

MICROMECHANICAL MACHINING PROCESSES AND THEIR APPLICATION TO AEROSPACE STRUCTURES, DEVICES, AND SYSTEMS

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Abstract

Micromechanical machining processes are those micro fabrication techniques which directly remove work piece material by either a physical cutting tool or an energy process. These processes are direct and therefore they can help reduce the cost and time for prototype development of micro mechanical components and systems. This is especially true for aerospace applications where size and weight are critical, and reliability and the operating environment are an integral part of the design and development process. The micromechanical machining processes are rapidly being recognized as a complementary set of tools to traditional lithographic processes (such as LIGA) for the fabrication of micromechanical components. Worldwide efforts in the U.S., Germany, and Japan are leading to results which sometimes rival lithography at a fraction of the time and cost. Efforts to develop processes and systems specific to aerospace applications are well underway.

Micromechanical Machining Processes

The micromechanical machining processes are divided into two distinct categories based on the method of material removal. The force processes include single point diamond micromachining (SPDM), micromilling, microdrilling, and sawing, grinding and polishing. These processes are spinoffs of traditional mechanical processes but have been specifically adapted to machine features as small as several micrometers with sub-micrometer tolerances. Merely shrinking the traditional processes has not proven entirely successful. The micromechanical processes have undergone specific changes for adaptation at the microscale. The second category is the forceless processes which include laser ablative micromachining, micro electrical discharge micromachining (mEDM), and focused ion beam machining. Although it is more akin to microlithographic processes, laser-based photopolymerization (micro stereo lithography) is also included in this category. All of these processes are undergoing various levels of integration to provide much more flexibility to the microsystems designer. A summary comparison of the various micromanufacturing processes in common use are shown in **Table 1**.

The micromechanical processes directly remove material in a single step rather than many serial steps found in lithography. To create a microstructure by the LIGA method, for example, an x-ray mask must be first fabricated. This requires CAD layout of the pattern, an electron beam writing step to transfer the pattern to a thin photoresist. The resist is then developed and electroplated with chromium to form an optical lithography mask. The mask is then used to transfer the pattern to a photoresist which is typically 2-3 micrometers thick. The developed pattern is then electroplated with gold to form an intermediate x-ray mask. This mask is used with an x-ray source, a synchrotron for example, to form a final x-ray mask with a gold absorber 10-15 micrometers thick. The final mask is then used to transfer the pattern to a resist up to centimeters in thickness. The exposed pattern is developed and electroplated with nickel or other metals to form the final microstructure. A portion of a mold for a micro fluidic device, produced by x-ray lithography, is shown in **Fig. 1**.

It is readily seen that the walls are vertical, straight, and smooth. In addition the top edge is sharp and without burrs, and the ratio of the vertical to lateral dimensions (aspect ratio) is large. These are typical advantages of molds and structures made by x-ray lithography and are attributes which a final product may need to have. The disadvantage is that

Table 1. Process Comparison

	Micromechanical Machining	X-ray Micromachining	Bulk Si Processing Techniques	Surface Processing Techniques
Feature Height	um's - mm	1000 um - cm's	500 um - mm's (using bonding techniques)	10 - 20 um
Cross-Sectional Shape	Very Good	Very Good	Fixed by Crystal	Very Good
Cross-Sectional Shape Variation with Depth	Good	Limited	Limited	Very Limited
Materials	Wide Range Possible	New Materials Being Developed Continuously	Fixed	Fixed
IC Compatibility	Good	Good	Fair	Excellent
Process Maturity	Developing	First Products	Fairly Mature	First Products
Aspect Ratio	Large	Large	Small	Medium
Low Volume	Excellent	Poor	Fair	Poor
High Volume	Possible	Good	Excellent	Excellent

an x-ray mask made with a gold absorber typically costs \$10K to \$30K or more depending on the dimensional tolerances required. The cost for using a 100keV electron beam writer to create an x-ray mask in one step, thus eliminating the need for the optical and intermediate masks, has been quoted at \$1K per hour. Gold electroplating must still be performed and this process uses toxic and environmentally hazardous materials such as cyanides. The cost of a synchrotron is tens-of-millions of dollars and the annual operating costs are over a million dollars. For component and system prototyping where low cost and rapid turn around are important, the lithographic processes have distinct disadvantages.

