AC 2007-99: MICRO-MANUFACTURING IN THE CLASSROOM AND LABORATORY

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Micro-Manufacturing in the Classroom and Laboratory

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Abstract: The products that occupy the attention of manufacturing engineers can be separated, in one context, into three categories, determined by geometric dimensions: ordinary or customary; very small; very large. The engineering challenges of manufacturing parts in customary dimensions have migrated, in large part, from the technological into the arena of lean thinking.

The technological frontiers of manufacturing, in the early portion of the 21st century, lie in the very small and the very large. It is arguable that manufacturing in the very large is a mostly straight-forward extension of how we make parts of ordinary size, albeit with significant challenges of scale and rate. In the micro- and nano-realms, however, the technology is most-definitely-not a simple extension of the well-known. Here, the governing physics are different, new or vastly modified processes are required, and fixturing, gauging and assembly demand completely different approaches. Innovation rules. And applications of products centered on micro- and nano-technologies are now the fastest-growing segment of commerce. Hundreds of nano-enabled new products appear every year. Thus, one of the critical challenges of manufacturing engineering education is to devise means of introducing knowledge of processes and production for fabrication at micro- and nano-dimensions.

This paper opens with a brief summary of sub-millimeter and sub-micron manufacturing and assembly processes, both in research laboratory and in factory. Then, an assessment of micro-machining processes is presented, paired with representative applications. The paper concludes with an outline and critique of a new course in mechanical micro-machining initiated by the author.

A View of the Landscape of Manufacturing Technology: New technology in manufacturing is migrating to the very large and the very small. Technological innovations are essential for manufacturing companies to maintain a competitive edge with aggressive firms in Europe, Asia and, increasingly, Latin America. While there remains much mileage in lean enterprise methodologies, those methods essentially address existing and mature manufacturing technologies. The lean mantra concentrates attention on more effective utilization of existing and established manufacturing technologies. Technological innovation is, typically, incremental, rather than dramatic.

Established manufacturing technologies are available to anyone. Factories anywhere in the world can acquire even the most advanced machine tools based on mature technologies. The principles and practices of lean thinking are published in enormous variety. Pursuing this logic, it is postulated that continuing global competitiveness in manufacturing must also embrace innovation at a fundamental technological level. Such innovation depends on relentless pursuit of the new in manufacturing technologies and engineering. Perhaps most prominent among the current opportunities for innovation in manufacturing processing are those at the very small dimensional scale.

Applications of micro-manufacturing are exploding. The flow of new products with dimensions shrunk to sub-millimeter size has become a torrent in medical device, automotive, portable energy, electronics, sensors and other industries. The manufacturing processes supporting this product flood contain significant differences from traditional macro-dimensioned processing. When workpiece dimensions shrink to millimeter-size and less, tool-workpiece interactions change. The micro-world follows a different set of rules from the macro-world.

A Summary of Micro-Manufacturing: An examination of micro-manufacturing begins with a familiar categorization procedure. Much as in the conventional environment, processes can be categorized as ‘parts fabrication’ or ‘assembly’. While there are some processes that combine both functions, the distinction serves a useful taxonomic purpose.

Up to the present time, fabrication of sub-millimeter parts has been enabled principally through migration of processes from microelectronics. Deposition-and-removal lithographic processes familiar in micro-circuitry manufacture have been employed for production of micro-electro-mechanical systems (MEMS) with some notable success. Likewise, applications of such processes as ion beam implantation and chemical vapor deposition are being researched for non-electronic products. MEMS devices and similar products have so far been, typically, created from monolithic pieces of silicon, relying on the very small dimensions to provide for flexing of components when functionally necessary.

