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Improving hole exit quality in rotary ultrasonic machining of ceramic matrix composites using a compound step-taper drill

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ABSTRACT

Mechanical-machining-induced tearing defects at hole exits restrict the application of C/SiC composites. Rotary ultrasonic machining (RUM) is suitable for hole manufacture in brittle composites, providing reduced tearing size as compared with conventional grinding. Even so, substantial tearing defects at the hole exit remain with RUM. In this study, a novel compound step-taper diamond core drill for RUM of C/SiC was developed to further improve the hole exit quality. Contrastive machining tests were conducted to evaluate the effectiveness of the new type drill. Experimental results show that the compound drill can help reduce the tearing size by 30% on average. Results of variance analysis indicate that there is little dependency of tearing size on processing variables with the compound drill, whereas the common drill shows substantial dependence. Detailed observation of the thrust force reveals that the tearing size reduction using the compound drill is due to the reprocessing effects of its taper face. In the reprocessing process of the taper face, the thrust force gradually decreases at the hole exit. Increasing the ultrasonic amplitude can help further improve the hole exit quality when using our compound drill.

1. Introduction

In the twenty-first century new stronger and tougher structural materials are needed to meet the challenges of diverse strategic fields from construction to transportation and energy. Fiber-reinforced ceramic matrix composites (FRCMCs), including C/C, C/SiC, and SiC/SiC, have emerged as potential candidates for their superior physical and mechanical properties [1]. They are heterogeneous materials which combine the ceramic's high strength, hardness, and temperature stability with the reinforcing fiber's high toughness. Compared with their pure ceramic analogues, FRCMCs are more resilient against crack propagation, resulting in no reported disastrous accidents to date [2]. FRCMCs have proven to be useful structural materials for jet engine exhaust ducts, aero foil leading edges, nose cones, and other heat-stressed components [3].

To manufacture products from FRCMCs, a shape-forming technology is necessary. Machining is usually needed to make the FRCMC material satisfy the assembly and application requirements [4]. The hardness and brittleness of FRCMCs however make them one of the most difficult-to-machine materials available. Improving the efficiency and reducing the cost of machining FRCMCs has thereby drawn considerable research attention. In the past two decades various conventional and novel methods have been introduced to attempt to improve the machining of FRCMCs, including rotary ultrasonic machining (RUM) [5–8], grinding [4,9–13], electrical discharge machining [14], laser machining [15], abrasive water jet machining [16], ultrasonic machining [17], ultrasonic vibration-assisted grinding [18], and ultrasonic vibration-assisted filing [19].

A hole is one of the most common features that must be machine into FRCMCs. Usually, the primary concern when drilling brittle materials such as ceramics and glasses is edge chipping at the hole exit [20,21]. Due to the local inhomogeneity of FRCMCs however, tearing is a more significant concern [5]. Such tearing at the hole exit can significantly impact the reliability of the final component. The hard ceramic phase of FRCMCs furthermore prevents the use of conventional drilling methods, such as with a twist drill, which would normally suffice for carbon-fiber reinforced polymers. Rotary ultrasonic machining (RUM) is a hybrid machining process that is considered suitable for hole production in hard and brittle materials [7]. It combines the material removal

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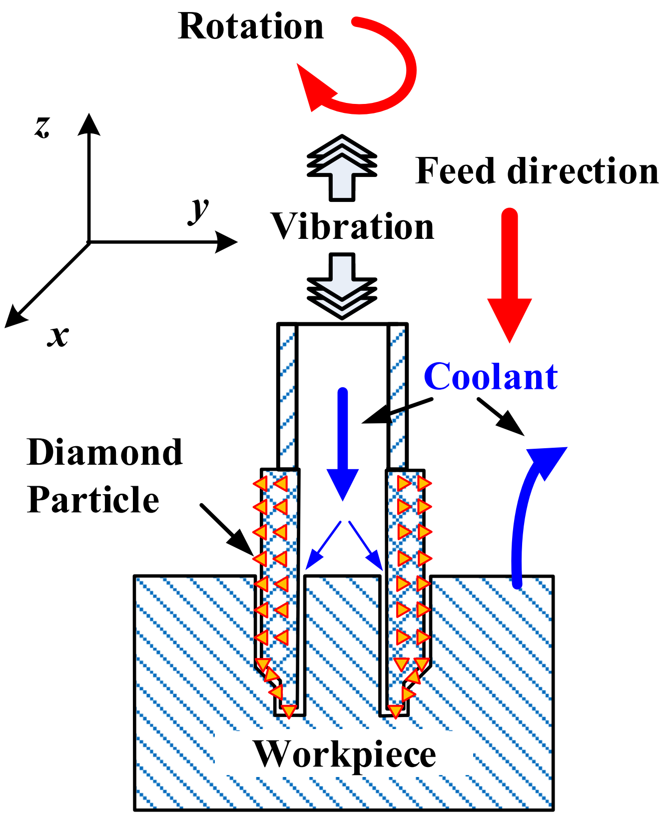

