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On the mechanism of edge chipping reduction in rotary ultrasonic drilling: A novel experimental method

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ABSTRACT

Edge chipping induced by the mechanical machining of holes in brittle materials restricts the applications of the brittle materials. Rotary ultrasonic drilling is a suitable approach for the machining of holes in brittle materials with a smaller size of edge chipping. A good understanding of the mechanism of edge chipping reduction when employing rotary ultrasonic drilling is helpful to the application and optimization of the drilling technique. In this study, a novel edge chipping mechanism for the machining of holes considering machining-induced cracks was proposed and verified by experiments on quartz glass. The size of the machining-induced crack was evaluated experimentally. Experimental results indicate that the initiation of edge chipping is determined by both the magnitude of the driving force and the size of the machining-induced crack. However, the size of edge chipping strongly depends on the undrilled thickness following a directly proportional relation. Moreover, the geometric similarity of edge chipping is evidence for the consistency of the crack propagation direction when edge chipping begins. Finally, experiments conducted under various machining conditions demonstrate that the reduction of the size of machining-induced cracks in rotary ultrasonic drilling is another important factor contributing to the reduction of the size of edge chipping in rotary ultrasonic drilling, comparing with conventional diamond drilling.

1. Introduction

Brittle materials, represented by advanced engineering ceramics and optical glass, possess superior properties such as high hardness and strength at elevated temperatures, high chemical stability, and high wear resistance. Because of these advantages, brittle materials play an important role in various fields such as the aerospace, information and life science industries. Generally, brittle materials must be machined to satisfy the requirements of assembly and application. Holes are a commonly required feature of products made from brittle materials. However, the manufacturing of holes in brittle material remains tricky owing to the high hardness and low fracture toughness of the material [1].

Rotary ultrasonic drilling (RUD) is a hybrid process that combines the material removal mechanisms of diamond grinding and ultrasonic machining. As illustrated in Fig. 1, in RUD, a rotating diamond core drill is ultrasonically vibrated along the *z*-axis direction with a very low amplitude and moves towards the workpiece at a constant feed rate. As suggested by Kumar, RUD is best suited to the manufacturing of holes in brittle materials [2]. Cong et al. reviewed the process of RUD. They reported that, compared with conventional diamond drilling (CDD), RUD has advantages including improved surface roughness of the holes, a higher material removal rate, a low cutting force, low energy input, low tool wear, and reduced edge chipping [3]. Among these advantages, the reduction of edge chipping deserves special attention because the size of edge chipping strongly affects the performance of the component and the positioning accuracy of the component in an assembly.

Jiao et al. investigated the effects of processing variables on edge chipping by conducting RUD experiments on alumina ceramics. Their results indicate that the cutting force is the main parameter affecting edge chipping, and a higher spindle speed or lower feed rate results in a smaller chipping thickness accompanied by a weaker cutting force [4]. Cong et al. also observed this positive relationship between the cutting force and edge chipping in the RUD of silicon [5]. Li et al. proposed a possible solution of reducing the edge chipping thickness by increasing the support length on the basis of finite element model (FEM) simulations [6]. They

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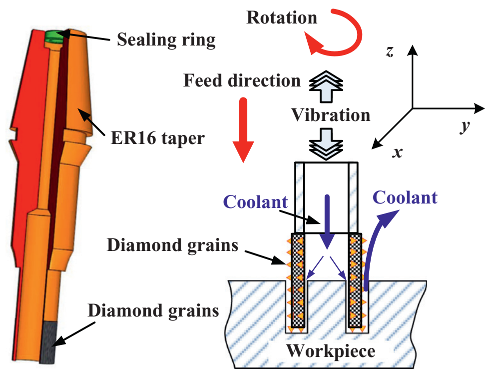

Fig. 1. RUD and a diamond core drill.

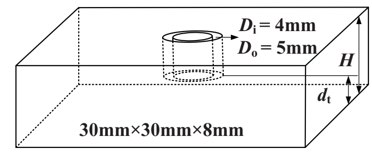

Fig. 2. Illustration of a specimen used in subsequent crack evaluation.

used the maximum von Mises stress criterion in their study; i.e., edge chipping will initiate if the von Mises equivalent stress reaches the tensile strength of the workpiece material. This criterion was also used by Gong et al. in their study on a strategy of reducing machining-induced edge chipping based on FEM simulation [7]. Geometric features of diamond drilling, such as the drilling angle, wall thickness, and drill type, are considered as tool variables that affect the edge chipping of machined holes. Qin et al. proposed that an outer tool whose outer side is shorter than its inner side could be used to reduce edge chipping [8]. There is also literature exploring a chipping minimization strategy employing statistical optimization; e.g., Liu et al. applied response surface analysis and desirability functions in the experimental optimization of edge chipping in the RUD of ceramic materials [9].

