Machining Characteristics in Cryogenic Grinding of SiCp/Al Composites

Li Zhou · Shutao Huang · Xiaolin Yu

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Abstract In this study, liquid nitrogen was applied to grind SiCp/Al composites with high volume fraction and large SiC particle at different levels of cutting conditions, and the effects of grinding depth and speed on grinding force, surface morphology, and surface roughness were investigated. At the same time, the effect of cryogenic cooling was also compared with that of conventional wet grinding. The experimental results indicated that cryogenic cooling is effective in enhancing supporting function of Al matrix to the SiC particles and improving surface quality. Additionally, the brittle fracture of SiC particles was suppressed and some ductile streaks on SiC particle could be observed.

KEY WORDS: SiCp/Al composites; Grinding; Cryogenic machining; Surface quality

1 Introduction

Due to the superior mechanical and physical properties, SiCp/Al composites are being used to replace conventional materials in many applications, such as the aerospace defense and automotive industries [1–3]. However, in spite of all the advantages, the wider applications of SiCp/Al composites have been impeded by their high machining costs. Since the mechanical properties of SiC particles are very different from those of matrix alloys, the Al matrix and SiC particles do not deform uniformly under the cutting force. Therefore, it is difficult to ensure the dimensional accuracy and high surface integrity of machined workpieces during machining of these composites. It is well known that the surface quality generated during machining is important as it influences the performance of the finished components to a great extent. In addition, with

the increasing of the volume fraction and SiC particle size, the conventional tool materials and machining technology are unsuitable to machine these materials. Therefore, a proper machining process is highly desired for the application of these composites.

In recent years, experimental machining of SiCp/Al composites has been extensively carried out to investigate the tool wear, cutting force, surface roughness, and sub-surface damage. Owing to the addition of reinforcing ceramic particles which are much harder and stiffer than the matrix, machining becomes significantly more difficult and results in rapid tool wear. Therefore, many of the literature concentrated on the study of wear characteristics of various tool materials during machining of SiCp/Al composites [4–9]. Ciftci et al. [8] examined the effects of SiC volume fraction and size on the tool wear in machining SiCp/Al composites with different tools. It was reported that the volume fraction and size of the reinforcement in the composites have the most important impact on the tool wear, and coated carbide cutting tool produced a longer tool life, but uncoated type provided a better surface quality.

Most of the investigations indicated that conventional cutting of SiCp/Al composites leads to excessive tool wear

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L. Zhou (✉) · S. Huang · X. Yu
School of Mechanical Engineering, Shenyang Ligong
University, Shenyang 110159, China
e-mail: lizhou@imr.ac.cn

and possible sub-surface damage, and only polycrystalline diamond (PCD) tools showed better wear resistance and produced better surface finish than the other tools. Particularly, for some components, the production of good surface finish is essential. Therefore, a number of studies also focused on the effects of cutting parameters, tool geometry, and SiC particles characteristics on the surface finish of the machined samples [10–14]. It was reported that the surface quality depends on the shape, the size, and the volume fraction of the reinforcement, and some of the SiC particles are pulled out of the surface, while others are fractured. Voids and cracks initiate around the particles due to the plastic deformation in the matrix material, and a good surface finish is generally produced when the particles are cut cleanly instead of being pulled out of the matrix material. Among traditional machining methods, grinding operation is important for SiCp/Al composites, since it could be applied also in heavy-duty machining, in addition for obtaining desired dimensional tolerances and surface quality.

Although some grinding experiments proved that cryogenic cooling can reduce the magnitude of the tensile residual stresses in machining of different tool steels [15] and hardened steels [16], few works have been reported on the cryogenic machining of SiCp/Al composites. Recently, numerical modeling has been used in understanding the machining mechanism of SiCp/Al composites. Many finite element simulations of the cutting process are performed using the explicit method, which includes studying the failure at the particle-matrix interface [17], tool-particle interaction [18], residual stress, surface damage [19], and so on. Additionally, the artificial neural network, analytical mechanics model, and the other methods have also been used to predict the surface roughness [20], cutting force [3, 21], and cutting temperature [22] during machining of SiCp/Al composites.

The literature review above indicates that most studies for machining of SiCp/Al composites were focused on dry and wet machining and generally the fraction of the reinforcement is about 20 vol%. However, little work has been done to investigate the grinding characteristics of SiCp/Al composites with high volume fraction and large particle size, especially under cryogenic grinding condition.

