VIBRATION ASSISTED DIAMOND TURNING
USING ELLIPTICAL TOOL MOTION

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1 INTRODUCTION
Diamond turning has been used to create optical quality surfaces quickly and efficiently. However, it is limited to certain workpiece materials [9] based on tool wear. To expand the choice of workpiece materials, several innovative machining methods and equipment modifications have been tried to varying degrees of success. Evans attempted to machine stainless steel at cryogenic temperature [1] and Casstevens experimented with diamond turning of carbon steel in a carbon-saturated environment [2]. Another approach taken by Moriwaki and Masuda utilized CBN tools, with their low chemical reactivity to iron, to produce an optical quality surface on steel [3,4]. While acceptable surface finishes were produced and tool life was extended, no single method achieved both [6].

In the mid-70’s, a new class of machining was born. This new technique involved independent, cyclic displacement of the cutting tool with respect to the workpiece. This class of machining was referred to as vibration cutting. Early experiments were primarily carried out at frequencies greater than 20 kHz. However at these “ultrasonic” frequencies, little practical value was demonstrated. It took nearly two decades of slow growth before the technology started to show promise. Finally in the early 90’s, research into vibration cutting at both low and high frequency produced results sufficient for industrial applications [5]. This mature class of machining is called Vibration Assisted Machining (VAM).

The VAM path motion can be either 1D or 2D; that is the tool can be vibrated in a line or in a circular or elliptical path. Moriwaki has shown that 2D vibration cutting produces lower cutting forces and longer tool life than 1D vibration assisted cutting [6,7]. But what makes elliptical vibration cutting superior? What is the relationship between elliptical path, surface finish and tool forces? It is by understanding the dynamics and mechanics of an elliptically driven tool servo that these questions will be answered.

2 DESCRIPTION OF THE APPARATUS
A sketch of the cutting tool actuator is shown in Figure 1. A steel frame (A) is attached to the tool post on the DTM. A cam mechanism is used to apply approximately 45 N of tension to a pair of 0.25 mm diameter music wires (B). These wires serve two purposes: 1) to preload the piezoelectric stacks, and 2) to keep the head firmly seated on the stack ends during the elliptical motion. Two 44-layer piezoelectric actuators (C) form the engine of this tool servo. These 6.35 mm diameter stacks measuring 25.4 mm in overall length and produce 22 μm of displacement. Seated on the end of each
The tool stack is a 6 mm long, 1.58 mm diameter half round hardened steel pivot pin (D), that mates to a V-notched groove in the tool head mount (E). The aluminum tool head (F) is attached to this mount using a kinematic mount for precise realignment. A standard diamond tool insert (G) completes the assembly. The first natural frequency limits the operating range from 0-400 Hz.

2.1 Tool Motion
The tool motion derived from this design depends on the excitation of the two actuators and the geometry of the mount. The specific geometry of interest is the horizontal distance between pins at the end of each actuator and the vertical distance from this line to the cutting edge of the tool. For the mechanism described here, the pins are 6.3 mm apart and the tool is 23 mm above the pivot line. This geometry should produce an ellipse with a major axis, \( a = 50 \, \mu m \), and a minor axis, \( b = 7 \, \mu m \). The actual motion is slightly distorted due to small differences in response of the two actuators.

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 2 shows the motion of the tool (exaggerated in the vertical direction for clarity) and defines some important parameters discussed next. Only two cycles of the tool are shown in this figure and the emphasis is on the second revolution shown as a dotted line. This is the steady-state motion that removes material from the workpiece.

![Figure 2. Tool motion and chip definitions for elliptical cutting](image)

2.1.1 Duty Cycle
One of the important parameters defined for vibration cutting is the duty cycle. For linear vibration cutting, the duty cycle was defined as the percentage of one vibration cycle that the cutter rake face of the tool contacted the chip. This definition is somewhat misleading because the flank face of the tool is always in contact with the workpiece. For elliptical cutting, a new definition has been adopted to be more like flycutting; that is, the duty cycle is defined as the percentage of tool/workpiece contact during one vibration cycle. From Figure 2 this means the difference between the time the tool enters and leaves the part divided by one period of tool operation. This new definition will produce larger values of duty cycle than the old definition.
Figure 3 shows the duty cycle as a function of the tool ellipse, the workpiece speed and the vibration frequency. The horizontal axis is the ratio of the part speed to the maximum speed of the tool vibration along the tool motion direction. The three lines represent different depths of cut with respect to the minor axis of the ellipse; a range from 20 to 100%. For a given depth ratio, decreasing the speed of the part or increasing the frequency of vibration will reduce the duty cycle. However, the graph shows that there is a lower limit to the duty cycle that is a result of the new definition. For example, at a depth equal to the minor axis of the elliptical motion (depth/b = 1), the minimum duty cycle is 25%; that is, the tool will always touch the workpiece for at least one-quarter of each vibration cycle.

