1 INTRODUCTION
Diamond turning has become a mainstay of optical fabrication. However, it is limited to certain workpiece materials [1] due to tool wear. To address this issue, a new class of machining was born. This technique involved independent, cyclic displacement of the cutting tool with respect to the workpiece and was referred to as vibration cutting. In early experiments, the tool was moved in a straight line along the cutting path at ultrasonic frequencies. It took nearly two decades of research before the technology began to show practical value. In the early 90’s, research into vibration cutting at both low and high frequency produced results sufficient for industrial applications [2]. This mature class of machining is called Vibration Assisted Machining (VAM). Moriwaki has shown that when the tool was moved in an elliptical path rather than a straight line, lower cutting forces and longer tool life were achieved [3,4]. However the evidence presented was anecdotal. There were no specific measurements of force during ultrasonic operation or tool wear details. The PEC has been working on this technology for several years and reported tool force and wear details using a low speed system in 2001 [5]. This paper describes a new design of the Ultramill with details of the tool path, chip shape, forces and surface finish.

2 APPARATUS
Mechanical Structure A photograph of the two Ultramill designs developed at the PEC are shown in Figure 1: the new high speed version is in the foreground at left and the original low-speed version [5] is shown in the background at right. The basis for each design is a pair of piezoelectric actuators that support the tool and allow it to move with small displacements at high speed. The original version uses a pair of long, thin cylindrical actuators whereas the new design uses a pair of larger cross-section triangular actuators (base 30mm, height 13 mm, depth 22 mm) shown in cutaway. This shape was optimized for stiffness using a finite element model. The original tool head was fabricated from steel and aluminum with a standard diamond tool attached with a screw. The new design uses a hollow alumina head and a diamond tool attached with high-temperature epoxy. The shape of the head was optimized to keep the center-of-gravity near the center line of the stacks and to minimize the mass moment of inertia. The first natural frequency of the new design is 5000 Hz as compared to 500 Hz for the original design. Unfortunately the constraints on the shape and material of the head made it difficult to fabricate and therefore expensive.
The head rests on a pair of ceramic half-cylinders that allow the head to displace and pivot as required for the desired motion. A thin titanium flexure pushes the head onto the actuators and seals the actuator cavity for cooling. High-voltage signals (up to 1000 V\text{p-p} at 10 KHz) in the shape of a sine wave and cosine wave drive the two actuators. This excitation produces an elliptical motion of the diamond tool with the minor axis (up to 7 µm) and the major axis (up to 33 µm) determined by the stroke and phase of the actuators and the geometry of the head.

**Cooling System** The large piezoelectric actuators used to drive the tool at high frequencies generate a significant amount of heat and an active cooling system is required for sustained operation. The system, shown in Figure 2, consists of a thermoelectric cooler and pump to circulate a dielectric fluid (3M Flourinert 3283) over the stacks at a flow rate of about 1 liter/min. The system uses the chiller to modulate the temperature of the inlet to the actuator cavity such that the outlet temperature (as measured by the resistance thermometer – RTD - in the return line) is kept constant. The chiller has a capacity to remove 400 watts, sufficient to operate the system constantly at full voltage.

3 **TOOL MOTION**

The desired tool motion for the Ultramill is generated in a different manner than other vibration assisted designs. In this case, the goal is to operate the system below its first natural frequency so that the motion can be changed in a controllable manner to study the details of the machining process. For elliptical cutting, the motion of the end of the tool is a combination of the elliptical motion from the actuator and the linear motion from the workpiece. Figure 3 shows the motion of the tool (exaggerated in the vertical direction for clarity) and defines the important parameters. Only two cycles of the tool are shown and the emphasis is on the second revolution (dotted line) which is the steady-state motion that removes material from the workpiece.

