WTEC PANEL ON MICRO-MANUFACTURING

Sponsored by the National Science Foundation, the Office of Naval Research, the Department of Energy, and the National Institute of Standards and Technology of the United States Government.

Kornel F. Ehmann (panel chair)
Department of Mechanical Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208

Beth Allen
Department of Economics
University of Minnesota
960 Heller Hall
Minneapolis, MN 55455

Thomas R. Kurfess
Department of Mechanical Engineering
Georgia Institute of Technology
813 Ferst Drive
Atlanta, GA 30332

David Bourell
Mechanical Engineering Dept.
The University of Texas at Austin
1 University Station C2200
Austin, TX 78712-0292

Marc Madou
Department of Mechanical and Aerospace Engineering
University of California at Irvine
S3231 Engineering Gateway
Irvine, CA, 92697

Thom J. Hodgson
Department of Industrial Engineering
University of Nebraska at Lincoln
176 Nebraska Hall
Lincoln, NE 68588

WTEC, Inc.

WTEC provides assessments of international research and development in selected technologies under awards from the National Science Foundation (NSF), the Office of Naval Research (ONR), and other agencies. Formerly part of Loyola College’s International Technology Research Institute, WTEC is now a separate non-profit research institute. Michael Reischman, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF or directly through separate grants to WTEC.

WTEC’s mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and disseminates the final reports.
WTEC STUDY ON

Micro-Manufacturing
- WTEC U.S. Review Workshop Report -

Kornel F. Ehmann, Panel Chair, Northwestern University
Beth Allen, University of Minnesota
David Bourell, The University of Texas at Austin
Richard E. DeVor, University of Illinois at Urbana-Champaign
Thom J. Hodgson, North Carolina State University
Thomas R. Kurfess, Georgia Institute of Technology
Marc Madou, University of California at Irvine
Kamlakar Rajurkar, University of Nebraska at Lincoln

November 2004
FOREWORD

The World Technology Evaluation Center, Inc. (WTEC), under the sponsorship of the National Science Foundation (NSF), The Department of Energy (DOE) and the Office of Naval Research (ONR), was commissioned to perform a worldwide assessment of the status and trends in Micro-manufacturing research and applications in comparison to that in the U.S.

As a first step in this process a U.S. Review Workshop was held on August 12, 2004 at the National Science Foundation in Arlington, VA. The purpose of this workshop was to establish a base line of U.S. capabilities. Towards this end, WTEC has invited leading industry experts and researchers for a critical assessment of the status and needs in their particular fields of expertise. The presentations given at the Workshop are available on the Internet at http://www.wtec.org/.

The purpose of this document is to present a synopsis of the workshop findings grouped into six (6) areas that comprise Chapters 2-7 of the report. Each of these Chapters discusses the subject matter in relation to micro-manufacturing activities in the U.S. These Chapters are:

Chapter 2: Design
Chapter 3: Materials
Chapter 4: Processes
Chapter 5: Metrology, Sensors and Control
Chapter 6: Applications
Chapter 7: Business, Education and the Environment

In each of these Chapters, an Overview is presented that is largely based on the review of the relevant technical literature. The Overview is followed by specific observations and conclusions derived from the Workshop presentations and discussions.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>i</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iii</td>
</tr>
<tr>
<td>1. <strong>Introduction</strong></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>Markets for Micro-Manufacturing (IC/MEMS/MST)</td>
<td>1</td>
</tr>
<tr>
<td>Some Useful Observations</td>
<td>2</td>
</tr>
<tr>
<td>Micro-Manufacturing Kick-Off Workshop Overview – Key Issues</td>
<td>2</td>
</tr>
<tr>
<td>References</td>
<td>3</td>
</tr>
<tr>
<td>2. <strong>Design</strong></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>5</td>
</tr>
<tr>
<td>Workshop Findings</td>
<td>7</td>
</tr>
<tr>
<td>References</td>
<td>8</td>
</tr>
<tr>
<td>3. <strong>Materials</strong></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>9</td>
</tr>
<tr>
<td>Workshop Findings</td>
<td>11</td>
</tr>
<tr>
<td>References</td>
<td>12</td>
</tr>
<tr>
<td>4. <strong>Processes</strong></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>13</td>
</tr>
<tr>
<td>Workshop Findings</td>
<td>17</td>
</tr>
<tr>
<td>References</td>
<td>18</td>
</tr>
<tr>
<td>5. <strong>Metrology, Sensors and Control</strong></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>23</td>
</tr>
<tr>
<td>Workshop Summary</td>
<td>30</td>
</tr>
<tr>
<td>References</td>
<td>31</td>
</tr>
<tr>
<td>6. <strong>Applications</strong></td>
<td></td>
</tr>
<tr>
<td>Overview</td>
<td>35</td>
</tr>
<tr>
<td>Workshop Findings</td>
<td>39</td>
</tr>
<tr>
<td>References</td>
<td>40</td>
</tr>
<tr>
<td>7. <strong>Business, Education and the Environment</strong></td>
<td></td>
</tr>
<tr>
<td>Workshop Findings</td>
<td>41</td>
</tr>
<tr>
<td>References</td>
<td>43</td>
</tr>
<tr>
<td><strong>Bibliography</strong></td>
<td>45</td>
</tr>
<tr>
<td>1. Books on Top-Down and Bottom-Up Miniaturization</td>
<td>46</td>
</tr>
<tr>
<td>2. Journals and Periodicals on Micromachining and Sensors</td>
<td>51</td>
</tr>
<tr>
<td>3. Series on Micromachining and Sensors</td>
<td>52</td>
</tr>
<tr>
<td>4. Market Studies on Micromachining and Sensors</td>
<td>52</td>
</tr>
<tr>
<td>5. Important Proceedings/Conferences on Micromachining and Sensors</td>
<td>53</td>
</tr>
<tr>
<td>6. MEMS</td>
<td>53</td>
</tr>
<tr>
<td>7. Chemical Sensors</td>
<td>54</td>
</tr>
<tr>
<td>8. International Conference on Solid-State Sensors and Actuators (Transducers), International conference held on odd years and rotates sequentially between North America, Asia, and Europe</td>
<td>54</td>
</tr>
</tbody>
</table>
CHAPTER 1. INTRODUCTION

BACKGROUND

The miniaturization of devices associated with a large number of application fields is today demanding the production of components with manufactured features in the range of a few to a few hundred microns. These fields include optics, electronics, medicine, bio-technology, communications, sensors and avionics to name just a few. Specific applications include medical implants, diagnostic and remediation devices, micro-scale batteries and fuel cells, fluidic micro-chemical reactors requiring micro-scale pumps, valves and mixing devices, micro-fluidic systems in general, micro-holes for fiber optics, micro-nozzles for high-temperature jets, micro-molds and deep X-ray lithography masks, optical lenses, etc. [1-5]. Functional requirements demand tight tolerances and the use of a wide variety of engineering materials, e.g., steels, titanium, brass, aluminum, platinum, iridium, ceramics, polymers, and composites.

A series of workshops, including a NIST/NSF-sponsored workshop held in Gaithersburg, MD in May of 1999, a NSF Workshop on Micro/Meso Mechanical Manufacturing (M4), held in Evanston, IL on May 16-17, 2000, and a NSF-EC sponsored Nano-manufacturing and Processing Workshop, held in January 2002 in San Juan, Puerto Rico, have all identified a broad spectrum of devices and products representative of the trend toward miniaturization. These workshops targeted critical thrust areas for new scientific developments and engineering applications in the emerging field of nano- and micro-manufacturing, and emphasized the need to bridge the size-scale gap between NEMS/MEMS technologies and the macro-scale. The 2nd, 3rd and 4th International Workshops on Microfactories (2000 in Switzerland; 2002 in the US, 2004 in China) have further confirmed the existence of a global effort toward the miniaturization of manufacturing processes and manufacturing equipment.

In the United States, the development of high relative accuracy 3D micro-scale fabrication and assembly methods and equipment is still largely centered around Si and MEMS. This fact was addressed in a World Technology Evaluation Center (WTEC) report on Microsystems Research in Japan (2003) wherein is was observed that, “In the 1990s, the United States focused on exploiting silicon planar lithography as the core technology for microstructure fabrication, whereas Japan explored a much wider variety of technologies.” The ten-year Micromachine Technology Project (MTP) initiated in 1991 in Japan focused on both a wide range of fabrication technologies and a wide range of materials, including extensions to more traditional machining processes. In Japan, where MEMS was driven by mechatronics and mechanical engineering, there was more focus on the fabrication and assembly of discrete products, whereas MEMS in the US, being driven by the semiconductor industry, viewed such work as fundamentally violating the paradigm of batch fabrication.

Accordingly, in this WTEC study on “Micro-Manufacturing” we are interested in non-lithography based miniaturization and in applications of MEMS and NEMS to non-lithography machining. Compared to MEMS and NEMS this application area has been underreported. We will now briefly review Integrated Circuit (IC) and MEMS, and Micro Systems Technology (MST) markets. We then draw specific conclusions from that review that can guide us in our evaluation.

MARKETS FOR MICRO-MANUFACTURING (IC/MEMS/MST)

In the early years of Micro Electro Mechanical Systems (MEMS) (beginning of the 1980’s) it was projected that its market would be larger than that for integrated circuits (ICs). This notion was based on the expectation of many more applications for MEMS than for ICs. This market projection has not been fulfilled.
Only by applying very liberal criteria about what qualifies as MEMS (e.g., including non-silicon devices such as read-write heads and inkjet printer heads) can one claim a MEMS market of about 10% of the total IC market. The IC market for 2003, for example, was $155.4 billion worldwide, with 2004 increasing further by 31 percent to $202.9 billion (http://www.reed-electronics.com/electronicnews/article/). It is worth pointing out that China will control 5% of the IC market by 2010. According to a Business Communications Company, Inc. 2002 report "MEMS Technology: Where To?," the worldwide market for MEMS/MST (MST = micro system technology) for 2002 was estimated at $11 billion. Market revenues are projected to exceed $26.4 billion by 2007, thus growing at an AAGR (average annual growth rate) of 19.1%. Sales comprise pre-existing MEMS/MST products such as ink jet printer cartridges, as well as new products, including radio frequency filters for cell phones and motor controllers (www.bccresearch.com).

The Si MEMS market today consists principally of mass consumption products such as pressure sensors, accelerometers and gyros, which, except for gyros, all became commodity products very swiftly and are now primarily manufactured overseas. In the optical switching arena, digital micromirror devices (DMDs) are a very successful Texas Instruments product for portable projectors and for digital television; both consumer products. On the other hand, the more than 10 billion dollar investment by large telecommunication companies such as Corning, JDF Uniphase and Nortel in 1999-2000 for micro mirror devices for communication applications actually might have helped bring on the 2000 recession. There were not enough customers for the more than 80 start-ups in this area and the technology was oversold. No products resulted and the three large investing companies pulled back, leaving very few people very rich and many more jobless. The same scenario played out for all of the microfluidics investments in high throughput screening (HTS) applications. Early investments came from cash rich drug companies but there was no real market; too many competitors chased too few customers. The MEMS/STM lesson learned seemed to be: be wary of hype and MEMS applications should be geared towards mass consumption applications only. In other words, microfluidics might yet succeed when applied to diagnostics instead of applying it to HTS just as in the case of micro-mirrors that succeeded for portable projectors but failed for communication switches.

SOME USEFUL OBSERVATIONS

The authors of this WTEC report believe that the above market numbers for MEMS/MST are very misleading for three reasons: 1) Since these projections were made, both MEMS optical switches for telecommunications and microfluidics for high-throughput screening disappeared from the commercial scene, 2) These market studies do not define exactly what is meant with MEMS/MST and include traditional IC products and non-Si products that existed before the MEMS wave began, 3) they do not consider the fact that many micro-products are based on non-lithography techniques. In other words these numbers do not reveal what impact MEMS/MST as introduced in the early eighties has really had on the world economy. A more realistic number for MEMS products today is probably closer to 5% of the IC market (say roughly $10 billion of a $200 billion IC market for 2005).

MICRO-MANUFACTURING KICK-OFF WORKSHOP OVERVIEW – KEY ISSUES

The WTEC Micro-Manufacturing Workshop at the NSF on August 13, 2004 included presentations by a number of industry and government leaders in areas that today are seeing dramatic growth in micro-scale products and processes. Among the industry participants, several important sectors were represented: communications products (Motorola), medical implants/devices and life sciences (Medtronic, Medical Murray, NanoMedia), and micro-manufacturing processes and equipment (ESI, Miniature Tool and Die, Moore Nano Technology Systems, Timken). Several U.S. government laboratories were also represented including NIST, NASA Ames, Lawrence Livermore National Laboratories, and the Naval Research Laboratory. The University of Illinois at Urbana-Champaign provided insights from U.S. universities. During these presentations a number of recurring themes were introduced that provided the panel with important guidance for their trips abroad. These themes include the following:
• Difficulty in achieving *feature size and accuracy* with current macro-scale manufacturing equipment;
• The need for *multi-functional machines*, e.g., machines that combine processes such as micro-machining and measurement;
• Problems associated with *part handling, fixturing, and repositioning*, driven by part size and tolerance requirements;
• *Assembly* as a critical process, perhaps providing more challenges than processing;
• *Metrology* as a critical process, and the need for in-situ measurement and inspection methods;
• *Equipment cost reductions*, driven by the capital-intensive nature of micro-manufacturing;
• The need to better understand the influence of *scaling on process performance*;
• *Materials issues*, in particular, microstructure effects, consistency of properties, and multi-material integration;
• *Intellectual Property* concerns that inhibit cooperation and free exchange of information; particularly between suppliers and their customers;
• The need for *“out-of-the-box” thinking*; thinking should not be fettered by how we have done things in the past; talks by Chrisey and Cubbiociotti were inspirational in this regard;
• Need for *improved modeling and simulation tools* at the nano-to-micro-to-meso levels; this was an area that appears to need much more new thinking and attention.