The market for sub-millimeter products is, however, expanding rapidly, and demand for more complex, multi-component products is beginning to emerge. Clear examples are found in medical devices. Products comprised of sub-millimeter parts for have been emerging steadily, for example, for orthopedic, cardiac and eye surgery and for low-invasive medical diagnostics. Further, complex micro-sensors are at the forefoot of an enormous wave of application. Very small transportable energy devices are beginning to proliferate. The list is both broad and deep. Frequently, these products are more amenable to manufacture by extrapolation of machining technologies, than by adaptation of lithographic techniques. [1,2,3]

The terms ‘nano’, ‘micro’ and ‘meso’ are frequently employed to describe the small world of manufacture. These terms are rather imprecise, and there is no universal agreement as to where one realm stops and another begins. Some writers also employ the term ‘miniature’ in the spectrum.[3]

We describe our work at North Dakota State as being with products generally in the miniature and meso realms according to the spectrum suggested in Figure 1. Part features, however, are usually in the meso and micro realms. When working in micro-milling or micro-forming, for example, we might develop processing methods for an article up to perhaps 2 to 3 millimeters in overall outer dimension that will have part features dimensioned down to, say, 40 microns. When working in deposition processing, the part features are generally in the 10 to 500 micron range.

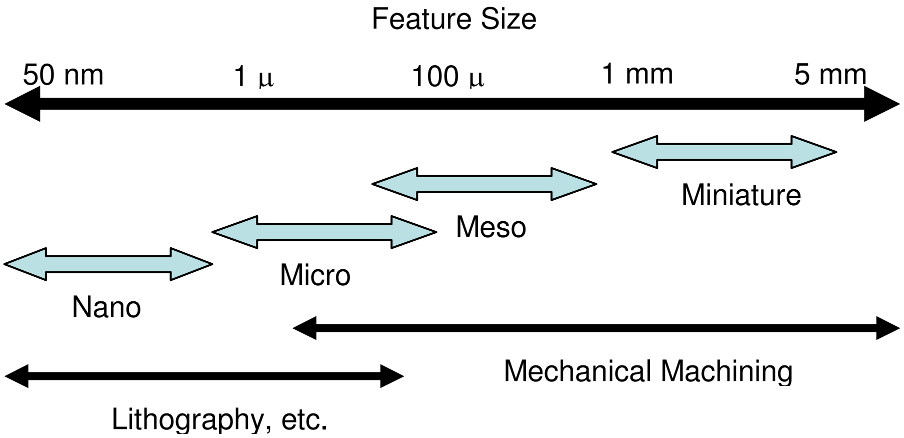

Figure 1: A dimensional spectrum for small-scale part manufacturing

Assembling of micro-components has also received important research attention, and several methods have been defined. In general, micro-assembly can be differentiated as either serial or parallel, or alternatively, as deterministic or stochastic.[4] Serial, deterministic assembly can be seen as an extension of robotic techniques to the sub-millimeter world.[5]

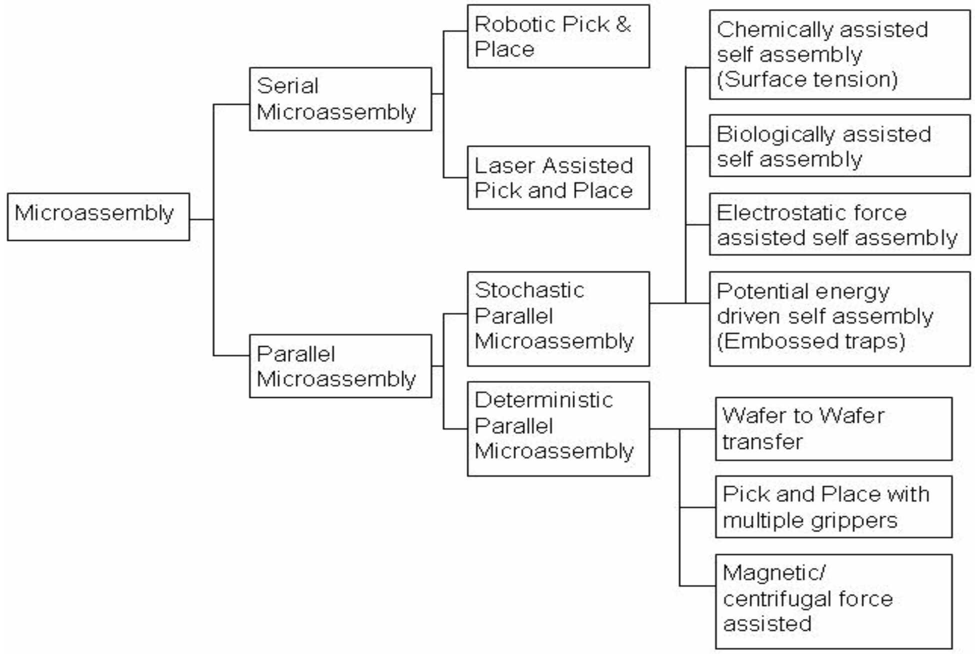

Figure 2: A taxonomy of micro-assembly techniques [4]

