MICRO-STRUCTURE FABRICATION USING ELLIPTICAL VIBRATION-ASSISTED MACHINING (EVAM)[1]

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INTRODUCTION

"Elliptical vibration-assisted machining" (EVAM) is a diamond-tool machining process that can be used to create 3-dimensional micro-structures. In EVAM, the tool tip is driven very rapidly through a small (tens of micrometers) ellipse at multi-kHz frequencies; this elliptical motion is superimposed on the normal tool feed motion. EVAM shows potential for fabrication of micro-scale devices in true 3-D geometry, with greater material and shape flexibility than lithography methods derived from the semiconductor industry. When feature tolerances of ~200 nm suffice, it is more economical than methods such as micro-electro-discharge machining, focused ion beam, or laser ablation. EVAM also avoids problems of tool deflection, chatter, runout, and vibration associated with chip-making processes like micro-milling [1]. It can achieve cut edges which are virtually burr-free. Finally, because the tool is cutting in the workpiece for only part of each elliptical cycle, average cutting forces, and tool wear from mechanical and chemical effects, are reduced compared to conventional machining [2].

An EVAM tool, the Ultramill, has been used to make microstructures with binary and non-planar geometries, with minimum feature dimensions of 10 µm. In the future, the Ultramill will be used to machine functional devices that require complex 3-D geometry, minimum feature sizes smaller than 5 µm, aspect ratios greater than 1:1, and optical quality surfaces.

PROCESS DESCRIPTION

Figure 1 shows how EVAM can be achieved using two parallel piezoelectric actuators to drive a diamond tool. Applying cyclic voltages to the stacks causes them to change length in a cyclical manner. The toolholder acts as a linkage to convert the linear stack motion into an elliptical path. By changing the voltage amplitude and/or phase difference between the stacks, the ellipse geometry (aspect ratio, tilt, and dimensions) can be varied through a wide range.

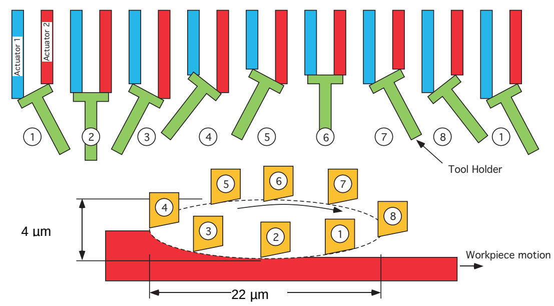

FIGURE 1. Ultramill EVAM concept

Figure 2 shows the tool motion in EVAM for two cutting cycles. During each cutting cycle, the work advances relative to the elliptical tool path. The overlapping toolpaths produce thin chips, resulting in greatly reduced tool forces compared to conventional cutting.

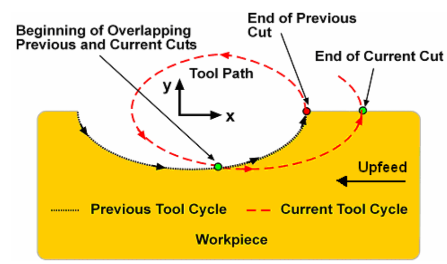

FIGURE 2. EVAM process cycle

Figures 3 and 4 show two different EVAM cutting conditions. In Figure 3, the depth of cut (DOC) is equal to or smaller than the length of the semi-minor axis of the toolpath ellipse. In this case the tool exits the workpiece each cutting cycle, creating small, discontinuous chips. This results in near-zero burr formation on the end and side edges of the cut. Figure 4 shows the case where the DOC exceeds the

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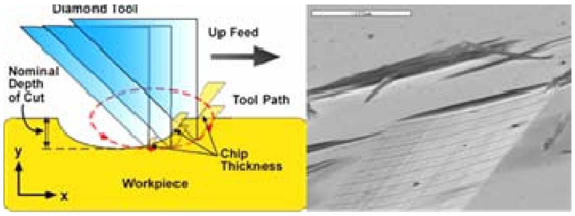

FIGURE 3. EVAM with DOC smaller than semi-minor axis of tool ellipse creates discontinuous chips and burr free edges.

semi-minor axis of the toolpath ellipse. In this case the tool still breaks contact with the uncut material during each cycle, but a long continuous chip remains attached to the workpiece. Thin segments are formed each cycle, attached to the continuous chip.