*The remainder of this report is written in six (6) chapters that summarize the current state of affairs in the U. S. and important findings of the August 13, 2004 WTEC Micro-Manufacturing Kick-Off Workshop in the areas of Design; Materials; Processes; Metrology, Sensors and Control; Applications; and Business, Education, and the Environment.*

**REFERENCES**


CHAPTER 2. DESIGN

OVERVIEW

The need for accelerated technological and scientific progress on micro/meso-scale component and system design and manufacturing methodologies is rapidly becoming of vital importance for the continued expansion of miniaturization technologies. The performance of this category of products can be increased and their cost decreased only when micro/meso-scale product development and manufacturing steps can be better streamlined and accelerated by the provision of suitable design/manufacturing tools, i.e., art-to-part-support, for their synthesis. At the macro-scale, such capabilities are partially fulfilled by the commercially available CAD/CAPP/CAM/CAE systems and methodologies encompassed by the acronym DFX (Design for X). Boothroyd, et al, [1] gives a comprehensive overview of the principles and benefits of DFX. Unfortunately, it appears that at the micro/meso-scale such tools are lacking, although many of the approaches and capabilities available at the macro-scale could be suitably adopted, modified and appended for use at the micro/meso-scale. The ideal design synthesis tool would facilitate rapid system development for a given set of performance measures and constraints.

A search of the technical literature does not seem to yield any specific references to design methodologies explicitly devoted to issues at the micro/meso-scale, although there are abundant and a growing number of references to MEMS design [2, 3] and even more so for conventional mechanical system design. As a consequence, in this section, a more conceptual and philosophical approach will be taken to the assessment of micro/meso-scale design issues rather than giving an in-depth treatment of the subject. This will be accomplished by projecting/extrapolating approaches and solutions from other domains into this domain.

For the sake of further discussions we shall draw parallels between the mechanical designs of VLSI, MEMS, micro/meso-scale and macro-scale systems. From the design standpoint, there are at least four factors at play that make the design considerations vastly different among the aforementioned categories. These are: scaling effects, range of materials, range of available manufacturing methods, and topological/geometrical complexity. Two additional factors also come into play as one traverses from the micro- to the macro-scale, that is, the number of distinct components constituting the system, which at the same time implies larger dependence on assembly, and the relative motion between constituent parts.

The complexity of the design problems that need to be addressed increases as one approaches the macro-scale because of the enormous diversity of the applicable design and manufacturing methods. This is perhaps the sole reason why systematic automated synthesis tools do not exist for general design. On the other end of the spectrum, highly automated design tools, based on a very clear-cut and extensive set of design rules, are being used for VLSI systems. The VLSI design problem is further simplified by the limited number of basic building blocks (logic gates), whose interactions are well understood, and the very limited number of well-defined materials and fabrication processes used for their manufacture. It should also be underlined that powerful functional simulation tools are also at the designer’s disposal.

The complexity of the design problem increases for MEMS systems and, in particular, for 3D MEMS devices; however, a consensus appears to be emerging that the development of automated synthesis tools for this class of devices is plausible and well in progress [4, 5]. These developments are facilitated by the close correspondence between topological and manufacturing features for VLSI and MEMS devices. Specifically, MEMS devices are largely 2D to 2½ D in nature and their manufacture is predominantly rooted in the same methods that are used for VLSI devices. The factors that lead to a higher degree of complexity are the multi-energy nature of many MEMS devices and their increased geometric and dynamic complexity imposed by moving (elastically deforming) components. These differences have led to the use of tools conventionally
used at the macro-scale, e.g., solid modelers, FEM analysis, etc. and to the development of MEMS-specific analysis and synthesis capabilities. However, most MEMS CAD/CAE systems to date work best in the specific domains for which they have been developed. Several start-up companies have developed MEMS software in the nineties, but these companies did not survive. Particular difficulties arise when solving electrochemical and microfluidic modeling problems in miniaturized devices. For a listing of software packages applicable to miniaturized devices consult Table 1 and References [6-9]. Two design packages specifically developed for MEMS, and still in use, are: IntelliSuite, [10], and “CoventorWare™”. In an interesting development Kyocera Corporation partnered with U.S. based Coventor Inc. to develop the latter package which contains Kyocera’s standard ceramic packages material and design data. This package enables MEMS device designers to simulate the behavior of coupled MEMS devices with the package in the developmental stage, reducing package development time and costs. A detailed review of MEMS related CAD/CAE is given by Madou [11].

<table>
<thead>
<tr>
<th>Software Package</th>
<th>Capabilities</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic NASTRAN</td>
<td>Linear statics, dynamics, normal modes</td>
<td>University of Georgia Computer Software Mgmt Info Center 382 East Broad Street Athens, GA 30602-4772 Phone: (706) 542-3265 Web: <a href="http://www.cosmic.uga.edu">http://www.cosmic.uga.edu</a></td>
</tr>
<tr>
<td>MSC/PATRAN</td>
<td>General pre- and post-processing package Linear statics, dynamics, normal modes, heat transfer Non-linear statics &amp; dynamics</td>
<td>MacNeal Schwendler Corp. 615 Colorado Blvd. Los Angeles, CA 90041-1777 Phone: (800) 336-4838 Web: <a href="http://www.msc.com">http://www.msc.com</a></td>
</tr>
<tr>
<td>ANSYS</td>
<td>Linear statics, dynamics, normal modes, heat transfer Highly non-linear statics &amp; dynamics capability</td>
<td>ANSYS, Inc. Southpointe 273 Technology Drive Canonsburg, PA 15317 Phone: (724) 746-3804 Web: <a href="http://www.ansys.com">http://www.ansys.com</a></td>
</tr>
<tr>
<td>IDEAS</td>
<td>General pre- and post-processing package Linear statics, dynamics, normal modes, heat transfer</td>
<td>Structural Dynamics Research Corp. 2000 Eastman Drive Milford, Ohio 45150-2789 Phone: (513) 576-2400 Web: <a href="http://www.sdrc.com">http://www.sdrc.com</a></td>
</tr>
<tr>
<td>FEMAP</td>
<td>General pre- and post-processing package Linear statics, dynamics, normal modes, heat transfer</td>
<td>Enterprise Software Products, Inc. 415 Eagleview Blvd., Suite 105 Exton, PA 19341 Phone: (610) 438-3660 Web: <a href="http://www.femap.com">http://www.femap.com</a></td>
</tr>
<tr>
<td>COSMOS</td>
<td>Linear statics, dynamics, normal modes, heat transfer</td>
<td>Structural Research &amp; Analysis Corp. 1221 Wilshire Boulevard, 7th Floor Los Angeles, CA 90025 Phone: (310) 207-2800 Web: <a href="http://www.cosmos.com">http://www.cosmos.com</a></td>
</tr>
</tbody>
</table>

As MEMS devices bear a close family resemblance to VLSI, so do micro/meso-scale systems to macro-systems. Therefore, the same deficiencies, i.e., the lack of general synthesis tools that exist at the macro-scale are also reflected at the micro/meso-scale. Compounding these difficulties are the not-negligible effect of scaling laws, which can be largely neglected at the macro-scale, and the non-trivial impact imposed by assembly constraints. It can be reasonably surmised that the limitations imposed by manufacturability and assemblability of micro/meso-scale components and products that will enforce, at least in part, a different set of DFX rules than those that apply at the macro-scale.

At the micro/meso-scale, production and assembly constraints may favor the minimization of the number of components and consequently assembly operations. This necessity may further be accentuated and imposed by limitations on achievable relative accuracies and surface finishes of the components. It is not clear, at this moment, what the overriding design philosophy should be in order to create a realizable and cost effective product. This impasse may also suggest that parallel design of the product and of the processes that affect it.
throughout its life-cycle, a method also known as concurrent/simultaneous engineering, may become an
dispensable necessity at the micro/meso-scale [12].

In summary, if the ultimate design tool for micro/meso-scale systems were to mimic the capabilities that
currently exist for VLSI system design, the current state-of-the-art does not look very uplifting. If one
considers the main constituents of a fully-blown design environment at the micro/meso-scale namely,
product synthesis, topology/geometry design, process simulation and functional simulation, only
topology/geometry design and functional simulation tools are developed (borrowed from the macro-scale).
The least explored aspects are related to process simulation. This also becomes evident if one assesses the
current micro/meso-scale product development practices, which predominantly rely on empirical and trial-
and-error methods given the limited process-related knowledge of the designers.

WORKSHOP FINDINGS

The presentations at the Workshop did not directly address the issue of designing miniaturized components
and products. However, the indirect implications suggest that design related issues are of paramount
importance for the successful growth of miniaturization technologies. Specific problems that were
highlighted address both ends of the spectrum, namely the design of miniaturized components and products
as well as the design of the equipment and processes required for their manufacture.

The absence of a more direct recognition of the significance of design issues perhaps rests in the fact that, at
the present, the bulk of the development effort is focused on making the product any way that it is possible,
with any tools available, rather than focusing on the development of more effective design methodologies
and tools or the minimization of development and manufacturing costs.

Ms. Donna Bibber of Miniature Tool & Die, Inc. explicitly identified several problems, namely:

1) industry standards that are indispensable at the macro-scale do not apply at the micro/meso-scale. The
   lack of standards for material characterization and for testing material properties is particularly
troublesome;
2) analysis software, e.g., MoldFlow™, cannot simulate the manufacturability of features at the micro-scale
   without significant modifications;
3) lack of funded developments to push the envelope and to test new methods that would lead to more
   commercialization of new innovative products.

Although these statements were made in the context of the problems faced by a leading micro-molding
company, they can certainly be viewed as endemic problems plaguing miniaturization and micro-
manufacturing which are repeatedly pointed out below.

A reoccurring theme in the presentations pinpoints the increased need for high levels of functional
integration, e.g., Dr. Iwona Turlik of Motorola, Mr. Phillip M. Leopold of Medical Murray, Inc., and Dr.
Darrel Untereker of Medtronic, Inc. These observations again imply the need for suitable design tools.

Dr. Darrel Untereker adds to the list the difficulties encountered by the push to reduce device size which
limits flexibility in the choice of the shape of the component/product. He also adds the uncertainty of
assessing risks, since assessments are usually made by extrapolating from larger scale experiences.

In the context of medical device manufacturing, Mr. Phillip M. Leopold reconfirmed the above statements
and identified additional issues, viz.,

1) extremely long development cycles, partly caused by design related issues,
2) lack of knowledge by the designers of miniaturized systems about state-of-the-art manufacturing
   possibilities, and,
3) cost and time-to-market delays caused by need to re-design.
The need for systematic and in-depth training and education for micro-structure design and manufacturing has clearly emerged in a number of presentations.

The realization of miniaturized products with intricate features and tight tolerances will undoubtedly depend on the ability to simulate physical phenomena at the micro/meso-scale. Therefore, the assessment by Dr. Deepak Srivastava of the NASA Ames Center for Nanotechnology of existing efforts on multi-scale modeling is of particular significance. He compellingly stresses the importance of multi-scale simulations and points to the fact that micro/meso-scale simulation efforts are in their infancy. And, that at the present, there is no commercial driver for software and simulation platform development.

In relation to the development of suitable manufacturing machines and equipment, Dr. Brad Damazo of NIST, notes the following:

1) novel machine designs (e.g., novel kinematic configurations, separation of metrology from load bearing loop, etc.), paired with new technologies can address the need for increased accuracy while lowering the cost, and,
2) new standards and methods for assessing the accuracy and performance of machines used for micro-manufacturing are needed.

Dr. Shiv Kapoor, from the University of Illinois at Urbana Champaign, reached similar observations and conclusions in giving an overview of new design efforts related to the development of miniaturized machine tool systems [13, 14] and component devices.

REFERENCES


CHAPTER 3. MATERIALS

OVERVIEW

Products of micro- and nano-fabrication have size scales spanning several hundred micrometers to tens of nanometers. Independent of the specific manufacturing process, these size scales impact material structure and concomitant mechanical and physical properties. The purpose of this Chapter is to review in summary fashion the microstructural changes that give rise to these property changes.

A principal feature of materials is the presence of grains. The boundaries between grains in polycrystalline materials are disordered crystallographically and serve as high mobility pathways for atomic transport. Typical grain size in materials varies between a few micrometers to approximately 100 micrometers. As the overall part size decreases below this size range, grains must either be removed or refined. If removed, the resulting part is a single crystal. Most physical and mechanical properties of single crystals are anisotropic, leading to directional variations in properties [1]. For the latter, reduction in grain size results in significant property changes. Strength of conventional polycrystalline materials obeys the well-known Hall-Petch relationship in which strength is proportional to the reciprocal square root of grain size [2]. Extension of this relationship to micro/nano grains results in sizeable strength increases. Departure of material behavior from this Hall-Petch relationship may occur at the nano-scale, with reports of an inverse linear relationship and even grain size weakening [3]. This is shown in Figure 1 for TiAl tested at room temperature and -30°C. For large grain size (0<d<0.22 nm^-1/2), the usual Hall-Petch strengthening is observed. For fine grain size (d<0.22 nm^-1/2), grain-size weakening is observed.

