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MICROMETER-SCALE MACHINING OF METALS AND POLYMERS ENABLED BY FOCUSED ION BEAM SPUTTERING

D.P. ADAMS, G.L. BENAVIDES
Sandia National Laboratories, Albuquerque, NM 87185
dpadams@sandia.gov

M.J. VASILE
Louisiana Tech University, Ruston, LA 71272

ABSTRACT

This work combines focused ion beam sputtering and ultra-precision machining for microfabrication of metal alloys and polymers. Specifically, micro-end mills are made by Ga ion beam sputtering of a cylindrical tool shank. Using an ion energy of 20keV, the focused beam defines the tool cutting edges that have submicrometer radii of curvature. We demonstrate 25μm diameter micromilling tools having 2, 4 and 5 cutting edges. These tools fabricate fine channels, 26-28 microns wide, in 6061 aluminum, brass, and polymethyl methacrylate. Micro-tools are structurally robust and operate for more than 5 hours without fracture.

INTRODUCTION

Currently there is a desire for alternative microfabrication techniques that complement existing processes such as photolithography/etching, LIGA, and laser drilling. In particular, techniques are required to fabricate a more diverse set of materials, including metals, alloys and plastics. These techniques must pattern high aspect ratio features and three-dimensional structures. Such techniques would be used for prototyping or production of microcomponents and MEMS-type devices.

In this work focused ion beam (FIB) sputtering is combined with ultra-precision machining for microfabrication. Using focused ion beam sputtering we fabricate small cutting tools which are capable of milling complex features in a host of materials. An advantage of focused ion beam systems for fabrication is their precise control over feature size [1]. Typically, the beam is a fraction of a micrometer in diameter, allowing for small features with sub-μm tolerances. A beam can be rastered across a target sample in a number of odd-shaped two-dimensional patterns. Furthermore, a sample can be positioned or rotated with respect to the beam to produce a fully three-dimensional object. This has found use in several applications, most frequently for cross sectioning[2] of integrated circuit electronic devices for failure analysis/reverse engineering. Also, focused ion beams are used to make sharp scanning probe microscope tips [3-5] and diamond indenters for hardness testing [6].

Typical ion currents used in commercial FIB systems are low, leading to small-volume production. Nanoamperes of current generate relatively slow material removal rates compared with other microfabrication techniques even when chemical assist processes are used. Typically 1-5 atoms are removed per incident ion depending on the target material, ion energy and other geometrical parameters. In this work we offset this slow rate by making tools which can be used repeatedly. Previous work by Vasile et. al.[7] and others [8] demonstrates various micro-tools shaped by focused ion beam sputtering. In this proceeding we show several different micro-end

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mills and demonstrate their usefulness by machining metal alloys. All micro-tools made in this study successfully mill for hours without breaking.

EXPERIMENT

The focused ion beam system [9] consists of a liquid metal ion source, beam deflectors, sample stage, and channelplate detector for imaging. The ion gun produces an energetic beam of Ga^+ ions. The beam intensity is roughly Gaussian with a full-width at half-maximum diameter of 0.4 μm. Currents are typically 2 nanoamperes giving a current density of about 0.5 Amp/cm^2. The beam is deflected by a digitally driven vector scan system with sub-micron resolution. A computer controls stage motion with 1μm accuracy, and samples can be rotated by 0.15 ° per step with an external controller. The Ga^+ source chamber is ion pumped and maintains a pressure of 10^{-9} Torr. The target chamber is oil diffusion pumped with working pressures of 10^{-8} Torr during sputtering. A small aperture separates the two chambers for efficient differential pumping.

Tool blanks are purchased from a commercial vendor and are made of M42 cobalt high speed steel. Blanks are 5.3 cm long and have a 2.28 mm diameter. One end of each tool is tapered by diamond grinding. This end is approximately 25 μm in diameter and cylindrical over a length of ~ 90 μm. Once mounted inside the FIB system, the tapered end is first shortened to 85 μm by sputtering. Facets are then fabricated into the cylindrical length by ion beam sputtering. The sharp edges of facets are designated as cutting edges for ultra-precision milling. All sputtering involves energies of 20 keV.

Ultra-precision machining with FIB fabricated micro-tools requires a high precision milling apparatus. In this study, a Boston Digital milling system uses laser interferometry to control x, y and z position to 0.5 μm resolution. Spindle speeds for this study are 10,000 or 18,000 rpm, and feed rates are 2 mm/minute unless otherwise specified. For milling, the radial runout of a tool is less than 2 μm, and the axial depth of cut is 0.5 or 1.0 micron per pass. Samples machined by micro-tools are cleaned afterwards by rinsing with methanol. Different lubricants are used during ultra-precision machining depending on the workpiece material.

