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# Experimental Study of Machinability in Mill-grinding of SiCp/Al Composites

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**Abstract:** An attempt was made to investigate the machinability of SiCp/Al composites based on the experimental study using mill-grinding processing method. The experiments were carried out on a high-speed CNC machining center using integrated abrasive cutting tool. The effects of combined machining parameters, *e g*, cutting speed ($v_s$), feed rate ($v_f$), and depth of cut ($a_p$), with the same change of material removal rate (MRR) on the mill-grinding force and surface roughness (Ra) were investigated. The formation mechanism of typical machined surface defects was analyzed by SEM. The experimental results reveal that with the same change of material removal rate, lower mill-grinding force values can be gained by increasing depth of cut and feed rate simultaneously at higher cutting speed. With the same change of MRR value, lower surface roughness values can be gained by increasing the feed rate at higher cutting speed, rather than just increasing the depth of cut, or increasing the feed rate and depth of cut simultaneously. The machined surface of SiCp/Al composites reveals typical defects which can influence surface integrity.

**Key words:** SiCp/Al composites; mill-grinding; machinability; mill-grinding force; surface roughness

## 1 Introduction

Metal matrix composites (MMCs) represent a new class of materials for their advanced mechanical properties such as high wear resistance, low weight, high strength and stiffness, lower expansion coefficient, *etc*. One major division of MMC is aluminum-alloy matrix composite with ceramics particulate reinforcement such as silicon carbide (SiC) and alumina[1-3]. SiCp/Al composites, as one kind of ceramics particulate reinforced aluminum-alloy matrix composite, are more widely used in the aerospace, defense and automobile industries today, particularly in various engine components as well as brake rotors[4-7]. The main concern when machining SiCp/Al composites is the extremely high tool wear due to the abrasive action of the ceramic reinforcing particles acting as abrasive between the cutting tool and work piece[8,9]. SiCp/Al composites are known as difficult-to-machine materials. Therefore, their further wide use in industry is impeded by their poor machinability. Although many high-quality SiCp/Al composites are mostly manufactured by near net shape through various manufacturing technique, the finish machining is needed to achieve the desired surface quality and dimensional tolerance, such as conventional turning or milling[10].

Over the past decades, numbers of studies have been done in order to investigate the machinability of SiCp/Al composites, which has been drawn much attention. Kilickap E *et al*[11] have investigated the tool wear and surface roughness with two types of K10 cutting tool (uncoated and TiN-coated) at different cutting speeds (50, 100 and 150 m/min), feed rates (0.1, 0.2 and 0.3 mm/r) and depths of cut (0.5, 1 and 1.5 mm) in machining of homogenized 5% SiCp aluminum MMC material. Ciftci I *et al*[12] have carried out studies on three SiC/Al metal matrix composites with different SiC particles mean sizes of 30, 45 and 110 μm, using



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cubic boron nitride (CBN) cutting tools to investigate the effect of reinforcement particulate sizes and cutting speeds on tool wear and surface roughness.

Chou YK and Liu J[13] made an attempt to investigate the cutting force, temperature and tool wear using chemical vapor deposited (CVD) diamond tools for machining Al/SiC composite material. The effects of process parameters were evaluated with finite element simulation of cutting temperature and micrograph study. Andrewes CJE *et al*[14] have used two types of diamond tools: brazed polycrystalline diamond (PCD) tools and chemical vapor deposition (CVD) diamond coated tools to do a compared study in machining of a SiC-reinforced aluminum metal–matrix composite (MMC). Manna A *et al*[15] have investigated the influence of machining parameters (cutting speed, feed and depth of cut) on the cutting force and surface finish in turning of silicon carbide particulate aluminum metal matrix composite using a rhombic uncoated carbide tool. Seeman M *et al*[16] have made an attempt to investigate the combined effects of cutting speed ($s$), feed rate ($f$), depth of cut ($d$), and machining time ($t$) on the flank wear (VB max ) and surface roughness ($R_a$), and optimize the process parameters using desirability-based approach response surface methodology in turning of homogenized 20% SiCp LM25 Al MMC. Bhushan RK[17] has done a turning machine test using tungsten carbide and polycrystalline diamond (PCD) inserts to investigate the influence of cutting speed, depth of cut, and feed rate on surface roughness during machining of 7075Al alloy and 10wt% SiC particulate metal-matrix composites. Metin K[18] has studied the effects of cutting speed, size and volume fraction of particle on the surface roughness in turning of 2024Al alloy composites reinforced with $Al_2O_3$ particles based on Taguchi method using coated carbide tools K10 and TP30 and has established a correlation between cutting speed, size and volume fraction of particle with the surface roughness in workpieces. El-Gallab M *et al*[19,20] have carried out a series of dry high-speed turning tests to select the optimum tool material, tool geometry and machining parameters and investigate the effect of the various machining parameters on the surface quality and the extent of the sub-surface damage due to machining for the turning of 20% SiC/Al metal-matrix composites.