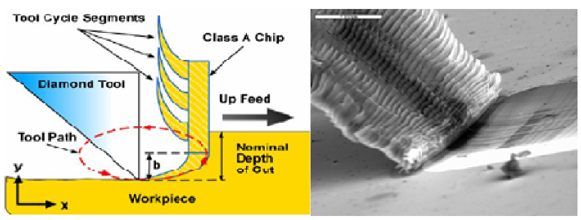

FIGURE 4. When DOC is greater than semi-minor axis of tool ellipse, EVAM produces a continuous chip with attached segments.

To create features that have a significant dimension in the depth direction, roughing passes can be made at a DOC larger than the semi-minor axis of the tool path ellipse. This economically achieves most of the required material removal. A finish pass is then made with DOC smaller than the ellipse semi-minor axis, to complete the part with burr free edges, excellent surface finish, and sub-micrometer feature tolerance.

EQUIPMENT

Figure 5 shows a cutaway view of the Ultramill. The two piezoelectric actuators are cooled by a dielectric fluid circulating continuously through the steel chamber. The hollow lightweight ceramic toolholder rests on alumina pins on the tops of the piezo stacks. A diamond tool is cemented to the toolholder. The titanium diaphragm exerts the required preload force on the piezo stacks and seals the coolant chamber. The Ultramill operates at frequencies up to 4 kHz.

Figure 6 shows the Ultramill installed on a diamond turning machine (DTM), which provides

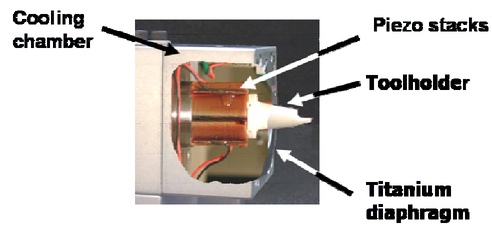

FIGURE 5. Ultramill EVAM tool

3-axis X-Y-Z motion for raster machining (the spindle is locked when using the Ultramill). The DTM's three axes are supported by hydrostatic oil bearings with nanometer-scale encoder resolution. The workpiece is held in place for machining by a vacuum chuck attached to the spindle. To facilitate touchoff, a video-microscope camera provides a view of the tool rake face and the work surface.

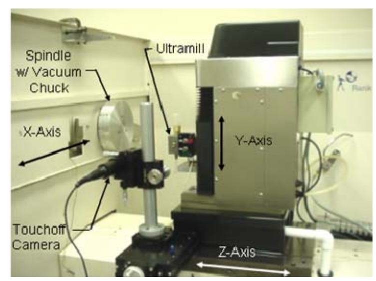

FIGURE 6. 3-axis diamond turning machine (DTM). Spindle is currently locked when using the Ultramill.

MACHINING RESULTS

Binary Microstructures

Figures 7 and 8 show white-light interferometer images of binary feature parts made with the Ultramill. These features are 500 nm tall. They were made using round-nosed diamond tools[2] with 0° rake angle and 10° clearance angle. The Angstrom symbols in Figure 9 are machined in hard-plated copper. The large Angstrom is 1 mm x 1 mm and was made with a 1 mm nose radius tool. The small Angstrom symbol (inset in Figure 7) is shown to the same scale as the large symbol, and is 200 µm x 200 µm. It was made using a tool with a 50 µm nose radius. Its smallest feature (vertical bar on the topknot symbol) is only 10 µm across. The Angstrom symbols have RMS surface roughness of 15-25 nm and are seen to be burr-free when imaged by SEM. The thunderbird logo in Figure 8 was machined in 17-4 stainless steel (34 RHC hardness, 0.1% carbon content) using a 1 mm

[2] Provided by Chardon Tool (Chardon, OH)

nose radius tool. It is approximately 1.08 mm x 1.08 mm, with surface roughness of 20 nm RMS with burr-free edges. Because of the shallow height of these structures, they were made with a DOC less than the semi-minor axis of the ellipse, as described in Figure 3.

