Research on Ultrasonic-Assisted Grinding Process of SiCp/Al Composites

Chuanmin Zhu\textsuperscript{1}, Zhan Tao\textsuperscript{1}, Peng Gu\textsuperscript{1*} and Yiqing Yu\textsuperscript{1}

\textsuperscript{1}School of Mechanical Engineering, Tongji University, Shanghai, 201804, China
*Corresponding author’s e-mail: 13122618035@163.com

Abstract. SiCp/Al is a kind of particle reinforced composites with good material properties, which can be used in the field of lightweight parts and electronic packaging. Ultrasonic-assisted grinding process is one of the processes which is suitable for machining hard and brittle materials, the surface quality can be improved by using appropriate ultrasonic-assisted process parameters. In this paper, the ultrasonic-assisted grinding process is used to improve the surface quality of SiCp/Al, meanwhile, the kinematics of abrasive particles in grinding is analysed to explain the effect of ultrasonic vibration. In addition, ultrasonic-assisted grinding experiment of SiCp/Al is conducted, it is found that the axial ultrasonic vibration can improve the surface quality of SiCp/Al in grinding, and the reduction percentage is up to 8.20% compared to the normal grinding. In addition, a regression model is proposed for surface roughness prediction, the result of t-test on the residuals shows that the model is accurate.

1. Introduction
As one of the most widely used particle reinforced composites. SiCp/Al has high specific strength, high specific stiffness, high thermal conductivity, low thermal expansion coefficient and good fatigue resistance. It can be used in many fields such as aerospace lightweight structural parts, electronic packaging and automobile brake discs [1]. Grinding is usually used for precision machining, Xu et al. [2] conducted grinding experiments of SiCp/Al, and investigated the influence of grinding process parameters on surface roughness, surface morphology and grinding forces. It’s found that the grinding depth has the greatest impact on the grinding force, and there are a large number of broken SiC particles on the surface of SiCp/Al. Zhu et al. [3],[4] studied the material removal mechanism of SiCp/Al in grinding process, and proposed a genetic algorithm-based grinding surface roughness prediction model of SiCp/Al. It is found that the grinding temperature of SiCp/Al is relatively low compared to other materials in grinding, meanwhile, a grinding temperature field model of SiCp/Al is established to explain this phenomenon. Yu et al. [5] investigated the ELID grinding characteristics of SiCp/Al. It’s found that ELID grinding helps sharpen the grinding wheel, And the SiC particles are removed in a ductile mode, which reduces the brittle fracture of SiC particles. SiCp/Al contains a certain volume fraction of SiC particles, which means SiCp/Al could be manufactured by a process suitable for hard and brittle materials. Ultrasonic-assisted grinding is suitable for processing of hard and brittle materials [6]. The tool wear can be reduced and the surface roughness can be improved by applying ultrasonic vibration in grinding [7]. Based on the dynamic analysis of single abrasive grinding of zirconia ceramics, Chen et al. [8] established a three-dimensional grinding force model for ultrasonic-assisted ELID grinding. The three-dimensional ultrasonic vibration makes the abrasive grain cutting trajectory longer, and the surface roughness is improved during grinding. Sun et al. [9] compared the material removal mechanism of Zerodur glass-ceramics and ULE glass under ultrasonic-
assisted scratching and normal scratching. With the assistance of ultrasonic vibration, the contact area and contact force between the workpiece and the indenter are periodic. The cracks in the contact area can expand on different directions, which increases the removal rate of the material. At the same time, the ductile-brittle transition rate of the material is higher under the assistance of ultrasonic vibration, and the material is easy to be removed in ductile mode during cutting.

