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ORIGINAL ARTICLE

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Ultrasonic assisted turning of an aluminium-based metal matrix composite reinforced with SiC particles

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Abstract In this study, diamond turning of an aluminium-based metal matrix composite (MMC) reinforced with SiC particles was conducted with the assistance of ultrasonic vibrations. A simple and small size vibration device was designed to mount a piezoelectric transducer and a diamond insert onto a CNC machine. Turning experiments were carried out using a factorial design to investigate the effects of vibration and turning conditions on the surface finish of the turned MMC samples. The experimental results show that surface roughness of the MMC sample turned with ultrasonic vibrations is better than that of the MMC sample turned without ultrasonic vibrations. Turning with vibrations creates regular surface profiles along the turning and vibration direction, resulting in a light dispersion phenomenon, which is not reported in other articles. This phenomenon can only be observed when the pitch of the regular profiles is within a particular range. The pitch is determined by the cutting speed when the vibration frequency is fixed.

Keywords Diamond turning · Light dispersion · Metal matrix composite · SiC particles · Surface roughness · Ultrasonic vibration · Vibration device

1 Introduction

In typical ultrasonic machining, high frequency electrical energy is converted into mechanical vibrations via a transducer/booster combination, which are transmitted through a horn/tool assembly. A load is applied to the tool and abrasive slurry is pumped around the machining zone. The tool vibration causes abrasive particles held between the tool and workpiece to impact the workpiece surface resulting in material removal by microchipping. Variations on this basic configuration include non-machining ultrasonic applications such as cleaning, welding and chemical processing, and ultrasonic assisted conventional/unconventional machining such as turning [1]. Piezoelectric actuators are widely used as the transducers in ultrasonic machining applications, as well as in precision positioning applications [2, 3].

However, the material removal mechanism in ultrasonic assisted turning of metals is not the microchipping that happens in the typical ultrasonic machining. In ultrasonic assisted turning of metals, materials are removed by the intermittent cutting.

It was reported [4] that two-directional vibrations were applied to the cutting edge, and orthogonal cutting experiments of copper were carried out within a scanning electron microscope (SEM). The chip thickness and the cutting forces were reduced significantly compared to conventional cutting. A vibration control system was also developed using piezoelectric actuators to control the two-directional vibrations independently [5]. The system was applied to diamond turning of hardened steel, and a mirror surface with shape accuracy less than 0.2 μm was obtained.

Aluminium-based metal matrix composites (MMCs) reinforced with Al_2O_3 or SiC particles are advanced materials. However, full implementation of MMCs is cost prohibitive, partially because of the materials' poor machinability. Therefore, diamond turning and grinding of MMCs have been carried out to improve the surface integrity [6–11].

In this study, diamond turning of an aluminium-based MMC reinforced with SiC particles was conducted with the assistance of ultrasonic vibrations. A low cost and small size vibration device was designed to mount a piezoelectric transducer and a diamond insert onto a CNC machine. Turning experiments were carried out using a factorial design to investigate the effects of vibration and turning conditions on the surface finish of the turned MMC samples.

2 Designed vibration device

Figure 1 shows the vibration device designed. A lead-zirconate-titanate type piezoelectric transducer with an outer diameter of

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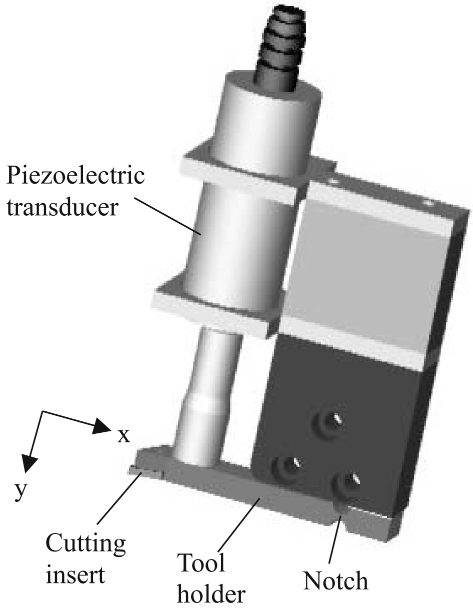


