

3-DIMENSIONAL MACHINING OF OPTICAL QUALITY SURFACES

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INTRODUCTION

Primary techniques for the production of optical quality surface finishes are turning and ruling. A third technique, milling, has been excluded from mass production due to the complexity of the machinery required to produce 3-dimensional (3-D) shapes and the increased machining time required to achieve finishes equivalent to other techniques. The research reported here focuses on the feasibility of a production technique utilizing stacked piezoelectric actuators to move the tool relative to the workpiece. The stiffness of the actuators and the ability to control their position at high speed and high resolution provide the capability to produce optical finishes and reduce the manufacturing time necessary to create complex amorphous contours.

Mounted on a Nanoform 600, a piezoelectrically actuated linear mill, called the UltraMill (UM), becomes capable of true 3-axis machining. Conventional milling encounters problems with varying angular cutting speeds during the machining of spherical contours, while the UM has the ability to uncouple the relative speed of the work piece and the tool. In addition, the UM has the potential to operate at speeds that are an order of magnitude higher than present day spindles. Equating the cutting frequency of the UM to its rotary counter part, an operating frequency of 17 kHz is equivalent to 1 million rpm.

The current effort involves a study of the unique cutting dynamics of the piezoelectrically actuated linkage system, evaluating the operational envelope of its 3-dimensional cutting ability and the UM's use in diamond milling of traditionally non-diamond tool capable materials, i.e. ferrous metals or ceramics.

DESIGN

Theory of Motion

The elliptical tool path produced by the geometry in Figure 1 is the result of two principles: first, the summation of two orthogonal sine waves will produce a circular path; and two, the strain of piezoelectric ceramics is a linear function of the voltage supplied. Two actuators support the tool and their motion makes it rotate and translate in the plane of the paper to produce the path shown. By changing the length of a, b and c, the shape of the path can be changed from circular to elliptical as shown on the left hand side of Figure 1.

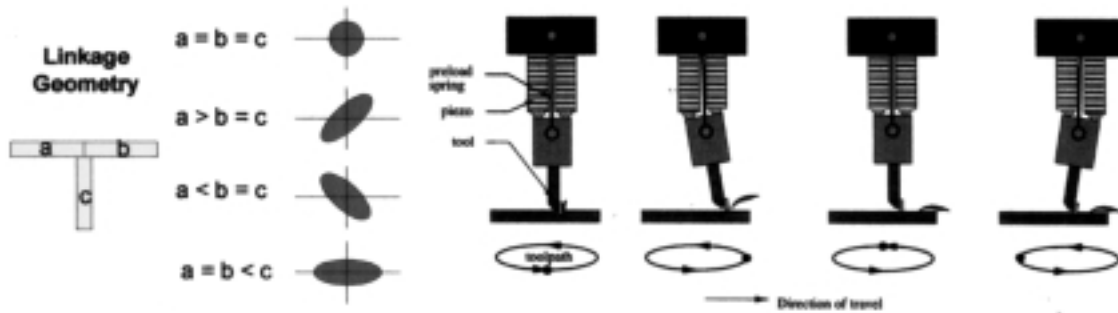


Figure 1. UltraMill Cutting Motion via Linkage Geometry

Advantages of Motion

The peak-to-valley (P-V) surface finish of an elliptically driven tool is:

$$\text{UM Elliptical: } P - V = \frac{bf^2}{8a^2}$$

$$\text{Circular: } P - V = \frac{f^2}{8R}$$

where f is the distance indexed per cycle and a and b are the respective major and minor axes of the ellipse. If a and b are equal, the path becomes circular and the equation reduces to the “circular” P-V expression (note: R is the radius of the circular motion). A large major to minor axis ratio would result in reduced P-V surface roughness. The surface finish can also be improved by increasing the apparent tool rotation (operating frequency), increasing the radius of motion or reducing forward speed of the tool.

Another advantage of the UM is the ability to uncouple the relative speed of the work piece and tool. For a turning operation, the surface speed of the tool decreases as it approaches the center of the part. For a rotating tool, the surface speed changes with the contact point on the flute of the tool. Varying cutting speeds over the surface of the part produces less than optimal results. With the constant cutting velocity of the UM, 3-D optical quality surfaces are now possible.