According to the recent research, the main surface quality problems of SiCp/Al in machining are related to the machining quality of SiC particles. Improving the processing quality of SiC particles is conducive to improve the surface quality of SiCp/Al. Ultrasonic-assisted grinding process is suitable for machining hard and brittle materials such as SiC. In this paper, ultrasonic-assisted grinding process is used to improve the surface quality of SiC/Al in grinding. In order to promote the application of SiCp/Al in more fields, such as guide rail and precise lightweight parts, it is of great significance to investigate the ultrasonic-assisted grinding process of SiCp/Al.

2. Analysis of effect of ultrasonic vibration in grinding

2.1. Kinematics of single abrasive in ultrasonic-assisted grinding

Ultrasonic-assisted grinding process is shown as figure 1, with the workpiece as the reference system, the trajectory of single abrasive grain is shown in equation (1).

\[
\begin{align*}
\text{trajectory along the feed direction in ultrasonic-assisted grinding:} \\
& x_u = v_w t + R \sin \left( \frac{V_w t}{R} \right) \\
& y_u = A \sin (2\pi ft) \\
& z_u = R - R \cos \left( \frac{V_w t}{R} \right)
\end{align*}
\]

The meaning of each parameter in equation (1) is shown in table 1.

| Parameter | Meaning |
|-----------|---------|
| \(v_w\)   | Feed speed |
| \(t\)     | Time |
| \(R\)     | Radius of grinding wheel |
| \(V_w\)   | Rotate speed of grinding wheel |
| \(x_u\)   | Trajectory along the feed direction in ultrasonic-assisted grinding |
| \(y_u\)   | Trajectory along the axial direction in ultrasonic-assisted grinding |
| \(z_u\)   | Trajectory along the radial direction in ultrasonic-assisted grinding |
| \(A\)     | Amplitude of ultrasonic vibration |
| \(f\)     | Frequency of ultrasonic vibration |

During the grinding process, the trajectories of abrasives form the microscopic topography of the grinding surface. Taking the workpiece as the reference system, in the normal grinding process, the axial displacement of the abrasive particle is zero, and the trajectories along the feed direction are parallel to each other. When axial ultrasonic vibration is applied in the process, the trajectories of the abrasive grains are staggered and interfered. Due to the addition of ultrasonic vibration, the cutting speed of abrasives is increased and the direction of cutting speed also changes with time, which can help to sharpen the grinding wheel and obtain better surface quality.

2.2. Ultrasonic vibration of abrasive during cutting process

As shown in figure 2, the abrasive particles start to cut the workpiece at point A and leave at point B to finish a cutting process. Taking the centre of the grinding wheel as the reference system, the path length of abrasive cutting is shown in equation (2).

\[
l = \sqrt{2Ra_{p}}
\]

The time of this cutting process can be calculated as:
\begin{align*}
\frac{t_0}{T} &= \frac{1}{v_s} = \frac{\sqrt{2Ra_p}}{v_s} \\
\text{Define } n \text{ as the ratio of } t_0 \text{ and the cycle of ultrasonic vibration, } n \text{ can be calculated as:} \\
\frac{n}{T} &= \frac{\sqrt{2Ra_p}}{v_s} \\
\text{In fact, } n \text{ refers to the number of ultrasonic vibrations during a single cutting process of abrasives. There will be a complete vibration process in the cutting process if } n \geq 1, \text{ so the vibration frequency should satisfy equation (5).} \\
f &\geq \frac{v_s}{\sqrt{2Ra_p}} \\
\text{Using the normal grinding parameters for calculation, set } v_s = 30\text{m/s, } R = 150\text{mm, } a_p = 10\mu\text{m, it can be found that the minimum value of } f \text{ is } 17.23\text{KHz. This frequency is closed to the ultrasonic frequency, in fact, ultrasonic frequencies are usually used to achieve vibration-assisted processing.}
\end{align*}

3. Experiment of SiCp/Al in ultrasonic-assisted grinding

3.1. Devices of experiment

The experiment was taking on SCHLEIFRING K-P36 surface grinder with the resin bond diamond grinding wheel, the K-P36 surface grinder is shown in figure 3.

