Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics


aProvince Key Laboratory of Stone Machining, Huaqiao University, Quanzhou, Fujian 362011, China
bDepartment of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
cSonic-Mill, 7500 Bluewater Road, Albuquerque, NM 87121, USA

Received 1 November 2004; accepted 20 January 2005
Available online 7 March 2005

Abstract

As one of the cost-effective machining methods for advanced ceramics, rotary ultrasonic machining (RUM) has attracted much attention and there exist numerous publications on the process. However, few investigations on tool wear in the RUM process have been reported. This paper, for the first time in literature, presents an experimental observation on tool wear in RUM of silicon carbide (SiC). It first reviews some related wear mechanisms for grinding wheels and some techniques for studying the wheel wear mechanisms. After describing the experimental procedures, it presents and discusses the results on tool wear and cutting forces in RUM of SiC. It also discusses some practical implications of the findings from this study.

q 2005 Elsevier Ltd. All rights reserved.

Keywords: Advanced ceramics; Cutting force; Diamond wheel; Grinding; Machining; Rotary ultrasonic machining; Tool wear

1. 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, widespread utilizations of advanced ceramics are constrained by high machining costs resulted from these superior properties. Therefore, there is a crucial need for cost-effective machining processes applicable to advanced ceramic materials.

Rotary ultrasonic machining (RUM) is regarded as one of the cost-effective machining methods for advanced ceramics. It is a hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining (USM) [1–3]. Fig. 1 is a schematic illustration of RUM. In RUM, a rotary core drill with metal-bonded diamond abrasives is ultrasonically vibrated and fed toward the workpiece at a constant feedrate or a constant force (pressure). Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill, and keeps it cool.

RUM was invented in 1964 [4–6]. The effects of RUM control variables (rotational speed, vibration amplitude and frequency, diamond type, size and concentration, bond type, coolant type and pressure, etc.) on its performances (material removal rate, cutting force, surface roughness, etc.) have been investigated experimentally. Efforts have also been made to develop models to predict the material removal rate in RUM from control variables [3,14,15].

As for the tool wear in RUM, specific tool wear (the ratio of the volume of material removed to the volume of tool wear) was used to evaluate tool wear [10]. The effects of process parameters (static load, ultrasonic vibration and amplitude, diamond concentration, diamond type, grit size, and bond strength) on specific tool wear were investigated experimentally. However, specific tool wear measurements can reveal little about the mechanisms of tool wear in RUM.

This investigation aims to understand the tool wear mechanisms in RUM of silicon carbide (SiC). Tool surfaces at different wear stages were observed under a digital
microscope. Cutting forces during the RUM process were measured and correlated to the stages of tool wear. Results from this study cannot only shed light on the tool wear mechanisms in RUM, but also provide some practical guidance for the design and manufacture of RUM tools.

The remainder of this paper is organized as follows. Section 2 reviews some related wear mechanisms for grinding wheels and some techniques for studying the wheel wear mechanisms. The experimental procedure is described in Section 3. In Section 4, experimental results are presented and discussed. Conclusions are drawn up in Section 5.

2. Brief review of related literature

2.1. Wheel wear mechanisms

Although no research work on tool wear mechanisms in RUM has been reported, extensive work exists in the literature on wheel wear mechanisms in grinding. A brief review of wheel wear mechanisms in grinding would be instrumental to the study of tool wear mechanisms in RUM.

Wear mechanisms of individual abrasive particles have been studied extensively (mostly done with single-grit wheels). Shaw [16] has devoted an entire chapter of his book to this topic, including a comprehensive literature review.

As for wear of grinding wheels, it is generally recognized that there are three main mechanisms: attritious wear, grain fracture, and bond fracture [16–18]. Attritious wear refers to dulling of abrasive grains and the growth of wear flat due to the rubbing of the abrasive grains against the workpiece. Grain fracture involves removal of abrasive fragments by fracture within the grain. Bond fracture causes dislodging of abrasive grains from the binder. It is generally agreed that attritious wear increases the area of wear flats and determines the magnitude of the grinding force and the quality of the ground surface; grain fracture and bond fracture expose new cutting edges and are responsible for the self-sharpening of grinding wheels and the loss of form and size of the grinding wheels.

It has been reported that grain fracture and bond fracture wear contribute to the overall grinding wheel wear, while attritious wear amounts to only a few percent of the total weight loss of a grinding wheel [19,20]. However, attritious wear has important effects on the grinding process. Peklenik [21] and Yoshikawa [22] found that with steel workpiece materials, grinding burn was observed when the wear flat area reached a critical value.

Much research has been done on wear mechanisms of conventional wheel (made of alumina or silicon carbide abrasives) in grinding of metallic materials [16,17]. Reports appeared recently have covered wear mechanisms of diamond wheels in grinding of ceramic materials [23–26].