RESULTS

Several micro-tools are made using FIB sputtering as shown in Figure 1. These micro-end mills have 2, 4 or 6 facets with 2, 4 or 5 cutting edges, respectively. With the tool stationary,

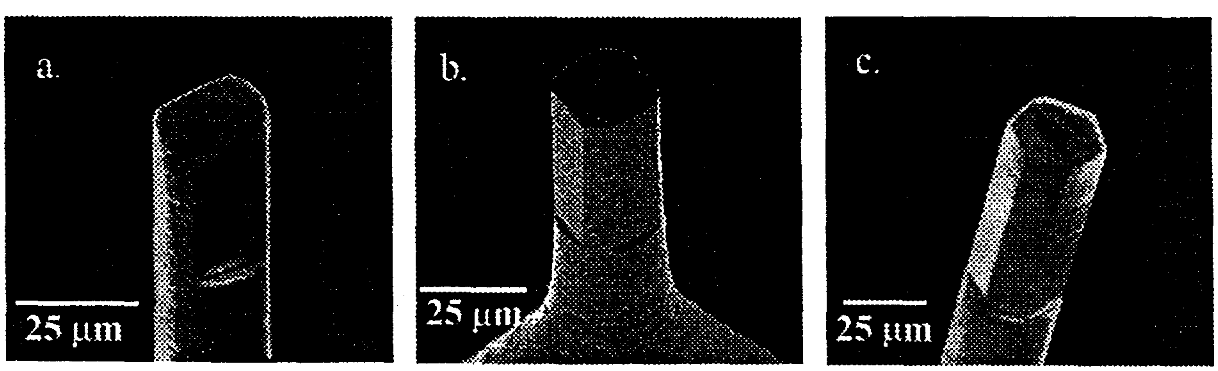

Figure 1. SEM micrographs of micro-end mills made with focused ion beam sputtering. Tools have 2, 4 and 5 cutting edges.

facets are patterned into an initially cylindrical stock with the ion beam impinging normal to the cylinder axis, but tangential to the circumference [10]. This ion-solid geometry is chosen, because it produces one edge per facet that is sufficiently sharp for cutting. The edge of a facet closest to the ion source is rounded. This rounding arises due to the Gaussian intensity of the beam; although a pattern boundary is defined for ion beam milling by the operator, the tails of the intensity distribution extend outside of this boundary leading to a curved surface. Typically this deviation is on the order of 1.0 micrometer. Nevertheless, continued ion beam sputtering with this particular geometry makes the edge furthest from the ion source sharp. A sharp edge is produced, because the ion beam has a truncated intensity distribution tail at the far side of a facet due to shadowing by the tool. The radius of curvature of the sharp edges is less than a micron.

As shown in Figure 1 the facet normal direction is perpendicular to the tool axis. We avoid making a conventional spiral flute geometry for several reasons. First, three-dimensional micromachining of curved surfaces is complicated by a variation in sputter yield with the ion/solid angle of incidence[11]. A spiral flute requires a distribution of angled features, thus complicating tool fabrication. Also, rigidity is required for cutting, and we desire to minimize fabrication time. In general, a small amount of material is removed from the tapered end to define the cutting edges and provide clearance for chip removal during machining. The rate of sputter removal for high speed tool steel is ~ $0.5\mu m^3/sec$. Fabrication of individual micro-tools takes approximately 2 hours depending on the design.

Multiple facets are made by rotating a tool to different orientations with respect to the beam. Rotation of a tool between sputtering steps can result in all but one sharp edge if desired. For example, the tool shown in Figure 1 c. (with 6 facets) has 5 sharp cutting edges and one round edge. In general, tools can be made to cut in a clockwise or a counter-clockwise rotation (or both) for ultra-precision milling. Although the sharper edge of each facet is designated for milling, the rounded edge of micro-end mills may also cut metals.

Micro-tools made by focused ion beam sputtering are tested on a variety of materials. Ultra-precision machining with micro-tools first involves polymethyl methacrylate (PMMA). All tools shown in Figure 1 successfully machine this plastic. An example of a channel micromachined by a FIB fabricated micro-tool is displayed in Figure 2. The channel shown in this plan view micrograph is 25 μm deep, 28.6 μm wide and 4.0 millimeters long. Compared with the tool diameter (26.2 μm), the channel width is slightly larger. We expect this difference is due to the radial runout of the tool, measured to be ~2μm or less. Viewing in cross section, we find that the slope of the channel walls is approximately 88 degrees.

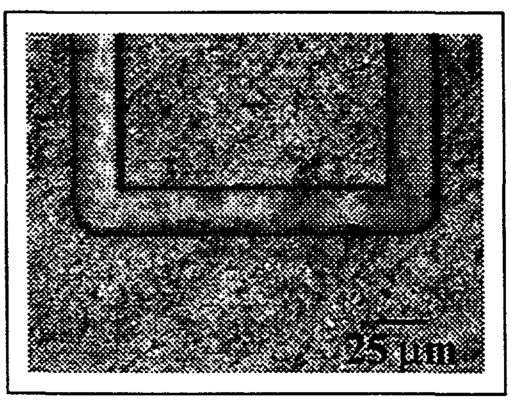

Figure 2. PMMA micromachined using a micro-end mill. Plan view optical micrograph.