Current understanding is that the reduction in edge chipping in RUD compared with the case for CDD is due to a reduction in the cutting force. The main method of investigating the edge chipping mechanism in the manufacturing of holes in brittle material is to make finite element calculations, where the edge chipping initiation criterion is the maximum von Mises stress criterion not considering the machining-induced cracks. However, the strength of a brittle material is related with the size of cracks rather than a fixed value. Furthermore, edge chipping during the manufacture of holes in brittle material is a specific fracture phenomenon that results from the propagation of a crack under the action of a driving force. The properties of the initial crack and the driving force are the two major factors that determine whether fracture occurs. A machining-induced crack will contribute to the initiation of edge chipping. We therefore cannot completely attribute the reduction in edge chipping in RUD to the reduction in the cutting force without considering machining-induced cracks.

It might be proposed that a weaker machining force is always accompanied by a smaller machining-induced crack. However, the material removal mechanisms of RUD and CDD are different, and we therefore cannot draw such a conclusion without physical observation or experimental evidence. Additionally, the cracks induced by machining in the manufacturing of holes are difficult to observe. In this study, a novel experimental method was developed to evaluate such machining-induced cracks according to fracture mechanics. The aim was to help reveal the mechanism of the reduction in edge chipping in the RUD of brittle material.

2. Experimental method

2.1. Design and materials of RUD tests

Series of RUD and CDD processes were conducted on a rotary ultrasonic machine (Sauer Ultrasonic 50, DMG, Germany) to prepare specific specimens for subsequent crack evaluation. The Ultrasonic 50 comprises an ultrasonic spindle system, numerical control machining system, and coolant system. The maximum ultrasonic spindle speed is 8000 rpm and the maximum power of the rotary ultrasonic machine is 300 W. The ultrasonic spindle system is an important unit of the ultrasonic machine. It consists of an ultrasonic spindle and a power supply. The power supply provides high-frequency (around 20 kHz) AC output converted by a 50-Hz electrical supply for the ultrasonic spindle. The ultrasonic spindle comprises a piezoelectric transducer, amplitude transformer and diamond core drill. The piezoelectric transducer converts the electrical input into longitudinal mechanical vibrations with ultrasonic frequency. Because the amplitude of vibration produced by the piezoelectric transducer is too small for the vibration to be used in mechanical machining, the purpose of the amplitude transformer is to amplify the ultrasonic vibrational amplitude to an appreciable magnitude. The electroplated diamond core tool (shown in Fig. 1) has an outer diameter of 5 mm, wall thickness of 0.5 mm, and diamond particle size (mesh) of D126. The diamond core tool is connected to the amplitude transformer by an ER16 cone fitting. It is well designed to further amplify the ultrasonic vibrational amplitude transformed by the amplitude transformer to about 1–10 μm. In order to suppress the bad influence of thermal effect of ultrasonic vibration on its vibratory stability, processing coolant (Blaser, Switzerland) is used as both the internal and external coolant. CDD can be realized on an Ultrasonic 50 by shutting down the ultrasonic function module.

The workpiece material was quartz glass. Its mechanical properties at ambient temperature are density $\rho = 2.2\,\text{g/cm}^3$, elastic modulus $E = 76.7$ GPa, Vickers hardness $H_v = 9.5$ GPa, Poisson's ratio $\nu = 0.17$, and fracture toughness $K_{IC} = 0.71$ MPa m$^{0.5}$. All workpiece specimens were machined to the same initial dimensions of 30 mm × 30 mm × 8 mm. Two surfaces of each specimen with dimensions of 30 mm × 30 mm were polished to 30–40 nm.

The specimens were not drilled through for a subsequent experimental evaluation of the cracks. Fig. 2 shows a specimen with a blind hole, where d_t is the undrilled thickness, H is the height of the specimen, D_o is the hole diameter, which is equal to the outer diameter of the tool, and D_i is the cylinder diameter, which is equal to the inner diameter of the tool. Owing to the specific form of the core drill, a cylinder was reserved in the blind hole.

Specimens for subsequent crack evaluations were produced under several RUD and CDD conditions. In order to compare the RUD and CDD at different machining conditions, we consider the spindle speed and feed rate as experimental variables. The experimental variables are provided in Table 1. The ultrasonic

Table 1
Machining variables and their values used in drilling experiments.

Experiment	Spindle speed (rpm)	Feed rate (mm/min)	Undrilled thickness d_t (mm)	Ultrasonic? (on/off)
1st group	1000	1.2	1.2	On, off
2nd group	3000	1.2	1.2	On, off
3rd group	5000	1.2	1.2	On, off
4th group	3000	0.6	1.2	On, off
5th group	3000	2.4	1.2	On, off
6th group	3000	1.2	0.8	On, off
7th group	3000	1.2	1.6	On, off