece material.The particles are pulled out of the workpiece material and form hole defects on the machined surface.

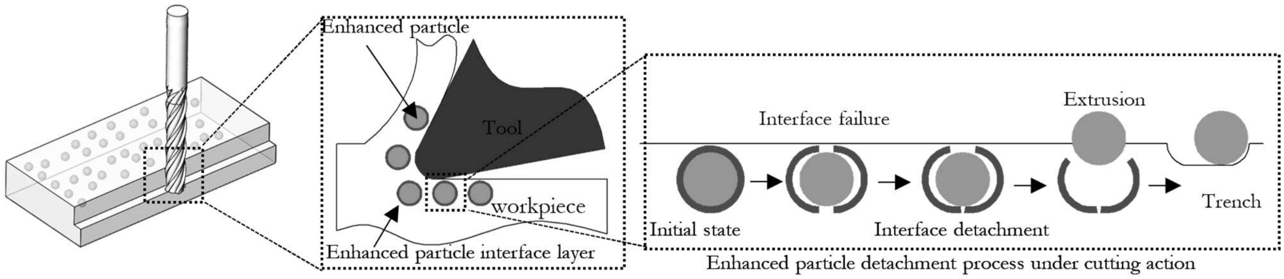



***Fig. 1*** *Enhanced particle detachment process during cutting*

The debonding force F of individual reinforced particles due to interfacial failure can be estimated as:

$$F=\tau \cdot S \quad (1)$$

Where τ is the shear strength of the interfacial layer and S is the area of the region where the interfacial layer shear stress acts, which is determined by the volume of SiC hard particles in the workpiece material. According to the Nardin-Schultz model[10] the interfacial layer shear strength τ can be expressed as:

$$\tau=\frac{W(E_m/E_p)^{1/2}}{\delta} \quad (2)$$

Where W is the adhesion between the metal matrix and the reinforcing particles, $E_m$ is the modulus of elasticity of the metal matrix and $E_p$ is the modulus of elasticity of the reinforcing particles. $\delta$ is the Nardin-Schultz model coefficient related to the type of reinforcing particles,size and shape, etc., which can be identified by the microfabrication milling cutting force experiments of SiCp/Al composites.

## 3 Experimental procedure

### 3.1 Test equipment and materials

The workpiece SiCp/Al material has 30% of SiCp by volume and an average particle size of 10 µm, with detailed performance parameters shown in Tab. 1. A 4-flute solid carbide coated end mill with a 35° helix angle was used and the workpiece was mounted in a 5-axis machining center Mikron MILLE 700 U. The profile and microscopic feature structure of the milled surface were characterized using a Bruker optical profiler and Aztec X-Max80 high-resolution field emission scanning electron microscope, respectively, as shown in Fig. 2.

***Tab. 1*** *Performance* parameters of 30vol% SiCp/Al composites

| | |
|---|---|
| Density (g/cm³) | 2.89 |
| Modulus of elasticity (GPa) | 125±5 |
| Strength (MPa) | 560 |
| Specific stiffness (E/p) | 43.3 |
| Coefficient of expansion ($10^{-6}$/K) | 13.0±1 |
| Thermal conductivity (W/m.K) | 175±5 |

### 3.2 Experiment method

The roughing stage requires low surface quality of the workpiece and can have a long roughing tool life. The research in this paper is to ensure the surface quality of the finishing stage, so the milling milling width of 0.1mm is selected under the condition that the back holding tool amount is 5mm. To slow down the tool wear too fast and lead to poor machining surface quality, this study does not choose high-speed cutting, but selects the milling speed v of 25, 30 and 35 m•min$^{-1}$, respectively, and the feed $f_z$ of 0.005, 0.02 and 0.0375mm/z for milling cross-tests, as shown in Tab. 2.

Since the workpiece is very hard due to the large volume of SiCp/Al, the milling tool was replaced with a new one for each set of milling parameters in order to avoid the influence of tool wear on the test results[11]. The machining site and experimental flow are shown in Fig. 2.