![Figure 1. Microhardness of Nanocrystalline TiAl as a Function of Grain Size. From Ref. [3].](image)

For nano-scale grained materials, as many as 15-50% of atoms are present in the disordered grain boundary regions [4]. This gives rise to grain boundary instability. For example, nanocrystalline palladium has shown grain growth at 0.16T_m (T_m is the absolute melting point), whereas typical materials do not exhibit significant grain growth until temperatures of approximately 0.5T_m are reached [5]. Ultrafine-grained materials have been shown to obey the traditional power-law coarsening relationship.
\[ D^n - D_0^n = kt \]

where \( D \) is the grain size, \( D_0 \) is the starting grain size, \( n \) is a constant equal to approximately 2, \( k \) is a constant and \( t \) is coarsening time [6]. Figure 2 shows the evolution of grain size for 9 nm iron prepared by mechanical attrition. As the starting grain size is reduced, grain growth is driven by coarsening time. Effectively, reductions in grain size are ineffective in delaying grain coarsening. Several traditional methods have been used to retard grain growth in ultrafine-grained materials, including second phase particles, solute effects and even fine porosity [7]. All serve as drag forces on moving grain boundaries.

![Figure 2. Grain Growth for 9 nm Iron as a Function of Annealing Temperature and Time. From Ref. [6].](image)

Grain boundary size reduction affects chemical diffusivity. The large volume fraction of atoms associated with the disordered grain boundary regions produce atomic mobility orders of magnitude higher than traditionally observed [8]. One effect is an increase in solubility, particularly for interstitial atoms such as hydrogen [9-11]. Another effect is reduction in the temperature associated with high-temperature plasticity. This latter effect has engendered a class of deformable ceramics with grain size less than 300 nm at temperatures on the order of 1200 °C [12, 13].

For most metals, mechanical properties are dominated by the presence of dislocations and their mobility. As grain size is reduced, the maximum spacing between a dislocation and a grain boundary is reduced. Since grain boundaries may act as a sink for dislocations, at grain sizes less than 20-30 nm, dislocations may literally vanish from the microstructure or may be present only in non-mobile, sessile orientations [4]. The inability to move dislocations results in high strength and usually vanishingly small ductility.

Reduced grain size also impacts the magnetic response of certain materials. As the grain size is reduced to below the domain size (on the order of 10-100 nm) in ferromagnetic materials, transition from multidomain behavior to single domain behavior occurs and easy magnetization disappears [7]. As grain size is further reduced, the coercivity decreases until a superparamagnetic state is reached. These effects allow materials designers to produce a wide variety of materials with outstanding hard and soft magnetic properties [14-17].

Several researchers have noted that size reduction can produce non-equilibrium crystallographic phases in certain materials, often associated with high-pressure phases. An example is nano-sized zirconia where the equilibrium monoclinic phase is partially converted to the high-pressure tetragonal phase [18]. Refractory metals including Cr, Mo and W have been reported in nanocrystalline form in the A15 structure, rather than the usual body-centered cubic form [19-21].
WORKSHOP FINDINGS

The performance of a material does not directly scale with size, because microstructural features giving rise to a number of engineering-important properties have a size range of the order of tens of microns. Examples are the grain size in metals, chain lengths in certain polymers and the domain wall size in certain magnetic materials. When the physical dimensions of a part decrease into the meso-, micro- or nano-scale, the microstructural morphology changes dramatically, resulting in a concomitant nonlinear change in properties and part performance. Therefore, understanding fundamental underlying materials science of polymers, metals and ceramics is crucial to successful application and optimization of micro-manufactured components and devices.

Donna Bibber of Miniature Tool & Die, Inc., reported on micro-injection molding of polymeric parts with features as small as one micron. The challenges are characterization of mechanical properties of micro-molded parts in the absence of testing standards and limitations on processing posed by injection screw flights that do not allow smaller sized pellets.

Materials are crucial in medical applications. Phillip Leopold from Medical Murray, Inc. described thermoplastic and silicone rubber parts 0.01 to 80 mm$^3$ with wall thicknesses to 120 microns. Current needs are for a larger selection of materials for implants, flow of plastic in very thin sections as it pertains to mold filling, understanding of bonding mechanisms of dissimilar materials at the micro-scale, methods for controlling and removing flash in molded parts and moisture control.

Edward Swenson of Electro Scientific Industries, Inc. described the use of lasers to ablate polymers and metals uniformly in the micro-scale range. Materials include nickel, copper, and polyimide.

The Naval Research Laboratory is involved in biological systems micro-manufacturing. Doug Chrisey described work involving both deposition of living matter using additive manufacturing and creation of scaffolds with variable pore size in the range of 2 to 5 $\mu$m.

As the size scale decreases, it becomes increasingly facile to model and simulate performance using molecular dynamics (MD) simulation techniques. Dr. Deepak Srivastava is using MD techniques at the NASA Ames Center for Nanotechnology to predict the behavior of hundreds to thousands of atoms in a nano-array. A few groups are working with a few million atoms and one group in the world has modeled a billion atoms (effectively less than 0.5 $\mu$m cube). The primary research issue is generation of atomic force field functions for a wider class of materials.

Considerable materials work is being performed by Kapoor, DeVor (University of Illinois) and Ehmann (Northwestern University) in the area of workpieces and machine tools. For the former, understanding of chip forming processes and its impact on surface finish is important. Repeatability and reliability are driving considerations in production of micro-milling tools with diameters as small as 10 $\mu$m.

Richard Knepper from Timken is developing and marketing miniature bearings and assemblies for medical, dental, instrument, aerospace, military and avionics applications. The market is for low-volume, highly engineered components. Materials issues at Timken are strength, thermal issues and polymer stability.

Darrel Untereker described micro-manufacturing at Medtronic, Inc., the world’s largest manufacturer of implantable medical devices. Materials issues for micro-manufactured human-body implants are improved strength and particularly fatigue resistance. Improved dielectric strength of miniaturized circuit boards and improved high-density capacitors are needed as the size scale of electronic devices decreases. The medical implant industry faces specific limitations in micro-manufactured materials since the list of acceptable materials is limited to only about ten types.

Several common themes persist in domestic micro-manufacturing. First, the need for improved mechanical properties is established. Strengthening mechanisms at the micro- and nano-scale must be better understood and more widely disseminated. Striving for the competitive edge and acquiring market share hamper open communication within and across industries. Second, it is unclear where materials development for micro-
and nano-scale applications will be performed. Private companies generally do not have the manpower to do materials development. Materials suppliers, traditional sources of improved materials, rely on future materials sales to compensate development efforts. This is problematic for micro- and nano-scaled materials applications since the volume of material is so small. This was put into perspective by Donna Bibber of Miniature Tool & Die, Inc., who mentioned that over 500 micro-manufactured parts could be injection molded from a single pellet of plastic.

REFERENCES

CHAPTER 4. PROCESSES

OVERVIEW

The need for and use of micro features, micro components and micro products is rapidly increasing in diverse fields of electronics, medical, automotive, communications and avionics. The world market for micro products/components is expected to be about 68 billion dollars by 2005. During the last five years, many workshops and conferences have focused on the application potential of micro products, required micro-manufacturing processes and research needs in micro-manufacturing. Although extensive research and development efforts have been directed towards micromachining of silicon-based components used in the microelectronic industry, the related technologies such as X-ray, lithography, galvanforming (electroforming) and molding (LIGA), are able to generate only 2 and 2½ D features on a limited number of materials. Many micro-manufacturing processes have been developed by downscaling existing precision engineering processes or up scaling MEMS processes. These micro-manufacturing processes vary in terms of their working principles (mechanical, thermal, dissolution, ablation, solidification and sintering), and material interaction (subtraction, mass containing, addition, and joining). However, the research and development efforts in all manufacturing processes need to address issues related to process modeling and simulation, process–material interactions, monitoring and control, process capabilities, tool and equipment design, metrology, economics and applications.

1. Additive Micro-Manufacturing

Additive Manufacturing represents a series of technologies referred to variously as Rapid Prototyping, Freeform Fabrication, Rapid Manufacturing, Solid Freeform Fabrication and Direct Digital Manufacturing. Common to additive manufacturing is direct production of parts with three-dimensional geometry without the use of part-specific tooling. While the mainstream of additive manufacturing is focused on parts and tooling on the macro-scale, numerous processes have been developed over the last 20 years that allow production of parts in the meso- and micro-size scales.

Gas Phase Deposition.

A focused laser beam may be used to pyrolytically or photolytically decompose gaseous species, resulting in deposition of solid matter. The initial work in freeform fabrication was developed by Marcus and co-workers [1, 2] who were able to draw lines and build columns of graphite that were 70-200 micrometers wide. This research was advanced by Professors Pegna at RPI and Maxwell at Louisiana Tech in the late 1990s. Production of 50 µm graphitic walls from ethylene precursors was demonstrated [3], as was production of amorphous graphite springs with 300 µm major coil diameter and 20 µm “wire” diameter [4] (see Figure 1). Production of 70 µm tungsten springs was effected by thermal decomposition of tungsten hexafluoride [4]. Dr. Maxwell demonstrated in follow-up research the ability to laser machine graphite and diamond-like carbon columns to sizes of the order of 30 µm after deposition from a variety of gases including acetylene, methane and ethylene [5].
Micro-Droplet Deposition.

Professor Sonin at MIT reported on the formation and deposition of fine droplets of Candelilla wax [6]. Using a piezoelectrically driven modified inkjet print head, droplets approximately 50 µm in diameter were created and deposited into a variety of shapes 200 µm to 800 µm in size. Dr. Orma at the University of California at Irvine demonstrated metallic droplet formation by mechanical-vibration induced Rayleigh instability of a molten stream forced through an orifice [7, 8]. Droplets of a lead-tin alloy less than 200 µm in diameter were deposited. Later developments at UC Irvine included deposition of <300 µm aluminum alloy droplets [9]. In both cases, the molten droplets are electrically charged as they exit the orifice, allowing control of their flight. Researchers at the University of Pittsburgh have developed a continuous inkjet printing technique for conductive inks [10]. Both drop-on-demand, piezoelectric and continuous stream modes have been developed, with 100 µm conductive ink droplets loaded with silver nitrate. Professor Sun at Drexel University has researched micro-fabrication of hard and soft tissue scaffolds using continuous and discrete droplet formation [11, 12]. Using nozzles varying in exit orifices from 30 µm to 500 µm, Dr. Sun has continuously extruded hydrogels as well as picoliter-sized droplets. He has produced hydrogel lines 30-40 µm in width.

Controlled Powder Spray.

Professor Li at the University of Wisconsin at Madison describes a meso/micro-manufacturing system based on piezoelectric feeding of dry powder followed by sintering [13]. Lines on the order of 100 µm have been laid and sintered using copper, invar and stainless steel powder in the particle size range of 3-20 µm. Combined with laser micromachining, lines less than 70 µm could be laid and sintered.

Mask Processes.

Dr. Maxwell at Louisiana Tech investigated photolytic decomposition of titanium tetrachloride to form 1-8 µm thick lines of titanium metal less than 100 µm wide [14]. Research at the University of Southern California developed a process termed EFAB, “Electrochemical Fabrication” [15]. A mask is created between electrodes using an “Instant Masking” technique. Material is electrodeposited through apertures in the mask. The mask is removed and a second material is uniformly deposited and machined to fill are regions initially occupied by the mask. These steps are repeated to build up a bi-material structure. If one of the materials is a sacrificial support structure, subsequent removal allows for creation of complex three-dimensional structures in the non-sacrificial material. The initial demonstration system was nickel with sacrificial copper. Features as small as 12 µm were obtainable. Similar work on laser-based electrochemical deposition is being pursued at the Laser Processing Research Centre at the University of Manchester in the United Kingdom.
Micro-Selective Laser Sintering.

Selective Laser Sintering (SLS) is a tradition freeform process in which a thin layer of powder, usually 100 µm thick, is scanned by a computer-controlled laser to sinter or melt together the particulate. By repeating the process with additional layers, a complete part may be created. Researchers at The University of Texas at Austin have probed the limits of feature size using commercially available machines [16]. Using fine zirconia powder, holes no smaller than 150 µm were obtainable. Peter Regenfuß of the Laserinstitut Mittelsachsen in Germany has developed a micro-SLS machine with feature resolution in the 10-30 µm range [17, 18]. Working with submicron tungsten powder in an atmosphere-controlled chamber, pyramidal structures, bihelical coils and nested spherical structures of wall thickness less than 100 µm have been created, Figure 2. Wood and Beaman at The University of Texas at Austin have explored use of direct write technologies for creation of micron-sized features in sol-gels [19]. Tetraethyl orthosilicate sol-gel precursor thin films less than 2 µm thick were spin-coated onto (100) silicon or borosilicate glass substrates. Drying produced a silica sol-gel. Scanning the thin layer with a focused continuous wave CO2 laser resulted in creation of densified lines less than 30 µm wide. These lines showed increased index of refraction, consistent with various micro-optical devices such as waveguides and optical fiber couplers.

Figure 2. Tungsten Parts Produced Using Laser Micro-Sintering. From Ref. [17].

Micro-Stereolithography.

Stereolithography involves laser photocuring of a photosensitive liquid photopolymer resin. A thin layer is scanned using a low-energy laser to selectively crosslink the layer. A new layer is deposited by recoating the previous layer, and the process is repeated to eventually create a part. The German Envisontec Perfactory photopolymer system has recently entered the stream of commerce. The light source for photopolymerization presents to the polymer from the bottom of the build chamber similar to the Japanese designs by Denken Engineering and Mitsui Zosen. Unique to the Perfactory is formation of the layer image using a 32-µm resolution micro-mirror array. The digital mask contains 1280 by 1024 mirrors that are digitally controlled to allow various shades of light to expose the photopolymer. This micro-mirror array concept has been utilized in to form micro-sized objects. Dr. Li at the University of Wisconsin at Madison has formed a line/grid array in photopolymer with features less than 25 µm [20]. Gears and a square micropillar have been fabricated with overall dimensions less than 800 µm. Dr. Rosen at Georgia Tech has developed a similar micro-mirror SLA device. He has created object in photopolymer with features as small as 30-100 µm [21], Figure 3.

