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# Reducing edge chipping defect in rotary ultrasonic machining of optical glass by compound step-taper tool

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ABSTRACT

The machining induced edge chipping of hole manufacturing restricts the productivity and design capability of products made from brittle materials. Rotary ultrasonic machining (RUM) has been sufficiently proved as a suitable approach for hole drilling in brittle materials with reduced cutting force and improved hole edge quality. However, apparent edge chipping is still an important restriction of RUM application. In this study, a compound step-taper tool for RUM was designed to further reduce the edge chipping defects via tool design. RUM tests on quartz glass were conducted to evaluate the effectiveness of the compound step-taper tool. The experimental results demonstrated that the compound tool could reduce the edge chipping size at the hole exit and entrance by 60%–80% and 35%–50%, respectively. The mechanism of edge chipping reduction at the hole exit is that cutting force decreased as the undrilled thickness decreased. This is due to the wedge-type contact structure between the tool's taper face and the workpiece material. Furthermore, the edge chipping reduction at the hole entrance occurs because of the shielding effect of residual cracks. Residual cracks produced by the second outermost abrasives of the tool's taper face suppressed the initiation and propagation of lateral cracks that were produced by the outermost abrasives of the tool's taper face. Theoretical analysis indicated that the compound tool step is beneficial for guaranteeing the effectiveness of tool's taper face.


## 1. Introduction

Brittle materials such as optical glasses and advanced ceramics are difficult to machine using a conventional metal cutting method [1]. Brittle materials usually have high hardness that results in severe tool wear, which suppresses the improvement of machining efficiency [2]. Meanwhile, low toughness can induce undesirable defects, reducing the rate of finished products [3]. The machining efficiency and quality improvement of brittle materials are still challenging and critical for corresponding application extensions [4]. Various conventional and unconventional methods have been introduced for machining brittle materials, such as conventional diamond grinding [5], ultrasonic machining (USM) [6], ultrasonic vibration assisted grinding [2,7–9], laser machining [10–12], electrical discharge machining [13], and rotary ultrasonic machining (RUM) [14–16].

Through-hole manufacturing is commonly required in products made from brittle materials. An improvement in the hole exit quality is quite desired because the severe edge chipping defect at the hole exit severely affects productivity as well as design capability [17]. RUM has been sufficiently proved as a suitable method for hole drilling in brittle materials with reduced cutting force and improved hole exit quality [18–21]. As illustrated in Fig. 1, a rotating electroplated diamond tool can vibrate ultrasonically with low amplitude while it moves in the feed direction toward the workpiece during RUM. Moreover, an apparent edge chipping defect at hole exits during RUM remains inevitable [22].

Many investigations have been conducted to reduce edge chipping in RUM. Wang et al. considered the edge chipping formation at the hole exit as the propagation of machine induced subsurface cracks under the cutting force (thrust force) [23]. Then, the relationship between the edge chipping size and the trust force was modeled mechanistically on the basis of the proposed formation mechanism of edge chipping [18]. It was discovered that the thrust force was the main parameter that affects the edge chipping size. Moreover, a higher spindle speed or lower feed rate results in a lower edge chipping size, and this is accompanied by a weaker cut-

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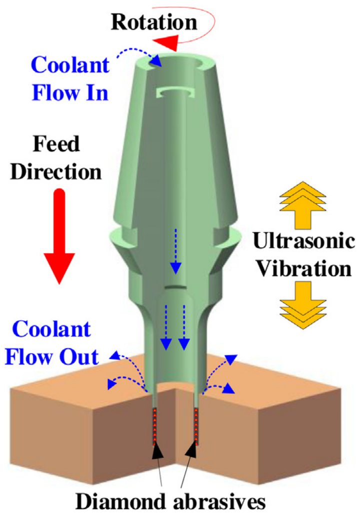


**Fig. 1.** Illustration of RUM.

ting force [18]. Also, Cong et al.'s work on silicon ceramics [24] and Jiao et al.'s work on alumina ceramics [25] indicated a similar relationship between the edge chipping size and the thrust force as the results documented in Wang et al.'s work. Liu et al. used the desirability functions and response surface analysis to minimize the edge-chipping size during RUM of ceramic materials [26]. In addition to optimizing the processing parameters, Gong et al. proposed an effective method to reduce the edge chipping size, which was additional support at the hole exit [27]. Moreover, Li et al. and Chen et al. also proposed that an increase in the support length contributed to improvement in the hole exit quality [22,28]. However, the support addition increased the manufacturing complexity, but cannot be used in many drilling situations.

