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Reducing cutting force in rotary ultrasonic drilling of ceramic matrix composites with longitudinal-torsional coupled vibration

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ABSTRACT

Drilling of ceramics matrix composites (CMCs) still faces challenges such as low efficiency and severe delamination. Reduction in cutting force is beneficial for improvement in drilling efficiency and suppression of delamination. Conventional rotary ultrasonic drilling (Con-RUD) using longitudinal vibration is regarded as a superior method for drilling CMCs. This study was devoted to establishing a novel RUD method utilizing longitudinal and torsional coupled (LTC) vibration to further reduce the cutting force. Helical flutes were produced on diamond core tool to generate LTC vibration. Machining tests showed that the LTC-RUD is beneficial for reduction in cutting force by more than 50% compared to Con-RUD.

1. Introduction

Ceramic matrix composites (CMCs) have emerged as novel high-performance materials for aerospace, energy, and other high-tech industries [1–3]. Though a near-net shape process is usually used for CMC manufacturing, machining is also essential to make CMC satisfy the requirements of products assembly and application [4–6]. However, machining of CMCs is extremely difficult due to their low resistance to machining induced defects and severe tool wear [7]. Drilling holes in CMCs is a main machining requirement, which still faces challenges of low drilling efficiency and severe defects, in particular hole exit delamination. Various machining methods including diamond grinding [8], ultrasonic machining [9], laser machining [10], and rotary ultrasonic drilling (RUD) [11], have been applied for drilling holes in CMCs.

Fig. 1 shows the schematic illustration of RUD with various modes of tool vibration. In RUD, a tool with electroplated diamond abrasives vibrates under an ultrasonic frequency and rotates while feeding towards the workpiece [12–14]. RUD has been successfully applied for drilling CMCs. Compared to conventional grinding, RUD can dramatically reduce the cutting force and improve the hole edge quality [15,16]. Cutting force in RUD of CMCs plays a crucial role in the formation of hole exit delamination [15]. Moreover, cutting force significantly affects the stability of tool vibration, which in turn affects the process performance of RUD. The efficiency of RUD is markedly limited by the above mentioned interactive effects between cutting force and ultrasonic vibration [17]. Therefore, reduction in cutting force is beneficial for improvement in efficiency and quality of RUD of CMCs. Optimization of processing parameters is useful to reduce cutting force, whereas its capacity is very limited.

The conventional RUD (Con-RUD) applies one-dimensional (1D) longitudinal ultrasonic vibration as shown in Fig. 1(a) [18–20]. Inspired by much better performance of 2D vibration than that of 1D vibration in ultrasonic assisted cutting, some studies have introduced 2D vibration into RUD to improve its performance. Tang et al. used longitudinal and bending coupled (LBC) ultrasonic vibration (see Fig. 1(b)) in RUD of rocks, discovering improved drilling efficiency compared to Con-RUD [21]. Geng et al. applied double bending coupled (DBC) vibration (see Fig. 1(c)) in RUD of carbon fiber-reinforced plastics (CFRPs), discovering reduced tool wear and improved surface integrity [22]. Fig. 1(b) and (c) illustrate that the vibration trajectory of diamond abrasives of LBC-RUD and DBC-RUD is not in the cutting plane, which is constituted by cutting direction and depth of cut (DOC) direction [22]. In ultrasonic assisted cutting technique, 2D vibration in the cutting plane also shows significantly more superior performance than 1D

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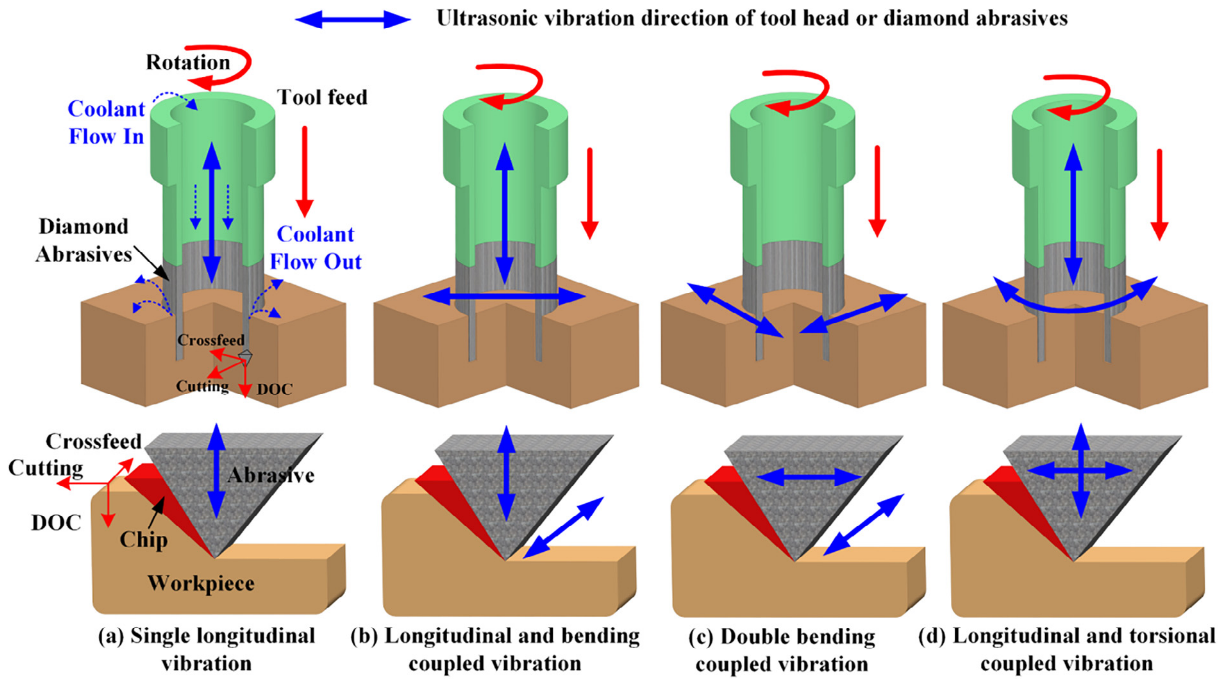

