

FOCUSED ION BEAM SHAPED MICRO-CUTTING TOOLS FOR FABRICATING CURVILINEAR FEATURES

David P. Adams*, Michael J. Vasile, Yoosuf N. Picard

*Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM, 87185

Institute for Micromanufacturing, Louisiana Tech University, Ruston, LA, 71272, USA

This work combines focused ion beam (FIB) sputtering and ultraprecision machining as a first step in fabricating polymer, ceramic and metal alloy microcomponents. Focused ion sputtering is used to shape a variety of miniature cutting tools including microgrooving / threading tools. Tools are made of cobalt M42 high speed steel or C2 grade tungsten carbide, and have cutting widths between 10 and 30 μm . FIB sputtering is useful for shaping tools, because this numerically controlled technique reproducibly affords sub-micron dimensional resolution, different tool geometries and sharp tool cutting edges. Micro-grooving /threading tools consist of nonplanar facets with well-defined lengths and relative angles. Facets provide back rake, side rake and clearance taper behind cutting edges. Selected results from ultraprecision machining are also presented. This includes lathe machining of helical grooves in PMMA and MacorTM cylindrical workpieces.

Keywords: *microtools; micromachining; ultraprecision*

INTRODUCTION

Alternative fabrication techniques are currently being explored to meet the manufacturing requirements of microsystems.[1] While a large variety of microcomponents and microelectromechanical devices have been demonstrated in recent years, most fabrication has involved inherently planar techniques, such as optical or x-ray lithography. Features are defined in polished substrates or thin film layers by exposure of a resist (using a mask) and etching. However, there is a desire to fabricate more complex shaped features in a variety of ceramics, metals and polymers. For example, nonprismatic features and nonplanar workpieces are needed for a variety of devices. These include micro-fluidic sensors, microinductors, and microactuators.

In present work focused ion beam sputtering is combined with ultra-precision machining. Focused ion beam (FIB) sputtering is used to shape micro-cutting tools intended for mechanical machining of various workpieces. FIB sputtering is attractive for fabricating micron-size tools or instruments, because this technique can precisely remove or add material. Most importantly, focused ion beam sputtering can be used to create and align a number of nonplanar features[2,3], such as facets required on cutting tools. Previous studies demonstrate FIB-sputtered microwrenches, microscalpels, and nanoindenters. Ultra-precision machining is beneficial for microfabrication, because of its accuracy and speed. The intent of current work is to fabricate micron size features over centimeter length scales in reasonable time. This is potentially achievable, since commercial ultra-precision machines have 5-nm resolution. Further, it is expected that tools having ~ 25 μm -diameters are robust and reproducibly define microscopic features. Initial work demonstrates that ~ 25 μm -diameter, FIB-fabricated micro-end mills machine trenches in polymethyl methacrylate (PMMA) and metal workpieces [4,5].

In this report, we present a number of cutting tools shaped by focused ion beam sputtering. This includes precision grooving/threading tools having well-defined cross-sections. Tools have sharp cutting edges with radii of curvature estimated to be 0.1 μm or less. Focused ion beam fabricated microtools are tested by machining helices into different workpiece materials.

PROCEDURE FOR SHAPING MICROTOOLS

Microtools are shaped by focused ion beam sputtering using a custom-made vacuum apparatus described previously [6]. A liquid metal ion gun produces a 20keV beam of gallium ions that is directed towards tool blanks. The ion beam has a Gaussian intensity distribution with a full-width at half-maximum diameter of 0.4 μm . In practice an operator outlines a desired shape for removal on a secondary electron image of the target, and an octapole deflection system steers the ion beam to designated areas with sub-micron resolution. Between sputter removal steps, a stage positions tools with 1 μm accuracy. This stage also provides for sample rotation with a minimum step size of 0.37°. Individual facets are sputtered with the tool blank fixed.

Tool blanks are purchased from National Jet, Inc. and are made of cobalt M42 high-speed steel or C2 micrograin tungsten carbide. The tool shank has a diameter of 1.02 mm and is brazed into a centerless ground mandrel. Tool mandrels are either 2.3 mm or 3.175 mm in diameter. One end of each tool is tapered by diamond grinding and polished; this end has a diameter of approximately 25 μm and is cylindrical over a length of 25 μm . The average rate of sputtering C2 tungsten carbide has been measured to be 0.76 $\mu\text{m}^3/\text{sec}$ at near-normal incidence when using a beam current of 2.8nA.

FABRICATED MICROTOOLS

A number of different microtools have been shaped by focused ion beam sputtering and tested. This includes microgrooving/threading tools and micromilling tools. An example microgrooving tool is shown in Figure 1. This tool is made of tungsten carbide and contains facets intended for cutting and raking chips. The tool has a cutting edge width of 18 μm and a rectangular cutting cross-section. Tools are made with well-defined back rake and side rake angles as well as clearance taper angles behind cutting edges. Clearance for minimizing frictional drag of a tool results from the sputter yield dependence on ion beam/target incidence angle. This particular tool has 7° back rake and side rake angles. In general the time required to shape a tool in the FIB system depends on the amount of material sputtered and the composition of the tool. The microcutting tool shown in Figure 1 was fabricated in 4-5 hours using an ion current of 2.8 nAmps (measured in a Faraday cup). Energy-dispersive x-ray spectroscopy reveals that the low electron yield features in Figure 1 (dark regions on facets) are Co-rich and C-rich regions.