![Figure 2. Active cooling system design for sustained high-speed operation of the actuator](image)

![Figure 3. Tool motion and chip definitions at the center-line of the chip during elliptical cutting.](image)
**Chip Geometry**  Figure 3 also shows the chip geometry at the center of the cut as the tool moves through its elliptical path. The thickness of the chip is reduced as the tool frequency is increased or the part speed or depth of cut are reduced. SEM micrographs of non-overlapping groove cutting experiments in aluminum illustrate that chip geometry is directly related to cutting conditions. If the depth of cut is smaller than the minor axis of the tool motion, the chips are discontinuous (Figure 4), and if larger they are connected at the center (Figure 5). The discontinuous chips have a thickness related to the feed/cycle and are as wide as the cut. The continuous chips are longer because of the increased depth of cut but are discontinuous at each edge where the round nose tool leaves the flat workpiece. Notice that the chips appear transparent in the 1000x image of Figure 5, indicating a thickness less than 10 µm.

![Figure 4. SEM micrographs of discontinuous chip where depth of cut is 32% of the minor axis (depth = 1.4 µm and upfeed/cycle = 3.3, minor axis of elliptical motion = 4.3 µm)](image)

![Figure 5. SEM micrographs of continuous chip where the depth of cut is twice the minor axis (depth of cut = 8.9 µm and upfeed/cycle = 6.7 µm, minor axis of elliptical motion = 4.3 µm)](image)
4 TOOL FORCES

To measure the forces, a specimen was attached to a three-axis load cell mounted on the diamond turning machine. The oscillating tool was fed across the surface at a constant speed and depth of cut. The measured forces were acquired using a high-speed data acquisition system.

![Figure 6](image)

**Figure 6.** Theoretical and measured cutting and thrust forces during tool contact (material = 6061-T6 aluminum under same conditions as Figure 5)

The measured forces in the cutting and thrust directions as a function of time are shown in Figure 6. The measurements are shown as a series of points connected by a line and the predicted forces are the solid and dotted lines. The workpiece was 6061 aluminum, the vibration frequency 1000 Hz, the depth of cut 8.9 µm and the upfeed/cycle 6.6 µm. Based on the geometry shown in Figure 3, the maximum chip thickness for this condition is 7.7 µm. For these cutting conditions, the maximum force in Figure 6 is about 1 N and the tool is in contact for 0.3 ms out of a cycle time of 1 ms (at 1000 Hz operation) or a duty cycle of 30%. The predicted values were in agreement within 0.1 N of the magnitude of the measurements. However, secondary vibrations due to the load cell dynamics are apparent, especially in the thrust direction with a 12 kHz frequency (the natural frequency of the load cell with specimen).

5 SURFACE FINISH

One of the advantages for vibration cutting is a reduction in the wear of diamond cutting tools as shown in [5]. However, the surface finish created must be of high quality for the technique to be accepted. To study the surface finish created using the Ultramill, PMMA test samples were cut at varying vibrational frequencies and amplitudes to thoroughly test the operation of the device. The example shown in Figure 7 illustrates the difference in the finish with and without the elliptical motion. Figure 7(a) shows the grooves created by the 1 mm nose radius tool with a feed rate of 12 µm/rev. The rms surface finish is 17 nm compared to the theoretical finish of 5 nm. When the 1 kHz elliptical vibration is added to the tool motion, the surface changes to Figure 7(b) where the cusps created by the Ultramill in the feed direction (left to right) are clearly visible and the rms finish increased by 40% to 24 nm as expected. There is, however, an additional vibration with a substantially lower frequency (60 Hz) that was evident on all of the samples. The DTM’s slide vibration normal to the workpiece has a natural frequency of 60 Hz.
and this frequency at an amplitude of 40-60 nm was recorded when the Ultramill and cooler were in operation. This vibration component is a significant contributor to the surface finish and will be addressed.

![Surface topography of PMMA surface cut with Ultramill](image1)

**Figure 7.** Surface topography of PMMA surface cut with Ultramill (depth of cut = 6 µm, cross feed = 12 µm/rev, spindle speed = 20 rpm)

6 REFERENCES