Recent findings also show an elliptical tool path reduces the cutting forces from a third to a half and nearly eliminates thrust forces [1]. In addition, surface roughness is reduced by up to 3.5 times over standard milling. Finally, a strong correlation exists between the diamond tool wear and the effective contact time of the tool and part associated with the elliptical cutting motion [2]. This reduced wear suggests that diamond machining of ferrous metals may be possible since chemical wear of the diamond tool is reduced.

EXPERIMENTAL APPARATUS

Design of Prototype

A prototype constructed at the PEC produces an elliptical tool path with a major to minor axis ratio of 9.4:1. This device, illustrated in Figure 2, consists of two 25 mm, high-voltage piezoelectric stacks each having a longitudinal displacement of 20 μm . Path motion was verified using a dual-channel fiber-optic displacement-measuring gauge (Opto-Acoustics® Angstrom

Resolver[®]) capable of sub- μm detection and evaluations of cutting trial specimens using a white light interferometer (Zygo[®] New View[®]). Figure 2 shows a sketch of the structure on the right along with details of the operating features on the left. The components include a cutter head that holds the diamond tool, the two piezoelectric stacks and the cam-loaded wire for preloading the actuators to prevent tensile loading.

Bandwidth: DC – 400 Hz (0 – 18000 rpm equivalent)

1st Natural Frequency: ~ 500 Hz

Piezo Material: PZWT100 (Kinetic Ceramics, Inc.)

Modulus of Elasticity: ~ 3000 ksi

Elongation: $\sim 0.1\%$ of Overall Stack Length

Density: 7.75 gm/cm^3

Active System Mass: 17.854 gm

Elliptical Tool Path:

Major Axis: $89.8917 \mu\text{m}$

Minor Axis: $9.6154 \mu\text{m}$

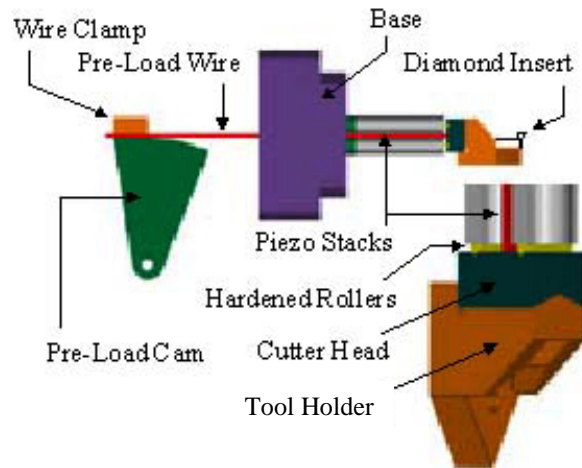


Figure 2. Main Components of UltraMill

Cutting Experiments

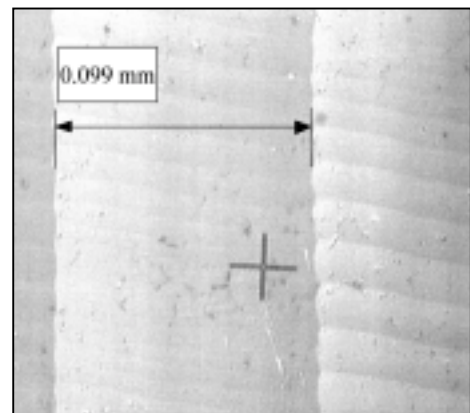
Initial cutting experiments have been directed towards understanding the cutting dynamics. Mounting a series 1100 aluminum blank on an ASG-2500 Diamond Turning Machine, three types of test have been conducted. The first was to measure the tool path and any resulting inlet and/or outlet effects with a series of plunge cuts. The second type of test consisted of machining flat optical surfaces. The third test involved surface texturing and surface pattern creation on the μm to nm level was investigated; that is, creating constant depth and spaced surface features on the mold masters as might be used for injection molding of anti-glare plastic surfaces.