Figure 3. Microparts Produced Using Micro-Mirror Stereolithography. The driveshaft has a 1 mm wheel base. The gear diameter is 750 µm. The “RPMI” letters are 40 µm tall. From Ref. [21].
2. Subtractive Processes:

The subtractive processes such as micro-turning, micro-milling, micro-grinding, and micro-electrical discharge machining are now applied to make 3D precision micro components [22-27]. Irrespective of the type of material removal, these processes are characterized by two factors; one is the Unit Removal (i.e., the amount of material removed in one cycle of removal action) while the second, is the equipment precision, which will determine the achievable accuracy of the machined components [23]. In general, micromachining processes can be classified as mechanical and thermal.

Mechanical Micromachining.

Mechanical micromachining processes with defined or undefined cutting edge have been used to produce high-precision micro-components for applications in optical systems for lasers, lens molds for visible spectrum or air bearings [28]. In cutting and grinding processes, the tools are in mechanical contact with the workpiece and therefore, a good geometric correlation between the tool path and the machined surface is obtained. In particular, the size effect and its characteristics and process-material interaction are extensively reviewed in [29].

Mechanical micro-machining processes (such as turning, drilling and grinding) have the advantage of higher material removal rate over microelectronic fabrication methods in machining 2D and 3D complex micro shapes. The effect of scaling on the process mechanism including chip formation, cutting forces, vibration and process stability, and the surface integrity of machined components are some of the important issues being addressed by researchers. Additionally, the work and the micro-tool deformation due to direct contact of the tool and workpiece and its effect on the micromachining accuracy are also important topics for further investigation.

Studies [30-32] of the impact of size effect on cutting forces and specific energy during micro-cutting processes have revealed that ploughing and elastic recovery of the workpiece play significant roles when chip thickness values are close to the edge radii of the cutting tool. The impact of size effect on minimum chip thickness [33, 34], on surface generation and burr formulation [35, 36] built-up edge formation [37], and microstructure effects [38-40] have been reported. Various modeling techniques including molecular dynamics (MD) simulation, FEM, multi scale simulation modeling and mechanistic modeling have been developed to characterize micro-machining processes and are discussed in [29].

Micro-grinding processes are being used in medical applications such as bone pins, guide wires, neurological catheters and dental implants where the requirements include components of up to 25 µm in diameters with tolerances up to 1 µm and finishes of 6-8 Ra. Although earlier micro-grinding research focused on axisymmetrical components of hard-brittle materials, a new grinding method using “high table reversal speeds” for reducing the “gritcut load” has been proposed to address the problem of edge chipping [42]. Deep slots (1.2 x 0.1 x 1.5 mm) with an aspect ratio of 15 were generated using table feeds of 88,000-55,000 mm/min.

Thermal Micromachining.

Laser technology is being used both to remove material and join micro parts. The formation of the re-solidified layer and the heat affected zone on the machined surface, non-uniform depth of cavity and tapered walls are some of the problems that need further study. An Excimer laser or a femtosecond laser can reduce or eliminate these drawbacks as the material is removed by vaporization. However, the use of such technologies results in lower machining efficiency and higher cost of the equipment. When a deep micro-hole is drilled, the diffusion of laser beam may cause low machining accuracy and needs further investigation [27].

In the Electrochemical Machining (ECM) process, the material is removed by controlled anodic dissolution. Many efforts of developing the micro-ECM process have been reported [43-51]. Recently a 2 ½ D micro cavity has been generated by considering the gap as a RC circuit consisting of a double layer capacitance and a resistance [52]. The continuous and uniform replacement of electrolyte in the gap and localization of anodic
dissolution poses difficulties in drilling a micro-hole and machining of 3D complex cavities and needs further study.

In micro-EDM, the material is removed by the electrical discharges between the workpiece and the tool which are immersed in dielectric liquid. Since there is no mechanical contact during machining, neither workpiece nor tool deformation occurs. Currently, micro-EDM is widely used to prepare micro-tools, drill micro-holes, produce micro parts and generate micro molds. Extensive research on the fabrication of micro tools, machining of 3D complex cavities and high aspect ratio holes by compensating tool wear and by applying planetary movement has been reported [23, 52-60]. However, tool wear, and difficulties in debris removal cause accuracy problems and unstable machining, respectively, and need extensive studies. To avoid arcing and short circuits at the gap, it is necessary to develop gap monitoring and control systems. A comprehensive model of the phenomena at discharge gap will help optimize the process.


Forming processes that are based on plastic deformation are extensively used for production of a wide variety of near net shaped parts of many different materials. However, similar to material removal processes, research and development effort are being carried out to address the issues related to size, shape and orientation of grains of the material to be formed. The flow stress, anisotropy, ductility and forming limit, forming forces, spring-back, and tribology are some of the many factors that need further study for micro-forming processes. Micro-molding (such as powder injection molding) processes have been extensively developed and being used in industries. The automation of powder injection molding process has been reported [61-74].

The process of extrusion has been studied to establish it as a viable micro-forming operation [61]. A forming assembly was fabricated and used in conjunction with a loading sub-stage to extrude micropins with a final diameter of 1 mm. The effect of grain size was investigated by using workpieces heat treated to produce grain sizes varying from 32 µm up to 211 µm. The effect of miniaturization on bulk metal forming has been evaluated through a series of double-cup extrusion experiments performed on CuZn15 brass alloy [68]. Samples varying in dimension from 0.5 mm to 4 mm, which were scaled in order to retain geometric similarity, were used and it was found that decreasing the sample dimensions increased the friction factor by 20 times. An increase in the workpiece surface roughness and larger coarse grains (150 µm vs. 50 µm) in the sample were found to cause the friction factor to increase.

Micro-forming is an appropriate technology to manufacture micro parts, in particular for bulk production. However, one of the main problems encountered in micro-forming is the scaling effect which occur in the tribological aspects such as the friction coefficient that increases with decreasing specimen size [74]. Scaling effects occur not only within the process but also through out the forming process chain. Laser techniques have been developed and used in the micro-forming area in order to smooth the scaling effects, especially in tool manufacturing.

WORKSHOP FINDINGS

Although many presentations at the workshop addressed micro-manufacturing processes indirectly, Ms. Donna Bibber of Miniature Tool & Die, Inc. and Professor Shiv Kapoor explicitly described the related application and modeling aspects, respectively. The importance and role of materials and their interaction with manufacturing processes, modeling and simulation of the manufacturability of micro features, and the lack of overall standards for micro-molding operations were stressed by Ms. Bibber. Professor Kapoor presented a detailed report on the progress made in understanding and modeling the cutting mechanics at the micro-scale.

Philip Leopold of Medical Murray, Inc highlighted not only the need for additional implant materials but for extensive research effort for understanding bonding mechanisms of dissimilar materials at the micro-scale and development of techniques to control and remove flash.
Doug Chrisey of the Naval Research Laboratory presented applications of additive manufacturing processes to deposition of living matter.

Deepak Shrivastava presented applications of molecular dynamics (MD) simulation techniques to model and simulate the behavior of thousands of atoms in a micro-array. It seems that there is a potential for applications of his technique to micro/nano-manufacturing processes modeling and simulation.

Richard Knepper (Timken) and Darrel Untereker (Medtronic, Inc) described the development of miniature bearings and implantable medical devices. Although totally different materials, processes and applications, the difficulties of generating the desired shapes by micro-manufacturing processes, accuracies, process-material interactions, and scaling-up issues are common and need further investigation.

The workshop presentations and literature review clearly indicated that there is a great need and potential for micro components and products in many industries (including medical, avionics, electronics and communications). However, the current industrial production of such components and devices uses the existing macro-manufacturing processes and equipment. The high equipment cost and the available resolution limit the economic production of highly accurate micro-components needed for applications mentioned above. Therefore, there is a need to develop miniature equipment, to modify the existing processes and develop new micro-manufacturing processes for economic production of precision micro products. The process mechanism and modeling based on scaling effect, process capabilities and accuracies, monitoring and control strategies and surface integrity issues need to be addressed. Efforts of creating a qualified workforce in the field of micro-manufacturing processes and equipment are equally important for enhancing the application potential of micro-manufacturing technologies.

REFERENCES


[40] R. E. DeVor and K. F. Ehmann, “Micromachining research with industrial applications for cutting force analysis”, SME precision micromachining technology and applications, May 2004


CHAPTER 5. METROLOGY, SENSORS AND CONTROL

OVERVIEW

Tools for MEMS metrology are primarily derived from techniques of the semiconductor industry. These tools are typically limited to measurements of critical dimensions. A critical dimension is typically represented by a line width or pitch width measurement [22]. These measurements are inherently one-dimensional and provide minimal feedback with respect to the overall part geometry. The relatively new area of MEMS microfabrication adds a third dimension to parts manufactured by traditional semiconductor processes. These three-dimensional parts require metrology tools that can measure in three dimensions; however, semiconductor metrology techniques are frequently the only feasible method for obtaining geometric information from MEMS devices. Furthermore, MEMS devices are mechanically dynamic by nature. Therefore, there is also a need to measure both static dimensions and dynamic motion of MEMS devices. Hibbard and Bono provide a good initial review of meso-scale metrology tools and a more in-depth review of the current tools and their fundamental limitations [14]. A more in-depth state-of-the-art review is currently being conducted and will be included in the report of this committee. Typical approaches that are employed include capabilities that are extensions of semiconductor tools, scaled down versions of conventional metrology tools, and entirely novel methods for MEMS inspection.

For dimensional metrology, there exist devices that can measure to the atomic scale such as the atomic force microscope. While this level is too detailed for micro-manufacturing, it demonstrates that extremely high resolution can be achieved. Several difficulties exist with respect to micro-metrology. In general, the major problem with dimensional metrology for micro-manufacturing is that most tools are 2-D in nature, and are extremely slow. These measurements can be made on the top or bottom of the micro-component, and then linked to provide a pseudo 3D (2.5D in reality) as no sidewall information is available [31].

While most metrology techniques focus on dimensional metrology and some dynamic metrology, few systems exist for measuring other properties of micro-systems. Quantities that must be measured include material properties (e.g., Young’s modulus, Poisson ratio, etc…). Thus, new sensors and techniques must be developed to not only measure distance (e.g., dimensions) but also a variety of other parameters such as force, compliance, natural frequency, etc… on a micro- or even nano-scale. Furthermore, distance measurements are also required for feedback on micro-manufacturing systems. If these devices are to be incorporated in such systems, they must be cost effective or they drive the price of the micro-manufacturing operation too high.

1. Sensing Systems

There are a variety of systems that are currently used in micro-metrology. Each system and sensor has its strengths and weaknesses. A brief summary of some of the more prevalent systems is presented in this overview. This is not an exhaustive list, but provides some insight into the current systems capabilities and their shortcomings.

Scanning Electron Microscope.

One of the primary tools used for analysis of MEMS devices is the scanning electron microscope (SEM). SEMs are capable of producing high resolution images of conductive objects on the angstrom scale. SEMs operate by scanning a focused beam of high energy electrons across a conductive sample contained in a vacuum. As the electron beam hits the conductive surface, secondary electrons are knocked loose. These secondary electrons are counted by and used to create an image of the sample. The accuracy of the images
captured is highly dependent on machine capability and the specific part being examined. Beam-sample interactions (i.e., charging) are shown to greatly influence the results of any measurement taken with the device. Additionally, despite the high resolutions of the SEM, the output is typically generated from the electron detector and displayed on a cathode ray tube rastered in synchronization with the electron beam. The final result is a two-dimensional image on a screen. Since no coordinate data are directly outputted from the SEM, performing any analysis other than line width measurements directly with the SEM software becomes difficult. Thus, SEMs are ideal for visualizing MEMS parts, but are inadequate tools for quantitative analysis of MEMS devices [37, 27, 45]. An alternative SEM process is called X-SEM. This process is destructive and requires the sample to be cross-sectioned. The cross-section is then imaged in an SEM. Often this technique is used to determine sidewall and height characteristics [34]. Lagerquist et al. [21] discusses use of the X-SEM process to characterize top-down SEM images, which require interpretation of intensity and are sensitive to sidewall geometry.

Top-down SEMs are frequently used to characterize microstructures. Mack et al. [24] uses top-down SEMs to create polygonal representations of printed lithographic patterns. Marschner et al. [28] describes a method of using two top-down SEM images, one taken with a small tilt angle (3° to 6°), to gain information regarding top edge rounding and the sidewall profile. The result of the two scans found to be very sensitive to the algorithm used to combine the two images. When compared to X-SEM images, the results did not match well.

Optical Microscope.

Optical microscopes are used to inspect relatively large MEMS such as those fabricated from the LIGA process, which has the capability of producing parts that are a few mm tall. The underlying operating principles for optical microscopes include spatial resolution determined by the Rayleigh criterion and detected edge sharpness determined by a combination of hardware (e.g., lens type, CCD camera) and lighting conditions (e.g., coaxial lighting, ring lighting). Optical microscopes have the advantage of being fast and non-destructive. Rarely do test parts have to be modified (e.g., coated with a conductive material) from their original form. Optical microscopes tend to be repeatable for features as small as 0.25 µm. The ultimate limiting factor for resolution of optical metrology hardware is diffraction and the ability of the microscope to produce images with clear intensity changes in order to accurately detect edges. Often locating the edge of a part is difficult, as observed location varies with lighting condition, noise, and assumptions made in the edge position algorithm [8]. Other significant errors of optical techniques typically stem from interference, resonance, shadowing, secondary reflections, and lens distortions [26, 46, 6].

