United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NIST Special Publication 849

Proceedings of the Joint DoD/NIST Workshop on International Precision Fabrication Research and Development October 27–29, 1992

J. D. Meyer, Editor

The National Institute of Standards and Technology was established in 1988 by Congress to "assist industry in the development of technology . . . needed to improve product quality, to modernize manufacturing processes, to ensure product reliability . . . and to facilitate rapid commercialization . . . of products based on new scientific discoveries."

NIST, originally founded as the National Bureau of Standards in 1901, works to strengthen U.S. industry's competitiveness; advance science and engineering; and improve public health, safety, and the environment. One of the agency's basic functions is to develop, maintain, and retain custody of the national standards of measurement, and provide the means and methods for comparing standards used in science, engineering, manufacturing, commerce, industry, and education with the standards adopted or recognized by the Federal Government.

As an agency of the U.S. Commerce Department's Technology Administration, NIST conducts basic and applied research in the physical sciences and engineering and performs related services. The Institute does generic and precompetitive work on new and advanced technologies. NIST's research facilities are located at Gaithersburg, MD 20899, and at Boulder, CO 80303. Major technical operating units and their principal activities are listed below. For more information contact the Public Inquiries Desk, 301-975-3058.

Technology Services
- Manufacturing Technology Centers Program
- Standards Services
- Technology Commercialization
- Measurement Services
- Technology Evaluation and Assessment
- Information Services

Electronics and Electrical Engineering Laboratory
- Microelectronics
- Law Enforcement Standards
- Electricity
- Semiconductor Electronics
- Electromagnetic Fields[1]
- Electromagnetic Technology[1]

Chemical Science and Technology Laboratory
- Biotechnology
- Chemical Engineering[1]
- Chemical Kinetics and Thermodynamics
- Inorganic Analytical Research
- Organic Analytical Research
- Process Measurements
- Surface and Microanalysis Science
- Thermophysics[2]

Physics Laboratory
- Electron and Optical Physics
- Atomic Physics
- Molecular Physics
- Radiometric Physics
- Quantum Metrology
- Ionizing Radiation
- Time and Frequency[1]
- Quantum Physics[1]

Manufacturing Engineering Laboratory
- Precision Engineering
- Automated Production Technology
- Robot Systems
- Factory Automation
- Fabrication Technology

Materials Science and Engineering Laboratory
- Intelligent Processing of Materials
- Ceramics
- Materials Reliability[1]
- Polymers
- Metallurgy
- Reactor Radiation

Building and Fire Research Laboratory
- Structures
- Building Materials
- Building Environment
- Fire Science and Engineering
- Fire Measurement and Research

Computer Systems Laboratory
- Information Systems Engineering
- Systems and Software Technology
- Computer Security
- Systems and Network Architecture
- Advanced Systems

Computing and Applied Mathematics Laboratory
- Applied and Computational Mathematics[2]
- Statistical Engineering[2]
- Scientific Computing Environments[2]
- Computer Services[2]
- Computer Systems and Communications[2]
- Information Systems

---

[1]At Boulder, CO 80303.

[2]Some elements at Boulder, CO 80303.

NIST Special Publication 849

Proceedings of the Joint DoD/NIST Workshop on International Precision Fabrication Research and Development October 27–29, 1992

J. D. Meyer, Editor

Manufacturing Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Sponsored by
U.S. Department of Defense and
National Institute of Standards and Technology

March 1993

U.S. Department of Commerce
Ronald H. Brown, Secretary
National Institute of Standards and Technology
Raymond G. Kammer, Acting Director

National Institute of Standards
and Technology
Special Publication 849
Natl. Inst. Stand. Technol.
Spec. Publ. 849
244 pages (Mar. 1993)
CODEN: NSPUE2

U.S. Government Printing Office
Washington: 1993

For sale by the Superintendent
of Documents
U.S. Government Printing Office
Washington, DC 20402

FOREWORD

An international workshop was held in Rockville, Maryland, on October 27-29, 1992 to discuss major research and development programs in precision fabrication. Approximately 25 leading experts attended the workshop, which was co-sponsored by the U.S. Department of Defense's Manufacturing Technology Program.

Several papers, each covering a specific geographic region or topic, were presented at the meeting. Copies of these presentations are included in these proceedings.

In addition to individual R&D programs and technology sources in North America, Western Europe, Eastern Europe, and Asia, the workshop participants also discussed R&D needs, priorities, underlying motivations, and opportunities for international collaboration. The results of these discussions will be summarized in a separate report. Information about the summary report may be obtained from the editor of these proceedings.

J . D. Meyer
Gaithersburg, Maryland
October 1992

Final Participants List

Precision Fabrication Research and Development Workshop October 27-29, 1992 The Woodfin Suites Hotel Rockville, Md.

Ekkard Brinksmeier
University of Bremen
F.G. Fertigungsverjahren
D-2800 Bremen 33,
GERMANY

Peter Brown
NIST
Metrology Bldg., Rm. A127
Gaithersburg, MD 20899
USA

Charles Carter
Association for Manufacuturing Technology
7901 Westpark Dr.
McLean, VA 22102
USA

Daniel Cundiff
OASD
8000 Defense Pentagon, Room 3B253
Washington, DC 20301-8000
USA

William Donnelly
U.S. Army
Bldg. 172, Attn: AMSMC-PBR
Picatinny Arsenal, NJ 07806-5000
USA

Russell Duttweiler
Lawrence Associates, Inc.
5100 Springfield Pike
Suite 509
Dayton, OH 45431
USA

Chris Evans
NIST
Metrology Bldg., Rm. A107
Gaithersburg, MD 20899
USA

Dan Gearing
Defense Logistics Agency
Attn: DLA-PRM, Cameron Station
Alexandria, VA 22304-6100
USA

Ted Hicks
U.S. Navy
Bldg. 75, Rm. 209, MC 205
Philadelphia, PA
USA

Richard Jackson
NIST
Metrology Bldg., Rm. B322
Gaithersburg, MD 20899
USA

Said Jahanmir
NIST
Materials Bldg., Rm. A329
Gaithersburg, MD 20899
USA

Bruce Kramer
National Science Foundation
1800 G Street, NW, ENG/DDM-Rm. 1128
Washington, DC 20550
USA

Lloyd Lehn
Office of the Secretary of Defense
OASD (P&L), PR/MM, Rm.3B253
Washington, DC 20301-8000
USA

John Meyer
NIST
Chemistry Bldg., Rm. B212
Gaithersburg, MD 20899
USA

Frederick Michel
Society of Manufacturing Engineers
8409 Felton Lane
Alexandria, VA 22308
USA

Robert Reynolds
NCMS
900 Victors Way, Room 310
Ann Arbor, MI 48108-1779
USA

Eugene Rivin
Wayne State University
5050 Anthony Wayne Dr.
Detroit, MI 48202
USA

John Simpson
NIST
Metrology Bldg., Rm. B322
Gaithersburg, MD 20899
USA

David Stieren
OASD
8000 Defense Pentagon, Rm. 3B253
Washington, DC 20301-8000
USA

Clayton Teague
NIST
Metrology Bldg., Rm. A117
Gaithersburg, MD 20899
USA

Sato Tomomasa
University of Tokyo
4-6-1, Komaba, Rm. 408, 45 Bldg.
Meguro-ku, Tokyo, 305,
JAPAN

Alex Wakulenko
Benet Laboratories
Watervliet Arsenal, SMCAR-CCB-SM, 40
Watervliet, NY 12189-4050
USA

Robert Warrington
Louisiana Technical University
P.O. Box 10348
Ruston, LA 71270
USA

William Zdeblick
Institute of Advanced
Manufacturing Sciences
1111 Edison Dr.
Cincinnati, OH 45216
USA

Table of Contents

Introductory Remarks

John Meyer
Manufacturing Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Precision fabrication technologies are extremely important to many manufacturing industries, from automobiles and consumer electronics to machine tools and computer hardware. The development and use of these technologies have a direct impact on the products being produced and, ultimately, a manufacturer's ability to compete successfully in world markets.

Major advances in precision fabrication technologies are being pursued by numerous organizations around the world. In a field once dominated by American and European researchers, much of this R&D is now being conducted in other geographic areas. Undoubtedly, these research efforts will yield advanced technologies capable of producing parts with much higher precision, better quality and lower costs.

In the midst of this high level of on-going international research, there is a need for a mechanism for examining such efforts on a worldwide basis in an open forum, with an eye towards identifying collaborative research opportunities among regions. Workshops serve as one such mechanism.

To this end, a workshop was jointly sponsored by the U.S. Department of Defense (DoD) and the National Institute of Standards and Technology (NIST). Both DoD and NIST are actively involved in the development and implementation of advanced manufacturing technologies and each is interested in exploring international collaborative research projects in this field.

The purpose of the workshop was to provide an international forum for discussing major research and development programs in precision fabrication technology. Specifically, the objectives of the workshop were to:

1. Identify major R&D programs and sources of advanced precision fabrication technology in Europe, Asia, North America and other parts of the world.

2. Determine the approximate level of resources being expended in each R&D area.

3. Examine the goals and strategies of these R&D programs, as well as the underlying reasons and motivations for undertaking such efforts.

4. Explore any unmet needs or high-impact research opportunities that may exist in the area of precision fabrication technology.

5. Discuss the potential for international collaborative R&D projects and any key issues associated therewith.

For the purposes of this workshop, the term "precision fabrication" was very broadly defined and included the following topics:

-- Machining
-- Grinding
-- Other precision material removal processes
-- Stamping and forming
-- Micro- and Nano-fabrication technologies
-- Welding
-- Other precision joining processes

In each of these areas (with the exception of micro-fabrication), the primary emphasis was on fabrication technology for metals as opposed to other materials. However, within these areas, the primary focus was on technologies that can be used to produce "precision" and "ultraprecision" parts and assemblies.