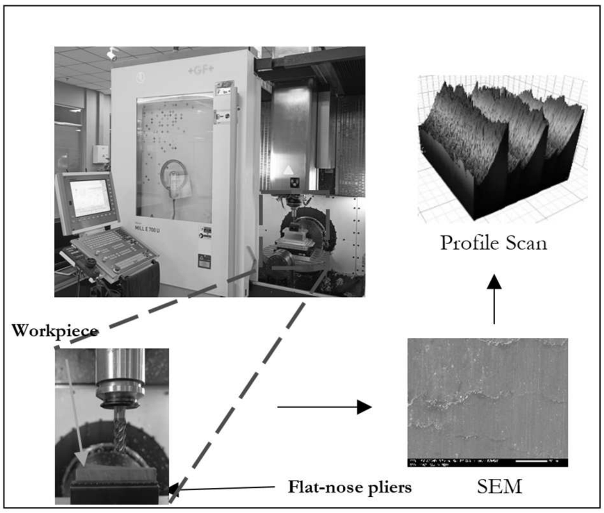



***Fig. 2*** *Processing site and experimental flow*

## 4 Test results and Analysis

### 4.1 Surface roughness

Fig. 3 shows the surface profile of the specimen surface roughness under different milling parameters, and it can be seen from the figure that the geometric texture of the specimen surface is not significant[12].When the feed is $f_z$= 0.005mm/z. And when the feed gradually increases, the surface texture starts to become complete and uniform, and the spacing between the crests increases with the feed. Fig. 4 shows the surface roughness values of the whole specimen under different milling parameters, and it can be found that the roughness increases with the increase of feed amount and milling speed, in which the influence of feed amount on roughness is greater than that of milling speed.

