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Short Communication

Kinematic view of tool life in rotary ultrasonic side milling of hard and brittle materials

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ABSTRACT

Experiments are conducted to study the mechanism of side milling in rotary ultrasonic machining (RUM). The study shows that RUM has less tool wear than grinding at the lateral direction of the cutter under the same conditions. The kinematics of diamond grits is employed for the theoretical analysis. In addition, by using slim diamond cutters, two different machining strategies are used to side mill a microstructure and grooves on a semi-sphere. An improvement strategy of material removal rate (MRR) is also discussed based on the experimental study.

1. Introduction

Since hard and brittle materials have many excellent properties, they have been widely used in aerospace, automotive, optical and semiconductor industries. For instance, ceramics have low mass density and great resistance to wear and high temperatures. They have been used to make tooth implants and brake pads. SiC ceramic is super hard and has a high thermal conductivity. Therefore, it finds wide applications in bearing and rotary seal parts. However, these applications are hindered in some degree by high-cost and time-consuming machining process. Grinding, the high-cost and low material removal rate machining, is still the most common method to machine hard and brittle materials. There is a great demand for cost-effective machining technology to improve the machining efficiency of hard and brittle materials.

Since the rotary ultrasonic machining (RUM) was invented [1], researchers in the machining field had conducted many studies on the process. Experimental studies showed that RUM would be a promising method to improve MRR for machining brittle and hard materials [2]. Pei et al. [3–6] proposed that plastic flow could be one of the material removal modes in RUM in addition to brittle fracture and further extended RUM to face milling. They also presented a model to predict the relationships between material removal rate (MRR) and the process parameters, such as vibration amplitude, static force, rotational speed, number and size of working diamond grits. The tool wear in RUM were studied by Spur, Holl and Zeng et al. [7,8]. Uhlmann and Spur [9] compared the grinding with and without ultrasonic assistance and found that ultrasonic assistance results in significantly higher materials removal rates without additional damage to the sub-surface. Onikura et al. [10] used ultrasonic grinding to make micro cylindrical tools. It would not only reduce grinding force but also avoid the breakage to the micro tools. Microholes with diameter of 10 μm were drilled in glass by ultrasonic vibration assisted machining using a micro tool [11]. The application of ultrasonic vibrations resulted in the decrease of cutting force and extension of tool life. Denkena et al. [12] pointed out that ultrasonic grinding is one possibility to minimize the influence of the micro geometry of the grinding tool. Ultrasonic grinding was used to minimize the influence of the micro geometry of the grinding tool. Li et al. [13] investigated the feasibility to machine ceramic matrix composites. Jiao et al. and Li et al. studied the problem of the edge chipping for RUM and a solution of reducing edge chipping was proposed based on the FEA analysis [14,15].

While there was a good progress on the study of RUM, most of previous studies focused on the end milling of RUM. In this study, experimental study is focused on the side milling of RUM.

2. Experiment on comparison of tool wear between RUM and grinding

2.1. Experimental setup and results

Ultrasonic 20 linear machine is used to conduct the experiments, which is a 5-axis RUM precision machine tool. It consists

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of a high-speed ultrasonic spindle kit with rotation speed up to 42,000 rpm, a water coolant system (internal coolant and external coolant), a HSK32 ultrasonic actuator system, and an integrated NC-swivel rotary table. Hollow diamond grinding tools are used to machine optical glass of K9 as shown in Fig. 1. To compare the tool wears between RUM and grinding, two sets of experiments are conducted using the same type of tools under the same conditions, as shown in Table 1. The machining conditions for RUM are listed as follows:

Vibration frequency: 20 kHz (actuated by special HSK32 holder).
Ultrasonic power: 25–28 W.
Amplitude: 4 μm (measured using SIOS Laser Interferometer).

The grinding experiments are conducted on the same machine tool, while the ultrasonic generator is shut off to realize the grinding machining.

In RUM, there was no tool wear observed using a Keynence high resolution tool maker microscope. In grinding, a heavy tool wear happened, as shown in Fig. 2. There were two obvious grooves in the binding material. Two deep grooves could be seen in the bond and several diamond grits disappeared at the lateral of the tool. According to three major mechanisms of tool wear [8], it should be bond fractures. How to explain this? Since the ultrasonic vibration amplitude is very small (it is only equal to 0.4% of the depth of cut) and the extra machined volume can be neglected. Therefore, it can be considered that the MRRs are same for RUM and grinding. Obviously, the only difference is the trajectories of the diamond grits. In the next section, an analysis based on the kinematics of diamond grits will be presented to explain this phenomenon further.