Because of the focused and specific nature of the workshop's objectives, the meeting was conducted on a "by-invitation-only" basis. The total number of participants was limited to a maximum of 25 people. Each individual was expected to be an active participant in the discussions. Thus, only knowledgeable experts in the field were invited to participate in the meeting. The workshop was truly international in flavor, with leading observers from all regions of the world taking part in the meeting.

The meeting spanned a three-day period. The agenda was as follows:

Day 1:
Morning: Registration and individual presentations and questions
Afternoon: Individual presentations and questions

Day 2:
Morning: Group discussion of R&D framework and research programs
Afternoon: Group discussion of R&D needs and priorities

Day 3:
Morning: Group discussion of collaboration opportunities
Afternoon: Adjourn

Approximately 25 people attended the workshop. A list of the attendees is included in this proceedings.

As can be seen from the agenda, a considerable portion of the workshop was devoted to group discussions of various issues concerning manufacturing systems R&D. A separate report summarizing these discussions is planned for preparation in 1993. More information about the report is available from the editor of these proceedings.

Precision Manufacturing Practice and Research: A North American Perspective

William J. Zdeblick, Ph.D.
Technology Director
Institute of Advanced Manufacturing Sciences
Cincinnati, Ohio

Prepared for
NIST Precision Fabrication R&D Workshop
October 27-29, 1992

INTRODUCTION

This paper summarizes key observations about the state of precision manufacturing practice and research in North America. The background of the author is in metalworking and machining and thus the majority of the discussion relates to these industries. However, many technologies that have emerged from other "clean" manufacturing, particularly from the microelectronics, microfabrication and pharmaceutical industries, have been adapted to precision machining.

Precision manufacturing focuses on improving part accuracy and process repeatability but the practical discussion often focuses on manufacturing errors. The historical precision research agenda has been structured by understanding the nature and types of manufacturing errors. Significant technology advances, as measured by the reduction of these focused upon error types, have resulted. Discussed later in this paper is a classifying of error types into *machine, environment* and *process*. A fourth group, *measurement*, is a whole science in itself and will not be addressed in this paper (although many of the scientific concepts of metrology have been applied in the reduction of manufacturing errors).

Driven by this taxonomy of manufacturing errors, individual research efforts tend to be narrow in scope and focused only at the highest impact areas, namely, the largest error sources. Advancements in individual hardware components (bearings, controllers, spindles, structures, etc.) are primarily driven by the individual machine hardware component builders. The rate of improvement and implementation of these precision technologies in general manufacturing is fairly predictable (see below) and is not sufficient to regain world leadership. An assessment of today's precision research agenda finds that gains are achieved in an evolutionary manner and that "the low hanging fruit has already been picked".

Unfortunately, today's precision research agenda is fragmented -- across the industrial, academic and federal government spectrums. As a result it is difficult to achieve a significant, revolutionary impact on precision manufacturing. The time has come to reassess the nation's precision manufacturing *research agenda* if we are ever going to "reach for the high fruit." With the error taxonomy understood, a more systematic, integrated view of precision research is needed which strives toward a greater synergistic benefit. A shift from component driven research to an integrated systematic agenda that includes widespread technology deployment strategies is needed.

PRECISION: A COMPETITIVE STRATEGY

A very important trend has been noted among machining system users -- accuracy requirements are dramatically increasing. The ability to consistently manufacture mechanical parts that are "straighter, rounder and flatter" yields significant product marketing advantages with respect to performance, reliability and life. For example, Cross Company is currently developing a machining system for the production of automotive engine components that will hold at least one dimension (a bore) to 67 microinches. Similarly, Texas Instruments anticipates that within 2 years, tolerance requirements for aerospace systems will be in the range of 50 microinches. Such levels of accuracy were unheard of in all but ultra-precision work a few years ago.

To achieve such accuracy requirements consistently, both builders and users will have to alter many of the fundamental principles under which they have traditionally operated. This presents a strategic opportunity -- to develop the capability to reliably achieve very high levels of precision in high-productivity manufacturing environments. There are a number of reasons why this strategy is achievable:

- All industries are extremely concerned with product quality, and ultimately, high quality levels rely on the ability of process equipment to hold tight tolerances. The demand for increasingly precise manufacturing processes will grow.
- Increased machining system accuracy -- in the range of 1 microinch -- can only be achieved technologically. Whereas higher productivity can often be realized by such operational tactics as Just-In-Time or moving manufacturing off-shore, the battle for higher-precision production capability will be won or lost on the basis of sound R&D integrated into shop practice.
- ROI is not a strong decision factor, since there are few viable alternatives to achieving higher precision other than investment in new equipment. This is not true, by contrast, in decisions involving investment in higher productivity (i.e., metal removal rates), since alternatives typically exist, (e.g., invest in the development of a machine that runs twice as fast as opposed to purchasing two standard machines).
- Much of the technological basis of high-precision machining has been developed with U.S. government funding and is available for use by U.S. companies. In fact, the ultra-precision technology that exists within the National Laboratories is the most advanced of its kind in the world.
- The achievement of very high precision capabilities in high-productivity operations will result from a <u>coordinated</u> series of developments, some small and some large in scope. This will require a concerted, continuing effort by many U.S. R&D organizations coordinated by a single entity.

Machine Tool Industry: The Dynamics of Change

Precision manufacturing capability is dynamic and it is constantly changing over time. The state-of-the-art of today leads to the State-of-the-Practice tomorrow. Knowing how this dynamic works is very important if programs that accelerate the rate of change of this process are to be developed. The general classifications of machining is defined as follows:

<u>Normal machining</u>:	That which is performed routinely in the widespread production base.
<u>Precision machining</u>:	That which is the state of the art in a high-quality production environment or laboratory.
<u>Ultra precision machining</u>:	Those processes/machines by which the highest possible dimensional accuracy is, or has been, achieved at a given point of time.

Historically, the time that lapses before techniques classified as "precision machining" move out of the laboratory environment and into the production environment, so as to be reclassified as "normal machining", is approximately 40 to 50 years. Furthermore, the time that lapses before "ultra precision machining" is reclassified as "precision" is another 15 to 25 years. In other words, there is a predictability for industry's ability to transfer technology from research to the production line. The transfer rate from "ultra" to "normal" is quite long indeed (55 to 75 years).

This historical time required for technology transfer can be projected onto the future, thereby producing considerable discouragement about chances for America's successful manufacturing or technological "comeback." On the other hand, by being fore-armed with such detailed knowledge about the phenomenon and expanding that knowledge in a structured way, it is possible that U.S. manufacturers could devise ways to significantly shorten the historical 50-75 year cycle.

To effectively introduce a fundamental change into the domestic machine tool industry, its inherent operational characteristics need to be understood. Through observation and discussion with a variety of users and machine builders, the following points tend to describe the industry's character:

- The machine tool industry is slow in accepting and developing new technology. For example, it was about 12 years from the first valid experiments on magnetic bearings until these bearings were implemented in a production machine tool in Japan (in 1988).
- New concepts, even if first thought of in the United States, seem to be implemented first in other countries. The first implementation of a truly unmanned machine tool, the first ceramic spindle, and a spindle operating at 100,000 rpm with a set of antifriction bearings occurred in Japan. The first known experimental spindle made of carbon-fiber reinforced plastics and the first precision bearings for high-speed spindles came from West Germany.
- Most of the advances made in recent years in the technology of the major building-block elements have come from sustained, long-term improvement efforts, with small steps or advances taken progressively, rather than as the result of a major one-time R&D push to leapfrog into a new realm of technology.
- In recent years, there has been a major increase in the amount and quality of R&D work that relates to machining systems in the United States as well as in other countries. The number of universities doing work in this area has increased greatly, and the number of R&D projects in manufacturing has increased. As a result, many of the potentially interesting projects that have been identified are already being investigated to some degree in R&D organizations.
- Many U.S. machining system builders feel they have little incentive to innovate. Several novel machine tools that were developed by U.S. builders (e.g., high-speed spindle, faster broaching machine) were not accepted by U.S. users and, as a result, some of the U.S. builders have become unwilling to invest in new technology.

MACHINING ERRORS

Sources and Classification

Several previous works have catalogued the sources of errors in machine tools. It is sufficient for this discussion to list the major sources of error and group them according to their type. They are:

Machine	Environmental	Process
Geometric: Displacement Straightness Squareness Parallelism Axes of Rotation	Staff Training Operator Maintenance Management Tooling Support	Tool wear Size/Shape Change Force Increase Heat Increase BUE
Controller errors: Hardware Faults Software Faults	Thermal Changes External Part Stability	Fixturing Part Deflection Dynamic Stability
Thermal Effects Internal Sources	External Vibrations	Surface Integrity & Finish Residual Stresses Material Damage
Mechanical Effects: Wear Loading Effects	Other Air/Liquid Part Handling	Dynamic/Static Stability Chatter Deflection

Several error categories (particularly the process errors and thermal errors) have remained more elusive because they are so process and part specific. Up until recently they have been addressed only by human operators, using their brains and senses, and have only recently become candidates for treatment by artificial means.

Machine Tool Hardware

Errors due to machine tool hardware have received the most attention over the years. Machine tool builders themselves can, and have, taken the lead in the research and development initiatives since they exert total control over the design and manufacture of their products. Traditionally, two approaches to reduce hardware-based errors are used; namely, *error reduction* in design and construction and *error compensation* through on-line measurement and control. Steady and significant improvements have occurred in reducing the geometric-based and control-based errors and well-defined research needs can be identified by continuing the evolution of current research.

Builders have steadily improved the structural design and manufacturing method of machine tools to improve precision. Improved spindles, bearings, leadscrews, transducers, etc. have systematically evolved to higher precision. The evolution of improved components is expected to continue. However, the application of more global systematic design engineering practices is not common.

For example, the use of CAE analysis tools to improve the static and dynamic behavior of machine tools is readily available for use in the industry today. A recent survey completed by IAMS on "Improving Machine Tool Dynamic Stiffness" found that, by and large, sufficient CAE technology is available in commercial software products to analyze machine tool structures. However, implementation levels are low due to many non-technical (skill levels, cost, time, lab equipment, ...) reasons.