In this paper, the ultrasonic vibration is added to the workpiece. As shown in figure 4, the vibration device consists of an ultrasonic generator, a transducer and a vibration platform. The ultrasonic generator generates a high-frequency electric signal, and the transducer converts the electric signal into a high-frequency vibration, which drives the vibration platform to produce the ultrasonic vibration. This device can generate ultrasonic vibration with frequency of 20KHz and amplitude of 5\mu m.

3.3. Cutting process of abrasive in grinding

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Ultrasonic-assisted grinding}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{Cutting process of abrasive in grinding}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{SCHLEIFRING K-P36 surface grinder}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure4.png}
\caption{Ultrasonic vibration device}
\end{figure}
3.2. Experiment details
The experimental material is SiCp/Al composite, and the volume fraction of SiC is 45%. Table 2 shows the material properties of SiCp/Al.

| Parameter                           | Value |
|-------------------------------------|-------|
| Elastic modulus (GPa)               | 143   |
| Tensile strength (MPa)              | 356   |
| Thermal expansion coefficient (10^6/K) | 8.5   |
| Thermal conductivity (W/(m·K))      | 182   |
| Density (g/mm^3)                    | 2.73  |

In this paper, the experiment parameters contain feed speed $v_w$, grinding depth $a_p$, rotate speed $v_s$ and amplitude of ultrasonic vibration $A$. The experiment parameters were designed as table 3.

| Feed speed (m/min) | Grinding depth (µm) | Rotate speed of grinding wheel (m/s) | Amplitude of ultrasonic vibration (µm) |
|--------------------|----------------------|-------------------------------------|----------------------------------------|
| 0.1, 0.3, 0.5      | 5                    | 30                                  | 0, 5                                   |
| 0.3                | 3, 5, 7              | 30                                  | 0, 5                                   |
| 0.3                | 5                    | 25, 30, 35                          | 0, 5                                   |

Before the experiment, a red copper workpiece was used to sharpen the diamond grinding wheel to enhance its cutting performance. The experiment was conducted without lubrication.

3.3. Experimental results
The surface roughness results of experiment are shown in figure 5.

![Figure 5. Experiment results of surface roughness](image-url)
It can be found that the surface roughness of SiCp/Al can be improved by axial ultrasonic vibration. In this experiment, the average reduction percentage of ultrasonic-assisted grinding is 6.28%, and the maximum value of the reduction percentage is 8.20% when \( v_w = 0.3 \text{m/min}, \quad a_p = 5 \mu\text{m}, \quad v_s = 25 \text{m/s} \) and \( A = 5 \mu\text{m} \).

### 3.4. Surface roughness prediction model of SiCp/Al in ultrasonic-assisted grinding

In this paper, multiple regression model is applied to predict the surface roughness of SiCp/Al in different ultrasonic-assisted grinding parameters. The frequency is fixed at 20KHz, so the initial formula is shown in equation (6). \( x_i \) means the i-th parameter in the four process parameters.

\[
R_a = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i<j}^{n} \beta_{ij} x_i x_j + \sum_{i=1}^{n} \beta_{ii} x_i^2 \tag{6}
\]

The coefficients are obtained by nonlinear fitting, the residual distribution of the prediction model is shown in figure 6, it can be found that the residual distribution is relatively uniform, and the maximum fitting error between prediction value and experimental value is 3.98%. Under the condition of the significance level of 0.01, the sample t-test is performed on the residuals, and the observation value of the samples is 2.4412, which is less than the critical value \( t_{0.995(13)} (3.0123) \). It means that the prediction model has good accuracy. The prediction model is shown in equation (7).

\[
R_a = 1.4586 + 0.0283 \cdot v_w - 0.0295 \cdot a_p - 2.0083 \cdot v_s - 0.0515 \cdot A - 0.0002 \cdot a_p v_s - 0.0003 \cdot a_p A - 0.6878 \cdot v_w A - 0.0008 \cdot v_s^2 + 0.3893 \cdot v_s^2 + 1.1061 \cdot A^2 \tag{7}
\]

