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Rotary Ultrasonic Machining of Advanced Ceramics

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Abstract. Rotary ultrasonic machining (RUM) is one of the cost-effective machining methods for advanced ceramics, which is a hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining (USM). This paper presents an overview of the investigations on RUM of advanced ceramics. The issues about the material removal mechanisms, process modeling, material removal rate, and tool wear in RUM are reviewed. Directions of future research on RUM are also presented.

Introduction

Advanced ceramics are attractive for many industrial applications due to their superior properties (such as high strength at elevated temperature and high wear resistance). However, the widespread utilizations of advanced ceramics have been constrained by high machining costs resulted from these superior properties with current technology. Therefore, there is a crucial need for cost-effective machining processes applicable to advanced ceramic materials.

The need for methods of machining the advanced ceramics has led to the introduction of some special machining techniques like ultrasonic machining (USM). Fig.1 is a schematic illustration of USM. The tool oscillates at a high frequency (typically 20 kHz) and is fed into the workpiece by a constant pressure. Abrasive slurry comprising water and small abrasive particles is supplied between the tool tip and the workpiece. Material is removed in the form of tiny particles by the successive impacting action of the abrasive particles into the workpiece. However, one key barrier of USM application is that there are some disadvantages of USM process such as low material removal rate (MRR) and low accuracy.

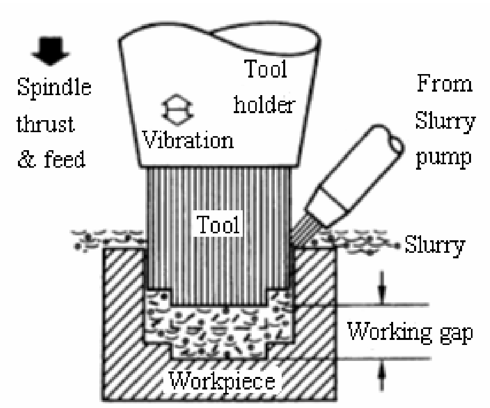

Fig.1 Illustration of ultrasonic machining

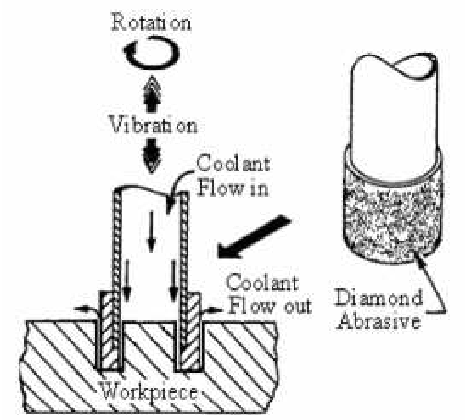

Fig.2 Illustration of rotary ultrasonic machining

One modification of USM to overcome its disadvantages is rotary ultrasonic machining (RUM). It is a hybrid machining process that combines the material removal mechanisms of diamond grinding and USM. Fig.2 is a schematic illustration of RUM. In RUM, a rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated and fed toward to the fixed workpiece at a constant pressure or a constant federate.

Experimental results have shown that the machining rate obtained from RUM is about 10 times higher than that form USM under similar conditions[1]. It is easier to drill deep holes with RUM than with USM. Improved hole accuracy is also reported[2]. Other advantages of this process are superior surface finish and light tool pressure[3].

Although a lot of research work on RUM has been conducted, However, few systematic studies on RUM have been published. This paper presents an overview of the investigations on RUM of advanced ceramics. The issues about the material removal mechanisms, process modeling, material removal rate, and tool wear are reviewed. Directions of future research on RUM are also presented.

Material Removal Mechanisms and Process Modeling

For rotary ultrasonic machining of ceramics, the material removal had been exclusively attributed to brittle fracture in the available literature. Markov and Ustinov [4] stated that, in RUM, "the role of ultrasonic vibrations consists in an intensive process of brittle fracture of the material being machined, as a result of network of micro-cracks and tear-outs forming on its surface."

Based on indentation fracture, Prabhakar et al.[5] developed a theoretical model for calculating material removal rate (MRR) in RUM. This is the first attempt to characterize the RUM process. It is very helpful in understanding the underlying material removal mechanisms at play in RUM. A mechanistic model was developed to predict MRR in RUM of ceramic materials by Pei et al.[6]. This model is mechanistic in the sense that a model parameter can be observed experimentally from a few experiments for a particular material and then used in prediction of MRR over a wide range of process parameters.

Pei et al.[7] employed rotary ultrasonic face milling in preparation of SEM specimens for observing machined surface and chips to overcome the difficulty of observation of machined surfaces and chips generated in RUM drilling process. Different types of machined ceramics materials (surfaces and chips) under different machining conditions in RUM process are observed and analyzed. The evidence was provided that, in addition fracture, ductile mode is another removal mode in RUM of ceramics. Based on the assumption that plastic flow is the primary mechanism of material removal, Pei et al.[8] proposed a theoretical equation of MRR in RUM.