Thermal effects are different and particularly troublesome because it is difficult to separate them from other error sources (such as deflections). The consideration of new approaches to address these errors may be appropriate. There is no means for measuring them directly or detecting their presence during actual machining processes. They must be inferred from measurements of the thermal condition of the machine and its environment. The treatment of thermal effects is still far from mature enough to suggest preferred techniques appropriate for routine usage.

The principal means of thermal error elimination is temperature control and heat isolation within the structure. Significant progress has been made in the past twenty years on designs for environments for precision machine tools as well as control of temperatures within the machines themselves. The best example of this technology is the Large Optics Diamond Turning Machine (LODTM) at Lawrence Livermore National Laboratory. The surrounding air temperature is maintained at 20°C±0.010° and the cooling water flowing through the machine is maintained at 20°C±0.001°. Machines with individual and integral controlled thermal environments were suggested at least as early as 1970 and are now commercially available.

The traditional compensation approach for thermal errors involves a method of determining correlation between temperature measurements at selected sites on and within machines and the resultant thermal effects errors. Further, they incorporate the temperature sensors in a system that inputs correction signals to a machine tool CNC which adjusts the machine drive systems. Historically, correlations are derived from the analysis of large amounts of data from tests performed on an existing machine by means of curve-fitting. Recently, at the Institute of Advanced Manufacturing Sciences, the use of Artificial Neural Network techniques are being explored as a method of building more generic and less engineering intensive thermal error compensation models.

A summary of some of the critical research and technology requirements for machine tools is presented in the Appendix. The science and research identified is intended to continue to push the technology envelope. However, to meet the challenge described above of widespread precision manufacturing improvement requires an effective and systematic technology deployment strategy, not necessarily a focused technology development agenda.

Environmental and Operational

The environmental and operational causes of machining and measurement errors are, for the most part, well understood. Much specialized work has been done to develop the technologies necessary to eliminate the effects of the environment that negatively impact precision manufacturing and precision measurement. In fact, a number of manufacturers have developed excellent techniques for controlling certain environmental factors in immediate proximity to precision equipment.

Examples of the degree to which methods currently exist for controlling the precision manufacturing environment are not difficult to find. Methods exist for:

1. Controlling ambient air temperature to a remarkable degree (better than +0.01°C).
2. Controlling aerobically borne particulate contamination (as is done routinely in Class 10 and less frequently in a Class 1 clean room in the semiconductor industry).
3. Controlling vibration within precision equipment and the vibration that is transferred to precision equipment from external sources (technology for blocking most external vibration greater than 5 Hz is available from vibration isolation suppliers).

The foregoing examples of the effective control of environmental impact on precision manufacturing were found within industries whose survival depends upon resolving highly specific problems in a focused way. The example of superb ambient air temperature management cited above can be found in manufacturing systems using electronically controlled, closed-loop feedback systems that connect the facilities' HVAC systems to precision manufacturing equipment temperature sensors.

A few semiconductor companies and equipment suppliers have demonstrated a remarkable capability for controlling airborne contamination. Such firms have met the stringent cleanliness demands of their industry by designing and implementing Class 1 clean room facilities.

Many examples of the control of precision equipment vibration can be found in U.S. industry. Designers have in fact developed highly sophisticated methods for controlling vibration within precision equipment and within the facilities that house precision equipment. Vibration control within precision equipment is currently focusing upon the use of advanced structural designs and advanced materials. The know-how needed to perform the difficult technical tasks of controlling the physical environment surrounding precision manufacturing (the facilities) currently exists and is available, providing that potential users are willing to apply adequate effort, thought, and money to proper implementation activities.

Much progress has also been made in the human resources arena of precision manufacturing management. Certain exemplary programs have been implemented and made effective in the task of developing personnel who can consistently perform state-of-the-art precision manufacturing work. By designing targeted training and education programs, organizations such as Lawrence Livermore National Laboratories have successfully trained employees in the operation of highly precise manufacturing equipment.

It is most important to note that even though many enabling technologies connected to precision manufacturing practices are highly specialized, each of those technologies contain principles and methodologies that may be utilized to considerable benefit in less demanding industries. A recent NCMS-sponsored assessment program has determined that state-of-the-art precision manufacturing technologies are in place within a number of companies and institutions across the U.S.; however, the documentation of those technologies is often not available, and has most certainly not been collected in a convenient , centralized repository. A notable exception is

Lawrence Livermore National Laboratory where documentation is quite good and, for the most part, available to industry at large.

In addition to the fact that many precision manufacturing technologies are not documented, it is also true that the documentation that does exist is often in a condition that reduces its usefulness to industry. Current literature generally lacks sufficient "how to" detail to allow an interested technologist to proceed with a similar precision manufacturing implementation. Those documents that do contain sufficient "how to" detail are frequently not readily accessible in a usable, public domain form.

In summation:

1. Most of the environmental and human factors technologies needed to make U.S. manufacturers nationally and internationally competitive in precision manufacturing do exist.
2. Very few new technologies have to be developed in order to allow U.S. manufacturers to be competitive in the current global precision manufacturing marketplace.
3. The needed expertise exists in various government laboratories, universities, and commercial enterprises.
4. Highly qualified people are available to help define and document the guidelines for precision engineering.

Process and Process Engineering

The activity of engineering the specific method to manufacture a precision part, including tooling, fixturing, NC programming, etc., is process engineering. The specific part material, shape and requirements must all be factored into consideration in addition to the machine tool and factory environment. The accumulation of all prior precision research and technology occurs in the process engineering activity; this is where the rubber meets the road!

Typically, as incremental technology is introduced to improve precision (e.g., reduce errors), process engineering absorbs the technology on an as-needed basis. For example, as touch probes were introduced by builders, the NC programmers learned to program on-line inspection actions to dynamically calculate tool offsets. Today, the implementation phase of precision engineering research is considered to be the training and upgrading of process engineering. The rate of technology introduction and absorption is poor and typically incrementally focused upon individual error types. As with the overall precision research agenda, "the low hanging fruit has already been picked". Clearly, improvements in the rate of implementation can be made through:

1) The collection of precision engineering best practices into a general guidebook and companion training program,
2) The development of Precision Analysis Software Tools to assist in the application of the best precision practices for specific situations, and
3) Use of CAD/CAM tools such as Computer Aided Process Planning (CAPP) systems to leverage the widespread implementation.

The opportunity to take a more systematic, integrated view of process engineering is available and a new paradigm for precision engineering research can be explored. Rather than focus independently on individual error types and attempt to eliminate or compensate each error, the use of Computer Aided Engineering (CAE) modeling and analysis techniques would allow the overall machining system to be viewed in an integrated manner. Research programs which specifically model and simulate (not just animate) the physical behavior of the process, equipment and environment and understand the interaction between each error type offers a tremendous opportunity to leapfrog current precision machining practices.

One paradigm which may be researched could be the general concept of open-loop compensation to reduce predictable and repeatable errors. Utilizing an improved CAE-based integrated process error model that is synchronized to a specific part, machine and environmental characteristics may drastically improve compensation strategies while maintaining (or even improving) production rates. A simple example to visualize this concept is the deflection of thin walls in airframe structures. To maintain low tolerances, extremely slow and conservative (low force) machining practices are typical. By having an improved process model able to analyze forces, deflection and , vibration an adjusted machining strategy, including a non-linear tool path allowing for part deflection and springback, could be developed. Sacrificing feed rates and thus productivity may not be necessary!

Another area of focus is in predicting and accounting for normal process changes, such as tool wear. Tool wear, like thermal effects, has been difficult to measure directly and has been attempted to be inferred through indirect measurements. Unfortunately, many researchers have overlooked the central problem; namely, the key objective is part size changes not necessarily only tool size changes. Extensive research efforts over the last 30 years have been too narrowly focused. Tool wear is now being practically measured and compensated for, in some cases on-line. Use is being made of tool setting stations with both touch and visual sensors. The common practice of the human operator to detect a worn tool by sound is being imitated by means of acoustic sensors.

However, the use of an integrated CAE-based model to understand the spectrum of errors would consider tool wear in an inter-related context with forces, deflection, vibration, thermal growth, etc. Without such an improved process model to formulate a predicted "open-loop" tool wear compensation strategy, the benefits of addressing tool wear errors alone are limited. Clearly, the effort to develop an on-line, integrated, intelligent sensor-based strategy for error compensation requires an integrated view.

Process errors have historically been the most elusive to systematically structure within a research framework since they are part and environment specific. Individual experience and expertise is the normal approach for improved precision. However, developing a systematic methodology to eliminate process errors has potentially the largest impact; namely, to implement precision engineering research into widespread practice and shorten the historical dynamic of machining precision evolution. Research in this area will not just focus on the physical science and must explore creative and revolutionary strategies. Only with this approach will "picking the high fruit" be achievable.

Summary: Next Steps

Technology

Machine tool design has evolved from basically mechanical mechanisms to highly sophisticated systems involving many different technologies. The following list represents critical technologies that affect the capability and competitiveness of machine tools in manufacturing.

- Metrology
- Dynamics of structures
- Electronic controls
- Advanced materials technology
- Metallurgy
- Advanced precision bearings
- Software
- Artificial intelligence
- Physics of materials
- Laser technology
- Sensors technology

Each of these technologies is critical to competitiveness because each affects the performance and capability of machine tools. They are universal in their application, although each one may not be used in every machine type. The performance and characteristics of a particular machine are determined by the:

- basic mechanical and physical design of the machine;
- materials used in its construction;
- selection and application of various bearings;
- controls that direct the motion and speed of movement as well as the repeatability of the machine;
- software that commands the controls;
- sensors and measuring devices that inform the software in the controls about the operation and positions of the various elements of the machine tool.