Microgrooving/threading tools are fabricated by ion beam sputtering to have a variety of shapes. This includes tools intended for cutting rectangular, trapezoidal and triangular cross-section grooves. A microtool having a triangular cross section is shown in Figure 2. This tungsten carbide tool has a 5° back rake angle. A particular ion beam/ target geometry is used to create extremely sharp cutting edges for this and all other microtools. In general, an edge created on the side of facets furthest from the ion source has the smallest radius of curvature. This effect is due to the Gaussian nature of the beam and is described in detail elsewhere[4]. A clear demonstration of a sub-micron radius of curvature along a cutting edge is shown in Figure 3.

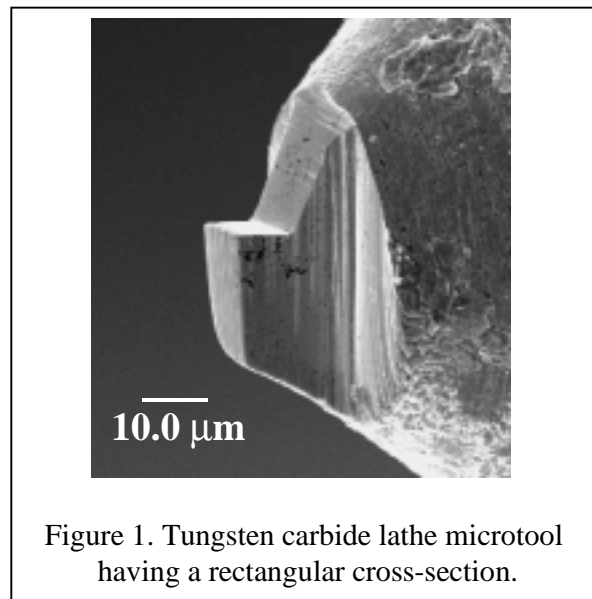


Figure 1. Tungsten carbide lathe microtool having a rectangular cross-section.

This image is taken from a symmetrical 4-facet micromilling tool having a tool width of 12 μm . The projection shown in Figure 3 is parallel to the tool axis and the micrograph displays the intersection of two ion beam sputtered facets. It is estimated that FIB sputtered facet edges have radii of curvature of 0.1 μm or less.

ULTRAPRECISION MACHINING

Focused ion beam fabricated microtools have been tested by machining a number of different materials including Al 6061-T6, PMMA and MacorTM. For this we employ a Precitech Optimum 2000 lathe. According to manufacturer's specifications this instrument has linear laser holographic scales and read-head assemblies that provide stable positional feedback for both axes with 8.6 nm-resolution. Machining of different materials has consisted of cutting helices such as those shown in Figure 4. For these experiments water continuously flushes workpieces during ultraprecision machining. After machining, workpieces are rinsed with isopropyl alcohol. The scanning electron micrograph in Figure 4.a. shows portions of a groove cut in 1.38 mm diameter PMMA. The pitch is 50 μm and the total groove length is 420 mm. The total time to cut PMMA is approximately 30 seconds using a feed rate of 10 mm/min (single pass). Measurements with a calibrated scanning electron microscope show that the micromachined groove is consistently 13.1 μm wide over the entire cylinder length, and nearly the same as the tool width, 13.0 μm . Figure 4.b. shows a Macor cylinder machined with a focused ion beam fabricated microtool. A series of helices are machined along the length of this workpiece bounded by several bands also cut with the same microtool. The grooves machined into this Macor sample are 20 μm deep and involved 10 passes. No offset error from multiple passes is detected using high resolution SEM. Using a microscope focused on the microcutting tool we observe chip formation during ultraprecision machining.