In the present work, an attempt has been made to study the influence of cryogenic grinding process on the surface quality as a function of machining parameters by analyzing grinding forces, surface finish, and the microstructure of machined surface of SiCp/Al composites. The conventional wet cutting was included for comparison.

2 Experimental

The material used for grinding experiments was SiCp/Al composite containing 56 vol% SiC particles, which were

Fig. 1 Micrographs of SiCp/Al composites used for experiments

produced with a pressureless infiltration technology, and the average size of the SiC particles was 60 μm, as shown in Fig. 1. In the SiCp/Al composite, the SiC particles are uniformly distributed in the aluminum alloy matrix, and most of them are polyhedral with sharp corners. The mechanical properties of the SiCp/Al composites are Vickers hardness is 200 MPa, elastic modulus $E = 220$ GPa, flexure strength $K = 405$ MPa, and density $\rho = 2.94$ g/cm³.

Grinding experiments were performed on a precision surface grinding machine MG7132, and a resin-bonded diamond grinding wheel was used with the grit size of 28 μm. The diameter and width of the wheel are 300 and 32 mm, respectively. The dimension of the specimen is 59 mm × 47 mm × 8 mm. Figure 2 shows the experimental set-up of surface grinding of SiCp/Al composites, and the details of grinding and dressing conditions are listed in Table 1. In this study, due to the limit of machining machine, a lower range of table speed was used.

Grinding was carried out on the 47 mm × 8 mm surface, and a 2% solution of a water-based coolant and liquid nitrogen were applied. The work pressure of the liquid nitrogen was less than 0.2 MPa, controlled by a regulator. To maximize the cooling effect, a nozzle was mounted on the wheel guard to provide a liquid jet to the grinding zone as closely as possible. Up-grinding was used to facilitate the penetration of liquid nitrogen into the grinding zone. During experiments, only one of the parameters, such as the table speed was varied while the cutting depth, was held constant to observe the effect of individual parameter on machining properties.

A 3D-piezoelectric dynamometer and scanning electron microscopy (SEM) were used in examining the grinding force and the quality of the machined surface.

Fig. 2 Schematic illustration of the experimental setup using liquid nitrogen

Table 1 Experimental facility, material, and grinding parameters and conditions

Grinding machine	MG7132
Workpiece material	SiCp/Al composites, dimension of 59 mm × 47 mm × 8 mm
Grinding method	Surface up grinding
Grinding wheel	Resin-bonded diamond grinding wheel, grit size of 28 μm, φ300 mm × 32 mm
Wheel speed	1,500 r/min
Table speed	3.3, 7.5, 9.7, 10.9, and 19 m/min
Grinding depth	1, 2, 3, 4, and 5 μm
Cooling	Wet grinding, water-based coolant; liquid nitrogen
Dressing method	Single point diamond

3 Results and Discussion

3.1 Grinding Forces

The grinding forces measured for the wet and cryogenic conditions by the dynamometer are presented in Figs. 3 and 4. It is clear that both normal grinding force and tangential grinding force increased with the increase of cutting depth, and the normal grinding forces were larger than the tangential grinding force at each set of grinding conditions. Due to the lower range of worktable speed, the grinding forces were complex and could not be simply considered to a monotonic function (see Fig. 3). Compared with those under the wet grinding, the grinding forces under the cryogenic condition were increased remarkably, and the variation trend of grinding force with the move speed of the worktable became more evident, i.e., the normal grinding force and tangential grinding force increased gradually with the increasing of the move speed of the worktable.

It is well known that the coefficient of thermal expansion of Al alloy matrix is much higher than that of the SiC particles,

and the cryogenic cooling would induce the compressive stress in the SiC particles and tensile stress in the Al alloy matrix. Thus, a better interfacial bonding state between the particle and matrix could be obtained under the cryogenic condition. Moreover, the effective cooling from the liquid nitrogen jet enhanced the mechanical properties of the workpiece material. Therefore, the cryogenic grinding approach caused the higher grinding forces in both the normal and tangential directions.