Developing these critical technologies requires significant multi-disciplinary research and development programs. Even within these general research needs lies a large range of prerequisite and application-specific research programs. For example:

- Precision improvement includes tool sensing to correct for deviation from programmed tolerances; hardware/software monitoring, mapping and correction procedures; and position and thermal sensing to compensate for structural errors.
- Sensing-research projects include the development of position transducers, so that sensors are accurate in increasingly higher-speed machining; sensor arrays to integrate the measurement taken during the various steps of the machining process; and the development of lower cost laser feedback systems.
- Computer software projects include expert systems and artificial intelligence; improved machine controls; and the development of a real-time, object-oriented computer language to develop numerically controlled machine software, as hardware development is constrained by the high cost of concurrent software development.

The complexity of these research undertakings is multiplied as advances in new materials and microelectronics continue. The scope and expense of such research efforts preclude all but the top few machine tool builders from undertaking the necessary effort. For the typical machine tool builder, with annual sales of about $7 million, mounting even a small research and development effort is prohibitive.

Infrastructure

The job at hand is the structure by which cooperative, shared research and development can be organized. The demonstration of technology in a single, isolated case does not necessarily generate widespread use. Funding a single builder to demonstrate new technology may not even assure that the technology will be duplicated within the builders product line and customer base!. The wealth of science available is, for all but the most extreme cases, sufficient and applicable. The access to, justification for and deployment of this available science is the challenge facing the industry. Coordination of the nation's precision research agenda is the mission.

Clearly, builders respond to the market requirements. Pushing technology onto the builders via focused research programs has not resulted in the technology being pushed onto the end users! Only the increase of market demand for precision will result in precision technology being pulled into use. To accomplish steady, sustained implementation of precision manufacturing technology, the focus of any stimulation must be on the end user -- through education, information products, engineering assistance and economic justification assessments.

A historical model of this strategy is available in the cutting tool industry -- the Machinability Data Center (MDC). As new materials (primarily aerospace) were quickly being developed and put into production, a flurry of isolated research efforts were initiated to develop new cutting tools. Material science and coating technology was foreign to most machining end users and keeping track of new developments was impractical. As a result, making the investment to change was done reluctantly, if at all. However, with the MDC serving as an independent clearinghouse of information, a central training resource and provider of engineering between tool vendors and end users, new technology was effectively introduced. As a result the niche markets for aerospace tooling grew. The business incentives for individual firms to undertake advanced cutting tool research was stimulated. The lessons learned from the MDC could be applied to stimulate the use of precision manufacturing technologies.

A unified, coordinated approach to help USA companies regain a lead position in precision manufacturing is needed. This unified approach will be complex in implementation, but it is simple in principle:

1. Make technology READY to be effectively and efficiently transferred.
2. Make human resources CAPABLE of receiving and implementing advanced manufacturing technology through the development and implementation of effective Manufacturing Education Programs.
3. FACILITATE the technology transfer by establishing predictable, reliable transfer methodologies and organizations.
4. IDENTIFY technology voids through direct interaction with the end users.

5. COORDINATE multi-organization research initiatives to pull research objectives that address these voids.

The nation requires a central Precision Manufacturing Access Point (P-MAP) to exchange and interact with technology. The Institute of Advanced Manufacturing Sciences is moving toward establishing itself as such a P-MAP.

Acknowledgment

The source of this paper's information is the author's 15 years of first-hand experience working in the machining industry. The majority of that time was spent at Metcut Research Associates and now at the Institute of Advanced Manufacturing Sciences which took over the Metcut operations. In addition, information was obtained through direct dialogue with several engineering directors at machine tool builders and from reviewing several recent NCMS-sponsored studies addressing machine tool research needs. The author also wishes to thank Mr. Nicholas Weil and Mr. Jack McCabe of NCMS for their input.

Bibliography

1. 66 Centuries of Measurement, 3rd Ed., The Sheffield Measurement Division, Dayton, Ohio, 1984.
2. Hayes, Donald J., et. al., Precision Manufacturing Guidelines: Human & Environmental Factors -- A State-of-the-Art Assessment. National Center for Manufacturing Sciences, 1990 (Contract number NCMS-66-MO-2).
3. Moore, Wayne, Foundations of Mechanical Accuracy, Moore Special Tool Co., Bridgeport, CT, 1970.
4. R. Hocken, Ed., Technology of Machine Tools, Vol. 5, Accuracy, Lawrence Livermore National Laboratory, UCRL-52960-5, October, 1980.
5. Blaedel, K., Error Reduction, MTTF Report, UCRL 529605, October, 1980, pp. 61-73.
6. Donmez, M.A., A General Methodology for Machine Tool Accuracy Enhancement by Error Compensation, PRECISION ENGINEERING, Vol. 8, No. 4, October, 1986, pp 187-196.
7. Taniguchi, N., Current Status in and Future Trends of Ultra-precision Machining and Ultrafine Materials Processing, Annals of the CIRP, Vol. 21, No. 2, 1983.
8. SRI International, High Productivity Machining Systems: State-of-the-Art Assessment, National Center for Manufacturing Sciences, 1989 (Contract number NCMS-88-PE-4).
9. Council on Competitiveness, Competitive Profile of the Machine Tool Industry, 1991 (Background Paper for CoC's Gaining New Ground Report).

APPENDIX: CRITICAL MACHINE TOOL TECHNOLOGIES

CRITICAL TECHNOLOGY: Electronic Controls

DESCRIPTION: Electronic controls are used to command and control the motions and functions of machine tools. These controls may be relatively sophisticated Computer-based Numerical Controls (CNCs) which use numerical part programming information to command the machine, or Programmable Logic Controls (PLCs) which utilize electronic components to effect the sequential control logic previously provided by electromechanical relays.

WHY IS IT A CRITICAL TECHNOLOGY: In order to meet the demand for increased machine versatility and to efficiently produce parts having complex shapes and/or close tolerances, which are increasingly used in aerospace, defense and consumer products, it is necessary that the machines producing these parts be electronically controlled. Such controls eliminate the variability and inefficiencies associated with human control of machines. The increased emphasis on product quality also dictates use of electronic controls that allow the manufacture of parts with close part-to-part consistency.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: Although the concept of numerical controls was created in the United States and further developed at MIT in the early 1950s, the dominant supplier of such equipment today is Fanuc of Japan, which accounts for over 70 percent of the world market. As a result of and the fact that the Japanese government subsidizes considerable industrial research conducted in their country, the United States will have a hard time regaining the lead it once enjoyed. Recently the Japanese have exploited U.S. developed capability which allows user-friendly programming of complex parts right at the machine.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: Electronic controls are technologically dependent upon advances made in the semiconductor and computer industries. The emerging popularity of 32-bit Central Processing Units (CPUs) has decreased their cost to both computer manufacturers and to suppliers of electronic controls for production equipment. This development has in turn allowed the design and development of electronic controls having both increased functions and speed.

CRITICAL TECHNOLOGY: Sensor Technology

DESCRIPTION: Sensors are devices that provide an indication of force, displacement, power, temperature, or other process variables. They typically provide inputs to the electronic controls used to control a production process or piece of equipment.

WHY IS IT A CRITICAL TECHNOLOGY: The control over a manufacturing process is a function of the degree to which process variables can be measured and of the relationship between these process variables and the attributes of the finished part. Because of this, sensor technology is critical to the efficient production of close tolerance parts. Of critical importance is not only the technology of the sensors themselves, but also the technology of signal processing and communication related to the sensor output.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: The U.S. machine tool industry is dependent upon others for much of the sensor technology it uses. Many of these are foreign firms. No U.S. firm is large enough or profitable enough to undertake research program of sufficient scope to compete with any of the foreign companies who of sufficient well-established footholds in these areas.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: In many cases the critical element of a sensor is made of semiconductor material, thus there is a dependence of the sensor industry upon the semiconductor industry. This dependence extends to the devices used for sensed signal conditioning for signal conversions, and for sensed signal mixing and decoding.

CRITICAL TECHNOLOGY: Software

DESCRIPTION: Software is the collection of programmed instructions used to define the responding, controlling and communicating functions of computer-based engineering and manufacturing equipment and systems.

WHY IS IT A CRITICAL TECHNOLOGY: Software defines the responding, controlling and communicating functions of manufacturing equipment, it is critical in determining the capability and efficiency of the equipment being controlled. (An even more critical first-step is having a clear understanding of the process to be controlled.)

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: The United States has been a recognized leader in software programming expertise. This exists primarily because electronic computers were first developed in the United States, and the installed base of computers, both main-frame and personal, is much larger here than in any other country. The rest of the world is rapidly catching up with the United States, as evidenced by the increasing number of Computer-Aided Design (CAD) systems available from overseas suppliers and by the increasing number of user-friendly features being added to Computer-based Numerical Controls (CNCs) produced abroad.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: As noted above, being able to efficiently program computer-based systems can only be done once the process to be controlled is sufficiently understood. Thus, the development of "good" software requires a background in manufacturing engineering, process engineering, and mathematics as well as a good background in computer programming. In effect, continuing state-of-the-art expertise in software is dependent upon continually updated experience and/or education in all of the aforementioned fields.

CRITICAL TECHNOLOGY: Artificial Intelligence

DESCRIPTION: Artificial intelligence as applied to manufacturing is that branch of science devoted to computer control of a product or a process using algorithms, logic and/or cause-effect relationships which might otherwise exist in the mind of a human operator or process designer.

WHY IS IT A CRITICAL TECHNOLOGY: Artificial intelligence has the potential to significantly improve the productivity of manufacturing operations by incorporating human experience and/or human thought processes in the control regimen. As such it has the potential to improve the competitiveness of those businesses which employ it.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: The United States has pioneered efforts to develop artificial-intelligence technology particularly as it relates to manufacturing and/or the organization of data bases. It is anticipated, as a result of international interest in the subject, that competitive advances in this field will come from around the world and will not be limited to those made by U.S. investigators.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: The utilization of artificial intelligence techniques, as is the case with the development of manufacturing-related software, is dependent upon a knowledge of both the manufacturing processes to be controlled and the science of artificial intelligence. A strong background in both manufacturing and in computer science is required.

