

Experimental Investigation on Ultrasonic Vibration-Assisted Milling of Silicon Carbide Particle-Reinforced Aluminum Matrix Composites

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ABSTRACT

The paper conducts an experimental study on ultrasonic vibration-assisted milling (UVAM), aiming at addressing issues such as high cutting forces and poor machining quality in traditional milling of silicon carbide particle-reinforced aluminum matrix composites (SiCp/Al). By comparing conditions with and without ultrasonic vibration, the effects of different spindle speeds and feed rates on cutting forces are analyzed. The results show that ultrasonic vibration-assisted machining significantly reduces cutting forces, with a maximum reduction of 34.4%. Cutting forces increase with higher feed rates, but the growth rate slows in the high-speed region. As the spindle speed increases, cutting forces decrease. Cutting forces continue to decrease gradually under ultrasonic conditions, whereas they slightly rebound under non-ultrasonic conditions in the high-speed region. These findings indicate that UVAM can improve the machinability of SiCp/Al composites.

KEYWORDS

SiCp/Al composites; Ultrasonic vibration-assisted milling; Cutting forces; Machining parameters

1. INTRODUCTION

SiCp/Al have emerged as ideal structural materials for high-end equipment manufacturing sectors such as aerospace and automotive industries, owing to its exceptional specific strength, specific stiffness, thermal conductivity, and hardness [1]. For the conventional milling process, not only tool damage happens easily but also the machining-inducing edge chipping and very poor surface integrity usually appear during the whole milling. Those limited the application scope of the method in precision manufacturing. But, using UVAM with high frequency vibration can modify tool-workpiece contact condition well, and it could lower the cutting force significantly, reduce the heat generation and improve the surface quality compared with normal machining processes. Those advantages make the composite materials precision machining using UVAM widely paid attention to.

Addressing tool wear issues in precision machining of SiCp/Al composites, Zhang et al. conducted UVAM experiments under supercritical carbon dioxide minimum quantity lubrication conditions. Combined with modeling and genetic algorithm optimization, they identified optimal process parameters that effectively mitigate wear, thereby enhancing machining quality and tool life [2]. In order to further study the machining mechanism of composite materials, Zhang et al. conducted a longitudinal-torsional ultrasonic-assisted milling experiment to establish a cutting force predicting model through an experiment which confirmed the noticeable decrease in cutting forces brought on by the experimental conditions and provided evidence of the application of ultrasonic-assisted machining technique [3]. To tackle problems concerning machining quality arising from high-

hardness reinforcements, Niu et al. employed longitudinal-torsional ultrasonic-assisted milling technique. Using kinematic analysis, finite element simulation, and experimental verification, material removal mechanisms were disclosed in a systematic manner. Longitudinal-torsional ultrasonic-assisted machining was more effective at increasing the fracture rates of silicon carbide particles than conventional milling, reducing cutting forces and cutting temperatures, as well as improving workpiece surface integrity compared with conventional milling [4]. Hu et al. using ultrasonic-assisted grinding, compared the influence of different reinforcement phase volume fractions on machining quality. Experimental findings revealed that 60% volume fraction materials exhibit higher cutting forces and surface roughness. Through increasing spindle speed, or reducing feed rate, surface quality can be effectively improved with reducing cutting forces [5]. Wang et al. established a tool-chip contact ratio model as well as microscopic finite element model with consideration of particles' distribution. These models were used to thoroughly analyze the material removal mechanism of UVAM. It has been discovered that the intermittent cutting characteristic is an efficient way to restrain the formation of surface defects and increase the quality of the machined part [6].

Ultrasonic-assisted machining has emerged as an effective method for processing SiCp/Al composites in recent years. Therefore, this study introduces ultrasonic vibration to conventional milling, and employs single-factor experiments to compare the magnitude of cutting forces under different machining parameters with ultrasonic-assisted (ultrasonic power set at 70%) and non-ultrasonic (ultrasonic power set at 0%) conditions. The findings can provide guidance for selecting ultrasonic-assisted machining process parameters of SiCp/Al composites.

2. KINEMATIC ANALYSIS

The motion trajectory projection in the XY plane of the tool in ultrasonic vibration-assisted milling and conventional milling is the same. The difference between them is that a high-frequency simple harmonic vibration is added along the Z axis in ultrasonic machining. This kind of composite motion consists of three parts: tool rotating motion, high-frequency vibration in the Z direction, and the feed motion on the XY plane.

