

# MICRO-MACHINING USING EVAM

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## INTRODUCTION

Elliptical Vibration-Assisted Machining (EVAM) uses two parallel piezoelectric actuators to drive a single-crystal diamond cutting tool in an elliptical path. This is done by exciting the actuators with sinusoidal voltage signals, with the rake face actuator leading that of the clearance face by 90 degrees as shown in Figure 1. During each elliptical pass of the tool, the workpiece advances in the upfeed direction relative to the tool. As a result, successive cycles of the tool overlap. In the Ultramill design developed at the PEC [1,2], the two piezoelectric actuator stacks are located in a closed chamber through which a dielectric coolant circulates continuously. A titanium diaphragm applies preload to the piezo stacks and seals the coolant in the chamber.

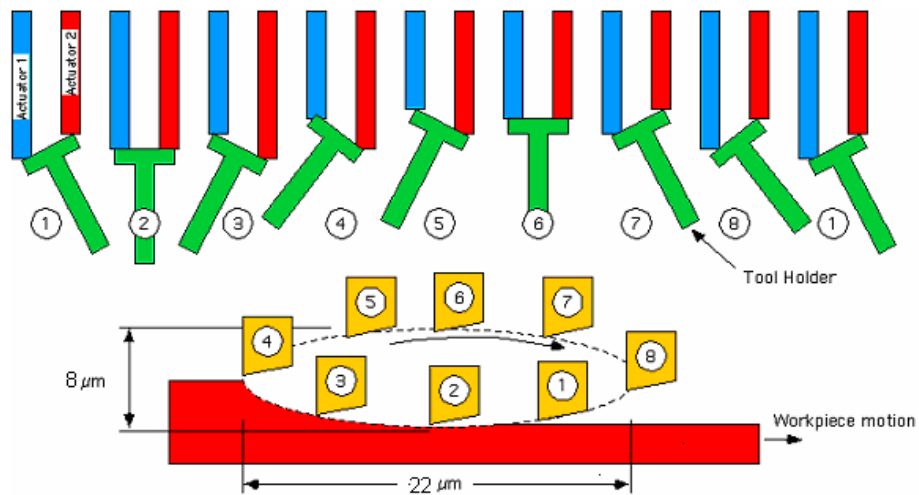


Figure 1. EVAM Using 2 Piezoelectric Actuators

EVAM avoids problems of tool deflection, chatter, runout, and vibration associated with other chip-making processes like micro-milling. It can also achieve cut edges which are virtually burr-free. Finally, because the tool is cutting in the workpiece for only about a quarter of each elliptical cycle, average cutting forces, and the opportunity for tool wear from mechanical or chemical effects, are reduced when compared to conventional machining. This means that EVAM can potentially increase the range of materials available for diamond turning.

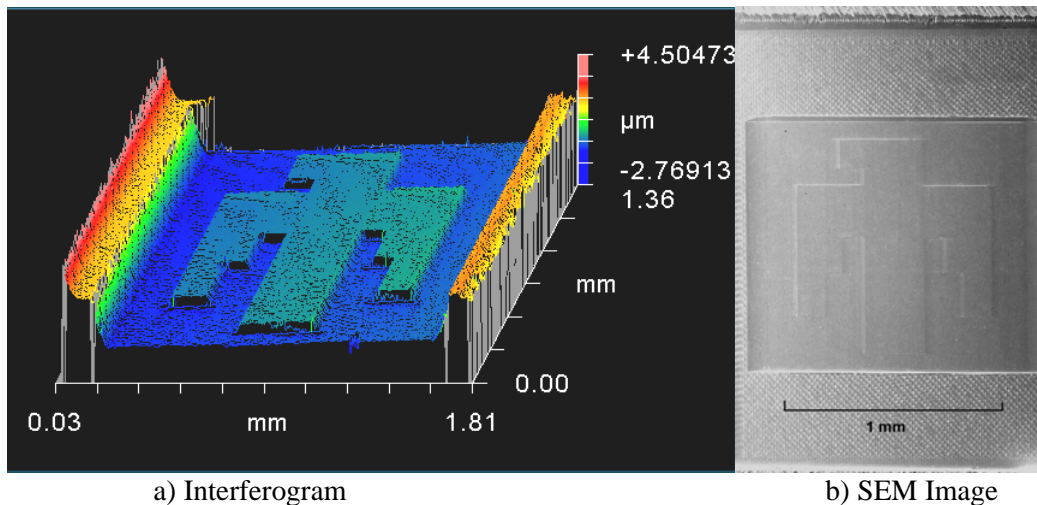
## EXPERIMENTAL RESULTS

For raster machining experiments, the Ultramill was installed on the vertical axis of Nanoform 3-axis diamond turning machine (DTM). The workpiece is held in place by a vacuum chuck. A 20x-140x zoom video microscope is used to monitor tool tip position for determining touchoff.