CRITICAL TECHNOLOGY: Laser Technology

DESCRIPTION: Laser technology is the use of narrowly-focused light beams for measurement, and processes requiring the discrete application of heat.

WHY IS IT A CRITICAL TECHNOLOGY: Possessing a continually updated inventory of state-of-the-art laser technology is critical to U.S. manufacturers because it can profitably be applied to such varied manufacturing tasks as measurement, cutting, joining, marking, etching, surface finishing, scribing, hole cutting, deburring, heat treating, chic breaking, etc. Indeed, many aerospace and commercial parts could not be economically produced without the use of laser technology.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: It is known that the Japanese have for some years had a program to develop a manufacturing system utilizing a high-powered laser and a split-beam delivery system. This and other Japanese and an research endeavors will challenge the leadership currently enjoyed by the United States in laser technology.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: Laser technology is dependent upon precision turning and finishing technologies for mirrors, and on optics and fiber-optics technologies for other aspects of the beam-delivery systems.

CRITICAL TECHNOLOGY: Physics of Materials

DESCRIPTION: The physics of materials relates to the measurable properties and characteristics of materials. For manufacturing, these properties are primarily those that relate to how the material cuts, bends, shears and welds.

WHY IS IT A CRITICAL TECHNOLOGY: In order to produce a manufactured part, it is necessary to design an efficient process to create that part. In order to design the process, it is critical that one understands the physical characteristics of the material of the part, and especially how the characteristics of the part and the selected tool(s) will interact.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: For a number of years the U.S. manufacturing engineers have maintained a wealth of data showing what feeds and speeds should be selected for the efficient production of parts produced by metal cutting techniques. These data were available for a variety of combinations of workpiece materials and tool materials. With the advent of new tool materials (such as coated carbides, ceramics and Cubic Boron Nitride (CBN) materials) the previously published data are no longer sufficient. Research and/or lab tests to establish appropriate feeds and speeds for workpieces made of newer alloys and for tools made of new materials must be developed.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: The magnitude of the project to develop new feed and speed information is a function of the rapidity with which new alloys are developed by the primary metals and how fast too develop new materials and/or coatings for tooling. It at the need for the development of information on the physics of new materials (for both workpieces and tooling) will be forever ongoing as new materials continue to be developed.

CRITICAL TECHNOLOGY: Advanced Materials Technology

DESCRIPTION: Advanced materials include those not considered primary metals or their common alloys. They include metal matrix composites, graphite, fiber glass, ceramics and other man-made materials.

WHY IS IT A CRITICAL TECHNOLOGY: Many industries require the use of special materials capable of withstanding the rigors of unusual environments. These industries include the aerospace and supersonic transport industries, nuclear industry, undersea exploration industry, petrochemical industry, etc. These industries require parts manufactured from materials capable of withstanding severe temperature, pressure, nuclear bombardment, corrosive, and similar environments. In order to retain our lead in the industries requiring these types of parts, it is necessary that we retain our lead in advanced materials technology.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY:

While the United States currently leads in advanced materials technology, this lead could be eroded by ignoring the research being pursued by firms in other countries including Japan, West Germany, France, Great Britain and Israel. The United States needs to be aware of and know the properties of these advanced materials in order to design and offer machines capable of producing parts made of such materials. The industry also needs to be aware and take advantage of the characteristics of these advanced materials when selecting the materials to be used in all newly designed machine tools.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES:

The U.S. machine tool industry depends upon other industries for the development of these advanced materials and must work closely with them in order to minimize the time delay between the availability of advanced materials and the availability of manufacturing equipment capable of processing and/or utilizing those materials.

CRITICAL TECHNOLOGY: Advanced Precision Bearings

DESCRIPTION: Advanced precision bearings are used in machinery and technical products where there is a high demand for accuracy and reliability. Applications in jet engines, navigation devices and precision machine tools are typical.

WHY IS IT A CRITICAL TECHNOLOGY: Modern machine tools require bearings of high geometric accuracy and low mechanical wear over time. Jet engines also require advanced precision bearings because of the necessary tolerance for high temperatures.

Precision bearing races are especially ground, checked and aired together. Many state-of-the-art bearings come with ceramic balls for longer life and increased accuracy. Ceramic bearing technology is relatively new and only a few countries -- Japan, West Germany and the United States -- have that capability. Japan has a considerable lead over the United States.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: The main threat is that these bearings are available from Japan at competitive prices. The has been relatively low an U.S. suppliers have not been eager to adopt this technology.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: Advanced precision bearing technology and especially ceramic bearing technology is dependent on the development of quality ceramic materials resistant to heat-induced cracking, and the availability of equipment to machine them. Here again, Japan has a the United States resulting from their previous work on ceramic rotors for automotive turbochargers and heat research and experimental work on developing components for the so-called "adiabatic engine."

CRITICAL TECHNOLOGY: Metrology

DESCRIPTION: Metrology is the science of measurement and comparison of these measurements to an established system of references. Metrology is used extensively in manufacturing industries and especially in the machine tool and related industries.

WHY IS IT A CRITICAL TECHNOLOGY: Present day technical products require accuracy unheard of a few years ago. The established "rule of thumb" requires that measuring instruments be at least ten times more accurate tolerance on the measured value. This necessitates the use of such technologies as optics, fiber-optics, laser beams, microelectronics, computers, etc. Without well-founded metrology principles and the associated precision instruments, the United States would be incapable of manufacturing the precision parts required for contemporary products.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: U.S. research and innovation in this area has been lagging behind that of Japan, West Germany and Switzerland. While in the past, Germany was at about the level of the United States, it continued with its thrust toward better, more complex measuring instruments. Japan has made great strides over the last 10-20 years, and is today neck and neck with West Germany. While the United States still maintains equality in the theoretical field, regaining superiority in the commercial metrology industry will take substantial investment in manpower and capital.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: Future advances in metrology may be fueled by new developments in fiber-optics, optoelectronics speed microcomputers. There is renewed interest sparked by the drive for product quality throughout the manufacturing sector, including the machine tool industry.

CRITICAL TECHNOLOGY: Dynamics of Structures

DESCRIPTION: The dynamics of structures is a scientific discipline based on the fundamentals of the strength and elasticity of materials. This science focuses on the minute elements of a structure, analyzing its behavior when subjected to a given set of external forces.

WHY IS IT A CRITICAL TECHNOLOGY: Mechanical structures deform when subjected to external forces, such as those incurred by a machine tool. It is advantageous if the resulting deformation can be calculated and if steps can be taken to either minimize it or to use it as an advantage. Although the fundamentals of the dynamic behavior of structures have been known for some time, modern day computers have made possible comparisons between different structures subjected to a given set of forces. By using a technique known as "finite element analysis," one can predict the static and dynamic behavior of such structures and undertake countermeasures by either redesigning the structure or by rearranging the applied forces. This technology makes it possible to design superior structures, be they machine tools, aircraft, automobiles, bridges or any other complex product.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: The United States acquired prominence in this field at the time of the first mass introduction of powerful commercial computers. Lately, however, several industrialized nations have caught up with the United States. Japan, West Germany, Great Britain, Italy and even smaller countries like Belgium and the Netherlands are becoming world players in this discipline.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: Computer technology plays a major role in this field. Proficiency in the use of computers and availability of the related software are of the utmost importance.

CRITICAL TECHNOLOGY: Metallurgy

DESCRIPTION: Metallurgy is the science of production and use of metals. It includes several disciplines, such as the extraction of metals from the ore, purification of the extracted metals, and their alloying, heat treatment and testing.

WHY IS IT A CRITICAL TECHNOLOGY: Modern high-technology metals are exposed to a variety of environments, such as high temperature in aerospace engines. Another key application for specialty metals is in hostile environments, such as highly corrosive environments, chemically aggressive environments, mechanically abrasive environments and the like. The rotor blades of the gas turbine portion of a jet engine are heavily stressed by centrifugal force and are subjected to thermal stress as well as to mechanical abrasion from ingested debris. In some applications, the requirement is based on the light weight of the metallic components and this is where light alloys come into play. In machine tools, the emphasis is on structural integrity, resistance to wear of moving parts and suppression of vibration induced by the cutting or on inertia forces due to the cycling of the machine.

THREATS TO U.S. RETAINING/GAINING PROMINENCE IN TECHNOLOGY: This is one of the areas where the United States once had overwhelming international superiority, some of which still exists. Much of this technology was first developed by the automotive industry and later by the aerospace industry, including NASA. Over the last several years, foreign auto manufacturers have at least caught up with the United States. The European "Airbus" consortium has made great strides in civilian aircraft technologies, including metallurgy. In addition, Japan is planning to develop a fighter plane based on the U.S. F-16. It is almost certain that they will learn some of the existing U.S. technologies. One of the factors working against future U.S. superiority in metallurgy is the fact that in the United States emphasis has shifted from metals to other man-made materials such as plastics, carbon fiber and different high-tech composites.

TECHNOLOGICAL INTERDEPENDENCIES -- RELATED TECHNICAL ISSUES: There is a high degree of competition between metallic materials and the newly developed high strength composites. In the automotive industry, plastics are replacing metal parts. All this directly affects the amount of funds budgeted for metallurgical research, chipping away at the historic U.S. preeminence in this field.

Precision Fabrication
Research and Development

Workshop October 27 - 29, 1992
Rockville, Md, USA

Western European R & D-Programs and Sources of Funding

Prof. Dr.-Ing. E. Brinksmeier
University of Bremen, Germany

Table of contents

1. Introduction

To give a survey on precision fabrication oriented R & D in Western Europe is an almost unsolvable task for several reasons.

First, the field of subjects and problems on which the scientific community and industry are working cannot be overseen from the knowledge point of view. There is no person who is able to be an expert in all spezialized items of this domain. To speak about research means to speak about the borderline of knowledge and shallow knowledge is obviously not enough.

Secondly, the number of researchers in universities and external research institutions is such that it is impossible to know them all or only the laboratories in which they are working. It is also impossible to read all their papers. Even the number of papers with original character (authors normally do not annouce the originality of their paper) would be too high.