To help reduce the cost and time for mask and mold fabrication at the prototype stage, or at the final stage if the component attributes meet the design requirements, micromilling has been developed [1-4] at the *IfM*. This is presented as an example of the use of the micromechanical machining techniques. Many of the other processes are also being adapted in a similar manner. At present, the process uses micromilling tools which are 22 micrometers in diameter and fabricated with focused ion beam micromachining. The tool material is M42 cobalt-high speed steel (Rc 65-67). A typical tool is shown

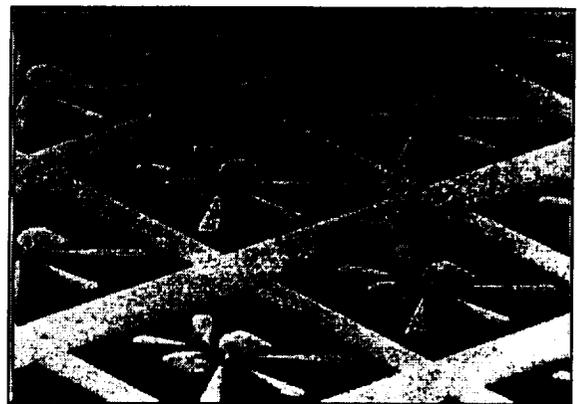


Figure 1 Lithography Mold

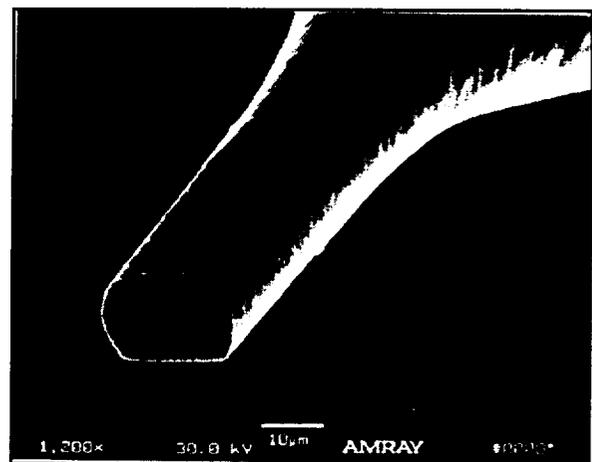


Figure 2 Micromilling Tool

in Fig. 2. The tools are used to directly mill polymethyl methacrylate (PMMA) mold and mask features. The deepest features to date are 62 micrometers and the thinnest walls are 8 micrometers wide. Sidewalls are very vertical (89.5 degrees or better) and the rms roughness is 0.1 micrometers. Complex shapes can be milled simply by programming the high precision micromilling machine used for this process. An example of this complex geometry is shown in Fig. 3 which is just a small portion of the overall pattern. The pattern is over 2mm in diameter and over 35 million cubic micrometers of material was removed in just three hours. A specially designed micromilling/micromilling/mEDM machine was developed which has nanometer-level positional resolution, sub-micrometer positional accuracy and repeatability, a massive granite structure for thermal and vibrational stability, and air bearing slides and spindle. Although the machine cost nearly \$300K to develop, the fact that it allows very rapid production of molds and masks gives this process considerable potential to become a mainstream micromanufacturing technique.

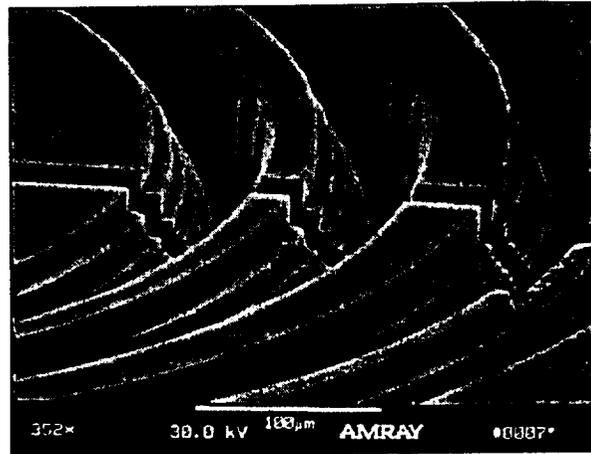


Figure 3 Micromilled Mold

Worldwide Programs in Micromechanical Machining

Because the micromechanical processes are evolving and being applied very rapidly, it is difficult to provide a complete overview of efforts. The programs shown for the U.S., Germany, and Japan are somewhat representative of those also taking place in England, Switzerland, The Netherlands, and Taiwan. Historically, Germany is known for high precision manufacturing at traditional scales. The LIGA process was commercialized for micromechanical structures in Germany and since that time (the 1980's) there has been a primary focus on that technique. As the technology has matured, the precision micromechanical processes are seeing increased use to support LIGA[5].