**Stainless Steel Machining Experiments** Stainless steel is extensively used for injection molding, micro-molding and micro-embossing dies. The ability to machine it to optical surface finishes is an important and tool steels would be a major breakthrough. To investigate the potential of EVAM, the Ultramill was used to machine a binary feature (Figure 2) in 17-4 PH stainless steel. This demonstration part is a

“thunderbird”, adapted from the logo of Sandia National Laboratory. The part was cut using a tool with 1 mm nose radius; the tool was freshly lapped for these experiments. The overall size of the background on this part is 1.2 x 1.2 mm. The flat background is cut 2  $\mu\text{m}$  below the surrounding material surface, and the raised thunderbird is 1  $\mu\text{m}$  above the background. Surface finish in both upfeed and crossfeed direction is approximately 20 nm RMS.

Unlike most parts made by the Ultramill, the surface of the stainless steel workpiece was not pre-machined to an optical surface, but was a ground surface. Touchoff was more difficult because the reflection of the tool in the workpiece was diffuse, making it difficult to establish when the tool tip initially contacted the work surface. To uncouple machining of the part from the need for a precision touchoff, the machining program was divided into 2 stages. First, a flat area was machined in the workpiece surface, to provide a plane to machine the feature. Then the thunderbird (consisting of a recessed background and raised feature) was cut, using the flat machined area as a datum in the Z (depth) direction. The initially-cut area appears in Figure 3b as a “diamond plate” texture, while the raised thunderbird and background present a “smooth” appearance. This is because the flat area was machined using a different set of cutting parameters (upfeed velocity and crossfeed increment) than the actual part. While this was done to minimize the overall machining time for the part, it also shows the capability of the Ultramill to create arbitrary finishes and textures in a surface. SEM images of the 1 mm radius tool were taken before and after machining a series of three parts. At this point the tool had accumulated 1.2 m total cutting distance, with no discernable wear.

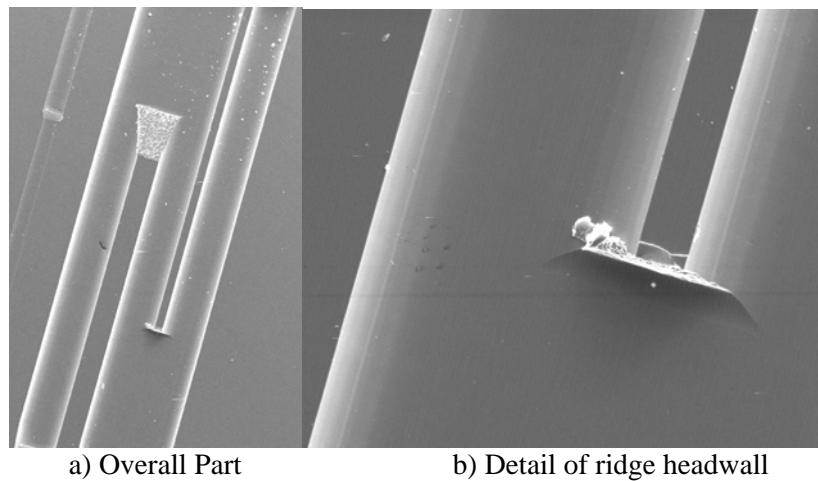


**Figure 2.** Thunderbird Machined in 17-4PH Stainless Steel

**High Relief Features** Raster machining requires multiple (in some cases, several hundred) upfeed (X-direction) passes, with the tool stepped incrementally in the cross-feed direction (Y-direction) between each upfeed pass. However, most of the parts made by the Ultramill to date have only required a single “cut”—the maximum depth of cut (Z-direction) and all features in the Z-direction are obtained by a single series of raster passes. The tool is never returned to the X-Y origin to make additional, deeper, machining passes over regions which have already been cut. More complex structures might need to be fabricated using multiple cuts in the Z-direction, in which the tool makes repeated series of raster passes at successively greater depths. Such structures include microfluidics applications requiring deep pockets or channels, and geometries which have variable cross sections in the Z direction.