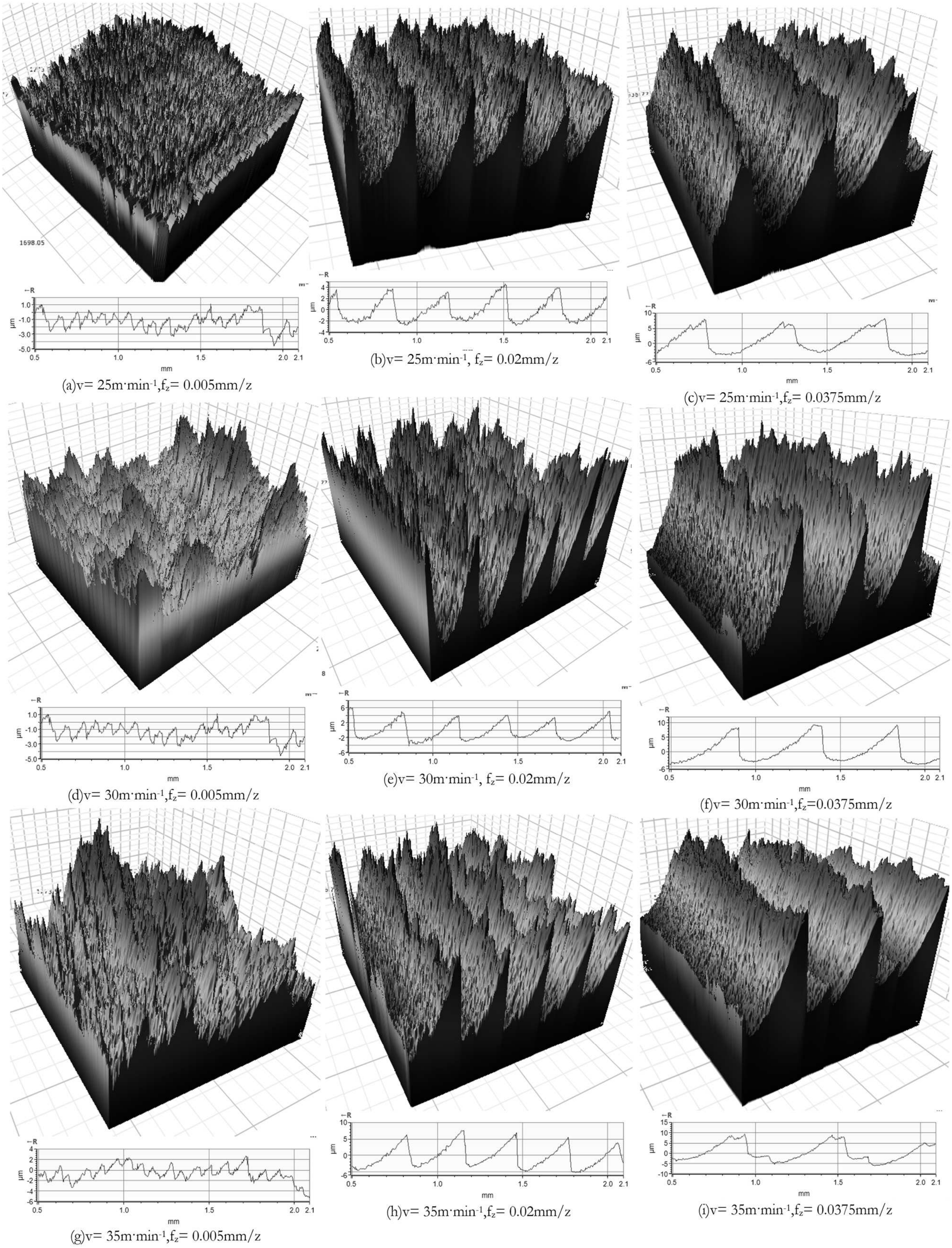



***Fig. 3** Surface roughness of the specimen with different milling parameters and surface profile along the feed direction*

High-speed cutting was not selected in this study, and the milling test for SiCp/Al composites in this paper found that the surface roughness value increased with the increase of milling speed, which was obviously different from the cutting law of common aluminum alloy. Coupled with the increased cutting force and better cutting temperature when machining hard SiCp particles, the aluminum material fully exhibits the plastic fluidity, the plastic side flow phenomenon is intensified, and the convex peak height increases, so the surface roughness increases.

***Tab. 2*** *The details of machine parameters and roughness*

| Cutting speed v（$m \cdot min^{-1}$）\ Feeds（mm/z） | 0.005 | 0.02 | 0.0375 |
|---|---|---|---|
| 25 | 0.42 | 1.634 | 2.941 |
| 30 | 1.195 | 2.061 | 3.265 |
| 35 | 2.118 | 2.416 | 3.701 |

### 4.2 Model construction of surface roughness

In order to clarify the quantitative relationship between surface roughness and milling speed and feed, an exponential model is used to express the relationship between process parameters and machined surface roughness[13], namely:

$$Ra = f（v，f）= Cv^{\alpha} f^{\beta} \tag{3}$$

In equation (3), v and fz are the milling speed ($m \cdot min^{-1}$) and feed (mm/z), respectively. α and β are the exponents of the corresponding parameters.

From equation (3) combined with the orthogonal test results in Tab. 2, the α , β , values are calculated by 25 iterations after taking logarithms and least squares operations.

***Tab. 3*** *Values of each parameter of the exponential model*

| Parameters | Value | Standard Error | Correlation |
|---|---|---|---|
| α | 0.35176 | 0.593 | 0.998 |
| β | 1.12218 | 0.472 | 0.998 |
| C | 0.49596 | 0.111 | 0.976 |
| Correlation coefficient $R^2$ | 0.85843 | - | - |
| Maximum residual sum of squares | 1.204 | - | - |

The empirical formula for surface roughness was obtained as $Ra = 0.49596 \cdot v^{0.35176} \cdot f^{1.12218}$.

