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Diamond tool wear when machining Al6061 and 1215 steel

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ABSTRACT

Different rates of wear of diamond tools depend on the physical and chemical nature of the workpiece material. Wear mechanisms for diamond tools can be either abrasive or chemical in nature, or a combination thereof. Differentiating the affects of these wear mechanisms can be accomplished by measuring the wear geometry of the cutting edge as a function of cutting distance. Orthogonal cutting experiments using 6061 aluminum and 1215 steel were conducted to illustrate abrasive and abrasive plus chemical wear, respectively. Wear of the diamond tool was measured using the electron beam induced deposition method. This method provides nanometer resolution images of the tool edge (edge radius and wear land) that can be used to calculate volumetric wear loss and wear rates. A method for determining the Archard wear coefficient for diamond turning based on measured wear and cutting forces is also introduced. Comparisons are made between the tool wear resulting from the two materials, and hypotheses related to the wear mechanism are presented.

1. Introduction

Diamond turning (DT) has revolutionized the fabrication of optics and precision surfaces since its inception in the early 1970s. Some materials, however, have proven to be difficult if not impossible to machine with good surface finish using a diamond tool. This difficulty is due to either the brittle nature of the material or excessive wear on the diamond tool. Aluminum and steel alloys are common engineering materials that pose challenges to standard DT due to tool wear. Al6061 is an aluminum alloy commonly used for both the optical and the structural components of reflective optical systems. It contains hard alloying elements such as silicon and chromium. The mode of tool wear is presumed to be abrasive in nature due to these hard inclusions. Steel alloys have broad application to injection molds for plastic components. However, machining these materials with diamond tools has proven to be even more challenging than Al6061. Wear rates of diamond on steel are exceedingly high, and have been found to be on the order of one carbon atom lost from the tool for every five atoms of clean metal passing over the diamond [1]. Wear, when cutting steel and other ferrous alloys, is a result of chemical interactions between the diamond and workpiece material [1–4]. 1215 steel is a mild carbon steel alloyed with sulfur and other elements that is more easily machinable than most steels [5]. The two candidate workpiece materials (6061 aluminum and 1215 steel) were chosen because they have similar hardness but very different chemical interaction with the diamond tool.

The cutting process is complicated; combining interactions such as plastic material flow, new surface generation, strain-rate and thermal effects, friction forces and surface heating, and chemical interactions. This process is simplified by selecting the 2D cutting geometry of orthogonal machining, where the tool rake face aligns with the cutting direction. This keeps the depth of cut equal across the face of the diamond tool. In addition, the width of the tool is wider than the material so that the center of the diamond edge can be worn by the workpiece material while maintaining unworn region at both sides for direct comparison.

In previous studies at the Precision Engineering Center (PEC) [7–9], a method for measuring tool wear was developed that is capable of spatial resolutions of less than 10 nm. Utilizing electron beam induced deposition (EBID) in a scanning electron microscope (SEM), a line is created perpendicular to the tool edge. This line adds contrast on the SEM image and can be used to accurately trace the worn profile of the diamond tool. Despite the high resolution of EBID wear measurements, its use has been limited outside of the PEC for wear measurements where it was used to relate a tool force models observed tool wear [9–11]. The EBID method is used extensively in this paper for the analysis of diamond tool wear.

2. Experimental setup

2.1. Workpiece material

The orthogonal cutting geometry is implemented in a cylindrical geometry with a narrow disk of the workpiece material as

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Nomenclature

d_s	cutting distance/sliding distance
DoC	depth of cut
w	material width, wear width
F_f	average normal force on tool flank face
F_r	average normal force on tool rake face
F_T	measured thrust force (perpendicular to cutting direction)
F_C	measured cutting force (parallel to cutting direction)
μ_f	friction coefficient between tool flank face and machined surface
μ_r	friction coefficient between tool rake and chip
A_w	worn area of tool (parallel to cutting edge)
V_w	worn volume of tool
k	constant

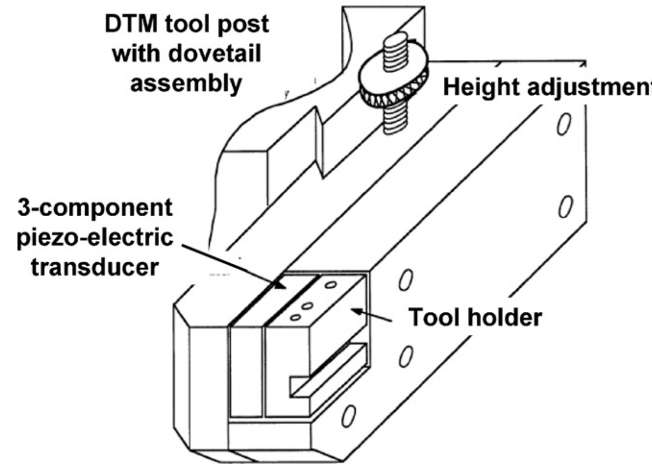

Fig. 2. Diamond tool post incorporating 3-axis piezoelectric load cell (reprinted from [9]).