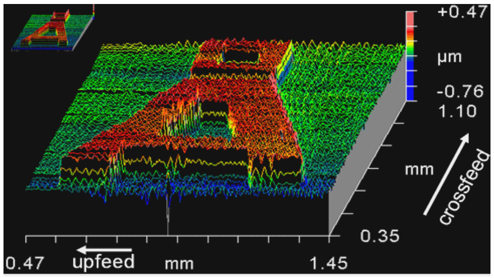

FIGURE 7. Interferegram of Angstom symbols in plated copper. Overall size 1 mm x 1 mm (main figure) and 200 µm x 200 µm (inset)

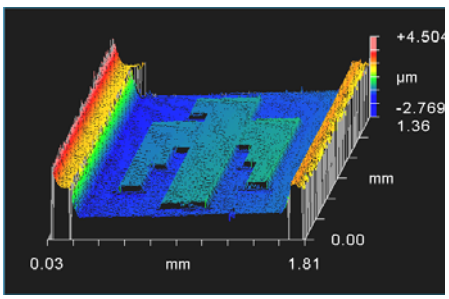

FIGURE 8. Interferogram of Sandia "thunderbird" logo in 17-4 PH stainless steel.

Non-planar Microstructures

Figure 9 shows an array of features with concave sculpted surfaces along the upfeed direction. The feature radius of curvature on the trailing side is 250 µm compared to 50 µm on the approach side. The features are 9 µm tall on a 9 µm deep background and were made in a single material removal pass. The depth dimension of the part is greater than the semi-minor axis of the ellipse (see Figure 4) so the tool entered and exited the workpiece at shallow angles to prevent burr formation.

To make non-planar surfaces, the motion of the center of the toolpath ellipse must be properly offset from the surface. For each point on the feature, the contact point on the toolpath ellipse is found which is mutually tangent to the surface. The ellipse center point location relative to the contact point is determined by the ellipse geometry, and is used in the DTM motion program. The offset from the surface contact point is different with different tangent slopes.

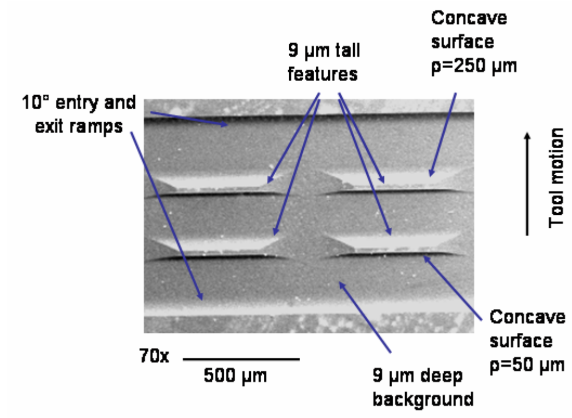

FIGURE 9. Non-planar microstructures with concave surfaces in direction of tool motion

Trihedrons

Figure 10 shows SEM images of trihedrons machined in hard-plated copper. The large trihedrons are 80 µm tall on a 112 µm side pitch. The small interstitial trihedrons are approximately 10 µm tall and show no burr at 4000x. These parts were created using a sharp diamond tool with an included angle of 70.6°, 0° rake angle, and 10° clearance angle. To make these parts, one set of parallel grooves was cut. The spindle was then rotated 60°, with the part also translating in X and Y as it was located off spindle center. The tool was moved to compensate for this translation and a second set of parallel grooves machined. Another 60° rotation was made and the process repeated for the last set of grooves. The interstitial features were obtained by offsetting the center of the machining coordinate system from the spindle center of rotation by 5 µm. Each groove was made by a series of roughing cuts 10 µm deep, followed by shallow finishing cuts to eliminate burrs.

ACTIVE and FUTURE PROJECTS

Microcontactor Pins

Figure 11 shows the contactor element for a microrelay. To increase device reliability, a groove pattern was machined into the contactor pins to provide clearance for particles that could otherwise interfere with operation. The contactor pins are 160 µm in diameter and made of a gold/glass matrix. The grooves are 5 µm deep with approximately a 1:1 aspect ratio. To make these small-scale features, a sharp-nose tool (included angle of 40°) was used. The pin tops have a sinusoidal profile of amplitude 2 µm in the upfeed direction.