Fig. 1. The ultrasonic vibration device designed

32 mm and a length of 146 mm was selected. The vibration amplitude at the tip of the transducer is 23 μm when the transducer is driven by 450 V AC. The power amplifier used has a maximum voltage of 200 V and a maximum current of 100 mA, which is good enough for this study. The waveform of the vibration displacement is confirmed to be sinusoidal. A booster is not necessary for using this transducer, as the displacement amplitude of the transducer alone is sufficient for the application. This is very important because without a booster the vibration device can be mounted easily and firmly, and the device can be small.

The function of the device is to not only hold the transducer firmly, but also limit the degrees of free movement. For turning with vibrations, one-directional translation movement is important because undesired movement affects turning results significantly. Therefore, a tool holder was introduced into the design. If the tool holder does not have a notch, the shape of the tool holder after deformation is a near parabola [12]. If the tool holder has a notch, bending can occur at the notch and there is no deformation at the rest of the tool holder. When the y-direction displacements for these two tool holders are the same, the displacement in the x-direction for the tool holder without a notch is much larger than that with a notch.

In this study, a 2-mm notch thickness was selected. The distance from the tool tip to the notch is 71 mm. If the vibration displacement at the tool tip is 6 μm along the y-axis, the displacement along the x-axis is 0.25 nm. The displacement along the x-axis is 0.0041% of the displacement along the y-axis. Such a small x-axis displacement is negligible. Therefore, the movement of the tool tip can be considered as pure translational movement in the y-direction.

A diamond insert is fixed to the device with the cutting edge facing downwards. Such an orientation makes the cutting force to be compressive to the piezoelectric transducer. The measured relationship of the ultrasonic displacement amplitude and the ultrasonic power supply voltage is shown in Fig. 2.

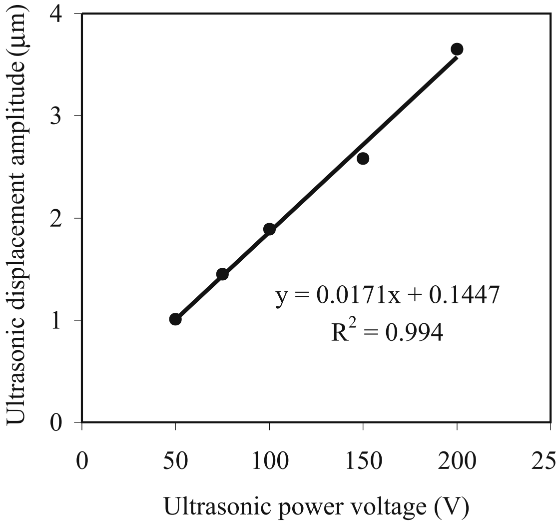


Fig. 2. Measured relationship of the ultrasonic displacement amplitude and the ultrasonic power supply voltage

3 Turning experiments, results and discussion

Experiments were carried out on a CNC lathe. Single crystal diamond inserts (nose radius = 0.8 mm; clearance angle = 11°; rake angle = 0°) were used. Aluminium was chosen for preliminary turning experiments before turning of MMCs. Figure 3 shows the vibration device mounted on the machine.