High-speed milling experiments were performed by Huang ST, *et al*[21] on SiCp/Al composites with higher volume fraction and larger particles using polycrystalline diamond (PCD) tools under dry and wet machining conditions. The results showed that the main tool wear mechanism in machining of this type of material was abrasion on the flank face. The end milling experiment was carried out by Reddy NSK, *et al*[22] to investigate surface quality and the extent of sub-surface damage of machined Al/SiC PMMC and Al alloy at different levels of cutting conditions using TiAlN coated carbide end mill cutters and finally proper selection of parameters made the end milling process better.

In view of the literatures mentioned above, most of the above studies during machining of SiCp/Al composites have referred to turning machining and only the wear mechanism of different kinds of tool materials based on machining parameters and surface finish were investigated. In recent years, the machining problem of complex cavity and curve parts fabricated by SiCp/Al composites with high volume fraction of SiC particles has attracted attention in industrial demand. Milling can realize machining of complex parts, however, due to brittleness of material, there are often broken edges at rectangular joints of SiCp/Al composite part during milling SiCp/Al composites with high volume fraction of SiC particles using conventional tool. PCD tools are effective tool, but have not been widely adopted due to high cost.

Therefore, in this study an attempt has been made to use a mill-grinding processing method with an integrated abrasive cutting tool installed on a high-speed cutting machine center. To the knowledge of the authors of this work, up to now there is seldom this kind of studies which has been carried out. In this study, the effect of material removal rate (MRR) based on different combinations of machining parameters *e g,* cutting speed ($v_s$), feed rate ($v_f$), and depth of cut ($a_p$) on performance indicators namely mill-grinding force and surface roughness was investigated. Also, the formation mechanism of machined surface defects was also analyzed.

## 2 Experimental

Experiments were carried out on a Deckel Maho machining center (Deckel Maho DMC 70V Linear, max speed: 18000 r/min, position accuracy: 1μm) manufactured by Gildemeister. The coolant was used in the tests. A piezoelectric dynamometer (Kistler dynamometer 9257B) was used to measure the mill-grinding force ($F_t$ and $F_n$), and the DynoWare (Version 2.4.3.2) processing software was adopted to perform the data acquisition. Fig.1 shows the view of the experimental set-up. The workpiece material used in this work was Al2024/SiC/45p, which was Al2024 alloy reinforced by 45% SiC particles with average particle diameter of 5μm and was shaped in the form of 50 mm×40 mm×30 mm blocks. Table 1 shows the physical and mechanical properties of SiCp/Al composites.

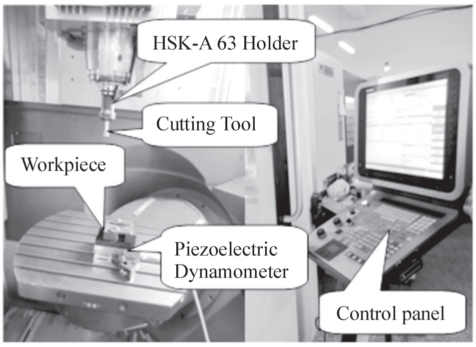


Fig.1 View of the experimental set-up

Fig.2 Image of the cutting tools

The integrated cutting tools, made by authorization of Zhengzhou Research Institute for Abrasives & Grinding in China, were used in this study. The image of the cutting tools is shown in Fig.2. The handle of cutting tool with diameter of 10 mm was made by high-speed steel through tempering heat treatment. Super-hard abrasive layer, which comprised diamond abrasive and binding agent, was the part for playing the role of mill-grinding. The total cutting tool attained dynamic lubrication value of G2.5 in order to satisfy machine tool's dynamic balancing requirements in high spindle rotation speed over 8000 r/min. The details of cutting tool are exhibited in Table 2.