Fig. 1. Illustration of RUM using our compound step-taper drill.

mechanisms of diamond grinding and ultrasonic machining. As shown in Fig. 1, in RUM, a hollow rotating tool with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction while feeding towards the workpiece at a constant feed rate. RUM have already been demonstrated to be suitable for machining FRCMCs, providing a lower cutting force, improved hole surface integrity, higher material removal rate, and smaller tearing size. Even so, obvious tearing is still observed at the hole exit [5].

In this study, a novel compound step-taper diamond core drill was designed to help further reduce the tearing size for RUM of FRCMCs. C/SiC was selected as the material for machining tests to evaluate the effectiveness of this new type of drill. Detailed observations of the thrust force were made to reveal the mechanism of edge chipping reduction.

2. Experiment design

2.1. Experimental setup

The rotary ultrasonic machine we used in this study as an Ultrasonic 50 (DMG). It is composed of an ultrasonic spindle, a feed system, and a coolant supply system. The maximum rotation speed of the ultrasonic spindle was 6000 rpm. The ultrasonic spindle, comprised of a power supply, a piezoelectric transducer, an ultrasonic horn, and a diamond core drill, is the key component of the ultrasonic machine. The power supply converts a 50 Hz AC electrical current to an ultrasonic frequency output. The piezoelectric transducer converts the AC input into mechanical vibrations with ultrasonic frequency (around 20 kHz). Because the output vibrational amplitude of the transducer is too small to be directly applied to machining materials, the ultrasonic horn is designed to amplify the ultrasonic vibration into a usable value. Simultaneously, the diamond core drill should be matched with the ultrasonic horn to guarantee that an efficient ultrasonic vibration at the drill nose can be produced.

As illustrated in Fig. 2, a fixture mounted on a dynamometer (Kistler 9256C2) was used to hold the workpiece using two clamps. A hole with diameter of 20 mm and depth of 12 mm was previously machined on the fixture to protect the drill against knocking. Two pieces of air-laid paper were used between the clamp and workpiece to protect the workpiece. Two different types of diamond core drills were used to machine the C/SiC workpiece. One was a common drill, the other was the compound step-taper drill. The dimensions of their drill heads are shown in Fig. 2(b) and (c). The diamond grit size of both drills was D107. The diamond core drills were mounted on the ultrasonic spindle with an ER16 cone.

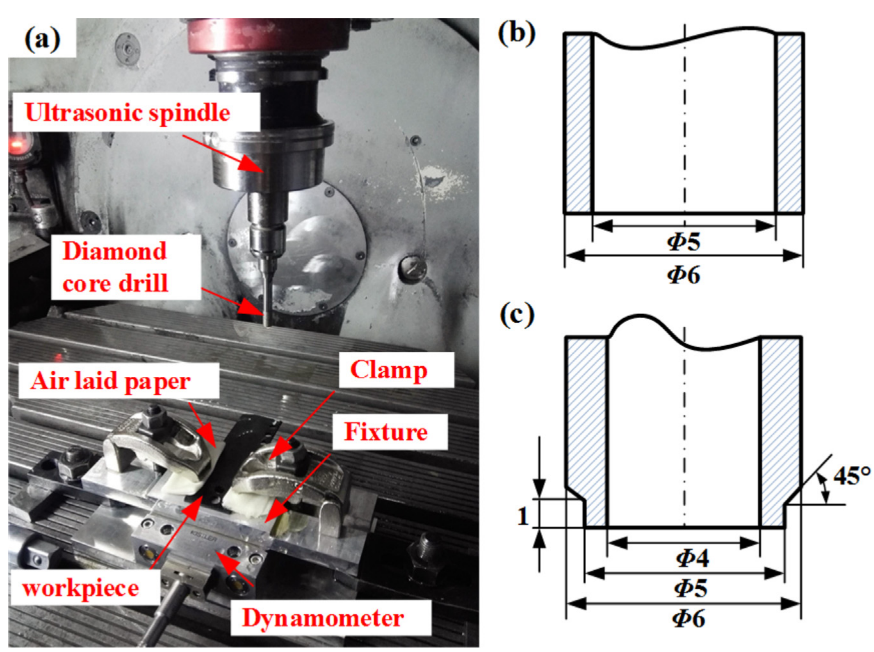

Fig. 2. Illustration of experimental setup. (a) Fixturing scheme (b) Dimensions of common drill. (c) Dimensions of compound drill.