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Edge-chipping reduction in rotary ultrasonic machining of ceramics: Finite element analysis and experimental verification

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Abstract

Rotary ultrasonic machining (RUM) is one of the machining processes for advanced ceramics. Edge chipping (or chamfer), commonly observed in RUM of ceramic materials, not only compromises geometric accuracy but also possibly causes an increase in machining cost. In this paper, a three-dimensional finite element analysis (FEA) model is developed to study the effects of three parameters (cutting depth, support length, and pretightening load) on the maximum normal stress and von Mises stress in the region where the edge chipping initiates. Two failure criteria (the maximum normal stress criterion and von Mises stress criterion) were used to predict the relation between the edge chipping thickness and the support length. Furthermore, a solution to reduce the edge chipping is proposed based upon the FEA simulations and verified by experiments.

Keywords: Ceramic; Edge chipping; Finite element analysis; Grinding; Machining; Rotary ultrasonic machining

1. Introduction

Advanced ceramics are increasingly utilized in industries such as aerospace, automotive, and cutting tools. Their mechanical properties (such as high hardness, excellent wear resistance, and high-temperature stability) result in superior performances. These very properties are also responsible for difficulties encountered in machining them into desired shapes and dimensions. It was reported that the machining cost for ceramic components could be as high as 90% of the total cost [1]. Therefore, there is a crucial need to develop more cost-effective machining processes for ceramic components.

Rotary ultrasonic machining (RUM) is one of the processes applicable to ceramic materials. It has the potential to achieve high material removal rates (MRRs) while maintaining low cutting pressures, resulting in relatively low surface damage and strength degradation [2,3]. The RUM process is illustrated in Fig. 1. A rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in its axial direction and fed towards the workpiece at a constant feedrate or a constant force. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill, and keeps it cool.

Since its inception in 1960s [4,5], many papers on RUM have been published. Pei et al. [6,7] reported that there exist two material removal modes in RUM of ceramic materials: brittle fracture mode and ductile model. Models for predicting the MRR based upon the two material removal modes were developed by Prabhakar et al. [8] and Pei et al. [6,9]. Spur and Holl [10], and Zeng et al. [11] investigated tool wear mechanisms in RUM. Effects of RUM-machining variables (spindle speed; feedrate; ultrasonic vibration amplitude and frequency; diamond type, size and concentration; bond type for the cutting tool; etc.) on the performances (MRR, cutting force, surface roughness, etc.) of RUM were investigated experimentally [2,12–17]. Extensions of RUM to face milling [18,19], disk grinding [20], and complex contour machining [21,22] were

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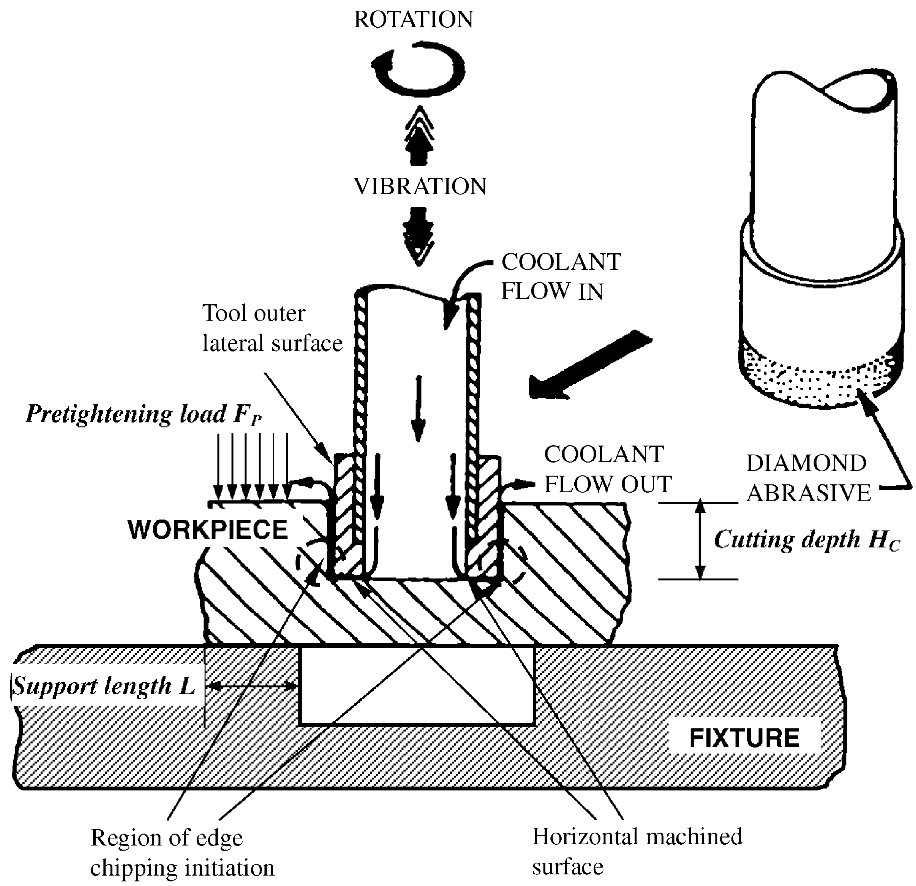

Fig. 1. Illustration of rotary ultrasonic machining (RUM).

developed. RUM was also introduced into machining of ceramic matrix composites [23,24]. More information on RUM can be found in several review papers [25–28].

One of the remaining challenges for RUM is edge chipping (or, chamfer) [29–30]. Fig. 2 illustrates the edge chipping induced in the RUM process. Shown in Fig. 2(a) is a workpiece that has been machined into two pieces by RUM. One piece is the machined part with the desired hole, the other is a rod (or slug) removed from the workpiece. Fig. 2(b) shows the side view of the bottom portion of the machined rod. An edge burr around the bottom of the rod is observable. When the cutting tool nearly drills through the workpiece, the rod breaks off from the workpiece, causing the edge chipping around the hole exit edge as shown in Fig. 2(c). The edge chipping thickness can be measured either on the rod as sketched in Fig. 2(b), or on the hole exit as shown in Fig. 2(d).

The edge chipping in a machined ceramic component not only compromises geometric accuracy, but also causes possible failure of the component during service [31]. Generally, edge chipping is not acceptable on finished products, and has to be machined off by other processes after the RUM operation. The larger the edge chipping thickness, the higher the total machining cost. Therefore, research efforts to reduce the edge chipping thickness in RUM are desirable.

Ng et al. [31] characterized the edge chipping in ceramic milling into three categories: entrance edge chipping, interior edge chipping, and exit edge chipping. They reported that the microstructure and stress distribution were the key factors for the initiation and propagation of the edge chipping. Yoshifumi et al. [32] studied edge chipping in slot grinding of Mn–Zn ferrite. They concluded that the size of the edge chipping was proportional to the MRR. Based upon Chiu et al.'s work [33] on edge chipping initiation in milling of brittle materials, Cao [34] studied the factors related to exit edge chipping in milling of dental ceramics using a two-dimensional (2-D) finite element analysis (FEA) model. In his model, a microcrack was used to simulate a critical flaw or pre-existing machining induced damage. His results revealed that the main influencing factors in determining the size of exit edge chipping were the size and length of the microcrack as well as the orientation and location of the applied load.

The aforementioned investigations dealt with the machining induced edge chipping in milling and grinding of brittle materials. Little research on edge chipping in RUM has been reported. Jiao et al. [29] studied the edge chipping