As with parts fabrication processing, assembly process and equipment design must cope with forces not usually encountered in macro-experience. Conventional mechanics customarily neglects minor forces as being too small to be influential. Such phenomena as surface tension, capillary action, electrostatic attraction or repulsion, hydrophobia or hydrophilia, and van der Waals forces (and others) can be construed as falling under the heading of 'small forces'. We are accustomed to applying simplifying assumptions to our mathematical models to exclude terms of small magnitude. However, as objects shrink in size, the small forces become of about the same order of magnitude as body forces. A convenient threshold for this occurrence is reached when the major dimension falls to about one millimeter. Thus, micro- and nano-manufacturing must account for, say, electrostatic forces of comparable magnitude to the gravitational forces acting on workpieces. Analysis becomes somewhat more complex, and certainly more subtle. Equations of motion become mixtures of theoretical and empirical terms, with primarily experimentally-determined coefficients and 'correction factors'.[6]

Often seen as an alternative to the deterministic processes of micro-robotics, self-assembly is one of the most promising emerging tools for parallel assembly of discrete parts into the patterns of multi-component products. The common factor throughout self-assembly processes is the mimicry and/or harnessing of naturally-occurring processes.[4] These processes exploit one or more of the 'small forces' that can be problematic for robotic grippers. While most are subjects for laboratory research, one such process has evolved into commercial utilization. In fluidic self-assembly (FSA), large quantities of trapezoidal micro-components are deployed in a fluid bath. Through interaction of gravity, hydrophobic rejection and surface tension forces, the micro-components self-assemble into prepared shape-matched depressions in a polymeric sheet or crystalline plate. FSA is in every-day use in the manufacture of millions of radio-frequency identification (RFID) tags.[1]

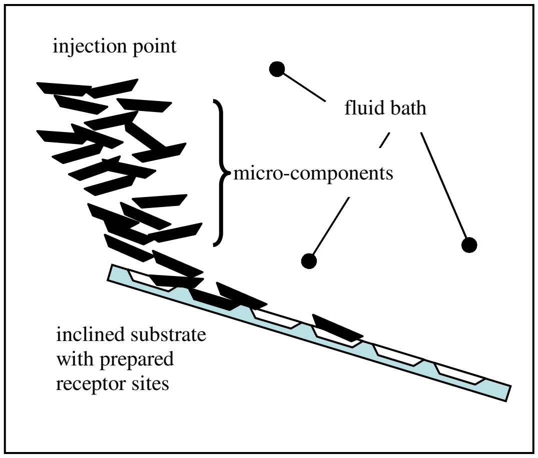

Figure 3: Fluidic self-assembly of micro-components

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[1] FSA is a registered trademark of Alien Technology Corporation. This company opened an FSA-based RFID factory in Fargo, North Dakota in mid-2006.

A First Step in Micro-manufacturing Instruction: In an archetype of the idealized translation of research into the classroom, the Manufacturing Engineering faculty at North Dakota State University have been introducing a steady stream of instructional initiatives derived from their research in advanced manufacturing topics. These faculty have been active researchers for the past half-dozen years in selected aspects of micro-manufacturing, and it has been a natural extension to migrate research topics into both graduate and undergraduate instruction. Among the most prominent of lecture-laboratory courses that exploit current research are the following:

* IME 427; Electronics Manufacturing -- includes lead-free assembly of printed circuit boards.
* IME 482; Automated Manufacturing -- includes applications of radio-frequency identification (RFID) tags in tracking of components through assembly processing.
* IME 630; Micro-manufacturing -- concentrates on tooling and processing for manufacture of components in the sub-millimeter dimension-range.
* IME 720; Surface Engineering -- concentrates on the processing methods for and characterization of sub-millimeter features of manufactured surfaces.