Generally, the mechanical and physical properties of the material depend on the temperature. A decrease in temperature generally increases the elastic modulus, hardness, and strength. The effects of temperature on the physical properties, ductility, and toughness, however, vary considerably [23]. For low-carbon steel, due to the distinctive ductility-to-brittleness transition, cryogenic machining can provide the ideal machining conditions, such as reduction in cutting force, power consumption, and tool wear rate, and improvement in surface finish and chip formation [23–27]. Zhao and Hong [23] have established some cryogenic cooling strategies for some materials depending on their behavior at low temperature. In the case of aluminum–silicon cast alloy A390, which has a large amount of primary silicon phase in the microstructure. The increase in bulk hardness by cooling the workpiece may not be a concern for cryogenic machining, but the increase in the micro hardness of primary silicon phase would make it more abrasive.

3.2 Surface Morphology

Typical surface morphology of machined SiCp/Al composites was observed under SEM to analyze the surface integrity. The SEM photographs of the machined surfaces under the wet grinding and cryogenic grinding are shown in Figs. 5 and 6, respectively. Magnified view of the surface morphology clearly shows that under the wet grinding condition, the brittle fracture was produced on the SiC particles, and most of the interfaces between particles and matrix failed (see Fig. 5b, c). By comparison, under the cryogenic grinding condition, fewer pits and cracks were observed on the machined surface, although there were some grooves on the machined surface since the small chips could not be removed immediately, as shown in Fig. 6a. At the same time, it is worth noting that the interfaces between the particles and matrix were very fine and there were some visible ductile streaks on the middle of the SiC particles (see Fig. 6b, c). This is attributed to that under the cryogenic condition, the plastic deformation took place in the Al alloy matrix, and the dislocation piled up in the matrix material which surrounds the rigid particles. It is well known that the supporting function of Al matrix to the SiC particles is very important during machining of SiCp/Al composites. Therefore, it may be concluded that the cryogenic grinding is relatively

Fig. 3 Grinding forces versus depth of cut under wet condition: **a** normal grinding force; **b** tangential grinding force

Fig. 4 Grinding forces versus depth of cut under cryogenic condition: **a** normal grinding force; **b** tangential grinding force

successful in improving the quality of machined surface during machining of SiCp/Al composites.

3.3 Surface Roughness

Seven measurements were conducted at different locations on the ground surfaces, and the average surface roughness value was calculated. Figure 7 presents the influence of grinding depth on the average surface roughness at different move speeds of the worktable. From Fig. 7a and b, it could be observed that the variations of grinding depth and speed of worktable did not affect the average surface roughness significantly. The reason is that the SiC particles on the surface of the workpiece were not perfect before the grinding tests, and the lower grinding depth (from 1 to 5 μm) and speed of worktable did not result in obvious change of the average surface roughness. Furthermore, due to the effective cooling of the liquid nitrogen, the supporting function of Al matrix to the SiC particles was

enhanced and the grinding zone temperature reduced greatly, and the softening of the Al alloy matrix was avoided. Therefore, comparing Fig. 7a and b, it is clear that the average surface roughness obtained under the wet grinding condition was much higher than that under the cryogenic condition at all levels of considered parameters.

4 Conclusions

An experimental investigation of the grinding characteristics of SiCp/Al composites under cryogenic and wet conditions was conducted using the surface grinding process. The main results can be summarized as follows:

- (1) With the increasing of the grinding depth, both the normal grinding force and tangential grinding force increased evidently. Due to the plastic deformation in the Al matrix under the cryogenic condition, the supporting function of Al matrix to the SiC particles

Fig. 5 SEM micrographs of ground surface of SiCp/Al composites under wet grinding condition with different magnifications of $\times 200$ **a**, $\times 1,000$ **b** $\times 5,000$ **c**

Fig. 6 SEM micrographs of ground surface of SiCp/Al composites under cryogenic condition with different magnifications of $\times 200$ **a**, $\times 1,000$ **b** $\times 5,000$ **c**

Fig. 7 Surface roughness versus depth of cut under wet condition **a** cryogenic condition **b**

was enhanced. Therefore, the grinding forces under the cryogenic condition were higher than those under the wet grinding.

- (2) Grinding under the cryogenic condition reduced substantially the brittle fracture of SiC particles, and the quality of machined surface was improved. This was attributed to the better cooling effectiveness of the liquid nitrogen, which reduced the grinding zone temperate and avoided the softening of the Al alloy matrix.

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