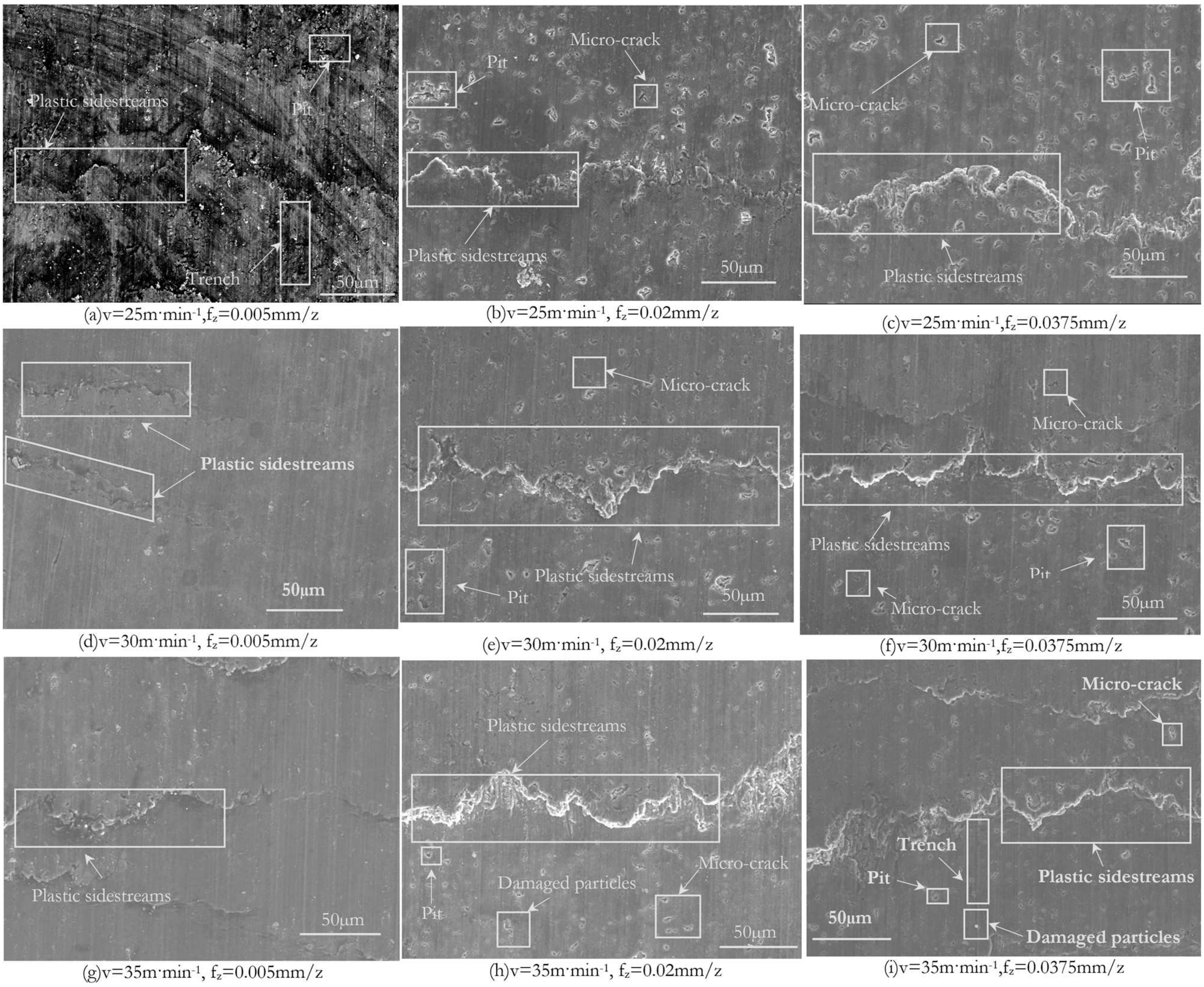
For the roughness measure, the solution is sufficient to meet the requirements of calculating roughness, and it also shows that the constructed model fits the regression with significant effect and acceptable accuracy.