The most recent of these courses is the new offering in micro-manufacturing. This course had its origin in research that, in part, required hot embossing of sub-millimeter features into substrate sheets of various thermoplastics. The legacy process for producing embossing punches was lithographic etching of silicon wafers. The process is tedious, slow, costly, capital intensive and filled with environmental hazards.[2] Moreover, the resulting silicon punches are fragile, and tool life, even under careful laboratory fabrication conditions, was very low.

A good engineering response to such a situation is, of course, to look for alternative methods of producing the needed goods. The end goal was embossed plastic sheets. More durable, and hopefully cheaper, alternatives to silicon punches were believed to exist. In this spirit, it was hypothesized that we could machine a stainless steel punch to the requisite specifications and that such a solution would be cheaper, faster and less environmentally hazardous that the etching of silicon. Experiments were then conducted to machine a prototype metal embossing punch in yellow brass. Results were highly encouraging.

A sample that represents the features of a micro-embossing punch was designed in a 7-millimeter square. Contained within the square are eight features: two 2-millimeter squares at 250 microns tall; one 1-millimeter square at 250 microns tall; two 1-millimeter squares at 150 microns tall; three 1.5-millimeter ells at 250 microns tall. The prototype was milled on a Haas VF-1 Vertical Machining Center, using 1/8-inch and 1/32-inch square two-flute end mills and a specially-made tapered one-flute end mill. The limitation of the 7500 rpm spindle on the VF-1 led to a very long machining time. Chip loads on very small end mills must be severely limited, as we learned through several occasions of tool breakage. Machine feeds were on the order of fractions of an inch per minute. Moreover, the slow cutting speeds yielded surface roughness from tool striations that are deemed to be unacceptable for embossing. Nonetheless, the machined product is true to nominal dimensions in the x-y plane within a few microns. Z-direction precision is not as good. While many of the z-measurements were within acceptable

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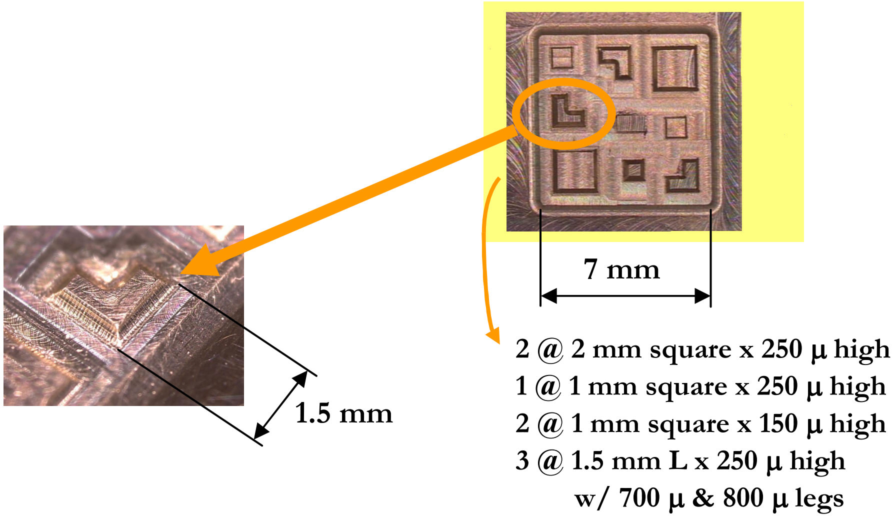
[2] The etching procedures, for example, use both hydrofluoric acid and potassium hydroxide in high concentrations.

tolerance, a few of the feature-heights deviated from nominal by as much as 40 microns (16 percent).