(a) Single longitudinal vibration (b) Longitudinal and bending coupled vibration (c) Double bending coupled vibration (d) Longitudinal and torsional coupled vibration

Fig. 1. Illustration of different modes of ultrasonic vibrations in RUD.

vibration [23]. For RUD, longitudinal and torsional coupled (LTC) vibration of tool can make diamond abrasives vibrate in the cutting plane with a 2D trajectory as shown in Fig. 1(d). Amini et al. verified the performance of LTC vibration in terms of cutting force reduction in ultrasonic assisted cutting of metal [24].

This study was devoted to further reduce the cutting force in RUD of CMCs by applying LTC ultrasonic vibration. The helical flutes were machined on diamond core tool to convert tool's longitudinal vibration into LTC vibration. Cutting force reduction in RUD by using LTC vibration was evaluated experimentally on carbon fiber-reinforced silicon carbide (C/SiC) CMCs and compared with the results of conventional longitudinal vibration.

2. Materials and methods

Fig. 2(a) shows that the LTC-RUD tests were conducted using the Con-RUD machine tool (Ultrasonic 50). In Con-RUD, a piezoelectric transducer converts alternate current (AC) signals of ultrasonic frequency into longitudinal mechanical vibration. An ultrasonic concentrator is applied to amplify the mechanical vibration of tool into practicable magnitude for material processing. Helical flutes were machined on the tool to generate LTC vibration. The dimensions of LTC tool are illustrated in Fig. 2(b). The longitudinal vibration of transducer was converted to LTC vibration by helical flutes. The maximum amplitude A_{lon} of longitudinal vibration of LTC tool was measured to be 5.5 μm at its resonant frequency of 17.60 kHz, using a laser displacement sensor (LKH008, KEYENCE Corporation). The amplitude ratio of torsional to longitudinal vibration was calculated to be 0.48 by finite element analysis (FEA) by using harmonic response analysis module of ANSYS. The vibration directions of tool obtained from FEA are also shown in Fig. 2(b). Both the end face and side face of the LTC tool were electroplated with diamond abrasives of grit D91.

A 2D C/SiC panel with size of 100 mm × 50 mm × 3 mm and density of 1.8 g cm^3 was used as workpiece. Fig. 2(c) shows the microstructure of workpiece material, consisting of SiC matrix, voids, and carbon fibers. The fiber bundles consisting of hundreds of carbon fibers are ranked in 90° and 0° orientations. The diameter of carbon fibers is approximately 5 μm. Fig. 2(a) shows that a fixture with clamps was utilized to fix the workpiece on the workbench of machine tools.

The machine variables for LTC-RUD experiments are listed in Table 1. The cutting force was measured using a dynamometer (9256C2, Kistler Corp, Switzerland) with sampling frequency of 100 Hz. A commercialized and professional software DynoWare provided by the Kistler Corporation was applied to record and analyze the data of cutting force. Only the thrust component of cutting force was analyzed considering its dominant effects on drilling efficiency and quality. The data of Con-RUD of C/SiC were obtained from our previous study [15].

A typical curve of thrust force versus time is shown in Fig. 2(d). By considering the comparative analysis of different drilling experiments, the cutting force per area of tool end face $F_{c,a}$ was used, which can be calculated as follows:

$$\begin{cases} F_{c,a} = \frac{4F_{c,ave}}{\pi(D_o^2 - D_i^2)} \\ F_{c,ave} = \frac{\int_{t_0}^{t_1} F_c dt}{t_1 - t_0} \end{cases} \tag{1}$$

where $F_{c,ave}$ is the average cutting force and D_o and D_i are outer diameter and inner diameter of tool, respectively. F_c is cutting force vs time, and t_1 is the time when the cutting force begins to abruptly decrease at hole exit, $t_1 - t_0 = 0.5/f_r$.

3. Results and discussion

The material removal process by the abrasives of tool end face is dominant in the generation of thrust cutting force; therefore, this research only takes the effects of the abrasives of tool end face into consideration. Fig. 3(a) and (b) show the trajectory comparison of abrasive on the tool end face in Con-RUD and LTC-RUD. The trajectory shape significantly affects the actual cutting rake angle γ_i, which can be expressed as follows:

$$\gamma_i = \theta_i - 90\circ \tag{2}$$