2.2. Techniques to study wheel wear mechanisms

One commonly used method to study wear mechanisms of grinding wheels is to examine the wheel surface with a microscope. This method has been used to study the attritious wear in terms of the area of wear flats of the abrasive grains on the grinding wheel surface [21,27–29]. Wear flats were observed by means of a microscope with a vertical illuminator. When viewing normal to the wheel surface, the wear flats reflect light back through the microscope objective and appear bright while the other area on the wheel surface reflect light in random directions and appear dark. Of particular interest are the results from Malkin et al., who found that both vertical and horizontal components of the grinding force increased linearly with the wear flat area [30]. Scanning electron microscopes (SEM) have also been used to observe the topography of the wheel surfaces [23,26].

To investigate fracture wear (grain fracture and bond fracture) of grinding wheels when grinding of metals, the grinding debris was collected and the wheel particles were
separated from the swarf \[25,30\]. The weight of the large particles was assumed as the weight of bond fracture wear, and the weight of the small particles was assumed as the weight of grain fracture. The main assumptions when using this technique were that particles removed by bond fracture were large, and there was only one bond fracture per grain. However, there are no reports on successful applications of this method to ceramic grinding. The reason could be the difficulty in separating wheel particles from ceramic swars because ceramic swars are non-conductive and smaller than metallic swars \[24\].

The lead-tape imprint technique \[24\] and acetate-tape replication technique \[31\] were used to study the wheel wear for large-grit wheels. In order to examine the wheel surfaces under an optical microscope or SEM, it is sometimes necessary to make replicas of the wheel surface by using acetate-tape or lead-tape (for example, when the wheel is too large to put on a microscope table). Liao et al. used the lead-tape imprint technique to trace the topographical change of hundreds of diamond abrasives and to subsequently quantify the percentages of different wear mechanisms \[24,25\].

In RUM of advanced ceramics, it is difficult to separate diamond grains from grinding debris. In addition, the RUM tools are small enough to put under microscopes, it is unnecessary to make replicas of the tool surface. The microscope method was used for this investigation into tool wear mechanisms in RUM of SiC.

3. Experimental procedure

3.1. Experimental set-up and conditions

RUM experiments were performed on a RUM machine (Sonic-mill 10 series, Sonic-Mill, Albuquerque, NM, USA). The experimental setup is schematically showed in Fig. 2. It mainly consists of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system comprises of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converts 50 Hz electrical supply to high frequency (20 kHz) AC output. This is fed to the piezoelectric transducer located in the ultrasonic spindle. The ultrasonic transducer converts electrical input into mechanical vibrations. The motor attached atop the ultrasonic spindle supplies the rotational motion of the tool and different speeds can be obtained by adjusting the motor speed controller. The fixture to hold the specimens was mounted on a dynamometer that was firmly attached to the machine table.

The cutting tool was metal-bonded diamond core drill (N.B.R. Diamond Tool Corp., outer diameter = 9.6 mm, inner diameter = 7.8 mm, grit mesh size = #100 ~ 120). The workpiece material was silicon carbide (SiC). Mechanical properties of the SiC material are listed in Table 1. Dimensions of the SiC specimens are $98 \times 56 \times 56$ mm.

To prevent the specimens from fracture during the RUM process, the depth of drilling was controlled as 1.5 mm. In other words, each drilling test did not cut a through hole. Other experimental conditions are listed in Table 2.

3.2. Measurement procedure

During RUM, cutting forces were measured using a data acquisition system comprising of a dynamometer (KISTLER type 9257B), a dual mode amplifier (KISTLER type 5010, Kistler Instrument Corp., Amherst, NY, USA), an A/D converter, and a computer. The controlling program was written by LabView 5.1.

After each drilling test, the cutting tool (a core drill) was removed from the RUM machine for observation under a digital microscope (Olympus DVM-1, Olympus America, Inc., NY, USA). The magnification of the digital microscope was from 50 to 200. The topography was observed on both the end face and lateral face of the tool.

---

Table 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>400</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>3900</td>
</tr>
<tr>
<td>Vicker’s hardness</td>
<td></td>
<td>2800</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed</td>
<td>rev s$^{-1}$ (rpm)</td>
<td>67 (4000)</td>
</tr>
<tr>
<td>Feedrate</td>
<td>mm s$^{-1}$</td>
<td>0.09</td>
</tr>
<tr>
<td>Vibration frequency</td>
<td>kHz</td>
<td>20</td>
</tr>
<tr>
<td>Coolant pressure</td>
<td>kPa</td>
<td>276</td>
</tr>
<tr>
<td>Vibration power supply$^a$</td>
<td></td>
<td>30%</td>
</tr>
</tbody>
</table>

---

$^a$ Vibration power supply controls the amplitude of ultrasonic vibration.
In order to ensure that the same area of the tool surface was observed every time, a special fixture was designed for holding the tool.