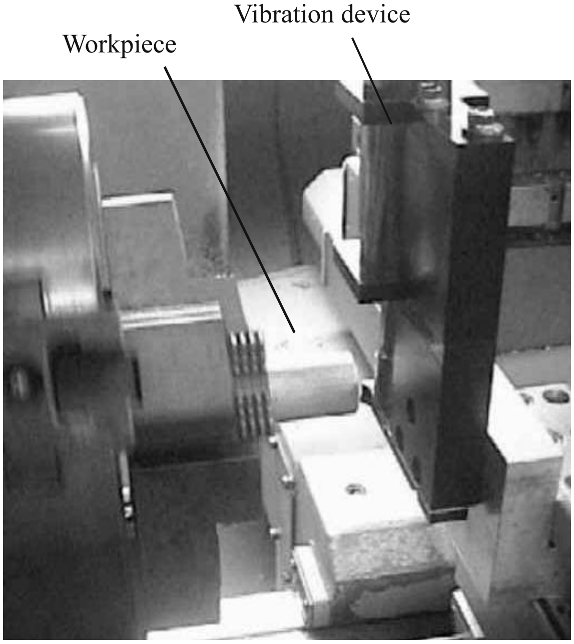


Fig. 3. The vibration device installed on the machine

An appropriate cutting speed is essential in order to obtain the expected effect of turning with vibrations. If the vibration speed is 10 times the cutting speed, the cutting speed v_c (m/min) can be given by

$$v_c = \frac{2\pi a f \times 60}{10} = 12\pi a f \,, \qquad (1)$$

where, a is vibration amplitude and f is vibration frequency. If $a = 3.7\ \mu\text{m}$ and $f = 20\,000\ \text{Hz}$, then $v_c = 2.8\ \text{m/min}$. Therefore, 3 m/min and 1.5 m/min were selected for the turning experiments.

A fractional factorial design was applied to samples A2, A3, A4 and A5 as shown in Table 1. For comparison reasons, samples A1 and A7 were turned without vibrations and sample A6 was turned with vibrations at a cutting speed of 20 m/min.

Selection of surface roughness measurement parameters is very important in measuring microtopography for the concerned feature [13]. The feed rates for the experiments are 15 μm/rev and 5 μm/rev. An 80-μm cutoff length can be a right choice because it is about 5 or 16 rounds of turning. The number of the cutoff lengths for the measurement is chosen to be five. Hence, the measuring length is 400 μm.

Surface roughness is a function of the measuring length, and a long measurement length will result in a high surface roughness value measured [14, 15]. With a 400-μm measuring length, the roughness values reported in this article can be higher than those reported in some articles in which very low surface roughness values are obtained using very short measurement lengths. However, one of the objectives of this study is to investigate the effect of the turning with ultrasonic vibrations and this can be achieved by relative comparison. Therefore, it is not necessarily important in this study to obtain and show very low absolute roughness values.

After the turning experiments, three measurements of surface roughness were performed for every sample. The average roughness values of the turned aluminum samples are listed in Table 1. Samples A4 and A7 were turned under the same turning conditions except sample A4 was turned with vibrations. The average of roughness heights of sample A4 is 11% better than that of sample A7. This proves the positive effect of turning with vibrations. Samples A2, A3, A4 and A5 were turned with vibrations. However, only two of them have better surface roughness than sample A7. This indicates that other turning conditions are also important.

Table 1. Details of experiments and average roughness heights of the aluminum samples

Sample Number	Ultrasonic Vibration	Feed Rate (μm/rev)	Vibration Amplitude (μm)	Cutting Speed (m/min)	Average R_a (μm)	Average R_t (μm)
A1	Without	15	—	3	0.093	0.723
A2	With	15	3.7	3	0.114	1.000
A3	With	15	2.2	1.5	0.142	1.020
A4	With	5	3.7	1.5	0.089	0.792
A5	With	5	2.2	3	0.107	0.991
A6	With	5	4	20	0.103	0.949
A7	Without	5	—	1.5	0.102	0.853

The effects of ultrasonic vibration and turning conditions on the surface finish of the turned aluminum samples are shown in Figs. 4 and 5. The average of the roughness heights for the aluminum samples turned with a vibration amplitude of 3.7 μm is 15% better than that for the aluminum samples turned with a vibration amplitude of 2.2 μm. The average of the roughness heights for the samples turned with a cutting speed of 1.5 m/min is 2% worse than that for the samples turned with a cutting speed of 3 m/min. The effect of cutting speeds of 1.5 and 3 m/min is insignificant. The average of the roughness heights for samples turned with 5 μm/rev is 19% better than that for samples turned with 15 μm/rev.