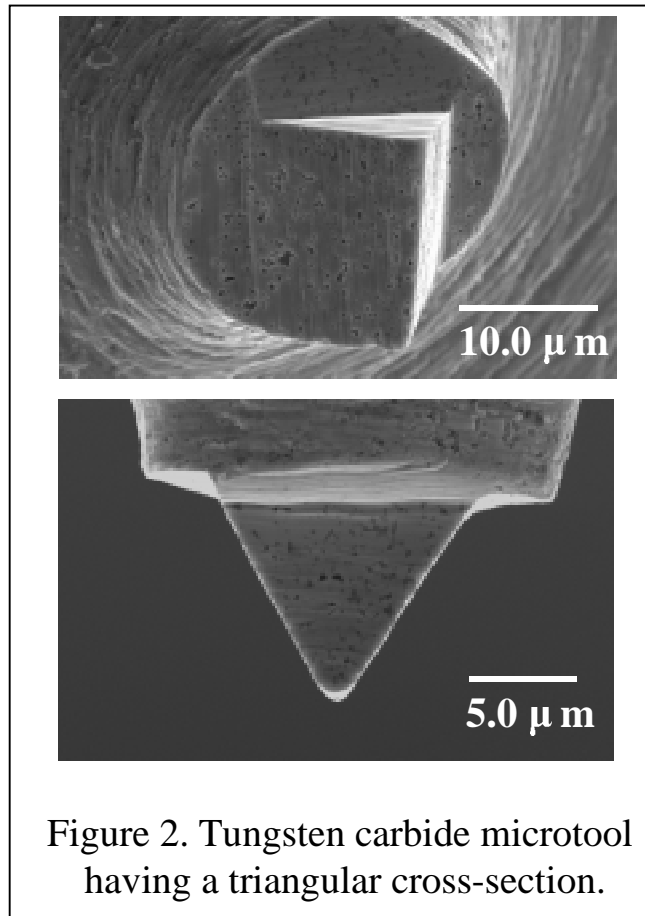


Figure 2. Tungsten carbide microtool having a triangular cross-section.

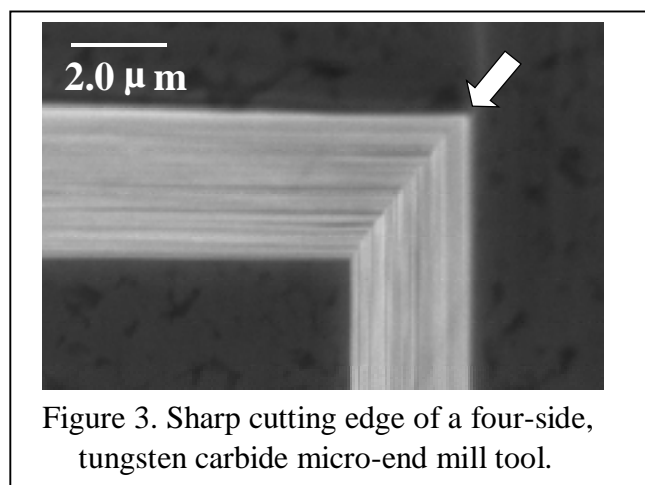


Figure 3. Sharp cutting edge of a four-side, tungsten carbide micro-end mill tool.

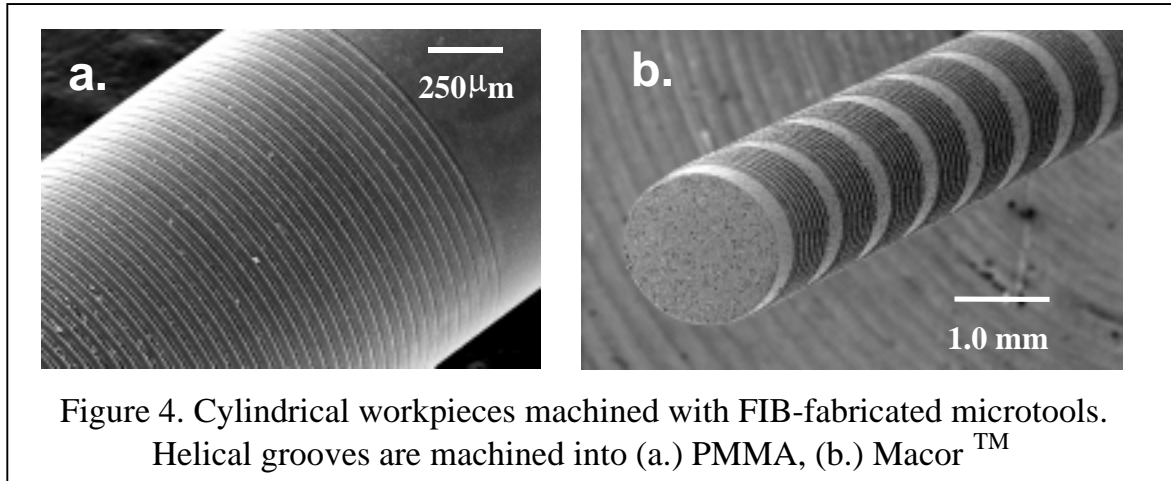


Figure 4. Cylindrical workpieces machined with FIB-fabricated microtools. Helical grooves are machined into (a.) PMMA, (b.) MacorTM

SUMMARY

This work successfully extends conventional machining techniques to the microscale in order to fabricate curvilinear features. Focused ion beam sputtering is used to shape micro-grooving / threading tools that have well defined back and side rake angles, cutting edge widths and cross-sectional shapes. A clear demonstration of cutting edges having sub-micron radius of curvature is presented. Focused ion beam tool fabrication has the advantage that almost any conceivable tool geometry can be fabricated on a scale that is well below those reached by grinding methods. This study demonstrates examples of micromachined curved features, including helices on cylindrical substrates.

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