A further problem is that temporal changes are a feature of any research activity. A survey has to be limited to a view over a certain time span. Any new R & D program or new topic which becomes interesting for the research on precision fabrication will change the situation and make the survey lose actuality.

And finally, there is the language barrier - which of course - is a general problem of Europe. There are valuable R & D activities published in languages which are not accessible to the person in charge of the survey.

That means that this survey will be incomplete. It cannot cover all items on precision fabrication R & D. Therefore the domain of this review has to be limited. This limitation will be in a way that primarily the R & D efforts taking place in Germany will be described. However, some important resources for funding in Western Europe will be discussed too. As we almost don't have any specific funding for precision fabrication, the sources for funding of production engineering research in general will be described. Of course, scientists or groups of researchers can apply for financial support within the more general programs if they have a good idea and good motivations for precision fabrication research.

Therefore, the content of this paper will be as follows:

- Necessity for research and development

- Sources of National funding in Germany

- Sources of funding in Western Europe

- Examples for the needs in precision fabrication technology

2. Necessity for research and development

Research and development are the basis for technological progress and industrial competitiveness. Therefore, R & D is a permanent task for research institutes in universities and industry, because the life-time of a product or a certain type of production is limited (Fig. 1).

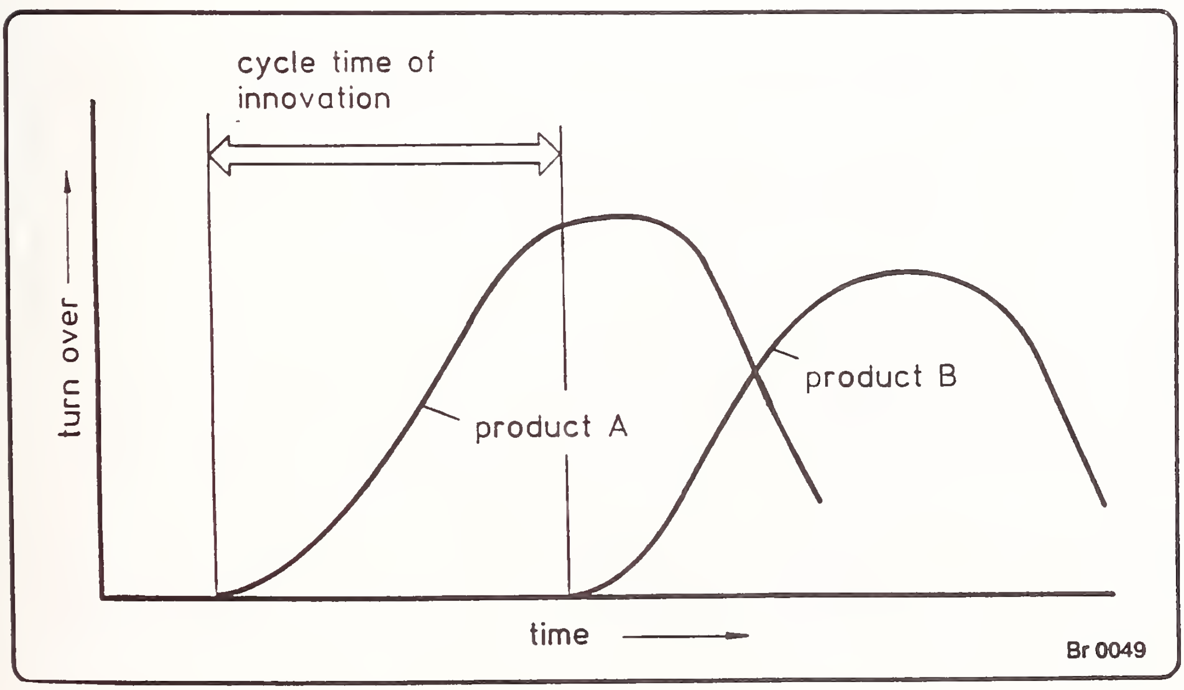


Fig. 1: Cycle of products

The reasons for the substitution of products may be

- a competitor with less costs,
- more and more competitors
- own development of a new product

However, the innovation process has to be enhanced because the life-time of products is decreasing more and more. This is underlined by an example for the life-time of machine tools:

life-time 1930:	25 years
life-time today:	5 years

The life-time is additionally accelerated by the microelectronic components. The cycle-time of NC-controls f.i. is only approximately 3 years. Thus, it can be concluded that standing still means stepping backwards.

Fig. 2, which results from an analysis in the machine tool industry, shows the sources for innovation. The machine tool industry belongs to the small and medium sized companies in Germany with an average number of 200 employees.

sources of technological knowledge

- own development
- customer's stimulation
- research institutes
- literature / seminars / consultants
- competitors' stimulation
- acquisition of licence

Br 0033

Fig. 2: Sources of innovation

Such companies are of major importance for the national economy because they produce 70 % of the national income. Although there is considerable engagement into research and development within these companies, three difficulties have to be mentioned which result from three factors:

- The critical time factor

  There is always been technological progress, but it was never combinded with such steep gradients as in the last years. An example can be concluded from the laser technology. The first CO_2-laser was available in 1971 and within only 10 years a new technology was established. Today, solid state lasers with glass fibres can be used in the production area.

  The actual application of lasers in the production area is, however, rather small until today. The main reason is that innovation speed is too high for small and medium sized companies. This leads to a critical time factor.

- The complexity factor

  Today, it is necessary to think on systems. The computer is penetrating into almost all fields of industy and has to be used as a system's tool. This will lead to the introduction of CIM-components in many areas which means a critical complexity factor for small companies.

- The critical depth factor

  A changing is noticeable within the distribution of labour which results in a decreasing manufacturing depth. Speciallized suppliers are needed and involved. A change in the companie's production philosophy may lead to a critical depth factor.

For these reasons, small and medium sized German companies have learned to use the R & D-potential of research institutes and universities.

Fig. 3 shows how R & D is financed in Germany. More than 50 % are covered by industry.

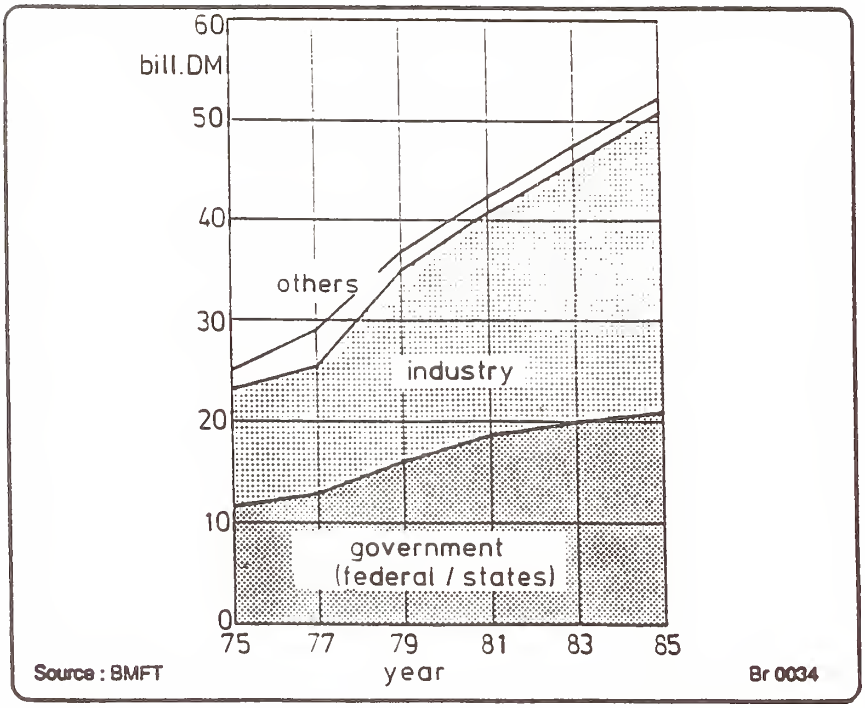


Fig. 3: R & D expenditure

Most of the research work is carried out in industry and at universities (Fig. 4). In production engineering, approximately 1000 scientific researchers are working at institutes and univiersities. The total number of employees in production engineering is about 2.500.