An important limitation of optical microscopes for MEMS inspection is inability to acquire true three-dimensional data. Some optical microscopes are integrated with software that uses image processing techniques to determine the Z-height at which the scan is taking place. The current state-of-the-art software uses a projected Ronchi grid to determine the height at which the microscope is focused in one region of the image [51]. If the region selected has multiple focus points (i.e., the region selected is not all on one plane), the algorithm assigns the average value for the Z-height. Further edge detection algorithms are run to extract X and Y data from the microscope image. This technique, in theory, produces three-dimensional data from an image; however, the algorithms used after finding the Z-height in one location of the image assume that all of the data are on the same plane. Thus, the data acquired from vision systems such as these can be characterized as 2 ½ D data sets.

Scanning White Light Interferometer.

A third method of meso-scale part inspection is scanning white light interferometry (SWLI). Although initially developed for surface characterization, such as finding surface roughness, it is currently being used to make dimensional measurements of meso-scale parts [30]. White light interferometers have sub-nanometer resolution in the scanning direction, at best sub-micron resolution in the lateral directions, and can be used on a multitude of parts with different surface finishes [11, 44].

White light is commonly used in scanning interferometers because it allows for higher resolution by comparing data from multiple wavelengths. Additionally, it is possible to resolve step height changes greater
than $\lambda/4$ [53]. SWLI has the ability to quickly measure step heights changes and deflections. Additionally, when integrated with an image processing system, SWLI can provide lateral dimensions. However, the lateral resolution of commercially available systems is lacking, except when equipped with high power objectives which severely limit the field of view. Additionally, these tools are limited in their ability to measure sloped surfaces. The largest slope that can be identified is typically around 30° with a 100x objective [54]. As the objective power decreases, the identifiable slopes also decrease.

Despite these limitations, white light interferometry is heavily used in the MEMS industry to determine surface roughness, structural support analysis, deflection curve verification, and material property analysis of parts [32]. Shilling [41] has also used SWLI to analyze meso-scale devices with relative success. SWLI provided good results except at the edges of parts which tended to be non-square. Because of the slope limitations inherent in the machine, data is not gathered from the edges of a part, resulting in an incomplete data set.

Confocal Laser Scanning Microscope.

Confocal Laser Scanning Microscopy (CLSM) combines a confocal microscope with a scanning system in order to image an entire specimen. Although scanning can be performed in several different ways, it is most often done by moving the beam which alleviates focus problems caused by objective lens scanning and is faster than specimen scanning [58]. Confocal microscopy is different from conventional microscopy in that it creates an image point by point. Also, because of the double pinhole lens system, when the sample is moved out of the focal plane of the objective, the light intensity at the detector decreases rapidly, in effect, allowing the system to focus on a single plane. By moving the detection pinhole, a different plane can be imaged. With a scanning system added, the system has the ability to scan multiple times on different imaging planes, resulting in a three-dimensional data set. Structure dimensional measurements are in the range of microns with nanometer accuracy.

Work has been done to use this system to perform 3-dimensional analysis of microstructures such as micro end mills and hot embossing tools, both with overall dimensions on the order of 1mm [49]. One of the most important advantages found was the ability of the microscope to measure steep slope, up to almost 90° on a part with minimal surface roughness. This measurement requires a high resolution, high numerical aperture objective, which has a limited lateral measuring field unsuitable for measuring the entire object. Because of this, a stitching procedure was used to combing scans taken with several objectives.

Scanning Probe Microscopy.

Scanning probe microscopes (SPMs) offer an alternative to non-contact techniques. SPMs are characterized by their high resolution (sub-angstrom). The two most widely used SPMs are the scanning tunneling microscope (STM) and the atomic force microscope (AFM) [4, 27]. Structural, chemical, and electrical properties can be measured with an STM. Sub-angstrom resolution is attainable in the normal direction of the surface, and angstrom-scale resolution is attainable in the lateral directions of the surface. Atomic force microscopy (AFM) is not limited to conductive surfaces [3]. The measurements of an AFM are performed with a sharp probe that collects a series of line scans across the surface of a part. The topography of the part is measured by bringing the probe close to the specimen and measuring the repulsive and attractive forces on the probe tip. In the Z-direction, AFMs have high sensitivity, typically with a resolution of 0.05 nm. Resolution in the X and Y-directions are also high, ranging from 2-10 nm [50].

An AFM is capable of working in both a contact and non-contact mode to collect surface data. In contact mode, the method of data acquisition is similar to a profilometer where the probe tip slides along the surface of the specimen and the relative height changes are measured. Shear stresses that arise from sliding the probe tip across the surface of a part can be eliminated by using a setup in which the probe tip oscillates as it traverses across the surface (i.e., tapping mode). AFMs can also be used in a non-contact method, where the Van der Waals forces between the probe tip and specimen are measured and converted to coordinate data. Though having the advantage not contacting the surface of the specimen and eliminating tip erosion [25], this method has lower resolution and is less stable than either the sliding or tapping modes.
Atomic force microscopes have been used to measure micro- and meso-scale parts with limited success. sidewalls of parts with heights of 2 µm have been successfully measured with AFMs [21, 52, 38]. The tip geometry (e.g., conical, flared, etc.) is shown to have a significant impact on the measurement results. Probes with sharp tips have been developed that have a full cone angle of less than 5° and have been used to successfully characterize bottom corner (foot) geometry of lines and trenches [30]. Li et al. [23] successfully used an AFM to measure an impression of a diamond tool to determine the edge radius at the nano-precision level.

There are certain limitations to SPMs, particularly in measuring high aspect ratio parts. STMs, as previously mentioned, are limited to parts with conductive surfaces. Electronic inhomogeneities can also have significant effects on the topographical image of the probe [4]. Vibrations in the probing mechanism also limit gap width stability, which, in turn, can affect the fidelity of the measurements. All SPMs are limited, in the same sense as white light interferometers, to the maximum, measurable slope changes in a surface or between surfaces. When features with perpendicular sidewalls are scanned, the data typically exhibit a slope or curtain that is actually not present [10]. The height of measurable features is also limited to the probe length which is typically < 10 µm in commercial systems. This limitation severely prohibits the inspection of high aspect ratio parts with dimensions on the order of mm. Though these tools have extremely high resolution, it is unfeasible to collect scans that cover all of the surfaces of a part, given the limited scan range of the tools.

**Computed Tomography.**

Computed tomography is a radiographic technique that provides a method for locating and sizing planar and volumetric detail in three dimensions. Computed tomography inspection consists of measuring a complete set of line-integrals involving the physical parameter of interest over the designated cross-section and then using some type of algorithm to recover an estimate of the spatial variation of the parameter over the desired slice [1]. The method uses a computer to reconstruct an image of a cross sectional plane through an object. Stacking these images provides a three-dimensional image appropriate for making quantitative measurements. A system for computed tomography has been developed by Aracor [1] that provides 0.40 mm resolution and 0.04 mm accuracy. However, at high resolution, it takes approximately one day to image a part. Lawrence Livermore is currently developing a system that combines x-radiography with computed tomography to non-destructively provide internal detail of meso-scale structures [13]. The goal of the Lawrence Livermore system is 1 µm resolution over a 1 mm field of view, with each scan taking 10s of minutes. In order to achieve this goal, an extremely small, bright x-ray source and/or a high collection efficiency x-ray imaging optics are required. A synchrotron is used as the x-ray source. The design of the imaging optic requires special considerations because x-rays penetrate most optical materials and mirrors. It was decided that Wolter multilayer imaging optics would be used to improve collection efficiency [29].

Computed tomography provides non-destructive characterization of internal structures of meso-scale devices. Also, it can be used to inspect metallic or non-metallic, solid or fibrous, smooth or irregular surfaced specimen. The results can be used for quality control, flaw detection, dimensional measurement, and reverse-engineering [43]. There is the possibility, however, of artifacts in the resulting image that are due to the physics and mathematics of the system and can not be removed. Additionally, complete scans are quite time consuming and require a significant amount of data processing.

**Digital Volumetric Imaging.**

Digital volumetric imaging (DVI) was developed by Resolution Sciences, Inc. is a destructive technique in which the test component is physically sliced in 0.25 to 4.4 µm layers and images of each layer are taken with a CCD camera with resolution of 0.22 to 4.4 µm, depending on the objective being used. The set of two-dimensional images are then converted into a three-dimensional image set. Special software allows the either individual slices or the entire data set to be viewed [7]. A big benefit to this type of analysis it that it produces a three-dimensional data set with fairly high resolution. Additionally, interior defects can be located and analyzed. However, DVI is a destructive technique. Also, for this technology to be applied to samples made
from hard materials, the process needs to be improved. The selection of the proper embedding material, additives to promote surface adhesion, sample orientation, sample location within the block and the embedding technique are all critical in imaging hard materials.

Several trials have been conducted to image meso-scale samples, specifically those made with the LIGA process [20]. A 664 µm nominal diameter gear was imaged to provide information regarding absolute dimensions and sidewall angles. A full three dimensional data set was collected. It was noticed that striations were created in the surface because of degradation of the cutting surface of the knife. These striations created noise problems at the surface boundaries. Additionally, a brass ball bearing was imaged as a potential calibration artifact. The image contained good surface detail, showing a spiral pattern, typical of the process used to manufacture ball bearings. Adhesion of the sample to the embedding material was a problem, with the ball bearing popping out during sectioning [55].

**Molecular Measuring Machine.**

The molecular measuring machine is in development at NIST. The goal of this machine is to achieve nanometer accuracy of two-dimensional point-to-point measurements over a 50 x 50 mm area [18]. The system operates in a vacuum and combines a custom scanning tunneling microscope with two Michelson interferometers. The scanning tunneling microscope probes the surface while the interferometers measure the probe movement in the x- and y-axes. The interferometers are designed with an inside, dual-pass, differential optical configuration, resulting in fringe spacing of 1/8 of the wavelength of the Helium-Neon light source. In order to achieve resolution in the 50 x 50 mm area, a set of two stages, one coarse and one fine, are used for each axis of movement. The machine also incorporates careful temperature and vibration control.

The molecular measuring machine has the advantages of a very high resolution and low uncertainty. A potential use for a machine with these abilities is in the calibration of standards. However, to achieve this resolution and accuracy, measurement time is sacrificed, resulting in slow operation. Because the tool uses scanning tunneling microscopy as its foundation, it is limited to measurement of conductive samples. In the future, the scanning probe microscopy tip could be replaced with an AFM tip to allow for measurement of non-conductive samples. Kramer et al. [19] have used the molecular measuring machine to make high accuracy pitch measurements on one-dimensional gratings. The line spacing for these gratings was found with a 5pm uncertainty. The sample, which was 100 µm by 1 mm, took 8 days to image.

**µ-CMM.**

Small-scale coordinate measuring machines (CMMs) are being investigated for their possible use in geometric characterization of MEMS [35]. These devices have working volumes up to 400 x 400 x 100 mm [42]. Sub-micrometer uncertainties are being targeted with nanometer resolutions [36]. Various approaches are being taken to the scaling down of components of a traditional CMM [5, 47, 33, 9, 48]. All current systems are in a developmental stage with no commercial systems yet available. The greatest potential advantage of these machines will be their ability to acquire true three-dimensional data from microfabricated parts, including parts with steep sidewalls. One of the main issues yet to be addressed is the size, quality and calibration of the probe tip used for inspection. The smallest size probes to date are on the order of 0.1 mm [40]. In addition, the design of a sensing system to detect the small displacement forces of the probe still proves to be a challenge. Most experimental results from small-scale CMMs have been basic, limited to mostly uni-directional measurements. The measurement of surfaces from three-dimensional vector positions, typical to conventional CMMs, is yet to be accomplished.

**Microfabricated Scanning Grating Interferometer - µSGI.**

The microfabricated scanning grating interferometer, or µSGI, has been developed to allow for parallel scanning of dynamic and static devices [16]. The µSGI is based on traditional laser interferometry, but operates on the micro-scale. The system, manufactured using standard silicon processing techniques, measures distance by using a reflective diffraction grating. The diffraction grating is located on a transparent substrate with a micro-lens, fabricated using a reflow technique. The light reflected from the diffraction grating and the sample is collected by photo diodes. The system is shown in Figure 1.
As with all interferometers, the intensity change due to displacement takes the shape of a sine wave. The diffraction grating is deformable to allow higher vertical displacement sensitivity by staying within the linear portion of the sine wave, allowing for a vertical resolution of 0.5 nm. The lateral resolution is 1 µm.

This system has a couple of distinct advantages over traditional interferometry. First, it has been designed to be produced in an array to allow for faster inspection by using several µGSI in parallel. Second, the system has the ability to make both static and dynamic measurements. Hall and Degertekin [12] show initial results for the displacement measurements of acoustic transducers. However, these tools are currently limited to changes in step height proportional to the wavelength of light used in the laser source, which limits the range of measurement for the device. In this case, the step height is limited to ¼ of the wavelength of the Helium-Neon laser, or 158 nm. Noise filtering has also been an issue in the development of the µSGI.

Kim et al. have performed a preliminary study on a MEMS microphone membrane, to determine the ability of the µSGI to perform dynamic measurements [15]. A lock-in amplifier was used to scan the vibrating microscope in steady state, allowing for phase sensitive detection. It was shown that the µSGI was able to provide nanometer resolution for a wide frequency range. Furthermore, the µSGI has the ability to track moving surfaces at over 20 MHz, allowing it to map operational MEMS devices [56].