Figure 7 shows the influence of grinding process parameters on surface roughness.
According to figure 7(a), (b) and (c), with the aid of ultrasonic vibration, the surface roughness increases when the feed speed $v_w$ or grinding depth $a_p$ increases. Otherwise, when the rotate speed $v_r$ increases, the surface roughness decreases at the same time. Among these parameters, $a_p$ and $v_r$ have greater influence on surface roughness, the surface roughness increases from 0.706µm to 0.860µm when $a_p$ increases from 3µm to 7µm. Meanwhile, when $v_r$ increases from 25m/s to 35m/s, the surface roughness decreases from 0.862µm to 0.715µm.

4. Conclusion
In this paper, the effect of ultrasonic vibration is analysed by kinematic analysis and ultrasonic-assisted grinding experiment of SiCp/Al, meanwhile, a multiple regression model is proposed for surface roughness prediction. However, the material removal mechanism of SiCp/Al in the ultrasonic-assisted grinding process is still unclear, and it is worth continuing to study. Through the analysis of kinematics of abrasives and the comparison of experimental results, conclusions can be summarized as followed:

1. The cutting speed of abrasives can be increased in ultrasonic-assisted grinding, and the direction of cutting speed changes over time, which is helpful for sharpening the grinding wheel.
2. The surface roughness of SiCp/Al can be decreased by applying ultrasonic vibration in grinding, and the reduction percentage is up to 8.20% according to this experiment.

Acknowledgments
This work was supported by Science and Technology Program of Shanghai, China (Grant No. 20ZR1462800) and Tongji University Experimental Teaching Reform Project (TJ1000104158).

References
[1] Chen, J.P., Lin, G., He, G.J. (2020) A review on conventional and nonconventional machining of SiC particle-reinforced aluminium matrix composites. Advances in Manufacturing, 8: 279–315.
[2] Xu, L.F., Zhou, L., Yu, X.L., Huang, S.T. (2011) An Experimental Study on Grinding of SiC/Al Composites. Advanced Materials Research, 188: 90-93.
[3] Zhu, C.M., Gu, P., Wu, Y.Y., Liu, D.H., Wang, X.K. (2019) Surface roughness prediction model of SiCp/Al composite in grinding. International Journal of Mechanical Sciences, 155: 98-109.
[4] Zhu, C.M., Gu, P., Wu, Y.Y., Tao, Z. (2020) Grinding temperature prediction model of high-volume fraction SiCp/Al composite. The International Journal of Advanced Manufacturing Technology, 111: 1201-1220.
[5] Yu, X.L., Huang, S.T., Xu, L.F. (2016) ELID grinding characteristics of SiCp/Al composites. The International Journal of Advanced Manufacturing Technology, 86:5-8.
[6] Eiji, S., Toshimichi, M. (1994) Study on Elliptical Vibration Cutting. CIRP Annals - Manufacturing Technology, 43: 35-38.
[7] Yang, Z.C., Zhu, L.D., Zhang, G.X., Ni, C.B., Lin, B. (2020) Review of ultrasonic vibration-assisted machining in advanced materials. International Journal of Machine Tools and Manufacture, 156: 103594.
[8] Chen, F., Mei, G.J., Zhao, B., Bie, W.B., Li, G.X. (2020) Study on the characteristics of zirconia ceramic in three-dimensional ultrasonic vibration-assisted ELID internal grinding. Journal of Mechanical Science and Technology, 34: 333-344.
[9] Sun, G.Y., Shi, F., Zhao, Q.L., Ma, Z., Yang, D.L. (2020) Material removal behaviour in axial ultrasonic assisted scratching of Zerodur and ULE with a Vickers indenter. Ceramics International, 46: 14613-14624.