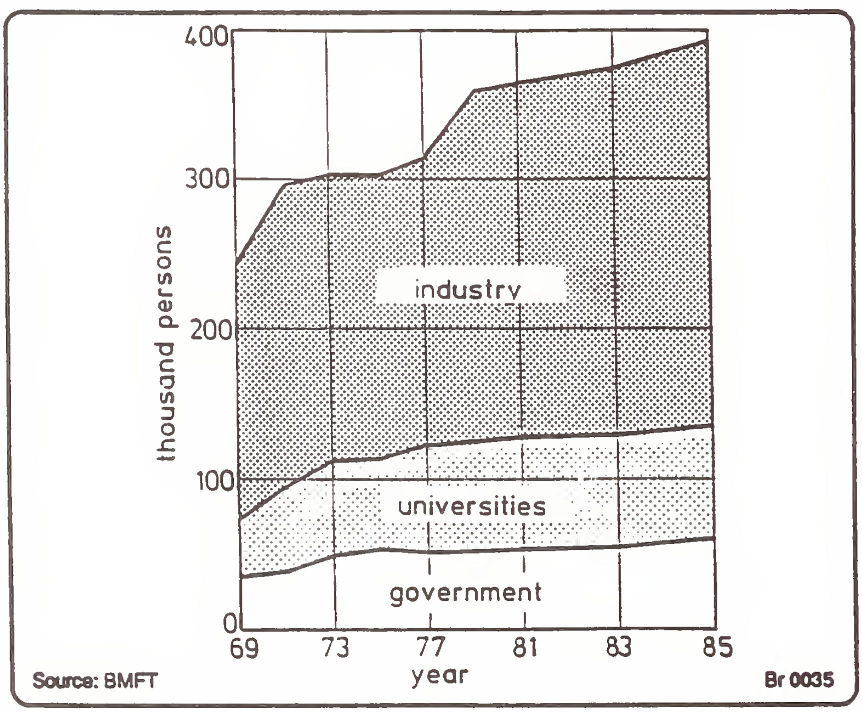


Fig. 4: R & D staff in sectors

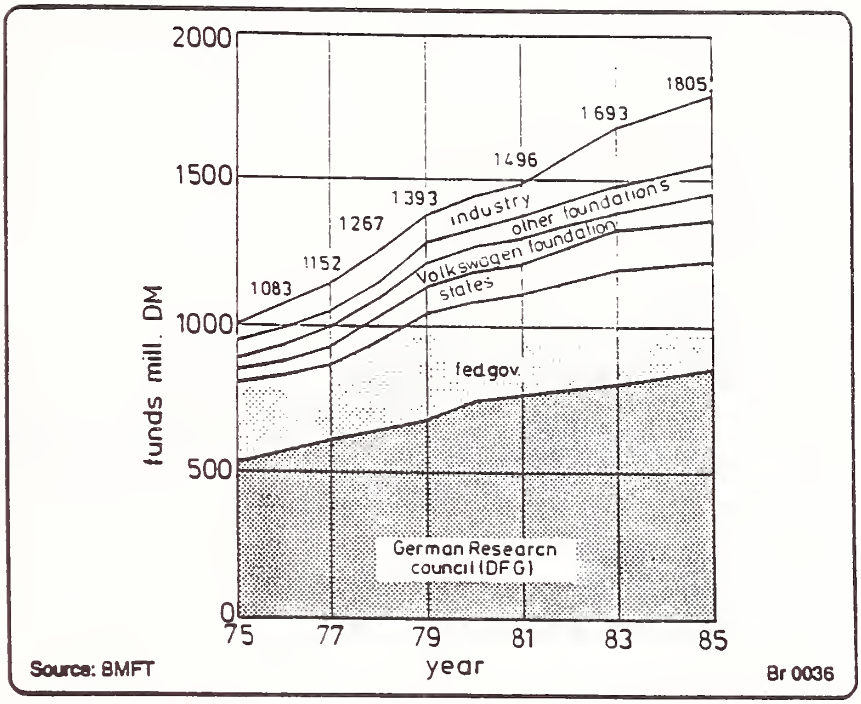


Fig. 5: Funding of R & D at universities

Fig. 5 shows a breakdown of the total funding of all German universities. It has to be recognized that in the field of production engineering the share of industrial funding is between 20 and 30 % of the total budget. The sources of funding in Fig. 4 will by explained in the following chapter.

3. Sources of National Funding in Germany

To have funds is a necessary, but by no means a sufficient condition for good research. However, especially in highly euipped fields like precision fabrication research, the necessary funding is a pre-requisite.

Laboratories in German universities receive their basic funding from the state because the universities are maintained by the 16 states of the Federal Republic. The basic funds for an average German laboratory of production engineering make between 10 % to 25 % of the whole expenditure including investment, maintenance of buildings, energy comsumption and administration. In addition, 75 % to 90 % have to be raised by projects.

Fig. 6 shows the sources where a german institution of an university can apply for support:

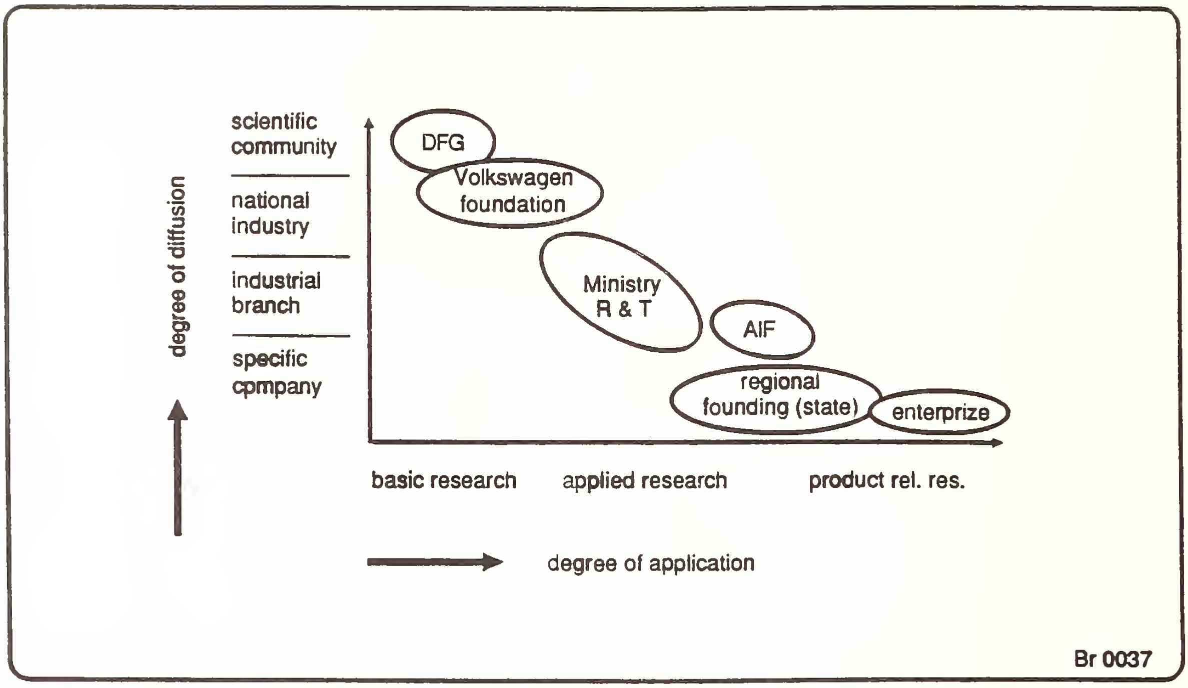


Fig. 6: Research in science and technlogy (Germany)

The figure shows a wide variety of different ways to support research, as there are basic and applied research and on a specific product or production of a company focussed development. At the same time a look on different sources for funds gives an idea how projects are defined and how priorities are set and who benefits form the output of R & D.

3.1. Funding of basic research by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG)

3.1.1. General information

For basic research the German Research Foundation DFG is competent. This institution is comparable to the National Science Foundation NSF in USA. Basic research in this sense does not only mean e. g. physics, mathematics or chemistry. It also stands for an applied discipline, like mechanical engineering and precision fabrication in this case.

The DFG performs the task of funding basic research as an autonomous body within the German scientific community, electing the academic members to its own organs /1/.

The scientists and scholars choose their own subjects for research, and through electing their own peer reviewers contribute their influence to decisions on resource allocation in universities and research institutes. The DFG's major sponsors, the Federal Government and the Federal States, grant those engaged in research the liberty of action they require.

State and industry are currently investing some DM 57 billion in research and development. The share allocated to the Deutsche Forschungsgemeinschaft, just over DM 1 billion (Fig. 7), is relatively modest in comparison. Nevertheless, as the largest external sponsor of university research, the DFG plays a major role in basic research.

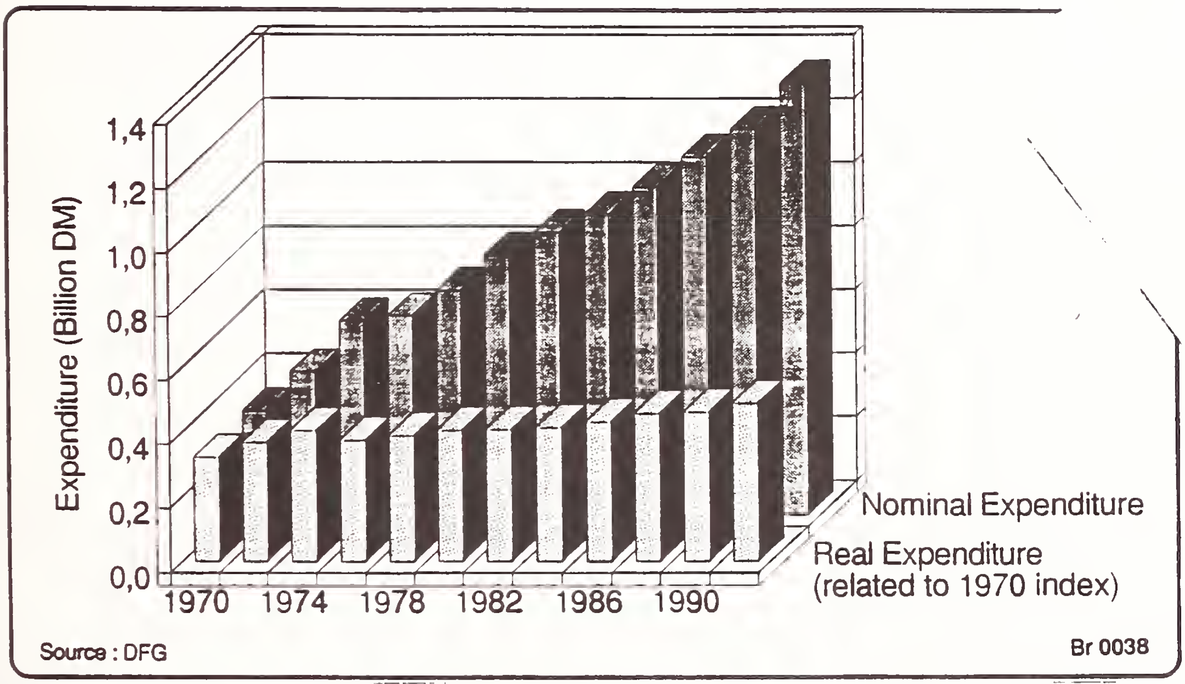


Fig. 7: Growth of DFG Expenditure

The Deutsche Formungsgemeinschaft was founded in 1920 as the "Notgemeinschaft der Deutschen Wissenschaft". In 1949 is was re-established under the same title, but after merging with the "Forschungsrat", it was called the Deutsche Forschungsgemeinschaft. In legal terms, the DFG is a registered society with its seat in Bonn.