2.1.2 Chip Geometry
Figure 2 also shows the definition of the maximum chip thickness as the tool moves through its elliptical path. Figure 4 indicates the change in this thickness as a function of the same variables as in Figure 3. In this case, the chip thickness is reduced as the tool frequency is increased or the part speed is reduced. The chip thickness can also be made thinner by reducing the depth of cut. Notice that as the speed parameter on the horizontal axis gets larger, the chip thickness approaches the depth of cut. This means that the chips do not overlap and the chip shape looks like the first cycle of the tool in Figure 2.
3 TOOL FORCES
The tool geometry is needed to calculate the tool forces during elliptical cutting. A simple explanation for the force reduction for VAM is that the cutting distance is increased. For example, if the blade of a circular saw is locked and pushed through the board, the cutting distance is the board width, the chip thickness is the board thickness and the force is high. However, if the blade is rotating, each tooth creates a thin chip and the cutting force is low, but the total length of the cut, that is, the sum of each individual tooth contact, is much higher.

3.1 FORCE MODEL
The force model is based on work done by Carroll, Drescher and Arcona [8] to develop a tool force model for diamond turning. For the case of elliptical cutting, the chip geometry was first calculated and then the model was applied to this time varying geometry. Figure 2 illustrates the change in the chip size along the centerline of the tool and this geometry can also be easily expanded to create the 3D chip geometry. Depending on the duty cycle, only a portion of each period of vibration will produce a force and that force will depend on the tool geometry (including wear) and the material properties.

3.2 FORCE MEASUREMENTS
To see if the model can be used to predict the forces during vibration cutting, a series of experiments were conducted using different workpiece materials and operating conditions. A three-axis tool force dynamometer was mounted on the fixed spindle of the DTM and the tool was moved across the surface at a given depth of cut. A picture of the apparatus is shown at the right.

One example of the forces measured and predicted is shown in Figure 5. The workpiece was copper, the vibration frequency was 10 Hz, the depth of cut is 6 \( \mu \text{m} \) (depth/b = 0.85) and the

![Figure 5. Theoretical and measured forces cutting copper workpiece](image)
velocity ratio was 7.5%. From Figures 3 and 4, the duty cycle is 26% and the maximum chip thickness is 4.7 µm. The measured forces as a function of tool displacement are shown in Figure 5 as a series of points and the predicted forces are the solid lines. For these cutting conditions, the maximum force was on the order of 1 N and the predicted values were in agreement with the shape and within 0.2 N of the magnitude of the measurements.

4 STEEL MACHINING EXPERIMENTS

One of the advantages reported for vibration cutting is a reduction in the wear of diamond cutting tools. To test this hypothesis, a series of machining experiments was performed using both standard diamond turning and vibration assisted diamond turning of steel. The workpieces were mounted in the spindle of the DTM and turned at low spindle speeds as indicated in Figure 6. Two 5 mm wide bands were machined on each sample that were centered at 22.5 mm and 16 mm from the center of rotation. Each band required about 10 meters of machining. A higher cross feed was chosen for the conventional turned work piece to put the theoretical radial surface roughness of both specimens in the same range. Figure 6(a) and 6(b) show a comparison of the reflectivity of the two surfaces created indicating the advantages of VAM.

4.1 SURFACE FINISH

The conventionally machined sample, Figure 6(b), has a peak-to-valley roughness of 0.161 µm and RMS roughness of 0.034 µm. This is an order of magnitude higher than the VAM steel sample, Figure 6(a), which has a peak-to-valley roughness of 0.024 µm and a RMS roughness of 0.006 µm. Optimizing the VAM parameters could make this difference even larger.
5 TOOL WEAR

Conventional diamond turning cannot achieve a high quality finish due to high tool wear. SEM micrographs comparing the cutting edges of the tools used in the steel cutting experiments are shown in Figure 7. The dramatically worn edge on the diamond used in conventional turning, Figure 7(a) can be compared to more uniform wear on the tool used during the VAM process in Figure 7(b). The tool used for conventional turning shows indication of wear regions at the 25 µm feed spacing and a greatly enlarged edge radius. The VAM diamond tool, on the other hand, shows uniform wear across the width of the contact region and a smaller change in edge radius.

![Figure 7. Comparison of Worn Diamond Tools (SEM images at 800x)](image)

6 REFERENCES