In addition, FIB fabricated micro-tools are tested on two metal alloys, 6061 Al and brass. The results of micromilling 6061 Al with a five edge tool are shown in Figure 3. These micrographs show a channel which is milled ~4.5 mm long. As shown in this figure, the channel is ~25 μm deep and approximately 28.2 μm wide. The diameter of the tool used for this test, 26.2 μm, is slightly smaller than the channel width. Again, this difference is most likely due to the small radial runout of the tool during machining. For the channel shown in Figure 3, Al is machined at a feed rate (rate of movement in the plane of the workpiece) of 2mm / minute and an axial depth of cut equal to 1.0 μm/pass. It is clear that micro-end mills made by focused ion beams can operate at higher feed rates. The four facet tool shown in Figure 1.b. machined a number of 25μm deep channels in 6061 Al using different feed rates ranging from 2 mm/minute to 5 cm/minute (axial depth of cut = 0.5 μm/pass). Machining of the Al alloy totaled approximately 5 hours and the tool did not fracture. Furthermore, observation with a video microscope during micromachining of 6061 Al (without lubricant) demonstrates that these tools cut, not burnish. We observe chip removal for feed rates of 2mm/minute and 18,000 rpm using 2-facet micro-tools.

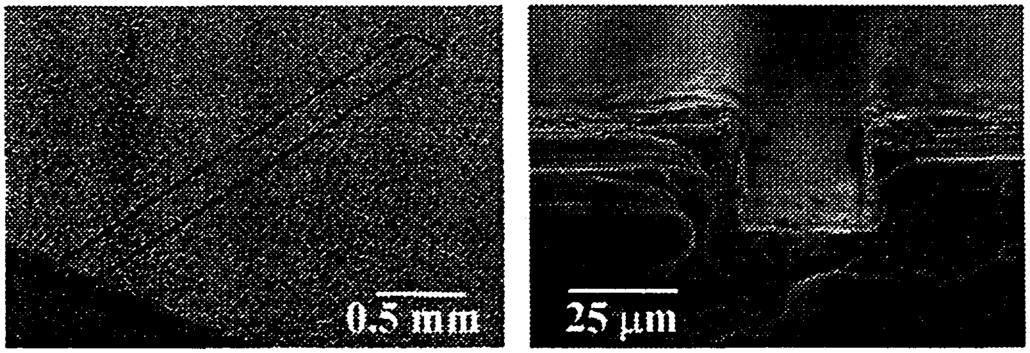

Figure 3. 6061 Al micromachined using micro-end mill. Plan view and edge-on SEM micrographs. Image on right shows exit point of micro-tool from edge of workpiece.

Machining of channels in brass using a 6-facet micro-end mill is demonstrated in Figure 4. Using a tool with a diameter of 26.6 μm, a channel is milled 26.5 mm long. It measures 28.7 μm wide (at half depth). However, SEM analysis of the channel shows a large amount of material accumulation at the top edge compared with the machining of 6061 Al and PMMA. It is possible that these micro-tools burnish brass.

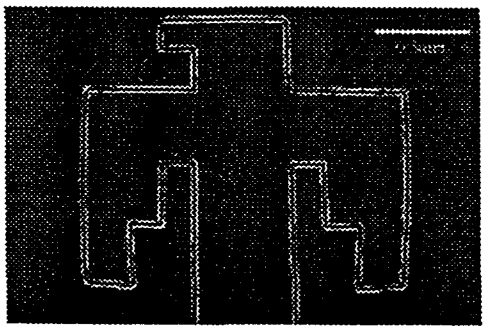

Figure 4. Brass micromachined with micro-end mill tool having 6 facets. Plan view SEM micrograph.

CONCLUSIONS

This work demonstrates that focused ion beam sputtering can be used to extend conventional machining processes to the microdomain. Several micro-end mills are fabricated having different numbers of cutting edges. A particular ion beam – sample geometry described herein permits fabrication of cutting edges having submicrometer radii of curvature. All tools fabricated by FIB sputtering successfully machine various materials, including at least two metal alloys. Trenches that are 25 microns deep and millimeters long are approximately 26-28 microns wide - closely matching the tool diameter. Micro-end mills cut metal alloys for hours without tool fracture. This suggests that other cutting tools (e.g., drills, scalpels) of similar dimension may function at micron length scales.

Future work will determine the optimum micro-end mill design for ultra-precision machining of different materials. In addition, we will explore additional materials for tool fabrication. Attempts to enhance the rate of material removal by chemical assisted sputtering will be made, provided that edge sharpness is not compromised. It is expected that additions of commonly used assist gases containing Cl and F increase the rate of FIB sputtering [12], particularly for tools made of steel and tungsten carbide. We expect that even smaller micro-tools can be fabricated and operate successfully.

ACKNOWLEDGMENTS

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