**Autofocusing Probe.**

The autofocusing probe combines a 6-axis micro-positioning stage with an autofocusing laser probe commonly found in CD and DVD players to create a non-contact measurement system. The autofocusing laser probe works on the principle that when laser light is projected through specific optics (beam-splitter, quarter-waveplate, and objective) and reflected (through quarter-wave plate and on to photodiode array), it will take on different shapes depending on if the light is focused on the sample surface. The sample surface can then be focused by actuating the objective lens through the use of a voice coil until the focused shape is achieved. Because the lens position is proportional to the current passed through the voice coil, a measurement of the current will provide displacement information [57]. The displacement of a number of discrete points can be collected into an image showing the surface of the sample [17].

Similar to many measurement techniques that rely on reflected light, the DVD probe can not focus on areas in which the light is not directly reflected back to the probe, such as in the case of chamfers and fillets. Additionally, relatively high reflectivity is required to achieve focus. The probe has been used in a preliminary study to image micro-gears on the order of 1mm in diameter, created using the LIGA process. The results achieved using the DVD probe were compared to those using SWLI. Different results were obtained from each of the two systems, with the results from the DVD probe underestimating the amount of
material present. It is believed that this is a result of the inability of the system to focus on surfaces at an angle to the probe. The advantage of the DVD probe is its low cost (approximately $30), making it an inexpensive option for metrology of flat highly reflective components.

2. Control

Metrology is the first step in system control as well as process control. Without measurements and feedback control is not possible. Once process data have been generated they can be used to enhance performance. To accomplish this task, two primary elements must be present. The first is a process model. The second is control algorithms employing the model to determine the system inputs necessary to achieve the desired process output (performance, quality, etc...). Currently few industrial controllers are capable of addressing these needs. However, a new class new flexible and reconfigurable control systems based on graphical programming languages and reprogrammable hardware are beginning to emerge. In particular, controllers based on the Field Programmable Gate Array (FPGA) devices feature a reconfigurable digital circuit architecture with a matrix of Configurable Logic Blocks (CLBs) surrounded by a periphery of I/O Blocks. A typical FPGA layout is shown in Figure 2. Signals can be routed within the FPGA matrix in any arbitrary manner by Programmable Interconnect switches and wire routes. The FPGA basically permits the complete reprogramming of the controller at a hardware level. The FPGA hardware reprogramming is equivalent to reprogramming a standard CPU by modifying its software or program. However, the FPGA hardware programming results in significantly shorter cycle execution times as well as parallel operation capabilities that are independent of program complexity. This makes such a controller ideal for monitoring and controlling systems that have multiple inputs and outputs such as multiple axes, and multiple sensors and actuators.

Figure 2: FPGA Diagram.

Figure 3 demonstrates how the FPGA is currently embedded into a control system. It is basically integrated with a variety of input output lines that permit it to communicate with the external world, and is linked with standard real-time programming capabilities. This configuration makes the FPGA transparent to the control engineer. It is programmed in the same fashion as any controller (e.g., motion controller, data acquisition, process controller, etc.). The FPGA controller can be programmed using a wide variety of tools. For example, Figure 4 demonstrates that graphical programming of the FPGA for pulse width modulation of a servo motor. The graphical programming tools permit the quick and easy programming of the FPGA, and allow it to be rapidly reconfigured based on the needs of the user. Furthermore, system identification tools are available from a variety of sources enabling these advanced controllers to determine system parameters from empirical data. Thus, initial process models may be developed with nominal process parameters. These parameters may be monitored by the controller and updated based on real-time information. Subsequently, adaptive control algorithms may be employed to optimize the process for increased quality and throughput. The reconfigurable hardware nature of the FPGA permits this to occur in a rapid and efficient manner. It is
In summary, the ability to fully quantify the three-dimensional characteristics of MEMS is quite limited. There is a significant gap in capabilities for MEMS inspection. Tools exist that have exceedingly high resolution, but are limited in range \((\text{i.e.}, \text{only a few square } \mu\text{m’s can be measured})\). Other tools exist which have sufficient range, but are limited to drastic slope changes on the surface of the part, a characteristic typical of high aspect ratio MEMS. The current solution to quantifying meso-scale MEMS parts is to use a combination of tools. The combination of these techniques, at best, provides geometric information about localized regions of a specific part, but a technique that provides geometric information for an entire MEMS device has yet to be realized. Once metrology tools are available, process models must be developed such that the feedback from the sensors can be used to close the loop. These models are quite likely to have some empirical nature to them and will most likely be time-varying. Thus, the systems controls employed on these machines must be flexible, easily programmed and extremely powerful. Furthermore, it is anticipated that many micro-production systems, and certainly micro-metrology systems will operate in a parallel fashion, requiring easily expandable controls with parallel processing capabilities. Once measurements have been made, and the micro-machines are well controlled, then process control, process enhancement and yield improvement will be viable. However, this will be a long and arduous path.

**WORKSHOP SUMMARY**

The need for process improvement was stressed by several of the speakers in the meeting. Process improvement was defined in several manners, and typically manifested itself in one of three categories:

1) Improved Yield
2) Enhanced Accuracy and Repeatability
3) Superior Product Quality

To address these issues, several focus areas were identified in the area of process control and improvement. First of all, to determine the quality of a product, and subsequently a process, some form of measurement must be taken. This measurement falls under the realm of metrology, and links directly to the ability to produce micro-parts. Several speakers noted that there were significant issues to be addressed in successfully fabricating these micro-components including Phillip Leopold (Medical Murray, Inc.), Sinan Badrawy (Moore Nanotechnology Systems, LLC), Brad Damazo (NIST), Shiv Kapoor (University of Illinois), Dick Knepper (Timken), Steve Patterson (LLNL) and Iwona Turlik (Motorola). The primary problem that was identified by all of these speakers was the ability to measure the micro-systems with high accuracy and repeatability. Measurement of the micro-systems was defined not only in terms of static dimensions, but in terms of material properties and dynamic performance (many of these devices have functions that require specific dynamic responses or actuations). The metrology needs that were identified ranged from the single sensor level, to sensor arrays to entire metrology platforms that need to be integrated into production systems.

Metrology on a micro-scale appears to be just the tip of the iceberg; however, it is critical in understanding the product and process in both the design, debugging and production phases of micro-manufacturing. In the
design and debugging phase of system implementation, designers and process planners need to validate that their designs and production protocols are performing to specifications. Thus, metrology tools are required at a laboratory scale for testing individual devices and processes. Once the device design and manufacturing process plan have been finalized, full scale production must be monitored. To monitor full scale production, metrology technology must be scaleable to inspect hundreds, if not thousands, of micro-devices in parallel as this is how many of these devices are produced (e.g., lithography). These points were highlighted by Badrawy, Damazo, Knepper and Kapoor.

Once measurements have been made, feedback must be provided to production systems to better control and ultimately improve production process characteristics. This was a point that was highlighted by the industry presenters in a variety of areas. Thus, process models must be available that can utilize the metrology system feedback. Several of the speakers indicated that process models at the micro- or even nano-levels are not well understood. Professor Kapoor highlighted this fact in his talk as did Dr. Badrawy. Combining metrology with a thorough understanding of the process model will enable process, and ultimately product, improvement. Of course, the metrology itself will provide input to the models which may have empirical elements to them. Thus, it is anticipated that the models will continue to evolve and adapt based on feedback from sensors in the production systems.

To utilize these adaptive models, enhanced sensors and evolving production systems, new and inexpensive control technology must be deployed. The controller is the subsystem that provides the integration platform for the new technology in metrology, process modeling and control. The controller architecture must make use of state-of-the-art technology for parallel computing to operate parallel sensors and production systems. It must also be easily programmable and integrated into standard network protocols for real-time information sharing and control. Several speakers mentioned the necessity for such advanced control systems in their production lines for micro-components. Professor Kapoor also mentioned several very futuristic concepts of plug-and-play elements in the next generation micro-factory that would operate in a similar fashion as USB devices function on modern operating systems. In this scenario, the controller would need to be expandable and quickly reprogrammable to function with a wide variety of actuators, sensors, subsystems and overall systems. The programming of these controllers will necessarily have to be a simpler format that current PLC’s (ladder logic) and more powerful that standard CNC controller (G-code), as a wide variety of tasks will be required from them. Nominally, this will be a simplified graphical programming language that has the ability to integrate advanced analysis and signal processing tools with control design tools to provide a powerful platform from which to control individual as well as networks of micro-machining systems. Such a controller must also be flexible enough to address the variety of systems that will be employed, those that are more traditional and those that are new and novel technologies.

REFERENCES


CHAPTER 6. APPLICATIONS

OVERVIEW

1. Non-lithography Microproducts and Applications.

Introduction.

In addition to non-lithography based micromachines we are also interested in establishing the impact of MEMS and NEMS (Nanoelectromechanical machining) on non-lithography based machining. Examples include the use of MEMS to make a micromold for plastic micro-molding or the fabrication of fibers using MEMS spinnerettes. Our definition non-lithography machining includes traditional machining i.e., mechanical machining and what is called non-traditional machining such as electrochemical machining and ultrasonic machining, i.e., machining with non-mechanical means.

The continuing progress in non-lithography microfabrication techniques is very underreported due to the overwhelming expectations invested in Si MEMS technology. In this current WTEC report we are making a distinction between micro- and nano-devices made by lithography based techniques and those made by non-lithography techniques and the emphasis is on the latter. Micro-manufacturing by its very nature is very applied and usually more can be gained from industry than from academia in this respect. We believe that to succeed in non-lithography based machining a stronger than usual link with industrial partners and academia is required.

Non-lithography Based Machining.

Non-lithography machining does encompass both traditional and non-traditional machining. For over a hundred years, precise macromachines have been designed and built with mechanical removal techniques achieving part-per-million relative tolerances. Today, macromechanical machines have entered the realm of 0.1 ppm relative tolerances [1]. In comparing Si micromachines with mechanically machined macrostructures Slocum makes some important observations [1]. He notes that, while lithography based micromachines are impressive for their small size, their relative accuracy is two orders of magnitude worse than is typically achieved in macromachines, which, moreover, are much more complex. Typical lithography based micromachines today, Slocum points out, are comparable with the macromachines of the early 1700s with respect to complexity and accuracy. The surface roughness of lithography based micromachines looks high compared to the specular finishes of bearing surfaces. In reality, the absolute roughness is about the same, but in micromachines surface forces such as friction are relatively more important. Thermal errors in a micromachine are generally more relaxed; the small scale and fast thermal equilibrium of the smaller structures is their saving grace. Another key issue Slocum brings up is that of position measurement systems; verification of fabricated geometry and tolerances are much more difficult for micromachines since measurement of a displacement of one part in ten thousand will typically get one down to the nanometer level.

Some Recent Applications of Non-lithography Machining.

Higher accuracy machining is needed to provide computer memory disks and optical mirrors and lenses with accuracies to a fraction of the wavelength of light. A better understanding of the limits of lithography and nontraditional machining methods would help the mechanical engineer make the best choice in machining tools. At the same time, as micromachine mechanical complexity increases, it seems appropriate for the designers of micromachines, who are typically electrical engineers, to study macromachine design.
Ultraprecision manufacturing is still the commercially preferred technique for the production of computer hard discs, mirrors for X-ray applications, photocopier drums, commercial optics such as polygon mirrors for laser-beam printers, consumer electronics such as mold inserts for the production of compact disc reader heads and camcorder viewfinders, in addition to high-definition television (HDTV) projection lenses and VCR scanning heads.

State-of-the-art for Non-lithography Applications.

In Figure 1, we show an SEM photograph of a single-crystal diamond cutting tool. The radius of the edge on this tool is estimated at less than 0.05 µm; with such a tool submicron grooves equivalent to those produced by silicon micromachining can be generated (Figure 2) [2]. Using such a diamond tip and numerical control (NC) rice-grain-sized cars were machined at Nippondenso (one car was 4.5 mm long and another was 7.5 mm long) (Figure 3) [3]. The shell of the car was made by the sacrificial mold technique. A piece of Al was NC-machined and plated with 30 µm thick electroless Ni; after cutting off the lower part of the body with EDM, the Al was removed by KOH etching. Finally, the Ni car shell was Au coated to protect it from oxidation. The stainless chassis and wheels were also made by NC machining, and the core shaft and coil of the motor were made by NC machining and EDM. The zirconia wheel shaft was machined down to a 250 µm diameter. The electromagnetic step motor is driven by an external magnetic field, and the car’s permanent barium ferrite rotor runs at a maximum speed of 100 mm/sec developing a torque of about 10⁻⁶ Nm (at 3V and 20 mA). To assemble the various micro parts into a complete car, a mechanical micromanipulator, ordinarily used for handling biological cells, was employed [3].

Figure 1. Diamond ultra-high precision tools. Single-crystal diamond tool. Angle of tool is 20°. Maximum depth of cut is 500 µm.

Figure 2. Micro groove produced by diamond machining a 100 mm thick Al foil. Width is 85 µm, depth is 70 µm.
Chapter 6. Applications


The single-crystal diamond tool refinements are not the only reason for the high precision achieved with mechanical machining today; submicron precision is also being achieved through high-stiffness machine beds, air bearings (air bearings with a rotational precision of 0.01 µm and better are available now), and measurement systems such as laser interferometry. Furthermore, highly precise instruments such as servomotors, feedback devices, and computers have been implemented, and many types of machine tools are now equipped for computer numerical control, further improving precision and reproducibility of the manufactured parts.