RESULTS

UM Frequency	=	300 Hz
Cross Feed Rate	=	0.1 mm/min
Spindle Speed	=	1 rpm
Surface Rough (rms)	=	20 nm
Diamond Radius	=	1.02 mm
Part Radius	=	22.58 mm

Figure 3. Turning with UltraMill

Figure 3 shows a micrograph of a flat surface machined with the UM. The cross feed rate and spindle speed shown should produce cusps with the 0.1 mm spacing shown. The features in the vertical direction are a result of the motion of the UM. Note that these features are not exactly aligned with the tool



motion meaning that the tool face is not exactly perpendicular in the cutting direction. However, the surface finish is excellent and indicates optical quality surfaces are possible.

CONCLUSIONS AND FUTURE WORK

Analysis of the cutting dynamics through both simulated and actual cutting experiments has established control parameters for the precise control of the UM. The UM has been used to machine flat and textured surfaces with RMS surface finishes ranging from 6 to 25 nm. The knowledge obtained in these initial tests also forms the foundation from which to expand the systems capabilities to the ultimate goal of radically contoured surface production.

A compact, high-speed (> 8 kHz) version of the UltraMill is under development. Once completed it will replace the low-speed version for use in the 3-D cutting trials. These experiments will also examine the feasibility of milling different materials such as plastics, infrared optical materials and ferrous metals.

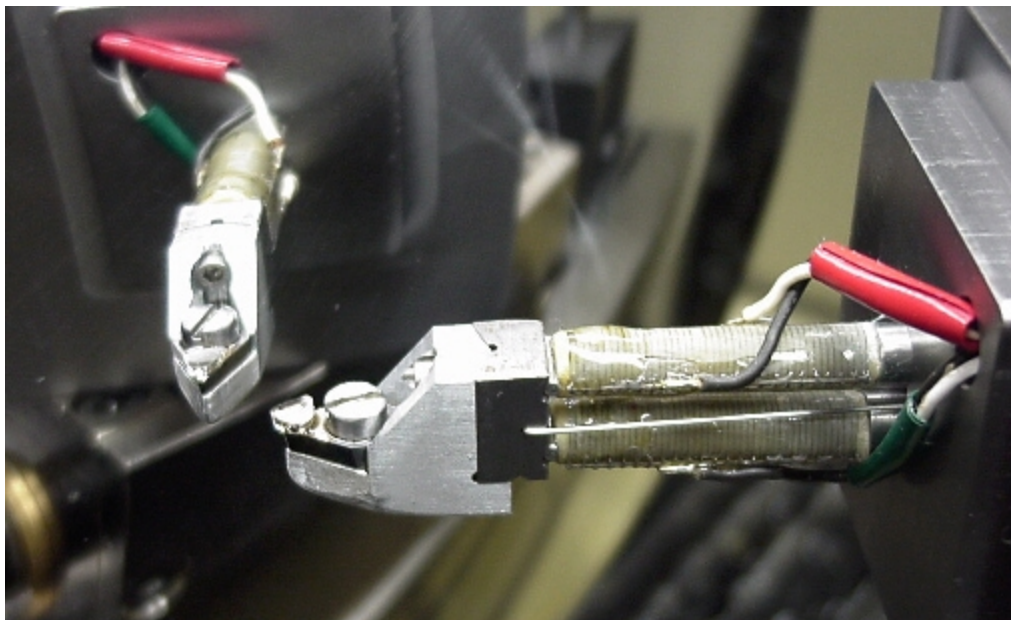


Figure 4. Photograph of UM (cover removed) reflected in machined aluminum sphere.

REFERENCES

1. Ahn, Jung-Hwan, et.al., "Improvement of Micro-machining Accuracy by 2-Dimensional Vibration Cutting," ASPE 1999 Annual Meeting, Vol. 20, pp 150-153, 1999.
2. Brinksmeier, E. and Glabe, R., "Elliptical Vibration Cutting of Steel with Diamond Tools," ASPE 1999 Annual Meeting, Vol. 20, pp 163-166, 1999.