2 @ 2 mm square x 250 μ high
1 @ 1 mm square x 250 μ high
2 @ 1 mm square x 150 μ high
3 @ 1.5 mm L x 250 μ high
w/ 700 μ & 800 μ legs

Figure 4: Micro-milled prototype embossing punch

The tapered end mill was required to create the special features of the punch, intended to match the natural angle that is etched in single crystal silicon along the {111} plane. This angle is 37.3 degrees, and there are no standard commercial products that match this requirement. In order to test the feasibility of an end mill of this specification, the project technician set about making a prototype tool from drill rod stock. The result is seen in Figure 5, with an end flat of about 200 microns produced with a 5 degree relief angle.

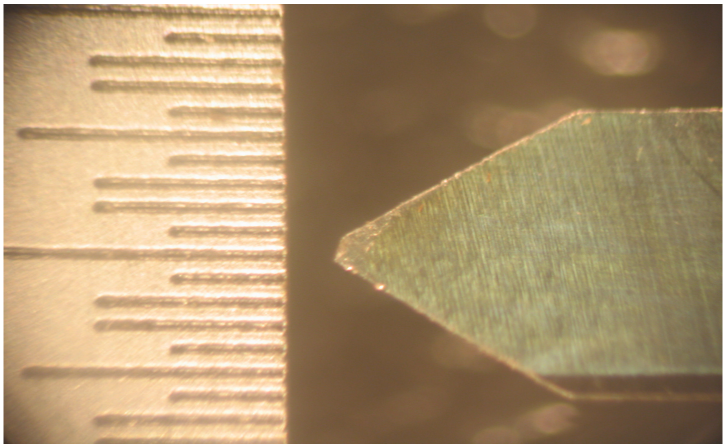


Figure 5: In-house-produced tapered one-flute end mill
[scale divisions are 1/100" (~250 microns)]

In the process of testing this hypothesis, a very steep learning curve led, rather naturally, to the perception of a rich opportunity to explore micro-machining in the context of a course in the Manufacturing Engineering major. It was concluded that the pre-requisite knowledge derived from advanced undergraduate coursework in manufacturing processes would be essential, and it was decided to offer a micro-machining course at the level of first-year graduate students.

First Offering: The first offering of IME 630 is described in the syllabus as follows: "This course offers an introduction to process engineering for micro-machining. The course is presented in two segments. Course content in the first segment will include … an overview of micro-assembly and micro-machining processes; perspectives on quantitative aspects of machining at the micro-scale; an examination of the normally-neglected forces that become significant in sub-millimeter dimensions. Then, the class will focus on mechanical micro-machining, with emphasis on drilling and milling of sub-millimeter features. Content in this segment will include … machine tool specification; cutting tool selection; operating parameters; optical inspection and gauging. Throughout both segments, the coursework will be illustrated with examples of micro-machined products. The mechanical micro-machining segment will also include laboratory experimentation and observation."

Five learning objectives were specified in the syllabus: At the conclusion of this course, the successful student will be able to …

1. … create comprehensive models for fabrication of metal micro-parts and micro-tooling;
2. … set-up and conduct measurements of dimensional characteristics of micro-machined parts;
3. … identify, develop and organize data necessary for cost-effective selection of machine tools and measuring apparatus for production of micro-machined parts;
4. … design complete processing solutions for production of metal micro-parts;
5. … develop and deliver effective engineering written and oral reports that explain a micro-machining process design.

Prerequisite skills for a course with the orientation indicated are those of manufacturing process engineering. Students should enter a micro-machining course with well-established abilities in quantitative modeling of conventional manufacturing processes, process planning, and tooling and fixture design and selection. These skills should be based on the foundation of strong understanding of the engineering science underlying traditional manufacturing processing. The planned concentration was in micro-machining; so, the prerequisite skills were specified with a machining emphasis.

There are few textbooks available on this topic, and an examination of the marketplace indicated that very little text material was available in the form of published books that had the topical focus planned for the course. Thus, reading material was provided in a coursepack that contained reprints of some twenty published journal papers. The basic papers were summaries of micro-engineering [7], micro-robotics [5] and self-assembly [4].