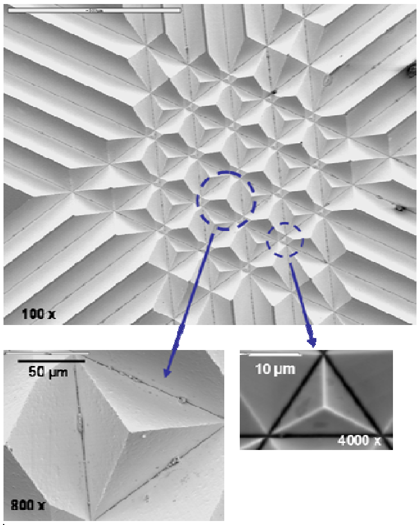

FIGURE 10. (Top) 80 µm tall trihedrons in plated copper. (Lower left) Detail of 80 µm trihedron (Lower right) Interstitial trihedron 10 µm tall.

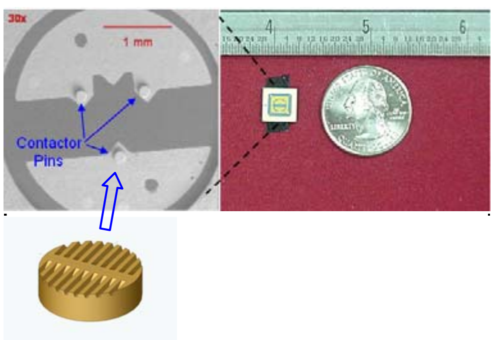

FIGURE 11. (Top) Microcontactor element (Lower left) Groove pattern to be machined onto each pin.

Machining the groove pattern into each pin required the Ultramill tool tip to be placed precisely on the part. Figure 12 shows a videomicroscope camera installed beside the Ultramill. This camera gives a plan view of the part. The X and Y axes are jogged to position the camera crosshairs on the part. The axes are then moved through a set offset distance (determined during setup) to place the tool tip at the desired location.

Microgripper

To demonstrate its ability to fabricate functional microdevices with integrated mechanical and optical elements, the Ultramill will make the microgripper shown in Figure 13. The transparent polycarbonate gripping elements act as light pipes. As the gap between the gripper tines changes, the amount of light coupled

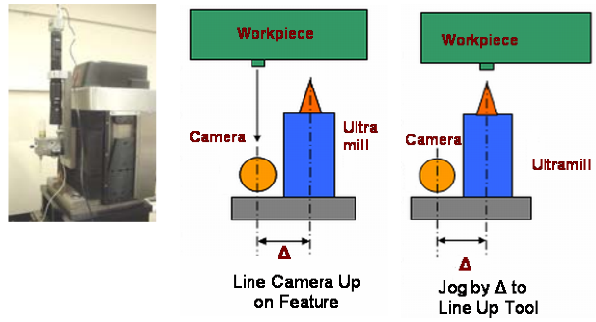

FIGURE 12. Tool tip positioning in X-Y coordinates, using Y-axis camera.

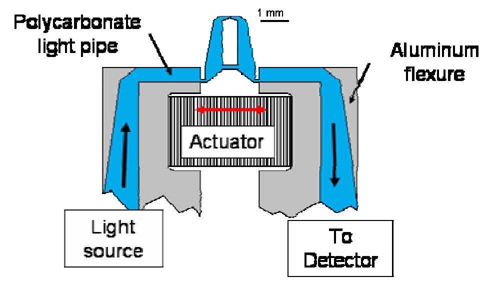

FIGURE 13. Microgripper

through the gap changes proportional to displacement. This provides feedback of gripper separation. When the gripper encounters an object, the light between the tines will be blocked. Successful operation of the gripper requires light pipe surfaces to be machined to an optical quality finish, to achieve total internal reflection. To facilitate fabricating the gripper's complex geometry, a rotational (C) axis will be added to the diamond turning machine, for precision angular positioning of the work relative to the tool tip.

CONCLUSIONS

The Ultramill has been used to create binary, nonplanar, and trihedron microstructures up to 80 µm tall. Diamond tools with round and sharp nose geometry have been used successfully. Roughing and finishing passes can be used to achieve large depth dimension features while avoiding burr formation. Fabrication is planned of functional devices with complex geometry and requiring optical quality finishes.

REFERENCES

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2 Cerniway, M., "Elliptical Diamond Milling: Kinematics, Force, and Tool Wear", MS thesis, North Carolina State University, 2001.