In the U.S., deep x-ray lithography for micromechanical applications has primarily resided at the University of Wisconsin. Recently, LSU-Baton (Center for Advanced Microstructures and Devices/CAMD) and Louisiana Tech University/IfM, are applying deep x-ray lithography for production of microstructures and systems. Because the LIGA process technology had been widely published prior to the establishment of the IfM, it was known that the micromechanical machining processes would have widespread utility and were therefore included as an integral part of the Institute. The IfM operates all of the micromechanical processes previously identified.

Japan still lags behind in the area of deep x-ray lithography primarily due to an apparent lack of interest or economic driver[6]. Because of this, Japan has many successes in the micromechanical techniques, especially in micro EDM, silicon-based technologies, and microsystem concepts and designs. The Japanese government, through MITI, continues to aggressively fund the microtechnologies and there is considerable support and involvement from the leading technology companies based in Japan. This support is also evident from the establishment of the Micro Machine Center (MMC) several years ago. This center has served as a clearinghouse for R&D information from around the world.

Aerospace Applications of Micromechanical and Lithographic Fabrication

Smaller, lighter weight, more reliable, and less expensive are adjectives for components and systems used in aerospace applications. These are also phrases often used to describe micro-manufactured components and systems. Such devices are inherently smaller and therefore lighter weight. Often, these devices are designed to have very few independent parts because of the difficulty in assembly. With fewer parts, greater reliability can be achieved. With smaller parts also comes reduced

statistical incidence of material defects or non-homogeneities. Using mass fabrication techniques pioneered by the semiconductor industry, or direct fabrication techniques during prototype development, the unit cost of micromanufactured parts can be less than by traditional processes. The following examples represent a summary of applications worldwide and is not all inclusive. The components, systems, and processes are generally for both aeronautical and space applications.

The cost of placing payloads in Earth orbit or for planetary missions is continually increasing. Therefore smaller analytical instruments are the obvious next step. Microspectrometers have been designed and built to the commercial stage in Germany[7,8]. The device operates in the 2.75-3.35 micrometer spectrum by using a reflection grating patterned in a PMMA layer by x-ray lithography. After development, the PMMA is given a reflective coating. Light is introduced onto the grating by a 150 micrometer diameter multi-mode fiber. The resolution of the device is 31 nanometers. A total of 2000 of the devices have been placed into production.

An electrochemical microanalytical system has been developed[9] where potentiometric microsensors are combined with solid state ion sensitive membranes, plastic molded micropumps, a microchannel system for connecting the components, and microelectronic components for signal processing and system control. At present, the system has been developed to measure pNa and pH.

In Japan, reactive ion etching has been used to fabricate an electromagnetically driven resonant angular rate sensor[10]. A silicon mass, 60 micrometers wide by 190 micrometers thick, is caused to resonate along one axis by electromagnets. Rotation about a second orthogonal axis causes a vibration along the third axis by the Coriolis effect. This vibration is sensed by a capacitance change. The device had a reported sensitivity of 6 fF sec./deg. and rates in the range of 240 deg./sec. to 360 deg./sec. were measured.

Applications which are being studied or have been developed to the prototype stage at the IfM include electrostatically driven rotary and linear actuators, self diagnostic bearing elements which can report several factors concerning the bearing operating environment, micro scale surface modifications to increase heat transfer in micro heat exchangers and to reduce drag on free and enclosed surfaces, small "smart" projectiles on the scale of a 0.50-caliber bullet and the control surfaces required at this scale, micro antennae for near-infrared communication systems, and large L/D micro channel plate detectors for night vision applications.

Summary

As with many process technologies, there are a variety of ways in which they can be applied to solve development problems. The micromechanical machining processes should be viewed as an additional set of tools available to the microsystems designer and fabricator. The processes can be used as standalone techniques or integrated with more traditional lithographic techniques by pre- or post-processing. These techniques include substrate preparation such as polishing for smoothness and dimensional control, for planarizing thick resist layers by polishing or direct diamond machining, for planarizing multiple layers of resist and electroformed structure materials in the so-called "step LIGA" process for creating variable vertical geometries, to using microdrilling to remove taper left in deep holes by electron beam lithography. The current challenge is to develop standard procedures, fixtures, and reference location schemes so the integration of these processes will not detract from productivity or dimensional quality of the finished parts and systems.

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