To explore issues related to multiple cuts, several surfaces were machined with multiple Z-direction passes. These include the ridge and channel structure shown in Figure 3. Figure 3(a) is an SEM image of the overall structure. It was cut in copper using a tool with 50  $\mu\text{m}$  nose radius. This part has a 20  $\mu\text{m}$

height differential between the ridge tops and deepest part of the adjacent channels. It was made by making 4 successive series of raster passes, each 5  $\mu\text{m}$  deep. Figure 3(b) is a detail of the center of Figure 3(a) and shows characteristics common to all the parts made in this set of tests. Because of the tool nose radius, the side walls of the channels have a 50  $\mu\text{m}$  radius which also sets the minimum distance spacing between ridges for this depth of cut. This limitation can be overcome by using a tool with sharper nose radius, or one with a square nose profile. The headwall, formed in the upfeed direction, is near-vertical and is visually smooth. The wall on the adjacent ridge, formed in the trailing direction relative to tool upfeed motion, is a 10-degree ramp deriving from the clearance angle of the tool. The pebbled finish of this ramp was caused by the clearance face of the tool impacting the work surface during the initial plunge to cutting depth on each series of raster passes. This finish could be avoided by programming the tool to make a simultaneous moves in Z and X, to keep the tool moving parallel to the portion of the ridge created by the preceding set of cuts. The sharp headwall and ramped trailing wall are characteristic of what can be achieved with the Ultramill in the present 3-axis raster machining mode. This limitation can be overcome with 4-axis machining; that is, rotating the spindle which holds the part and thus changing the part orientation relative to the feed direction of the Ultramill. In this case, all walls can be made on the upfeed side of the machining ellipse achieving features like the headwall in Figure 4b.



**Figure 3.** Ridge-and-Channel Part, 20  $\mu\text{m}$  Maximum Height Differential

The sides of the ridges and channels show near-zero burr. Burring and damage is visible at the top of the headwall. This is believed to be the result of selection of machining parameters. The DOC on this part was larger than the semi-minor axis of the machining ellipse. This condition causes continuous chips to be produced, which break off from the workpiece, leaving a burred or irregular edge.

#### **AXIS VIBRATION ANALYSIS**

The effect of axis vibration on surface finish of parts made by the Ultramill has been explored [2]. In particular the vibration response in the Z-direction was investigated for the Nanoform's X-, Y-, and Z-axes, and the locked spindle holding the vacuum chuck. A mechanical shaker was used to impart a known oscillatory motion to each axis, and the Z-direction response of the system was measured using the DTM's position-feedback interferometers. FFT analysis was applied to the system response. Table 1 reports the 2 frequencies with the greatest displacement amplitude, and the associated peak displacement, for each axis. It is seen that the Z-axis, X-axis, and spindle amplitudes are much smaller than those of the Y-axis. Also the frequencies with the greatest amplitude for the Y-axis and Z-axis are similar, 95 and 102 Hz. Finally, the second largest amplitude response for the Z-axis is of the same magnitude as the peak displacement amplitude for the X-axis.

		<b>Resonant Frequency (1st)</b>	<b>Displacement Amplitude</b>	<b>Resonant Frequency (2nd)</b>	<b>Displacement Amplitude</b>
<b>Axis</b>	<b>Direction</b>	Hz	μm	Hz	μm
X	X	120	0.1		
	Z	275	0.01		
Y	Z	95	8.2	50	1.9
Z	Z	102	1.8	70	0.33
Spindle	X	300	0.1		
	Z	190	0.01		

**Table 1.** Nanoform Axis Resonant Frequencies and Associated Displacements

Flats were machined and the spatial frequency determined for surface profiles along the upfeed direction. The component frequencies were found using FFT, and compared to the axis response frequencies from the shaker tests. The 2 frequencies associated with greatest feature size in the part were 100 Hz and 60 Hz. These are very close to the Z-direction resonant frequencies determined for the Y- and Z-axes. It is theorized that vibration of the Y- and Z-axes, in some combination, is therefore responsible for much of the surface roughness beyond the theoretical finish from upfeed and crossfeed, found in parts machined to date.

## CONCLUSIONS

The Ultramill is capable of creating binary features in stainless steel, with surface finishes of 20 nm RMS or better. Structures have been created with height differentials of up to 20 μm between adjacent features. Smooth feature sides and walls can be achieved. Proper selection of values for process variables (DOC vs machining ellipse dimensions) is important to avoid burring-type damage to edges perpendicular to the upfeed direction.

Z-direction vibration of the current air-bearing Y-axis appears to be responsible for much of the surface roughness beyond the predicted theoretical finishes. A new vertical axis made by Moore Nanotechnology Systems will be installed in August, 2005. This oil-bearing axis has significantly greater static and dynamic stiffness in the Z-direction, approximately 2.0 MN/m, compared with 0.5 MN/m for the present axis. This is expected to reduce the amplitude of Z-direction vibration of the vertical axis, with corresponding potential improvement in surface finish.

Future work includes experiments to evaluate tool wear when machining stainless steel for extended cutting distances (100 meters or more), development of 4-axis machining procedures and creating programming routines for complex structures.

## REFERENCES

1. Brocato, B, Dow, T. and Sohn, A. "Micromachining Using Elliptical Vibration Machining", Proceedings of the 2004 ASPE Annual Meeting, October 2004, Vol 34, Pg 80-83.
2. Brocato, B., "Micromachining Using Elliptical Vibration Machining", MS Thesis, North Carolina State University, 2005

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