Material removal rate (MRR) mostly decided by machining parameters is one of the evaluation criterion of processing efficiency, and can be changed through different combinations of machining parameters which can have influence on the indicator of machining performance, *eg,* cutting force, surface roughness, *etc*. Material removal rate can be defined as the material volume removed in unit time during cutting process and can be calculated using the relation: $Q_w=v_f\, a_p b$ ($mm^3$/min), where $v_f$ is the feed rate, $a_p$ is the depth of cut and $b$ is the width of cut, respectively. In this study, only the effect of cutting speed ($v_s$), feed rate ($v_f$), and depth of cut ($a_p$) was considered to investigate on performance indicators, therefore the width of cut of $b$ was set to constant 8 mm. Given this, the material removal rate can be changed in one of three ways: just change the feed rate; just change the depth of cut; and change the feed rate and depth of cut simultaneously.

**Table 1 Physical and mechanical properties of SiCp/Al composites**

| Material | Elastic modulus/GPa | Thermal conductivity (W/mK) | Density/(g/cm$^3$) | Tensile strength/MPa |
|---|---|---|---|---|
| Al2024/SiC/45p | 145 | 181.4 | 2.844 | 329.9 |

**Table 2 Characteristics of cutting tool employed**

| Tool type | Cutting part diameter/mm | Handle diameter/mm | Cutting part width/mm | Total tool length/mm | Abrasive | Grit size | Bond |
|---|---|---|---|---|---|---|---|
| ZZSM-1 | 16 | 10 | 12 | 75 | Diamond | 230/270# | Ceramic |

**Table 3 Parameters of material removal rate value**

| Symbol | MRV /($mm^3$/min) | Cutting speed $v_s$ /(m/s) | Condition 1 | | Condition 2 | | Condition 3 | |
|---|---|---|---|---|---|---|---|---|
| | | | $v_f$/(mm/min) | $a_p$/mm | $v_f$/(mm/min) | $a_p$/mm | $v_f$/(mm/min) | $a_p$/mm |
| 1 | 2.4 | 10.05 | 60 | 0.005 | 50 | 0.006 | 30 | 0.01 |
| 2 | 4.8 | 10.05 | 60 | 0.01 | 60 | 0.01 | 60 | 0.01 |
| 3 | 9.6 | 10.05 | 60 | 0.02 | 80 | 0.015 | 120 | 0.01 |
| 4 | 19.2 | 10.05 | 60 | 0.04 | 100 | 0.024 | 240 | 0.01 |

So performance indicators such as mill-grinding force and surface roughness ($R_a$) can be investigated through changing of material removal rate (MRR) based on different combinations of machining parameters in the present work. Parameters of variational material removal rate are listed in Table 3. The surface roughness ($R_a$) was measured by a surface roughness instrument made in Beijing and the cutoff length of the instrument was 0.80 mm. The values of surface roughness were recorded at four different positions and the average value of the four was adopted as the final results. In addition, the images of machined surface by the means of SEM were used to analyze the formation mechanism of machined surface defects.

# 3 Results and discussion

## 3.1 Mill-grinding force

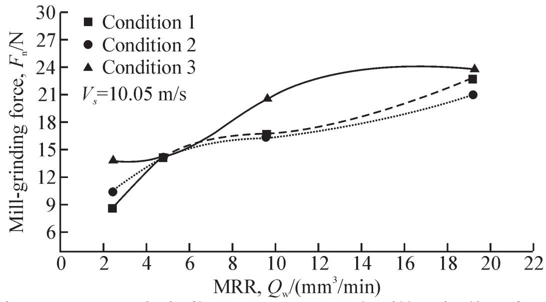


Fig.3 Parametric influence on normal mill-grinding force with the same change of MRR