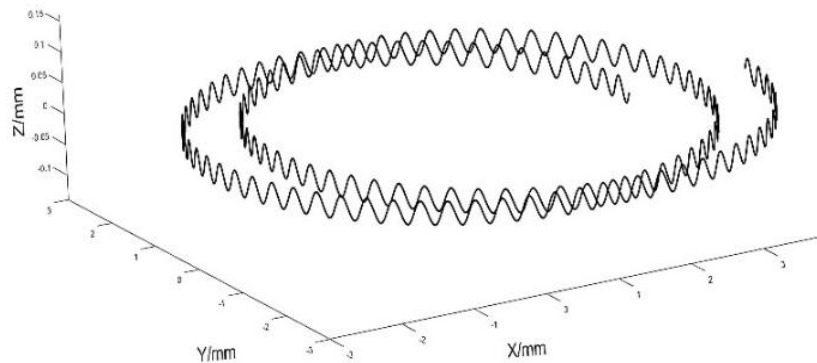


Figure 1. Trajectory of Tool Tip

As shown in Fig. 1 is the spatial trajectory of the ultrasonic milling tool tip, obtained with the help of the MATLAB software. The movement of the ultrasonic milling tool center can be expressed as the following formula:

$$\begin{cases} x_u = v_c t \\ y_c = 0 \\ z_u = v_c t + \gamma \sin\left(\omega t - \frac{2\pi i}{z}\right) \end{cases} \quad (1)$$

The motion trajectory equation for the i th cutting edge can be expressed as:

$$\begin{cases} x_u = v_c t + r \sin\left(\omega t - \frac{2\pi i}{z}\right) \\ y_u = r \cos\left(\omega t - \frac{2\pi i}{z}\right) \\ z_u = A \sin(2\pi f + \varphi_0) \end{cases} \quad (2)$$

Where A is the amplitude, f is the frequency, r represents the tool radius, φ_0 is the initial phase angle, and i is the sequence number of cutting edge the (1, 2, 3...). By overlapping Z-axis sinusoidal vibration onto conventional milling motion, the UVAM effectively changes the kinematic characteristics of the cutting process. The actual path length of the ultrasonic machining process is obviously longer than that of ordinary milling. In addition, the periodic separation contact between the tool and workpiece creates an intermittent cutting mode and combining it with the optimized kinematic condition produces much smaller cutting force, thereby improving the machining quality.

3. EXPERIMENTAL METHODOLOGY

The milling operation was done using a three-axis vertical CNC milling machine that could vary its spindle speed from 0 r/min to 6,000 r/min and its feed rate from 0 mm/min to 8,000 mm/min. The ultrasonic vibration-assisted machining system that is integrated included the self-developed ultrasonic power supply, energy transmission device, piezoelectric transducer, and specialized tool holder. The ultrasonic vibration system has an amplitude control range up to 0~4.79 μ m. Target amplitude values were achieved through power percentage settings, with the relationship between amplitude, resonant frequency, and ultrasonic power detailed in Table 1. Machining employed a polycrystalline diamond two-flute end mill with 4 mm diameter.

Table 1. The Relationship between Amplitude, Resonant Frequency, and Ultrasonic Power

Ultrasonic power (%)	Amplitude (μ m)	Resonant frequency (kHz)
20	1.02	20.154
40	1.91	20.147
60	2.89	20.138
80	3.80	20.127
100	4.79	20.110

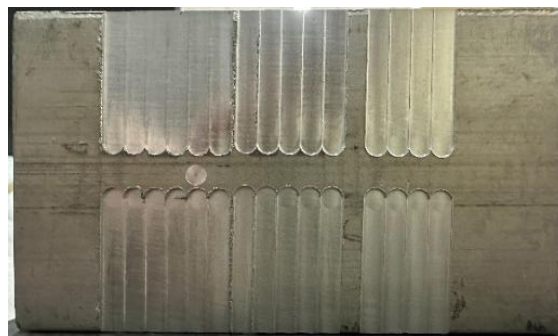


Figure 2. Surface Morphology of SiCp/Al Specimens after Face Milling

Using single-factor analysis method, the experiment systematically compared the influence of different process parameters on cutting forces under ultrasonic vibration-assisted machining (ultrasonic power set at 70%) and conventional machining (ultrasonic power set at 0%) conditions. Surface morphology of SiCp/Al specimens after milling is shown in Fig. 2, where the upper row represents ultrasonically machined surfaces and the lower row conventional machined surfaces. Experimental group numbers increase sequentially from left to right with constant cutting depth of

0.1 mm, and measured resultant cutting forces under different process parameters are summarized in Table 2.