shown in Fig. 1. Previous studies on the wear of diamond on Al6061 required cutting distances on the order of kilometers before measurable wear could be observed [9,10]. This requires a workpiece holder that can incorporate multiple, replaceable disks. The fabricated holder on the left consists of a thick aluminum base and cover plate that fastens the workpiece disks with four cap screws. The thick base and cover plate limits plate waviness and runout in the spindle axis direction. Axial runout of the disks was measured prior to DT using a Federal electronic indicator gauge, and resulted in magnitudes of less than 15 μm. The disks were centered on the vacuum chuck with reference to the disk perimeter edge using a Federal electronic indicator gauge. The tool height was aligned with the workpiece and spindle centerline using a Vernier height gauge to ensure a 0° tool rake angle.

Initial attempts to machine 1010 steel disks resulted in severe vibration, excessive force and sizable wear after 34 m cutting distance. 1215 steel was selected based on its reported increased machinability and similar hardness properties to Al6061 [5]. Because the 1215 steel could not be purchased in sheet form, a series of fins were machined on a 4 in. diameter solid cylinder (Fig. 1, right). This produced the same geometry as the aluminum disks. The height of the 1215 steel fins was limited to 1/4 in to avoid any axial vibration due to cutting force induced deflection. Axial runout of the fin used in the experiment was found to be less than 10 μm. The fin to be cut was centered on the vacuum chuck with reference to the disk perimeter edge using a Federal electronic indicator gauge. Radial runout was reduced by initial cutting with a flat carbide tool. Radial runout was measured to be less than 1 μm.

2.2. Force measurement

The geometry of the tool plays a significant role in the forces generated during a machining process. As the tool wears this geometry changes as do the machining forces. To assess these changes, a force measurement system was incorporated into the tool post shown in Fig. 2. The post allows cutting forces to be freely resolved into the load cell axes while maintaining the high required preload. A Kistler 9271A three-axis load cell was used. The tool holder with diamond tool on the load cell had a natural frequency greater than 20 kHz.

Load cell charge signal was directed into a Kistler 3504 three-channel charge amplifier, and into a National Instruments SCB-88 data acquisition board. A NI Labview virtual instrument was programmed that allowed data acquisition of 1000 S/s and forces to be monitored real-time on a virtual oscilloscope display.

2.3. Cutting parameters

Initial experiments attempted several depths of cut (DoC) during orthogonal cutting of Al6061. Large DoC's (on the order of 10 μm) created chips that built up on the tool, even while using oil and an air stream to blow them free (cutting oil is Mobilmet Omicron). An

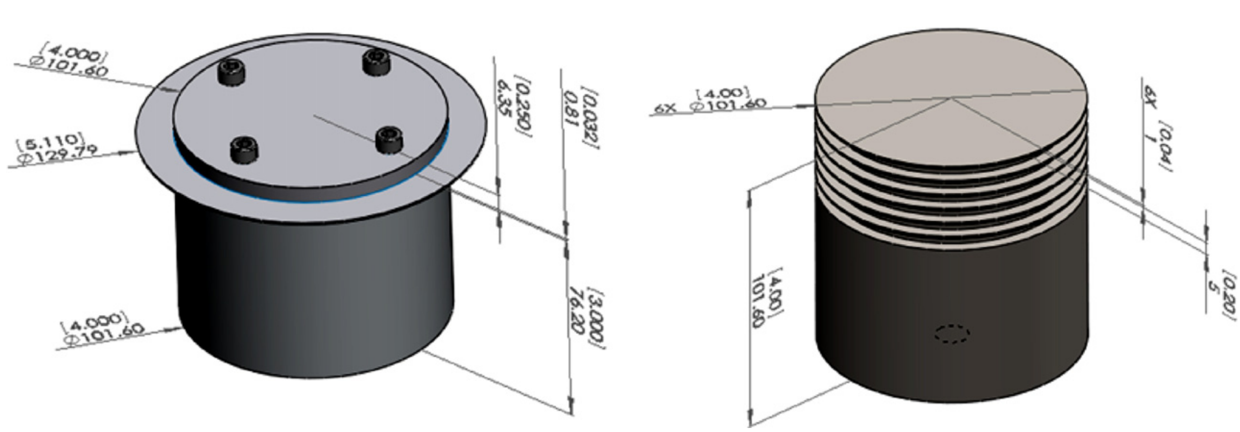

Fig. 1. (Left) holder for replaceable Al6061 disks. (Right) fins created directly in 1215 steel material.