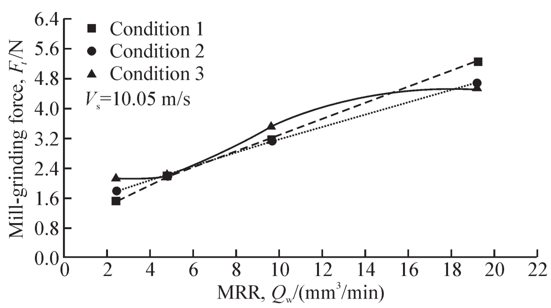


Fig.4 Parametric influence on tangential mill-grinding force with the same change of MRR

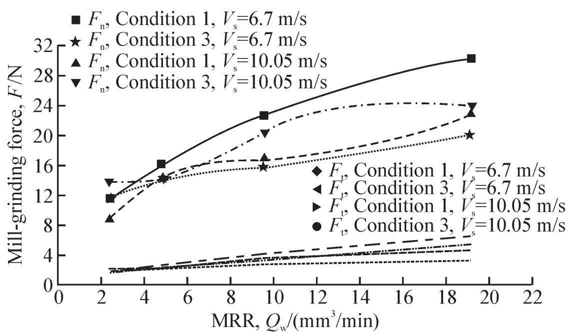


Fig.5 Influence of cutting speed on mill-grinding force with the same change of MRR

The cutting force plays a key role in analyzing the machining process of SiCp/Al composites. The parametric influences on normal and tangential mill-grinding force ($F_n$ and $F_t$) with the same change of MRR value in Table 3 are represented in Fig.3 and Fig.4, respectively. It is seen that both normal and tangential forces in mill-grinding of SiCp/Al composites exhibit gradually increase with the increase of MRR value at the cutting speed of 10.05 m/s. Observations on normal and tangential mill-grinding forces indicate that in general machining parameter combination of condition 2 experiences lower order force compared to that of condition 1 and condition 3. As presented in Table 3, the material removal rate increases by way of just increasing the depth of cut and feed rate under condition 1 and condition 3, respectively; while increasing material removal rate with the increase of depth of cut and feed rate simultaneously in condition 2. Hence, with the same change of material removal rate, mill-grinding forces decrease by way of increasing of depth of cut and feed rate simultaneously at the same cutting speed. In addition, Fig.3 and Fig.4 also indicate that both normal and tangential forces in machining of SiCp/Al composite increase with the depth of cut and feed rate, respectively.

Typical illustration on variation of parametric influence on tangential and normal mill-grinding forces with the same change of MRR value under conditions 1 and 3 at different cutting speed (6.7 m/s and 10.05 m/s, respectively) is shown in Fig. 5. At cutting speed of 6.7 m/s, parametric combination of condition 1 experiences relatively higher normal and tangential forces than that under condition 3. The opposite results are obtained at cutting speed of 10.05 m/s, which is consistent with the results of Fig.3 and Fig.4. This can be attributed to the softening of aluminum matrix with higher cutting speed, which reduces the contact pressure between cutting tool and workpiece. Therefore, normal and tangential forces decrease as the depth of cut increases in condition 1. It is better to increase material removal rate by just increasing feed rate with lower cutting speed, while just increasing depth of cut with higher cutting speed. From the comparison of mill-grinding force in Fig. 5, it can also be observed that the normal mill-grinding force in condition 3 exhibits gradually rapid increase at cutting speed of 6.7 m/s, this being attributed to increasing of undeformed chip thickness due to lower cutting speed and higher depth of cut. In general, the parametric combination of condition 1 at cutting speed of 6.7 m/s shows relatively lower mill-grinding force compared with the others.

### 3.2 Surface roughness

Surface roughness, as a factor of great importance in the evaluation of machining accuracy, plays an important role in the surface quality which influences the component performance. Many factors affect the surface roughness of a machined part, but machining parameters such as cutting speed, feed rate, and depth of cut have a significant influence on the surface roughness for a given cutting tool and workpiece setup[17]. Values of different parametric combination of feed rate and depth of cut are shown in Table 3.