Material Removal Rate

The experimental investigations about the effects of the RUM process parameters (static pressure, rotational speed, ultrasonic vibration amplitude and frequency, and diamond size, etc.) on MRR have been conducted[4,9-22]. The major conclusions are summarized in in this section.

Effect of Static Load. The static pressure has a great effect on MRR in the process of RUM. As the static pressure increases, MRR increases to a maximum value and then decreases.

Effect of Rotational Speed. Fig.3 shows the effect of rotational speed on MRR in RUM. It can be seen that higher rotational speed results in higher MRR.

Effect of Vibration Amplitude. As the vibration amplitude increases up to some value, MRR increases. A further increase of vibration amplitude above the value will result in a reduction, to some extent, in MRR as shown in Fig.4.

Effect of Vibration Frequency. Fig.5 shows the effect of vibration frequency on MRR in RUM. It can be observed that MRR increases as the vibration frequency increases.

Effect of Grit Size. The effect of diamond grit size on MRR is shown in Fig.6. It can be observed that MRR will increase as the diamond size increase up to an optimum value. A further increase in diamond size results in lower MRR.

Tool Wear

As compared with USM, it was found that RUM can increase tool life[23]. The effects of the process parameters (static load, ultrasonic vibration frequency and amplitude, diamond concentration, diamond type, grit size, and bond strength) on the tool wear during the process of RUM have been investigated experimentally[22,24-25]. It was found that Static load, rotary speed, vibration frequency and amplitude, diamond concentration, grit size, and bond strength have a significant influence on the tool wear in RUM.

Zeng et al.[26] firstly investigated the tool wear mechanisms in RUM. In this study, the topography of end face and lateral face of a diamond tool in RUM of SiC was observed under a digital microscope. It was found that bond fracture dominates in tool wear during RUM of SiC.

Conclusions and Some Directions for Future Research

From this review, the following conclusions can be drawn:

1. Compared with USM, RUM has superior performance.
2. There exist two material modes in RUM of ceramic materials: brittle fracture mode and ductile mode.
3. Static load, rotary speed, vibration frequency and amplitude, diamond concentration, grit size, and bond strength have a significant influence on the performance of RUM.

Direction for future work include determining the effect of machining parameters on subsurface damage, carrying out further study of brittle fracture and ductile material removal mode, studying the tool wear mechanisms in RUM.

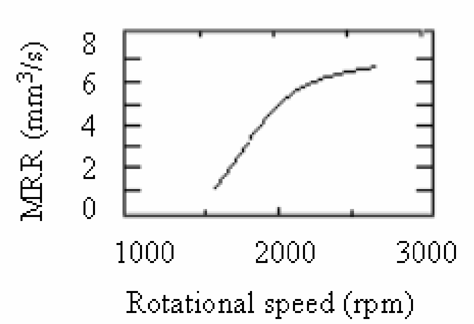

Fig.3 Effect of static load on MRR

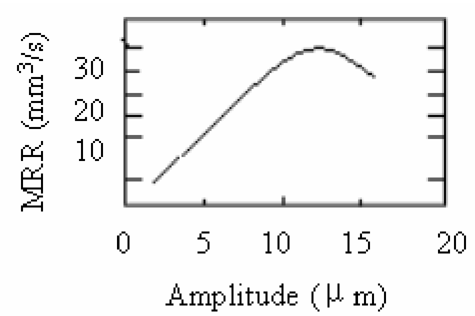

Fig.4 Effect of vibration amplitude on MRR

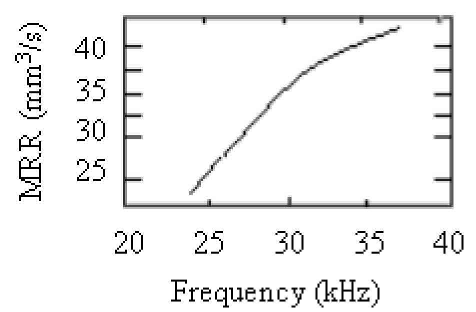

Fig.5 Effect of vibration frequency on MRR

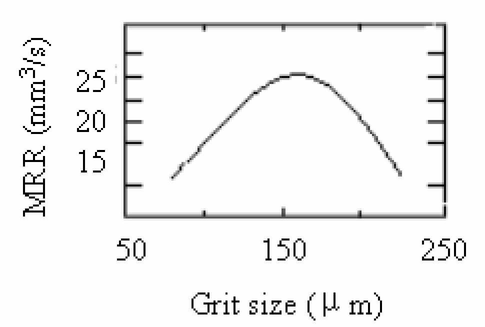

Fig.6 Effect of grit size on MRR

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