4. Results and discussion

4.1. Wear of tool lateral face

Fig. 3 shows the tool topography on both lateral and end faces before any drilling test was performed. After 16 drilling tests were performed, there are no visible differences in the appearances of the diamond grains on the tool lateral face except the diamond grains at the edge. This means that the wear of diamond grains on the tool lateral face was very small after 16 tests were performed. It suggests that it is unnecessary to have so many diamond grains on the lateral face of a RUM tool. Therefore, the length of the lateral face can be shorter, thus reducing the manufacturing cost of the RUM tool.

However, wear of the diamond grains at the edge of the lateral face (close to the end face) was quite severe. Two diamond grains (grain A and grain B as indicated in Fig. 3) at the edge were dislodged after 16 drilling tests.

4.2. Wear of tool end face

Fig. 4 shows the topography of the tool end face after 6 and 16 drilling tests were performed. Comparing Figs. 3(B) and 4(B), it can be observed that most of the diamond grains on the tool end face are pulled out after 16 drilling tests. It shows that the wear of tool end face is so severe that most of diamond grains are dislodged.

Attritious wear can be observed on some diamond grains on the tool end face. Fig. 4(A) shows the topography of the tool end face after six drilling tests. From this figure, large wear-flats can be observed that exist due to attritious wear of diamond grains.

Comparing Fig. 4 (A) and (B), it can be seen that few diamond grains are pulled out during the first 6 drilling tests. Furthermore, after six drilling tests, the number of diamond grains that were pulled out kept increasing. It is clearly shown that the diamond grain dislodgment is due to bond fracture in RUM of SiC. Some diamond grains were pulled out of the metal bond prematurely, before completing
their effective working lives. A grain completely pulled out of the mental bond results in a hole on the tool end face. Weakening of the interfaces between diamond grains and metal bond may be due to mechanical impact and high temperature.

As stated earlier, fracture wear includes grain fracture and bond fracture. Generally, diamond grains are more susceptible to grain fracture prior to their being finally dislodged from the bond [17]. However, grain fracture which is commonly seen in metal grinding and conventional grinding of ceramic materials has not been observed when RUM of SiC. It seems that diamond grains are more susceptible to bond fracture from the bond prior to grain fracture.

The tool wear in RUM of SiC seems to have two different stages. In the first stage, attritious wear dominates. In the second stage, bond fracture dominates. The tool fails to function any longer when the bond fracture becomes too severe.

Another interesting phenomenon is associated with the color of diamond grains. It has been observed that the surface color of these diamond grains is different, implying that the temperature on these grain surfaces during RUM was high. The reason could be that during the RUM process, the diamond grains become extremely dull, thereby causing large friction and high temperature at the interface of the diamond grains and the workpiece.

4.3. Cutting force

Fig. 5 shows the relationship between the maximum cutting force and the number of drilling tests. It can be observed that, in the first 6 drilling tests, the maximum cutting force increased with the number of drilling tests. However, the maximum cutting force decreased after six drilling tests. The reason could be due to the dulling of diamond grains. In the first 6 drilling tests, very few diamond grains were pulled out, and the number of active grains was relatively constant. At the same time, attritious wear led to the growth of wear flats on the active grains, causing higher grinding forces. However, starting from the 7th drilling test, because a number of active diamond grains were pulled out, the amount of wear flats decreased, and the grinding force decreased accordingly.

5. Conclusions

In this study, the topography of the end face and lateral face of a diamond tool in RUM of SiC was observed under a digital microscope, and cutting forces were measured. The following conclusions can be drawn:

1. Attritious wear and bond fracture were observed in RUM of SiC. However, grain fracture which is commonly seen in metal grinding and conventional grinding of ceramic materials was not observed.
2. In RUM of SiC, the tool wear on the end face is much more severe than that on the lateral face. At the same time, attritious wear dominates. In the second stage, bond fracture dominates.
3. The tool wear in RUM of SiC has two stages. In the first stage, attritious wear dominates. In the second stage, bond fracture dominates.
4. The maximum cutting force in RUM of SiC is related to tool wear stage. The maximum cutting force increases with the number of holes drilled during the first tool wear stage, and starts decreasing during the second tool wear stage.

Some of these findings have practical implications for the wheel design and process control in RUM. For example, since ‘the tool wear on the end face is much more severe than that on the lateral face’ (Conclusion #2), RUM tools can be designed in a way so that the lateral face is shorter. Tools with shorter later face use less diamond grains and hence have lower manufacturing cost. The relationship between the cutting force and tool wear stage can be used for indirect monitoring of tool wear during machining processes.

Acknowledgements

This work was supported in part by the Society of Manufacturing Engineers through a research initiation grant and by the Advanced Manufacturing Institute at Kansas State University. The authors gratefully extend their acknowledgement to Mr Dean Owens at Saint-Gobain for supplying the ceramic specimens, Mr Bruno Renzi at N.B.R. Diamond Tool Corporation for supplying the diamond core drills, Professor Youqi Wang, Mr Xueming Zhou, and Ms Yuyang Miao at Mechanical and Nuclear Engineering Department of Kansas State University for their assistance in observation of tool wear by a digital microscope.
References