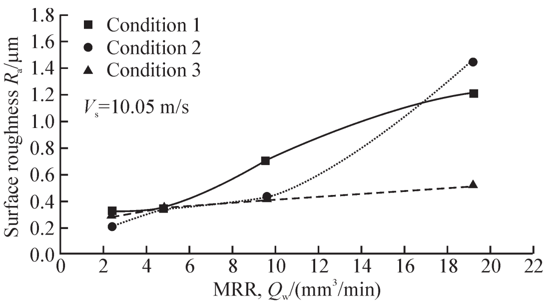


Fig.6 Parametric influence on surface roughness with the same change of MRR

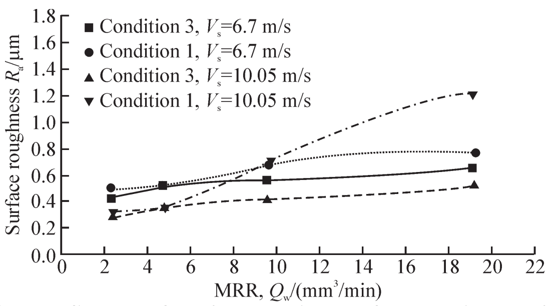


Fig.7 Influence of cutting speed on surface roughness with the same change of MRR

Fig.6 shows the parametric influence on surface roughness with the same change of MRR at cutting speed of 10.05 m/s. From Fig.6, it can be observed that surface roughness values exhibit gradually increase with increase of MRR value. Unlike the case of mill-grinding force, the parametric combination of condition 3 gives the better surface roughness value compared with condition 1 and condition 2. This can be attributed to the correspondingly smaller effect of feed rate on surface roughness during mill-grinding of SiCp/Al composites. Hence, with the same change of MRR value at cutting speed of 10.05 m/s, lower surface roughness value can be gained by increasing the feed rate, rather than just increasing the depth of cut, or increasing the feed rate and depth of cut simultaneously. From the test results, it can also be concluded that surface roughness value in mill-grinding of SiCp/Al composites increases by increasing the depth of cut and feed rate, respectively. It is observed that the surface roughness value is abruptly higher than the trend value with the combination of condition 2. The significant increase of surface roughness illustrated in Fig. 6 may be due to the combination effect of increasing the feed rate and depth of cut simultaneously.

Fig.7 represents the influence of different cutting speed on surface roughness with the same change of MRR under condition 1 and condition 3. Surface roughness values of SiCp/Al composite decrease with the cutting speed of 10.05 m/s using combination of condition 3. Additionally, the best surface roughness was gained, when using parametric combination of condition 3 at cutting speed of 10.05 m/s. However, it is observed that with the increase of MRR (at 5 $mm^3$/min), the value of surface roughness exhibits abruptly increasing trend using parametric combination of condition 1 at cutting speed of 10.05 m/s. The abrupt irregular increase of the values of surface roughness may be attributed to the sliding friction of hard abrasive reinforced particle when increasing the depth of cut at higher cutting speed. The temperature generated in mill-grinding of SiCp/Al composite increases with increasing depth of cut at higher cutting speed, and then aluminum matrix is softened. On one hand, part of softened aluminum matrix fills in the pores between abrasive particle and bonding agent due to the pressure action on contact region between cutting tool and workpiece, which leads to clogging of the cutting tool. On the other hand, due to the softened aluminum matrix, the hard abrasive SiC particle rolls over the machined surface during mill-grinding and plowing on the machined surface, which may generate grooves on the machined surface[15]. Hence, it can be concluded that just by increasing feed rate to improve MRR value at higher cutting speed may give better surface roughness.

### 3.3 Formation mechanism of typical machined surface defects

During machining of SiCp/Al composites, the cohesion damage of bonding surface combining the SiC particles and aluminum matrix often happens, which may be due to not only the effect of machining process, but also the interaction of SiC particles and diamond abrasive, as well as original properties of SiCp/Al composite. Typical views of the machined composite surface topography are shown through SEM images (Fig.8- Fig.11). From these Figures, it can be observed that the machined surface of SiCp/Al composites reveals many defects, which can influence the surface integrity.