FANUC’s ROBOOnano U_i is an ultraprecision micromachining station capable of making such high precision parts as the mold for diffraction gratings or aspheric lenses (http://www.fanuc.co.jp/eproduc/submain60.htm). This superprecision micromachining equipment consists of a diamond milling tool rotating at high speed on a superprecision positioning table with nanometer resolution. Using this setup, FANUC succeeded in relief engraving a minute, mirror-surfaced Noh-mask in copper with a “diamond end mill,” which results in a surface smoother than a mirror (Figure 4). The roughness of the forehead (R_max) of the mask is 60 nm. Thus, FANUC has realized a superprecision micromachining technique that allows mirror finishing in any direction except in a narrow groove.

Figure 4. Japanese NOH mask (source: Fanuc)

Besides high accuracy cutting, there is also significant progress to report in die punching. Aoki et al. [4] have pushed the art of die forming with a press for 3D, metallic medical microcomponents to new limits. Medical forceps, for insertion into an endoscope used to remove diseased tissue, have been fabricated as an example of the new capabilities. The forceps have a diameter of 0.6 to 1 mm, and a length of 10 mm, with assembly
holes measuring 0.3 mm, and 0.2 mm long teeth in the cutting tool. The final manufacturing time, including assembly, is about 3 min per piece.

**Flexible Manufacturing and Desktop Manufacturing.**

In response to the need for automation and the demands created by frequent design changes over a broad variety of products, the Flexible Manufacturing System (FMS) was developed. FMS is a combination of several technologies such as computers, CNC workstations, robots, transport bands, computer aided design (CAD), and automatic storage. The technique was developed to produce many varieties of a certain product in smaller quantities rather than many devices of one type. CNC workstations are linked by automatic workpiece transfer and handling, with flexible routing and automatic workpiece loading and unloading [5].

Despite all of this progress, the fact that it often takes a 2-ton machine tool to fabricate micro parts where cutting forces are in the milli- to micro-Newton range is a clear indication that a complete machine tool redesign is required for the fabrication of micromachines [6]. Along this line, in Japan the concept for desktop flexible manufacturing systems (DFMS) for building micromachines was proposed in the early 1990s [7]. The manufacturing units would be tabletop size and include universal chuck modules to which workpieces would be continuously clamped through most of the manufacturing process. The miniature die press from Aoki and Takahashi is one of the first examples of progress in that direction [4]. In the U.S. Vogler et al. [8] and Subrahmanian et al. [9] have developed a number of desktop size machine tools for meso-scale components. A large fraction of this current WTEC study is towards measuring progress in desktop manufacturing.

**Summary.**

We can summarize the above observations as follows: for truly 3D and complex shapes, better relative tolerances in all dimensions and smoother surfaces in all directions (x, y and z) non-lithography methods are preferred. For very small absolute tolerances and 2D shapes lithography is king. In this study we will make this delineation between lithography and non-lithography machining yet sharper by providing an extended comparison table and decision matrix.

2. The Emergence of Nanotechnology.

At the beginning of the twenty-first century, the performance criteria for top-down manufacturing techniques, that is, Moore’s law which projects the progress in achievable transistor density on a chip, and Taniguchi’s curves which predicts improvements in accuracy for mechanical machining have started to exhibit signs of a slowdown. In other words both lithography based and non-lithography based machining are facing a big challenge in the years ahead. Further miniaturization progress might be based on methods originating in nanochemistry, that is, bottom-up methodologies as well as combinations of top-down nanofabrication using lithography and non-lithography based techniques and nanochemistry. Over the next ten years, the size overlap of objects fabricated with either approach will become more significant. Consequently, molecular engineers and supramolecular chemists who are manipulating, with rapidly improving dexterity, nature’s building blocks such as atoms, molecules, proteins, and DNA will find new ways to combine top-down nanofabricated components with bottom-up “natural” products.

Humans tend to start with larger building blocks and use stiff materials (e.g., Si or stainless steel), whereas nature prefers small building blocks and mostly soft, low Young’s modulus materials (e.g., materials in muscle or skin). As an example of recent human engineering ingenuity, consider Si micromachining or MEMS. Si micromachining involves Si wafer slabs as thick as 500 µm, insulating layers up to a µm thick, Al and Au metal layers between a few hundred and few thousand Ås thick and, in general, three-dimensional structures with dimensions anywhere between 1 and 500 µm. Although MEMS has led to major advances, the method still presents a limited choice of materials and works with building blocks that are large and crude compared to nature’s arsenal.

Biomimetics is the study of how nature, building atom by atom, through eons of time, developed manufacturing methods, materials, structures, and intelligence. These studies are inspiring engineering and
design of manmade miniature objects. As nanochemistry is currently inspiring a new wave of biomimetic efforts, caution is in order since, as the legend of Icarus so pointedly reminds us, most previous attempts at biomimetics have resulted in failure. However, we believe that past failures mostly pertain to macroengineering and will not hold true in nanoengineering. In macroengineering, as S. Vogel points out in *Cats' Paws and Catapults* (W. W. Norton, New York, 1998) [10], human and natural technologies form a separate, well-integrated entity, operating in an internally coherent context. Nature, for example, does not use steel, nor does it favor the production of flat surfaces and sharp corners—all very useful in human manufacturing. Nature builds with proteins and produces mostly curved surfaces and rounded corners, resulting in such masterfully engineered objects as biological cells. In large-scale engineering projects, both natural and human manufacturing approaches have their merits within their own proper frame of reference. It is in the nano world that nature is way ahead of human engineering as it has learned to work with much smaller, more versatile building blocks and master the self-assembly of those building blocks. As mankind learns to build with the same construction set, we are bound to challenge nature in nanoengineering. Because it uses relatively large building blocks, human manufacturing is rapid and the expectation is that nature, because it uses much smaller building blocks, for example, atoms with a diameter of 0.3 nm, must be very slow. To offset the time it takes to work with small, basic building blocks, nature, in growing an organism, relies on an additive process featuring massive parallelism and self-assembly, the latter of which is one of the main topics of this section.

Early examples of successful biomimetics include artificial materials for implants [11], tissue engineering, an artificial retina based on the architecture of the human eye (http://www.etca.fr/CTA/gip/Projets/Retine/overview.html), and neural network software based on the human brain [12, 13]. The devices mentioned are relatively large, however, and are fabricated by top-down methodologies; the neural network software example is only a very crude approximation of a human brain. Human-made nano devices crafted with bottom-up methods will open up a much more rewarding paradigm in human manufacturing; nanochemistry holds the promise of the versatility of design offered by nature itself, and molecular self-assembly and replication add to the tremendous appeal of this type of nanotechnology. Obviously, there is something very attractive about the small size of nature’s preferred building blocks such as proteins. These biosystems have been tested and selected by eons of evolution, and, at a time when we find that micromachining tools are limiting the fabrication of ever smaller devices, exploration of some of nature’s tools and building blocks promises to be very rewarding. As one of the many motivating examples of the promise of biomimetics, consider enzymes. There is a plethora of enzymes that outperform synthetic catalysts by several orders of magnitude. For instance, there is no manmade catalyst for producing ammonia from its elements at ambient temperature and pressure, as the nitrogenase of nodule-forming bacteria does (the industrial Haber-Bosch synthesis of ammonia from nitrogen and hydrogen at high temperatures and pressures pales in comparison).

In this study we are looking for synergies between non-lithography machining and bottom-up manufacturing techniques.

**WORKSHOP FINDINGS**

While the Workshop produced considerable new insights, several things were missing for a deeper understanding of the overall status in micro-manufacturing. The mechanical manufacturing discipline still is quite isolated from the lithography based community (IC’s) and from the bottom-up manufacturing research people (molecular and genetic engineers). We did not hear much about continuous manufacturing ideas (roll to roll manufacturing-like printing newspapers say) or drop delivery systems, both manufacturing means of crucial importance in biotechnology. The jargon confusion between the different communities was also considerable. The manufacturing world still is mostly divided into dry (say CNC machining) and wet approaches (say electrochemical shaping and genetic engineering) and we need to bridge that gap better. Our upcoming visits to Asia and Europe will hopefully reveal how far other countries have advanced in making hybrid manufacturing approaches a reality. Examples would include MEMS tools and molds for traditional machining (pseudo-LIGA processes).

The most obvious realization from this meeting (something we probably knew but heard confirmed in several talks) is that U.S. machining today is mostly forced into niche markets with high-add-on-value-products. The
time for even those more sophisticated engineered products to become commodities is shrinking all the time though (e.g., bearings, but also Si pressure sensors, DRAMs, lenses, etc.). U.S. activities appear more and more relegated to early IP exploitation, product design and services.

An approach for the U.S. would be to launch a concentrated effort in very advanced, new manufacturing techniques and re-introduce the societal merits and value of actually making things. With IT down, and high paying jobs still scarce, this is a good time to launch such an effort. The current WTEC study could be a first attempt towards this goal. The hybrid manufacturing approaches, alluded to above could be a key to attract a new generation of motivated engineers and scientists into the science and engineering of manufacturing.

A good start could be to launch courses in: comparative machining methods, i.e., where do you use what machining option? Scaling laws; Continuous manufacturing methods; Bottom-up manufacturing methods; Self-assembly; Small portable machining tables; Wet/dry machining method combinations.

REFERENCES

CHAPTER 7. BUSINESS, EDUCATION AND THE ENVIRONMENT

WORKSHOP FINDINGS

In terms of business, education, the environment and other issues, in some sense, what was not said was more important than what, in fact, was said. The workshop rightfully dealt primarily with the technologies associated with micro-manufacturing. However, behind every presentation the issues of maintaining economic viability, retaining technologically competent workers, and maintaining the environment were lurking.

Currently manufacturing accounts for about 15% of GDP (Gross Domestic Product) (Dept. of Commerce). However, that measure does not account for many of the support services (security, some design services, etc.) that have either historically not been a part of the ‘manufacturing’ sector, or have recently been outsourced and are therefore not included. The point is that manufacturing accounts for far more than the diminishing share of GDP attributed to it.

1. Business Concerns.

Factors Driving Manufacturing Advantage.

Traditionally, manufacturing activity occurs in factories at fixed locations that are determined by the availability of inputs (raw materials, intermediate products, specialized labor, energy, and capital equipment) and the minimization of costs, including transportation costs. The United States has exhibited a historical advantage in manufacturing relative to much of the rest of the world due to our availability of plentiful land and cheap energy (i.e., hydroelectricity, coal) as well as a good labor force and natural resources such as iron ore. However, as the scale of manufacturing processes becomes smaller, plants may face diminished start-up costs, and massive investment in capital equipment is generally not needed, although certain pieces of micro-manufacturing equipment can nevertheless be very expensive. At the same time, the ratio of weight (or volume) to market value of finished products decreases, so that proximity to consumers becomes less important. Hence, from one point of view, sustained micro-manufacturing activity may be less likely to occur inside of the United States, despite our reputed advantages in research innovation. Further, while the regulatory environment and prevailing corporate cultures can also influence firms' location decisions, micro-manufacturing certainly makes it easier and cheaper to relocate a plant in response to economic and/or political factors. On the other hand, a transforming paradigm, such as the “micro-factory” concept initially developed in Japan but now widely pursued worldwide, could radically redistribute micro-scale manufacturing capability from a capital-intensive focus in the hands of a few to a low-cost enabling technology in the hands of many. This could transform micro-scale manufacturing into a “cottage industry”, playing directly into the U.S. traditional strengths in small business enterprise and entrepreneurship.

The WTEC study of Microsystems Research in Japan (2003) [1] noted that the commercialization process for research developments is developing nicely. ‘Industrial visitors’ at the universities facilitate the process. Intellectual property regulations have been rewritten to facilitate licensing of university patents to industry. At that time, the institutions involved were ‘still adapting’ to the changes. It will be interesting to see how that process has progressed. The WTEC report noted that while the U.S. development experience has emphasized small startup companies, the Japanese economy does not avail itself of this approach to any great extent. Intuitively it would seem that micro-manufacturing is ideally suited for small startup companies. Again, it will be interesting to see how prevalent small startups are in Japan, Korea, and Taiwan. In fact, the WTEC (2003) report [1] did note the impressive technical capabilities of some small Japanese manufacturers that are a ‘ready source of precision “piece parts” for micro-systems’ for the larger companies.
Raw Material Issues.

Several interesting observations made during Workshop presentations demonstrated unique influences of certain characteristics of micro-manufacturing that challenge the overall conduct of business and business strategy. One such characteristic is the small amount of raw materials required to manufacture thousands, perhaps millions, of micro-parts. This fact has a profound effect on the relationships that can (more specifically, that cannot) be developed between the micro-manufacturer and the raw material supplier. Donna Bibber of Miniature Tool and Die commented that material suppliers are reluctant to buy into/invest in the market with development efforts due to the small amounts of materials needed. This fact was further echoed by Phil Leopold of Medical Murray who pointed out that the low volume of materials needed by his firm’s micro-products was providing little economic incentive to materials suppliers to do needed development work to improve product performance or manufacturability. In a related materials economic issue, Darrel Untereker of Medtronic, Inc., pointed out that liability concerns for medical implants had completely driven certain major raw material suppliers away from such applications, further increasing difficulties that micro-manufacturers face with obtaining materials.

Market Size.

Another economic factor that is having a profound impact on business strategy and new product development is the current size of the market for certain micro-products and uncertainty in the ability to predict the future evolution of these markets. As pointed out by Richard Knepper of Timken, the projected small volumes associated with micro-bearing products that they would like to develop make it difficult to make large capital expenditures to commercialize the new processes required to manufacture those products. While R&D efforts have been successful in demonstrating the technical viability of these products, the need to lower cost and automate processes to make low volume micro-bearing markets viable will require large capital investments that are difficult to justify. Such concerns clearly bring into focus the need for a major paradigm shift in micro-manufacturing principles. In this regard, Donna Bibber also pointed out that small pockets of development in process innovations are not being shared across companies, slowing the evolution to commercialization.