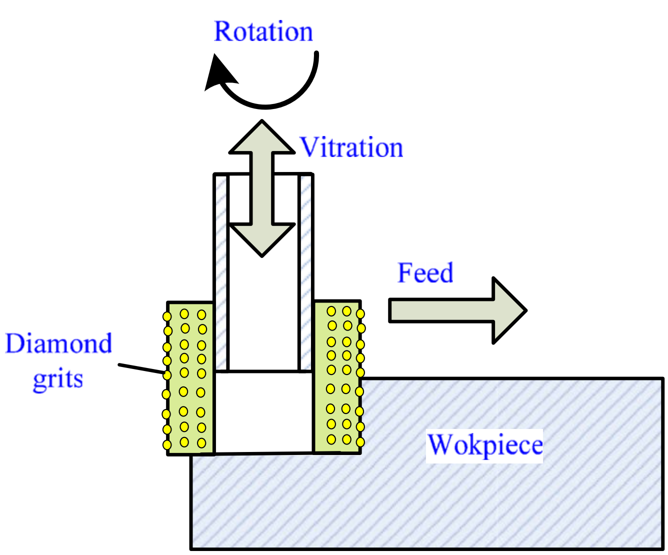

Fig. 1. Illustration of the rotary ultrasonic machining using the side of cutter.

Table 1
The common machining conditions for RUM and grinding.

Workpiece material	K9 optical glass
Cutter	Φ10 mm (cylindrical hollow grinding tool)
Rotation speed of spindle(rpm)	4000
Coolant	Water
Feedrate (mm/min)	300
Depth of cut (mm)	1
Stepover (mm)	5
Total length of tool path (mm)	200

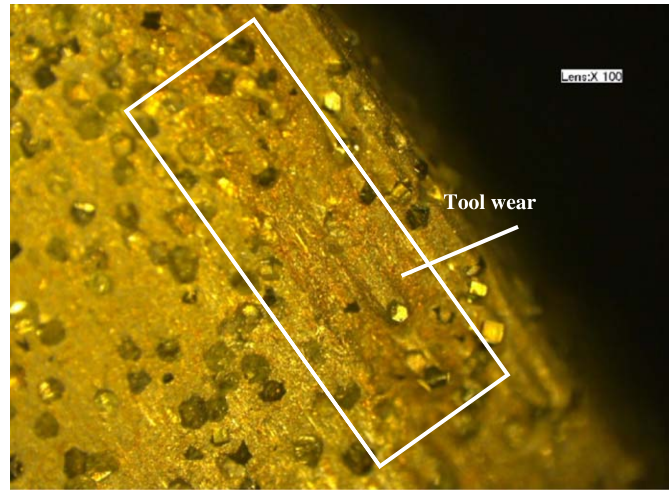

Fig. 2. Tool wears in grinding (observed under Keyence microscope ×100).

2.2. Analysis of tool wear based on the kinematics of diamond grits

RUM is a machining process that combines grinding and ultrasonic machining. The diamond grit's motion for RUM includes rotation, feed motion and ultrasonic vibration in the direction of tool axis. The trajectory of one diamond grit for RUM can be written as

$$r_{RUM}(t)=\begin{pmatrix} r\sin(\omega t)+x_{feed}t \\ r\cos(\omega t)+y_{feed}t \\ A\sin(2\pi ft)+z_{feed}t \end{pmatrix} \tag{1}$$

where r is the rotation radius, ω the rotational velocity, A the Amplitude, f the ultrasonic frequency, t the time and x_{feed},y_{feed},z_{feed} the feedrates in x, y, z directions, respectively.

From Eq. (1), the trajectory of one diamond grit for side milling can be drawn as shown in Fig. 3. Similarly, the trajectory of the diamond grit for grinding can be expressed as

$$r_{grinding}(t)=\begin{pmatrix} r\sin(\omega t)+x_{feed}t \\ r\cos(\omega t)+y_{feed}t \\ z_{feed}t \end{pmatrix} \tag{2}$$

The lengths of the diamond grit's trajectories for RUM and grinding in the time interval $[t_1, t_2]$ are, respectively, written as

$$L_{RUM}\Big|_{t_1}^{t_2}=\int_{t_1}^{t_2}|v_{RUM}|dt \quad L_{grinding}\Big|_{t_1}^{t_2}=\int_{t_1}^{t_2}|v_{grinding}|dt \tag{3}$$

where v_{RUM} and $v_{grinding}$ denote the velocities of the diamond grit for RUM and grinding, respectively.

According to Eqs. (1)–(3), the grit velocity of RUM is higher than that of grinding under the same machining conditions including rotation radius r, rotational velocity ω and feed x_{feed}, y_{feed}, z_{feed}. In addition, for the same time interval $[t_1, t_2]$, the trajectory length of RUM is longer than that of grinding, which means $L_{RUM}\big|_{t_1}^{t_2} > L_{grinding}\big|_{t_1}^{t_2}$.

In order to understand the mechanism of side milling, it is necessary to analyze the interaction between grits and the workpiece. As shown in Fig. 4(a) and (c), diamond grit a is supposed to cut the workpiece by using RUM and grinding, respectively, under the same machining conditions. When they both move from position A to B, diamond grits b and c cut into workpiece. Making a comparison between Fig. 4(b) and (d), it can