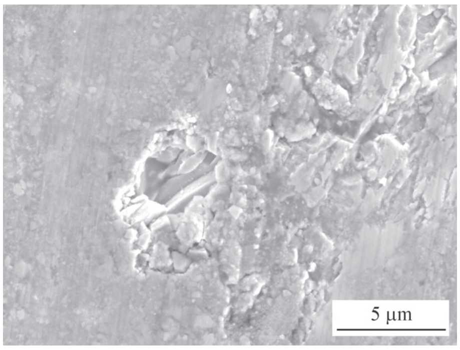


Fig.8 Void formed on the machined surface

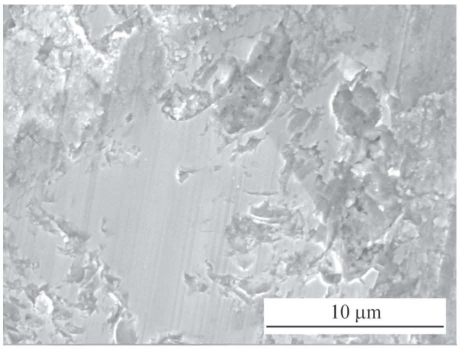


Fig.9 Smearing of softened aluminum matrix

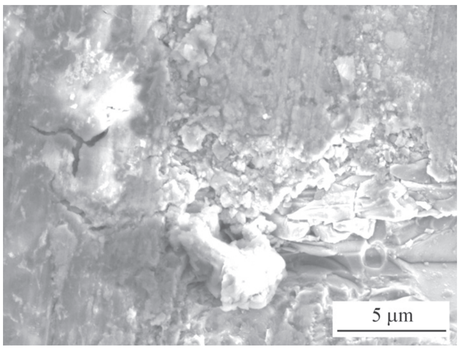


Fig.10 Fracture of SiC particle

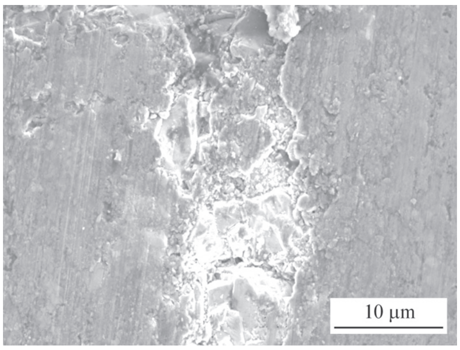


Fig.11 Material falling off from machined surface

Fig.8 shows the void formed on the machined surface, and this may be due to strain hardening of material itself. During the process of material removal, the aluminum matrix induces elastic-plastic deformation, while SiC particles just introduces elastic deformation, associated with the rotation of SiC particles. Not only that, the matrix material wrapping particle generates dislocation motion, which results in dislocation pile up in the matrix material. As a result, some SiC particles separate from the surface.

From Fig.9, it is observed that softened aluminum matrix smears on the machined surface. The reason may be attributed to the high temperature produced in the mill-grinding process, which leads to thermal softening of aluminum matrix and possible degradation in the performance of the cutting tool. Due to the normal mill-grinding force, the softened matrix material can easily smear on the machined surface by sliding effect. Fig.10 reveals the fracture of SiC particles. The fracture of SiC particles is formed due to the interaction of SiC particles and diamond abrasive. It is also observed that material falls off from machined surface in Fig.11. In the accumulation area of SiC particles and sharp corner of particle, the stress concentration is severe, easily producing cracks that often expand in the machining process, which results in material falling off from machined surface. And the un-cut surface forms in this process.

## 4 Conclusions

Based on the mill-grinding experiments carried out on a high-speed CNC machining center using integrated abrasive cutting tool the effects of combined machining parameters with the same change of material removal rate (MRR) on the mill-grinding force and surface roughness ($R_a$) were analyzed. Using the machining condition in this study, the major conclusions can be drawn as follows:

a) Lower mill-grinding force values can be gained with the same change of material removal rate improved by way of increasing of depth of cut and feed rate simultaneously at lower cutting speed. It is better to increase material removal rate by way of just increasing feed rate at lower cutting speed, while by way of just increasing depth of cut at higher cutting speed.

b) With the same change of MRR value at higher cutting speed, lower surface roughness of SiCp/Al composites can be gained by increasing the feed rate rather than just increasing the depth of cut, or increasing the feed rate and depth of cut simultaneously.

c) During machining SiCp/Al composites, the machined surface of SiCp/Al composites reveals many defects, such as void formed on the machined surface, smearing of softened aluminum matrix, fracture of SiC particles, and material falling off from machined surface, which can influence the surface integrity in practice.

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