2. Educational Concerns.

There was some mention of manufacturing education as an issue at the workshop. Both Donna Bibber of Miniature Tool and Die and Dr. Sinan Badrawy of Moore Nanotechnology Systems LLC indicated that their firms have ongoing staffing problems due to lack of education and training available in micro-systems and micro-manufacturing but there was little discussion of specific needs and ways and means to meet those needs.

During the mid-1980’s there was a resurgence of interest in manufacturing in U.S. universities, largely due to the IBM initiative in manufacturing during that timeframe. The IBM initiative was the genesis for many of the university manufacturing systems engineering programs that exist in the U.S. today. However, the academic reward process in many U.S. engineering schools still tends to value fundamental research more than applied manufacturing research and support from NSF more than support from industry.

The question that really was not asked or answered at the WTEC workshop is: What are the requirements for micro-manufacturing education that are different from current programs? One thing is clear. More than traditional manufacturing, micro-manufacturing requires people at all levels to be capable of crossing disciplinary lines. As a result, micro-manufacturing tends to require more highly educated people for product and process development and for actual manufacturing. This effect is exacerbated by shortened product life-cycles. In many cases, there simply may not be time in this environment to develop initial manufacturing processes into highly efficient (and relatively simple) manufacturing processes before there is a need and/or opportunity to move on to a more advanced follow-on product. Micro-manufacturing is now, and may continue to be, concentrated in high-margin and niche product markets. Finding applications in mass markets is the challenge. In instances where that can be achieved, it will be possible economically to invest in highly efficient manufacturing processes and thus make the micro device affordable to the mass market.
A concern that was voiced privately at the WTEC conference is that both Europe and Asia now exceed the United States in Ph.D. output. When this is coupled with foreign national U.S. Ph.D. students that (increasingly) return to their own countries after completing their educations, the relative size of the pool of development personnel available to U.S. industry for the development of micro-manufacturing may now pale in comparison to that available to foreign industry. Also, since it is relatively difficult to attract U.S. students to graduate study in engineering (particularly advanced graduate study), this situation probably will not improve in the short term, or even in the long term without intervention to change U.S. student attitudes and behavior.

3. The Environment.

From an environmental standpoint, there was little concern voiced at the Workshop. This is in terms of the relatively gross environmental issues. Processes are being made smaller, not larger, and naturally will not have the impact of conventional manufacturing processes unless manufacturing processes using dangerous materials are employed. However, there will certainly be workplace issues such as worker exposure to esoteric chemical processes and to very fine dusts emanating from micro-machining processes.

Indeed, WTEC has already studied Environmentally Benign Manufacturing (EBM, 2001) [2]. Several interesting points were made in that study in terms of the requirements for successfully pursuing EBM. First it is necessary for the government to provide standards, regulations and incentives for EMB. Second, companies must take leadership positions. Third, the definition of (expected) present discounted value (PVD) must be broadened to reflect long-term environmental issues and their impacts on public relations. Risks and benefits are difficult to put in monetary terms in this area, and the boundaries of analysis are different for each player (government, industry, public).

In the case of micro-manufacturing, it may be appropriate to concentrate on the front-end pollution potential. In most cases the back-end (recycling, reuse, etc.) simply will not be a strong issue.

REFERENCES


BIBLIOGRAPHY

The following is a listing of:

1) Books on Top-Down and Bottom-Up Miniaturization
2) Journals and Periodicals on Micromachining and Sensors:
3) Series on Micromachining and Sensors:
4) Market Studies on Micromachining and Sensors:
5) Important Proceedings/Conferences on Micromachining and Sensors:
6) MEMS
7) Chemical Sensors
8) International Conference on Solid-State Sensors and Actuators (Transducers). International conference held on odd years and rotates sequentially between North America, Asia, and Europe.
1. BOOKS ON TOP-DOWN AND BOTTOM-UP MINIATURIZATION

A


C


Davies, Kevin, Cracking the Genome: Inside the Race to Unlock Human DNA, Free Press, New York, 2001


E


F

Frank, R., Understanding Smart Sensors, Artech House, Boston, 1996.


G


Heuberger, A., Mikromechanik, Springer Verlag, Heidelberg, 1989 (German).


J


K


L


M


N


P


R


S


T


Vangbo, Mattias, *In the Structure of Microstructure Technology*, Uppsala University, Sweden, 1999.


Wagner, Gabriele, and George G. Guilbault, Eds., *Food Biosensor Analysis* (Food Science and Technology; 60), Marcel Dekker, New York, 1994.


2. JOURNALS AND PERIODICALS ON MICROMACHINING AND SENSORS

Analytical Chemistry
(Semimonthly) http://pubs.acs.org/journals/ancham/about.html
(American Chemical Society, Washington, D.C. 20036, USA).

Sensors
(Monthly) http://www.sensorsmag.com/
(Peterborough, NH, USA)

Micromachine Devices
News and updates on MEMS technology.
http://www.rdmag.com/archives/technews/MEMS.htm
(From the Editors of R&D Magazine, Cahners Business Information, Des Plaines, Illinois, USA).

Nanobiology.
(Quarterly) http://www.carfax.co.uk
(Carfax Publishing Company, Abingdon, Oxfordshire, UK).

Biosensors & Bioelectronics.
(Elsevier Science, New York, NY, USA).

Sensor Technology
(Monthly) http://www.insights.com/sensor_tech.html

Sensor Business Digest
(Monthly) http://www.sensorsmag.com/resources/businessdigest/.
(Vital Information, Foster City, CA, USA).

Journal of Microelectromechanical Systems (JMEMS)
A peer-reviewed scientific journal.
(Quarterly) http://www.ieee.org/organizations/pubs/pub_preview/MEMS/mems_bkissue.html
(A joint IEEE/ASME publication, New York, NY, USA).

Journal of the Electrochemical Society (JECS)
(Monthly) http://www.electrochem.org/journal.html
(Electrochemical Society, Pennington, NJ, USA).

Journal of Micromechanics and Microengineering (JMM)
A peer-reviewed scientific journal.
(Quarterly) http://www.iop.org/Journals/jm
(Institute of Physics (IOP), Bristol, UK, Philadelphia, USA).

Sensor Review
(Quarterly) http://www.mcb.co.uk/sr.htm

Nanotechnology
(4 issues per year) http://www.iop.org/Journals/na
(Institute of Physics (IOP), Bristol, UK, Philadelphia, USA).

MST News
An international newsletter on microsystems and MEMS.
http://www.vdivide-it.de/mstnews/
(VDI/VDE Technologiezentrum Informationstechnik GmbH, Teltow, Germany)

Sensors and Actuators (A,B &C)
A peer-reviewed scientific journal.
(Monthly) http://www.elsevier.com/locate/sensors
(Elsevier Science, Amsterdam, The Netherlands).
3. SERIES ON MICROMACHINING AND SENSORS

1. Sensors Update
   Sensors Update 1, 1996
   Sensors Update 2, 1996
   Sensors Update 3, 1997
   Sensors Update 5, 1999
   Sensors Update 6, 2000
   Sensors Update 7, 2000
   Sensors Update 8, 2000; Edited by H. Baltes, W. Gopel, and J. Hesse
   Sensors Update 9, 2001
   Sensors Update 10, 2001; Edited by H. Baltes, W. Gopel, and J. Korvink

2. Handbook of Sensors and Actuators
   Amsterdam, Elsevier Science B.V.(http://www.elsevier.nl/inca/tree/?key=B1HOSA)
   Series Editor: S.Middelhoek, Delft University of Technology, The Netherlands
   Volume 1 Thick Film Sensors (edited by M.Prudenziati)
   Volume 2 Solid State Magnetic Sensors (by C.S. Roumenin)
   Volume 3 Intelligent Sensors (edited by H. Yamasaki)
   Volume 4 Semiconductor Sensors in Physico-Chemical Studies (edited by L.Yu. Kuprianov)
   Volume 5 Mercury Cadmium Telluride Imagers (by A.C. Onshage)
   Volume 6 Micro Mechanical Systems (edited by T. Fukuda and W. Menz)
   Volume 7 Measuring Current, Voltage, and Power (by K. Iwansson, G. Sinapius, and W. Hoornaert)
   Volume 8 Micro Mechanical Transducers (by Min-hang Bao) – 2000

4. MARKET STUDIES ON MICROMACHINING AND SENSORS

   A Nexus Task Force Report
   Dr. Hans-Christian Petzold
   NEXUS Office c/o
   Fraunhofer IsiIT
   Trachenbergring 11A
   D-12249 Berlin, Germany
   Tel. 49(0) 30/76704020
   Fax. 49(0) 30/76704022

2. SPC Systems Planning Corporation (1997)

3. SRI Consulting (1997)

4. SEMI (1996)

5. Intelligent Microsensor Technology (1996)

6. Samsung & MRI (1996, focused on inertial sensors)

7. GB-176 Micromachining Technology: New Developments, Trends and Markets
   Pratima Mehta
   Thomas Abraham
   Published August 1995

8. MEMS: Powerhouse for Growth in Sensors, Actuators and Control Systems - Report #D199
   Technical Insights/Frost & Sullivan, 90 West Street, New York, NY 10006
   Tel: (212) 652-2755
   Fax: (212) 619-0831

9. MEMS Sensors Branch Out
   Greg Paula
   Mechanical Engineering, October, 1996

    Janusz Bryzek
    Sensors, July, 1996
11. *Microsensors and Microsystems Will Increasingly Exert a Global Impact*
   Industry Developments and Trends
   Sensor Business Digest

12. *Microelectromechanical Systems: A DoD Dual Use Technology Industrial Assessment*
   DARPA Report
   December, 1995 - available on web at DARPA/ETO site

13. *Invasion of the Micromachines*
    Hank Hogan,
    New Scientist, June, 1996

14. SPC-1999 MEMS Market Study - Memsmarket Sysplan
    http://memsmarket.sysplan.com

15. Mikrosystemtechnik98+
    www.vdivide-it.de

16. Delphi '98
    www.vdivide-it.de


18. MST Marktberichte – IZET; http://www.mst.izet.de

5. IMPORTANT PROCEEDINGS/CONFERENCES ON MICROMACHINING AND SENSORS

*Hilton Head Conferences*

1) Technical Digest of the 1984 Solid-State Sensor Conference; Hilton Head Island, SC, USA
2) Technical Digest of the 1986 Solid-State Sensor and Actuator Workshop; Hilton Head Island, SC, USA
3) Technical Digest of the 1988 Solid-State Sensor and Actuator Workshop; Hilton Head Island, SC, USA
4) Technical Digest of the 1990 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, USA
5) Technical Digest of the 1992 Solid-State Sensor and Actuator Workshop; Hilton Head Island, SC, USA
6) Technical Digest of the 1994 Solid-State Sensor and Actuator Workshop; Hilton Head Island, SC, USA
7) Technical Digest of the 1996 Solid-State Sensor and Actuator Workshop; Hilton Head Island, SC, USA
8) Technical Digest of the 1998 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, USA
9) Technical Digest of the 2000 Solid-State Sensor and Actuator Workshop, Head Head Island, SC, USA

6. MEMS

Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '89), Salt Lake City, UT, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '90), Napa Valley, CA, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '91), Nara, Japan
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '92), Travemunde, Germany
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '93), Fort Lauderdale, FL, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '94), Oiso, Japan
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '95), Amsterdam, The Netherlands
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '96), San Diego, CA, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '97)
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '98)
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '99)
7. CHEMICAL SENSORS

1st International Meeting on Chemical Sensors, Fukuoka, Japan, 1983
2nd International Meeting on Chemical Sensors, Bordeaux, France, 1986
3rd International Meeting on Chemical Sensors, Cleveland, OH, USA, 1990
4th International Meeting on Chemical Sensors, Tokyo, Japan, 1992
5th International Meeting on Chemical Sensors, Rome, Italy, 1994
6th International Meeting on Chemical Sensors, Gaithersburg, MD, USA, 1996
7th International Meeting on Chemical Sensors, Beijing, China, 1998
8th International Meeting on Chemical Sensors, Basel, Switzerland, 2000
9th International Meeting on Chemical Sensors, Boston, MA, USA, 2002

8. INTERNATIONAL CONFERENCE ON SOLID-STATE SENSORS AND ACTUATORS (TRANSUCERS). INTERNATIONAL CONFERENCE HELD ON ODD YEARS AND ROTATES SEQUENTIALLY BETWEEN NORTH AMERICA, ASIA, AND EUROPE

1. 1st International Conference on Solid-State Sensors and Actuators
3. 3rd International Conference on Solid-State Sensors and Actuators (Transducers ’85), Philadelphia, PA, USA
4. 4th International Conference on Solid-State Sensors and Actuators (Transducers ’87), Tokyo, Japan
5. 5th International Conference on Solid-State Sensors and Actuators (Transducers ’89)
6. 6th International Conference on Solid-State Sensors and Actuators (Transducers ’91), San Francisco, CA, USA
7. 7th International Conference on Solid-State Sensors and Actuators (Transducers ’93), Yokohama, Japan
8. 8th International Conference on Solid-State Sensors and Actuators (Transducers ’95), Stockholm, Sweden
9. 9th International Conference on Solid-State Sensors and Actuators (Transducers’97), Chicago, IL, USA
10th International Conference on Solid-State Sensors and Actuators (Transducers’99), Sendai, Japan
11th International Conference on Solid-State Sensors and Actuators (Transducers 2001), Munich, Germany