The material used for the main experiments in this study is a cast aluminium-based MMC reinforced with SiC particles. Details of the tested MMC A359/SiC/20p (20 vol. % SiC) are shown in Table 2.

The fractional factorial design was applied to samples M1, M2, M3, and M5, as shown in Table 3. For comparison reasons,

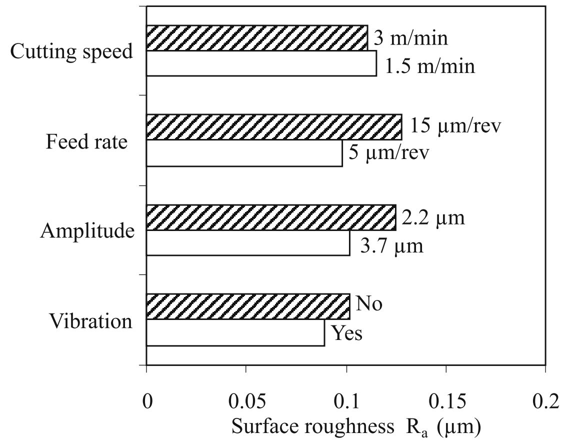


Fig. 4. The effects of ultrasonic vibration and turning conditions on the surface roughness R_a of the turned aluminum samples

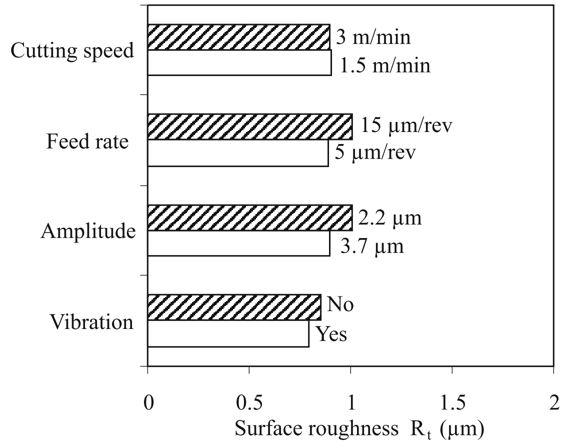


Fig. 5. The effects of ultrasonic vibration and turning conditions on the surface roughness R_t of the turned aluminum samples

Table 2. Details of the MMC used for the experiments

Material	A359/SiC/20p
Matrix	A359 aluminium alloy (Al, 9.27 wt. % Si, 0.15 Fe, 0.55 Mg)
Reinforcement	20 vol. % SiC particles, Aspect ratio 1.5:1, Median 12.8 ± 1.0μm, 97% particles ≤ 25 μm, 6% particles ≤ 5 μm
Process	Fabricated by the permanent-mold casting tecchnique. Pouring temperature 700–710 °C, average stirring rate 250 rpm

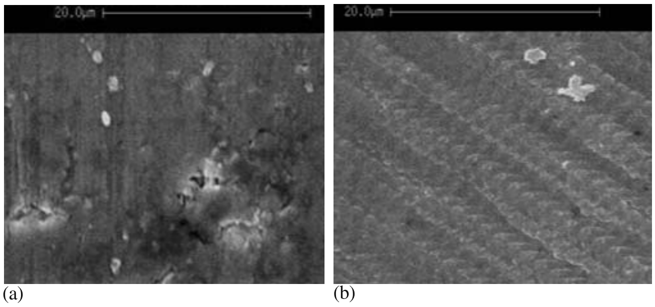
sample M4 was turned without vibrations. The sequence of the sample numbers was the sequence of the turning experiments, which was randomly selected.