The tool design constitutes another low cost approach for the edge chipping size reduction of the machined holes [17]. According to the positive dependency of the edge chipping size on the thrust force, the wall thickness decrease of the diamond core tool proved effective in further reducing the edge chipping size. This occurred because of reduced thrust force. However, decreasing the tool wall thickness would increase the tool manufacturing complexity because of the weaker rigidity of the thinner-wall tool, and also restrict the increase in drilling efficiency because of the strength limitation of the tool with a thinner-wall. Tool shape optimization is another method for reducing the edge chipping size. Two types of specially shaped tools have been reported to have superior potential for reducing edge chipping, and these are the step-type tool and the taper-type tool. Wang et al. used the step-type diamond core tool for RUM of sapphire and quartz glasses, and the experimental results demonstrated that the well-designed step-type tool reduced the edge chipping size by up to 50% [29]. From the experimental and finite elements modeling (FEM) results, Qin et al. reported that the taper-type tool was effective for improving the hole exit quality [30]. Wang et al. experimentally investigated the effect of the taper angle on the taper-type tool effectiveness in terms of reducing edge chipping [31].

In this study, the good performances of both the step-type tool and taper-type tool were taken advantage of by using a compound step-taper tool to reduce the edge chipping size at the hole exit during RUM of brittle materials. Drilling tests on quartz glass were conducted to evaluate the feasibility of the compound drill on reducing edge chipping. The cutting force variation at the hole exit was used to observe the reduction mechanism of edge chipping via the compound drill. A theoretical method was used for role analysis of the step face in the effectiveness of the compound tool.

## 2. Fundamentals of edge chipping reduction via tool design

When a common tool is used, the method of optimizing parameters cannot improve the hole exit quality completely, often at the sacrifice of machining efficiency. As presented in Fig. 2(a), when a common tool is used to drill holes in brittle materials, the undrilled thickness ($d$) decreases gradually as the drilling depth increases. The cutting force varies slightly. As illustrated in Fig. 2(b), when the undrilled thickness decreases to a certain value ($d_t$), edge chipping forms; $d_t$ is also called the edge chipping thickness. According to the authors' previous experimental results, $d_t$ is directly proportional to the edge chipping width ($d_s$) [23]. Moreover, $d_t$ and the

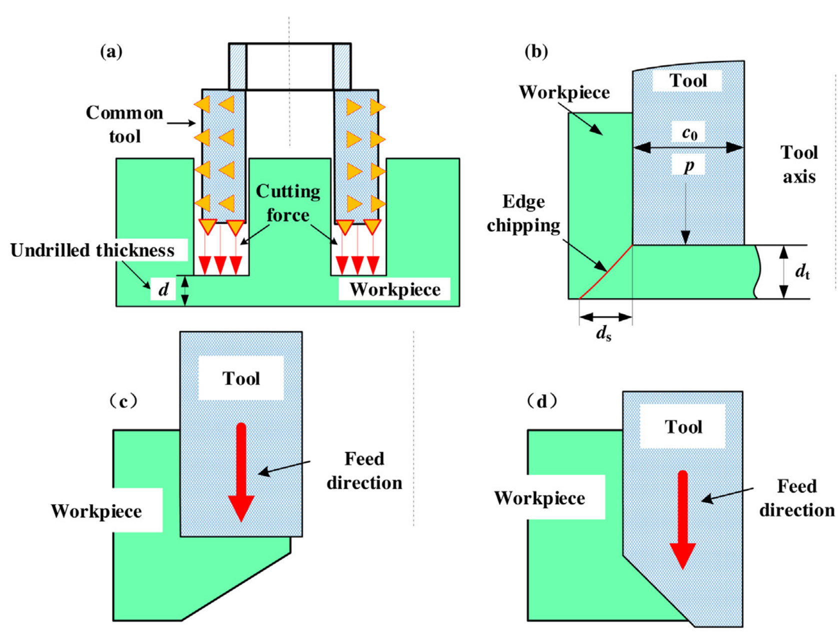


**Fig. 2.** Edge chipping formation. (a) Illustration of undrilled thickness using a common diamond core tool. (b) Relationship between edge chipping thickness and cutting force. (c) and (d) Two types of wedge-type contact structures between the tool and workpiece.