As suggested by the learning objectives, the course was planned as a mixture of classroom, project and laboratory experiences. Several mini-projects were assigned to introduce familiarity with a few fundamentals. These projects included …

… summarizing the characteristics of micro-components that make them amenable to assembly by means of various serial and parallel/deterministic and stochastic micro-assembly processes;
… taxonomic categorization of forces that influence manufacturing at sub-millimeter scale;
… measurement of surface striations left by cutting tools during end milling of sub-millimeter features and correlation with machining parameters;
… quantitative modeling of micro-milling: range of machining parameters, cutting forces, bending forces on end mills.

The principal focus of the course deviated somewhat from the originally intended mechanical micro-machining focus. The primary semester-long assignment was a combined analytical-laboratory project: back extrusion of a hemi-spherical lens from a polycarbonate blank. The overall process design called for the production of a shape approximately 1.5 millimeters in diameter by 750 microns tall from a polycarbonate button 10 millimeters in diameter by 3 millimeters high. Student work on the project began with a literature search to establish extrusion characteristics and properties of polycarbonate. Process engineering included elements of tooling, process design, experiment design and measurement:

… design of extrusion tooling (manufactured from AISI 316 stainless steel);
… quantitative analysis of micro-extruding: extrusion pressures and forces, process planning, dimensional measurement methods;
… experimental verification of extrusion parameters;
… extrusion experiments: variation of extrusion temperature and processing rate, measurement of dimensional characteristics of the extruded product;
… machining methods and tooling for separating the hemi-spherical polycarbonate pip from the button.

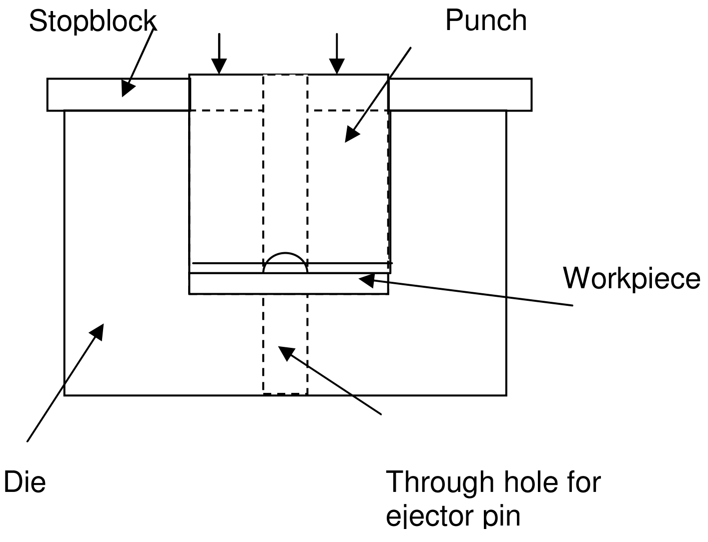


Figure 6: Die set for micro-back-extruding of polycarbonate

The back extrusion process requires heating the die set to a flow temperature for the polycarbonate workpiece. The glass transition temperature of polycarbonate is 150 °C, and a nominal extrusion working temperature was established at 185 °C. The die set, containing an unprocessed button, was placed on a hot plate, which was, in turn, mounted on the bed of an arbor press. The length of stroke necessary for displacing the volume of the back-extruded hemi-spherical lens was computed (26.7 microns), and a stainless steel stop block was machined to limit the punch travel to the distance that would displace just the correct amount of polycarbonate to form the lens. Stop block thickness was 1.211 millimeters.

Several buttons were extruded, and about half approached the targeted product dimensions. These samples were measured in an optical comparator. Four trials, at working temperatures between 171 and 188 °C, successfully produced cylindrical extrusions. However, two of these were not fully extruded, and the shapes were more ovoid than spherical. Of the two best products, the average dimensions were diameter of 1.559 millimeters and height of 0.709 microns.

extrusion temperature [°C]	diameter [mm]	height [mm]
188	1.538	0.710
171	1.580	0.708
188	1.562	0.454
179	1.555	0.330

Figure7: Measured dimensions of back-extruded pips

The principal shortcomings were in temperature control and in materials handling. The temperature precision of a hot plate, manually controlled from reading of a thermocouple, is modest, at best. Inability to maintain a correct extrusion temperature was responsible for nearly all of the “failed” trials. In addition, it was quickly determined that the workpiece had to be cooled before ejection from the die cavity. This was accomplished through forced convection by means of shop air -- again, a rather imprecise process.