After the turning experiments, three measurements of surface roughness were performed for every sample. The average roughness values of the turned MMC samples are listed in Table 3. Sample M5 has the best surface roughness. The surface finish of MMC samples turned with ultrasonic vibrations is not always better than that of sample M4 turned without ultrasonic vibrations, indicating that turning and vibration conditions do affect the surface finish. The roughness heights, R_a and R_t, of sample 5 are 21% and 33% better than those of sample M4, respectively. SEM study revealed regular texture with a 1.25-μm pitch of the ultrasonic vibration marks along the turning and vibration direction on the surface of sample M5 (Fig. 6b), while no regular marks were found on sample M4 (Fig. 6a). Sample M5 was the last one to be turned (meaning more wear on the cutting edge of the cutting tool) but still had the best surface roughness. This demonstrates the promising result of turning with ultrasonic vibrations when various ultrasonic vibration and turning conditions are properly selected.

The effects of ultrasonic vibrations and turning conditions on the surface finish of the turned MMC samples are shown in Figs. 7 and 8. The averages of the roughness heights for samples turned with a depth of cut of 1 μm are 47% better than those for samples turned with a depth of cut of 3 μm. The averages of R_a and R_t for samples turned with a cutting speed of 1.5 m/min are 28% and 22% better than those for samples turned with a cutting speed of 3 m/min, respectively. However, feed rates of 5 μm/rev and 15 μm/rev seem to have contradicting effects on the surface roughness values.

Table 3. Details of the experiments and average roughness heights of the MMC samples

Sample Number	Ultrasonic Vibration	Depth of Cut (μm)	Cutting Speed (m/min)	Feed Rate (μm/rev)	Average R_a (μm)	Average R_t (μm)
M1	With	3	1.5	15	0.134	1.415
M2	With	1	3	15	0.099	1.016
M3	With	3	3	5	0.187	1.548
M4	Without	1	1.5	5	0.090	0.859
M5	With	1	1.5	5	0.071	0.578



(a) (b)

Fig. 6a,b. SEM pictures of **a** sample M4 and **b** sample M5

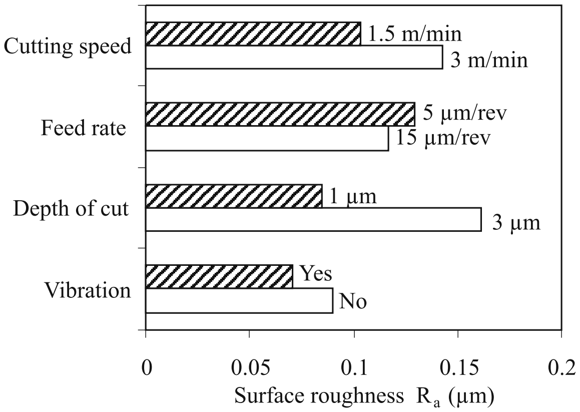


Fig. 7. The effects of ultrasonic vibrations and turning conditions on the surface roughness R_a of the turned MMC samples

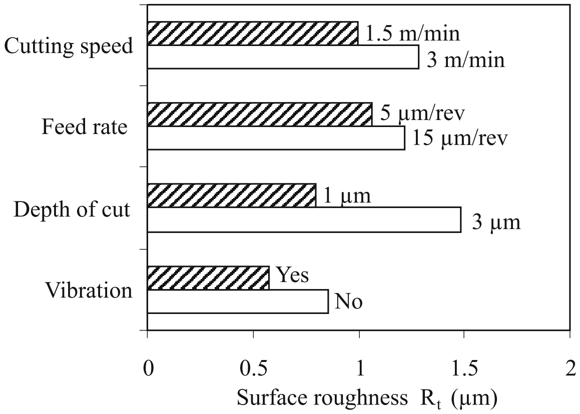


Fig. 8. The effects of ultrasonic vibrations and turning conditions on the surface roughness R_t of the turned MMC samples

4 Light dispersion phenomenon

Light dispersion was observed on the surfaces of all of the samples turned with vibrations, except sample A6. All of samples turned without vibrations had no such phenomenon observed. Two examples are shown in Fig. 9.