Table 2. Cutting Force in Milling

Group	Spindle speed (rpm)	Feed rate (mm/min)	Ultrasonic power (%)	Cutting force (N)	
1	1000	40	70	52.07	
2			0	64.12	
3	1500		70	32.89	
4			0	44.78	
5	2000		70	31.56	
6			0	43.74	
7	3000		70	29.32	
8			0	43.64	
9	4000		70	29.76	
10			0	45.41	
11	3000		80	70	32.45
12				0	44.86
13			120	70	35.73
14				0	48.86
15			160	70	37.38
16				0	49.63
17			200	70	37.76
18				0	50.56

4. RESULTS AND DISCUSSION

As shown in Fig. 3(a), under different machining conditions, the resultant cutting force increases with higher feed rates. But when the feed rate exceeds 120 mm/min, the growth trend noticeably attenuates. The physical essence of this phenomenon lies in: the increase in feed rate directly leads to elevated material removal rate, consequently causing cutting force rise.

From Fig. 3(b), it can be observed that the spindle speed has an impact on the cutting forces. With an increase in speed, the resultant cutting force presents a decreasing trend and when the speed is greater than 1500rpm, conventional machining condition experiences a marginal recovery in force, whereas ultrasonic-assisted machining still keeps on reducing the force in a steady manner. It is because of the following reasons: as the speed increases, cutting forces decrease via the reduced tool-workpiece friction and cutting temperature increase, while in the high speed region, due to the thermal softening effect of the material for conventional machining, the cutting force slightly rises and on the other hand, the vibration-induced frictional reduction in ultrasonic machining continues to cause further decrease in cutting forces.

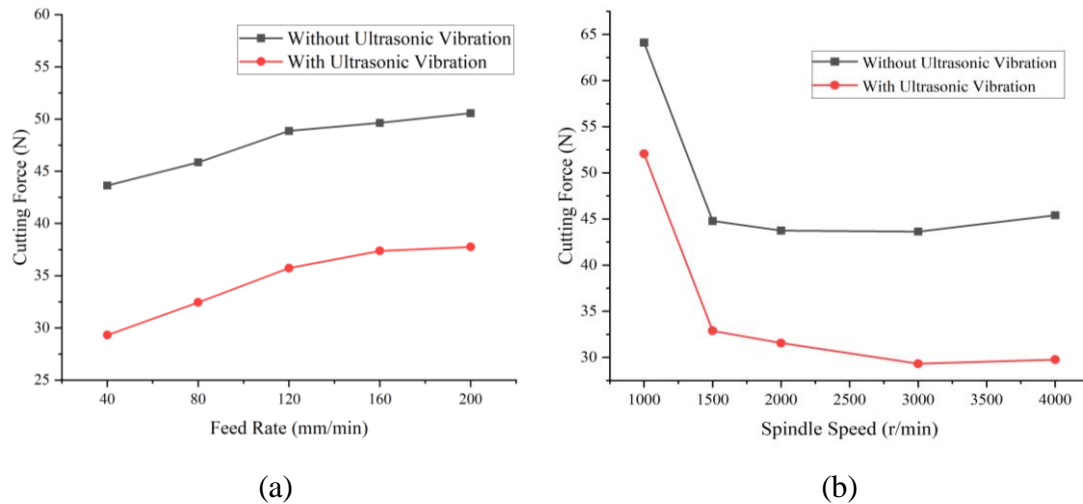


Figure 3. The Relationship of Machining Parameters with Cutting Forces

The effects of machining parameters on cutting force can be seen when machining SiCp/Al composites under different process parameters. Ultrasonic vibration-assisted face milling cutting forces were always smaller than conventional methods, showing good stability of the system regardless of the load conditions of the transducer. Compared to conventional machining, the milling force achieved a maximum reduction of up to 34.4% utilizing this method.

5. CONCLUSION

This experimental study, which makes a systematic comparison of ultrasonic vibration-assisted milling and conventional milling processes, reached the following conclusions:

- (1) Ultrasonic vibration-assisted machining decreases the cutting force during SiCp/Al composite milling, achieving maximum 34.4% reduction and improving the machinability of the material.
- (2) The cutting force increases as the feed rate is increasing; however, the tendency flattens in the high-speed region. With the spindle speed, ultrasonic-assisted machining keeps reducing the cutting force stably, but the force values of conventional machining exhibits force value recovery at high-speed regions. Therefore, selecting lower feed rates and appropriate spindle speeds can be further improve Machining quality.

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