Materials handling is always a serious issue with micro-parts. At these dimensions, it is easy to lose the product. After extrusion, the next processing step is to separate the hemi-spherical lens from the mass of the button. A variety of machining methods were proposed by the students. Analysis revealed that the simplest method was to plunge cut from the back of the button with a square end mill of about the same diameter as the extruded pip. A 1/16-inch (1.5875 mm) two-flute end mill was selected. After a very few trials, appropriate feeds and speeds were determined, and pips were successfully separated. Handling the pips was quite a challenge, and one was dropped -- and lost. As is also seen in Figure 8, a small burr was formed during separation of the pip, and it is clear that further development of process controls would be necessary for this step of manufacture.

Figure 8: Micro-extruded polycarbonate lens-like part
[approximately 1.5 millimeters in diameter]

Course Operation and Lessons Learned: As actually conducted, the first offering of the micro-machining course differed somewhat from the original concept. As the course progressed, several modifications had to be introduced. Some confounding aspects make it difficult to reach accurate interpretation of course effectiveness and underlying reasons for successful course features and those aspects where expectations exceeded reality.

The fundamental reality is that the first offering of this course did not fully realize expectations. On the positive side, successful experiments were conducted. A functional die set and machining fixture were designed and produced in stainless steel (AISI 316). Several near-hemi-spherical polycarbonate shapes were extruded. Dimensional measurements and photographic images were captured. Machining to free the extruded shapes from the buttons was successfully undertaken. Similarly positive, the students liked the course very much; the composite Student Rating of Instruction was 4.233, as compared with departmental, college and university means for all offerings during that semester of 4.052, 3.973 and 4.047, respectively (on a five-point scale). In the negative, one planned project had to be deleted. Learning objectives 1, 3 and 5 were not achieved to the instructor's satisfaction by about half of the class. Learning objective 4 was only partially realized. Only in learning objective 2 was achievement assessed as satisfactory.

It is clear that the original concept of this course was intellectually and time aggressive. Full realization of the planned learning objectives is recognized as a challenge for fully-prepared students, provided with focused explanatory text materials and well-developed laboratory tools. In practice, the six students enrolled in this course varied significantly in preparation. About half of the class proved not to have achieved the expected level of analytical ability and project skill, despite having been awarded a bachelor's degree in engineering from their undergraduate universities. In particular, abilities normally associated with undergraduate courses in strength of materials, engineering materials and manufacturing process engineering were lacking. Further, about half of the class had not acquired fundamental skills in organizing and conducting engineering projects. Use of professional journal presentations as text material was not adequate for the under-prepared students. Likewise, expectations were that the students would be able to assemble the experimental apparatus from individual components supplied in the laboratory. This was not well-fulfilled, and significant instructor intervention became necessary. Fortunately, the class was able to call upon the services of an experienced technician, and through his effort, the time schedule was rescued.

Thus, it is not clear how much of the underperformance in this class was due to over-optimistic objectives and how much to under-prepared students. The lessons learned include adapting the course to micro-manufacturing from micro-machining and, possibly, shifting technical focus from a large, open-ended design project to smaller (perhaps two or three) more contained laboratory exercises in experimental demonstration of micro-manufacturing. While our principal research interest remains in micro-machining, a broader orientation for a first instructional course seems more suitable. It is probably a better solution to create a second graduate-level course to house student work in process design in specific micro-manufacturing applications.

The gap between introductory courses in manufacturing process engineering and strength of materials and the application of the fundamental principles in a first-year graduate course in micro-machining was too wide for the enrollees in this first offering. The next offering of a micro-manufacturing course will include a significant lecture review of the relevant analytical methods.