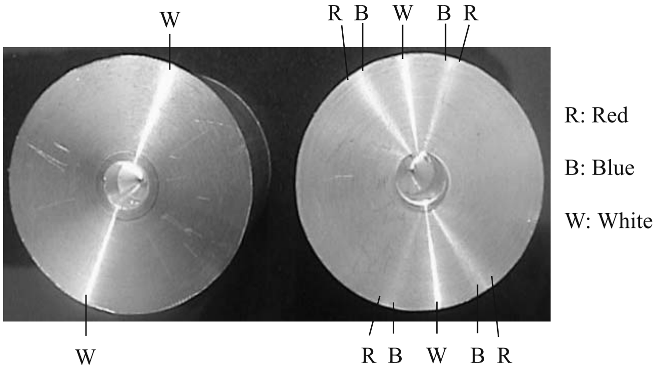


Fig. 9. Light dispersion phenomenon is observed on the surface turned with vibrations (right), but not observed on the surface turned without vibrations (left)

During the turning with vibrations, the cutting tool moves forward and backward in the cutting direction reciprocally. The intermittent cutting produces regular texture on the turned surface. The pitch or groove spacing, d, is determined by the cutting speed v_c and vibration frequency f:

$$d = \frac{v_c}{f} . \tag{2}$$

Because $f = 20\,\text{kHz}$ in this study, $d = 1.25$ and $2.5\,\mu\text{m}$ when $v_c = 1.5$ and $3\,\text{m/min}$, respectively.

It is observed that light dispersion is along the cutting direction. The dispersion is not caused by the tool feeding. That is why light dispersion cannot be seen on the surfaces turned without vibrations. The dispersion is generated by the constructive interference of the diffracted light. To have the constructive interference, the optical path difference (OPD) has to be one or more integer multiples of the light wavelength. The OPD for the path of collimated incident light and diffracted light between two adjacent "grooves" is

$$\text{OPD} = d(\sin\beta - \sin\alpha) , \tag{3}$$

where α is the light incident angle, β is the light diffraction angle, and d is the distance between two adjacent "grooves".

If $\alpha = \beta$, then $\text{OPD} = 0$. This is the reflection condition and no interference can be seen. When $\text{OPD} = m\lambda$ (where $m = 1, 2, 3, \ldots$), constructive interference occurs. The equation for constructive interference is

$$m\lambda = d(\sin\beta - \sin\alpha) . \tag{4}$$

The wavelengths of visible light are in the range of 0.4 to $0.7\,\mu\text{m}$. When pitch d equals $1.25\,\mu\text{m}$ or $2.5\,\mu\text{m}$, the constructive interference can be easily seen if m equals to 1 to 3.

Sample A6 was turned with vibrations at a cutting speed of $20\,\text{m/min}$. Using Eq. 2, the pitch d is calculated to be $16.7\,\mu\text{m}$. With such a high pitch value and the wavelengths in the visible range, m must be a high value according to the constructive interference condition, Eq. 4. A higher m value decreases the diffraction efficiency and reduces the diffraction angle, which makes colour dispersion difficult to be identified by bare eyes. This is why sample A6 had no dispersion phenomenon observed, even though it was turned with vibrations and also had regular texture on the turned surface.

5 Summary

A low cost and small size ultrasonic vibration device was designed. Diamond turning of an MMC was conducted using this vibration device attached to a CNC lathe to evaluate the effects of turning and vibration conditions. The roughness of the MMC surface turned with vibrations was better than that turned without vibrations. Cutting speed and depth of cut also affected the surface finish significantly. Turning with vibrations created regular surface profiles along the cutting and vibration direction, resulting in a light dispersion phenomenon. This phenomenon can only be observed when the pitch of the regular profiles is within a particular range. The pitch is determined by the cutting speed when the vibration frequency is fixed.

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