### 4.3 Surface morphology analysis

Fig. 4 shows the surface profile of the specimen with different milling parameters. At a feed of 0.02mm/z and a milling speed of 25 $m \cdot min^{-1}$, plastic sidestreams, trenches and pits exist on the machined surface. As the milling speed increases, the surface defects are mainly plastic sidestreams[14]. At a feed rate of 0.02mm/z, the surface pits gradually decreased and particle movement and damaged particles appeared as the milling speed increased. At a feed of 0.0375mm/z, the trend of surface micro features with milling speed was the same as that at a feed of 0.02mm/z. The differences in surface microstructure were smaller for different feeds at the same milling speed, which indicated that the dominant factor of milling surface microstructure is the milling speed.

The SiCp/Al composite consists of hard reinforced phase SiCp particles and soft phase Al-base, and the mechanism of removal of the two material tissues during machining is different. The strength of SiCp particles is much stronger than their base strength, and the SiCp particles are peeled off from the base to form pits during cutting and machining. The peeled SiCp particles are plowed by the interaction between the tool and the workpiece, thus forming a trench and the hard SiCp particles are embedded in the soft base as the machining continues. Continuing the analysis of the number of trenches, pits and SiCp particles broken in the SEM image, a pattern can be drawn from the statistics. At a feed rate of 0.005mm/z, no significant trenches and pits appear when the milling speed is increased to 30 and 35m/min. At feeds of 0.02 and 0.0375mm/z, the pits also decreased significantly with increasing milling speed. This was attributed to the fact that the stresses induced by the higher milling speed exceeded the fracture strength of the SiCp particles and the chance of particle breakage was greater than particle debonding. At milling speeds of 30m/min and feeds of 0.02 and 0.0375mm/z, the machining stresses exceeded the interfacial debonding stress between the SiCp particles and the Al substrate, and the SiCp particles moved. Meanwhile, at higher feeds(0.02mm/z,0.0375mm/z), the SiCp particles rotate to accommodate the plastic deformation of the Al substrate and form micro-cracks.

The above experimental results indicate that the cutting surface damage decreases with increasing milling speed, but the surface roughness increases with increasing milling speed. This further indicates that the surface roughness under low-speed milling conditions is determined by the tool-induced plastic lateral flow and is not related to defects such as surface pits, damaged particles, and micro-cracks.




(a)v=25m·min⁻¹,$f_z$=0.005mm/z (b)v=25m·min⁻¹, $f_z$=0.02mm/z (c)v=25m·min⁻¹,$f_z$=0.0375mm/z

(d)v=30m·min⁻¹, $f_z$=0.005mm/z (e)v=30m·min⁻¹, $f_z$=0.02mm/z (f)v=30m·min⁻¹,$f_z$=0.0375mm/z

(g)v=35m·min⁻¹, $f_z$=0.005mm/z (h)v=35m·min⁻¹, $f_z$=0.02mm/z (i)v=35m·min⁻¹,$f_z$=0.0375mm/z

***Fig. 4** Surface morphology of specimens with different milling parameters*

## 5 Conclusion

By cutting SiCp/Al composites with 30vol% SiCp content by carbide coated tools under different milling parameters, the changes of surface roughness, surface morphology and chip pattern of the specimens were studied and the following main conclusions were drawn:

- The surface roughness increased with the increase of feed and milling speed, with the feed having the greatest effect on the roughness. In addition, a surface roughness model with a correlation coefficient of 0.85843 was constructed.
- The surface pits of the specimen gradually decreases with the increase of milling speed. The differences of surface microstructure were small when the same milling speed with different feeds.
- SiCp/Al with carbide tools is also feasible as long as the appropriate cutting parameters are selected.

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