Laboratory apparatus is, of course, crucial. Assessment of both research and instructional experience suggests that, in the realm of micro-machining, several capabilities are essential. The first two are of nearly equal importance: [1] at least one machine tool adapted expressly for processing in the sub-millimeter dimensional range and [2] optical instrumentation capable of measuring features of these sizes. In machining, this would mean machine tool specifications that include …

… spindle speeds on the order of 80,000 rpm or more. Our laboratory response is to (a) identify a commercial micro-milling machine with 100,000+ rpm spindle and add this to our wishlist, and (b) begin in-house fabrication of a micro-milling machine of our own design with a 400,000 rpm spindle capability.

… modest machining envelope. Our estimation is that a very wide range of highly relevant applications can be addressed within a 150 millimeter square planform area. Practical z-dimensions for micromachining are likely to be quite small. Fifty millimeters may be adequate.

… modest machine feeds. At a spindle speed of 100,000 rpm, machine feeds are fairly small, as the chip loads that can be supported by cutting tools on the order of tens-to-a few hundreds of microns in diameter are quite small. For example, machining a soft stainless steel (e.g., AISI 316L) with a two-flute 1/64-inch (~400 μ) end mill calls for a chip load of not more than 0.00008 ipt (~2 μpt), a spindle speed of about 61,000 rpm and a machine feed of about 10 ipm (~4 mm/sec). End mill bending loads on the order of a few newtons (i.e., two figures) are limiting.

… low spindle power requirement. At chip loads and depths of cut that can be withstood by micro-cutting tools, spindle power expended will be in the range of two-digit watts.

… horizontal positioning resolution of 0.1 microns or better. It might be necessary to approach this degree of precision incrementally, but resolution of at least 1 micron is needed for basic lab work.

… capability for mounting cutting tools down to 25 microns in diameter. Cutting tools of this specification are commercially available. For example, 125 micron diameter two-flute end mills can be purchased at from several suppliers, and one source has been located that offers a 25 micron diameter cutter. There is similar availability in drill bits, enscribing tools and abrasive burrs. Cooling of the cutting zone is also an important machine tool feature.

In addition to the in-house milling machine under construction, two commercial machine tools have been identified -- one with a spindle capable of 100,000 rpm and a 15-inch x 14-inch x ~1-inch machining envelope, the other at 160,000 rpm and a 2.5-inch x 2.5-inch x 2.5 inch working volume. Specifications for other needed apparatus are not quite as fully developed. The NDSU micro-manufacturing team is developing specifications for optical measuring equipment, a purpose-specific hot press and a precision bench-top injection-molding machine. The measuring apparatus holds the highest priority. A general rule of thumb is that measuring apparatus should be able to resolve features of a tenth the size of the resolution of the fabricating machine tool. Thus, an optical measuring device with a resolution of 10 to 100 nanometers over a volume of 150 x 150 x 50 millimeters is the target, although a lower-cost solution may be obtained first.

Future Coursework: Our plans are to re-offer the micro-manufacturing course, remaining at the level of first-year graduate study. The scope in the next offering may be somewhat broader, but, if so, correspondingly less deep. Content may include, perhaps, micro-milling and drilling of metals and other materials, micro-extrusion and hot embossing of thermoplastics, and perhaps, micro-injection molding of thermoplastics. The learning schedule will include a purposeful component to review necessary concepts of manufacturing process modeling and strength of materials (e.g., beam bending analysis). We will retain a strong laboratory component. It is expected (hoped) that our in-house micro-milling machine will be ready for basic usage in time for a next course offering in the Autumn of 2007.

Ackowledgements: The micro-manufacturing course described in this paper owes a strong debt to one of our Manufacturing Technicians, Mr. Armon E. Myrick. He is a highly-skilled tool-maker (as evidenced by his fabrication of the cutting tool shown in Figure 5) and provided continuing strong support throughout the laboratory segment of the class. There are times when a highly skilled technician is a great value in both instruction and research. This is definitely one of the times. The entire micro-machining project is a partnership between faculty, technicians and students. The sample embossing punch (Figure 4) was prepared by Mr. Lewis Dailey, another of our creative Manufacturing Technicians. Other important contributions have been made by two undergraduate research assistants -- Tony Schwan and Sean Bittle, both baccalaureate students in Manufacturing Engineering..

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