3.1.2. Tasks and funding

The tasks of the Deutsche Forschungsgemeinschaft are:

- To promote research by furnishing financial support for research projects in all fields of science and the arts. The DFG places special emphasis on fostering the acitivites of young scientists.

- To counsel parliaments and public authorities on scientific matters.

- To harmonize basic research effort in co-ordination with the direkt support given by the State.

- To foster academic relations with countries abroad.

For the accomplishment of these tasks, the Deutsche Forschungsgemeinschaft is funded on a 50:50 basis by the Federal Government and the Federal States. For the Collaborative Research Centers, the ratio of funding is 75:25 by the Federal Government and the Federal States respectively. The DFG also receives an annual grant from the Donors' Association for the Promotion of Sciences and Humanities in Germany (Stifterverband für die Deutsche Wissenschaft), and the Federal Government and the governments of the Federal States may in mutual agreement place additional funds at the DFG's disposal for special purposes and projects.

In 1991 71,4 % of the funds within the Individual Grants and Priority Programs was approved for personnel, and 28,6 % to expenditure on equipment, material, printing costs and travel. Changes in percentage distribution have been negligible in recent years /2/.

3.1.3. Forms of support

The DFG offers various forms of funding. They are outlined in Fig. 8.

Individual Grants Program (Normalverfahren)

The promotion of research projects requested on the initiative of the individual researchers. These projects are financed for a period of one to two years.

Priority Programs (Schwerpunktverfahren)

The financing and coordination of the work of several researchers at different places on a certain topic - as a rule - for a period of up to five years.

Research Units (Forschergruppen)

Small groups of scientists who are working on one subject (new research projects) at the same place. As a rule promoted for period of six years.

Central Research Facilities (Zentrale Einrichtungen)

Central installations of research open to all scientists. Sponsorship by third parties is, in principle, desired.

Collaborative Research Centers (Sonderforschungsbereiche)

These are long-term, but not indefinite, research institutions of universities where scientists of various disciplines cooperate in the framework of a research program affecting inter-relating fields.

Graduate Collages (Graduiertenkollegs)

Institutions at universities for the promotion of young scientists working for their Ph D within the frame of an interdisciplinary orientated study program

Promotion of Young Scientists in Special Programs (Nachwuchsförderung)

Additional possibilities for qualified young scientists have been created with the Heisenberg Program, the Post-doctoral Program, the Gerhard Hess Program, and the newly established Professorial Qualification Fellowships. The Gottfried Wilhelm Leibnitz Program is meant for further promotion of excellent scientists.

Fig. 8: Forms of DFG support

The major programs will be explained in the following:

Individual grants program

The individual grants program, which accounts for approximatley 45 % of all funds disbursed, forms the core of the DFG's research promotion. Under this program any fully qualified research scientist may apply for financial assistance for his proposed project. He or she need not belong to a member instituion of the DFG. The initiative rests with the individual and, as a matter of principle, the DFG exerts no influence on the content of the project. However, applicants must be prepared to publish their results, to make them available for public consumption and to subject their project to the critical scrutiny of their peers in their capacity as elected reviewers.

The report which must be submitted after one or two years serves as the basis for deciding whether the project is to be extended or not. It also offers the elected reviewers a means of monitoring progress and checking whether the funds are being used economically and efficiently.

Fig. 9 summarizes the application and funding procedure of the German Research Foundation.

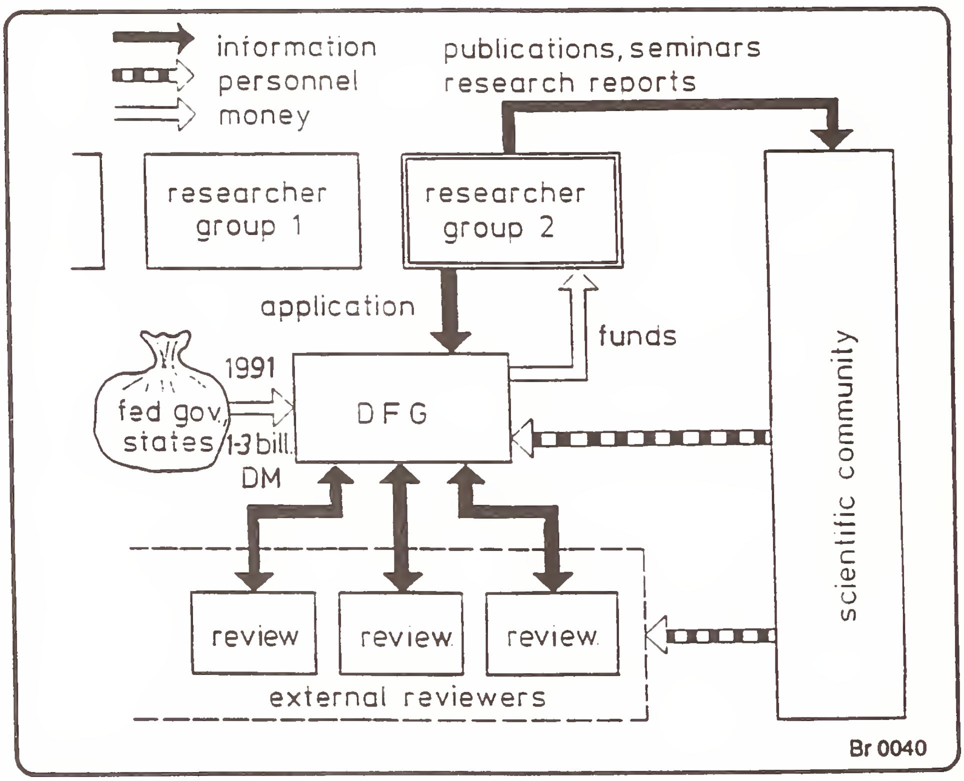


Fig. 9: Application and funding procedure by DFG

Within the individual grants program various modes of support are available, e. g. research grants, travel or printing grants. Young scientists and scholars are given special support in the form of training fellowships, research fellowships or fellowships to obtain a professorial qualification. The DFG regards the individual grants program as the cornerstone for all research promotion, and the indispensable pre-requisite for developing priorities.

Priority programs

Under the priority program, researchers working in different institutes and laboratories co-operate within the framework of a given subject for a limited period of time. Approval for the initiation of a priority program is given by the Senate on the basis of proposals submitted by scientists. Priority programs may be instituted if the co-ordinated assistance for the area in question promises to produce results of interest to science. Each participant in a priority program must contribute to the given framework, within which he is then free to choose his own project, research plan and methods. Assessment is performed viva voce by a group of elected reviewers and special reviewers, usually headed by the chairman of a reviewers' committee.

In 1992 a total of 113 priority programs with 1.510 projects and a total budget of 186,1 Mill. DM were granted. Within the engineering sciences 19 priority programs were existing in 1991 with a total budget of 34 Mill. DM.

For the subject of precision fabrication the programs listed in Fig. 10 are of major significance.

- Knowledge-based diagnostic systems for flexible assembly (2.9 Mio. DM)
- Crystal growth and nucleation-mechanisms and kinetics (0.5 Mio. DM)
- Ceramics of high performance (3.4 Mio. DM)
- Ion and plasma assisted surface technology (4.6 Mio. DM)
- Sensor systems (1.2 Mio. DM)
- Flexible metal forming (2.5 Mio. DM)
- Residual stresses and deformation caused by the effect of heat (2.5 Mio. DM)
- Working-surface friction in the inelastic deformation of metals (0.6 Mio. DM)
- Beam-material interaction when working with laser beams (2.9 Mio. DM)
- Microstructure and mechanical properties of metallic high-temperature materials (new program)
- Innovative quality assurance in production (new program)

Source: DFG

Br 0041

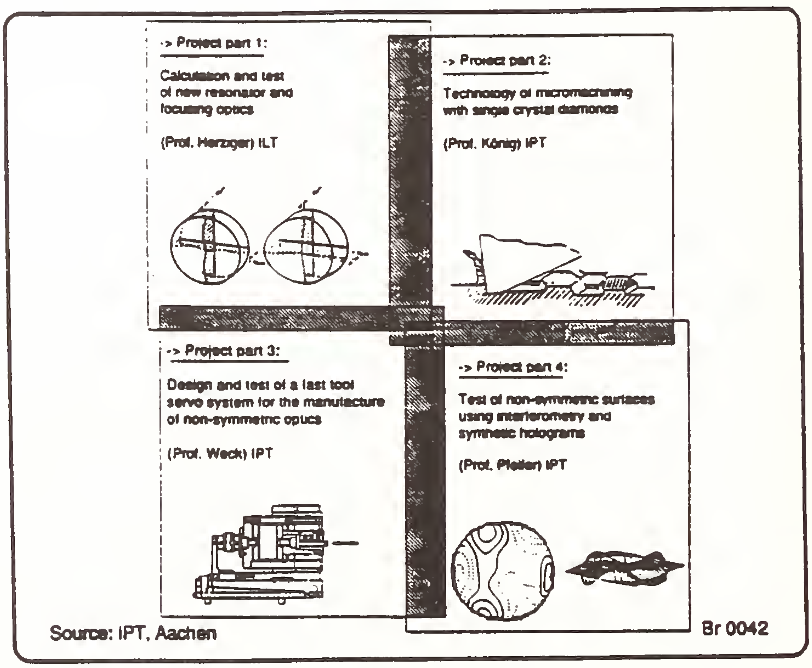
Fig. 10: Priority programs of DFG with relevance to precision fabrication

It should be mentioned that a big priority program on fine-machining started in 1985 and was disclosed 2 years ago. Grinding and metal cutting processes as well as the subject of ultraprecision machining were investigated within this program.

<u>Research units</u>

A research unit is formed by a number of scientists collaborating over an extended period of time, and usually in one location. These engage in joint research into some special subject whose thematic, temporal and financial scope demands more assistance than is possible from the individual support provided under the individual grants program. The assistance afforded to research units is designed to promote close, medium-term cooperation - normally for a period of six years - by ensuring the availability of the necessary staff and facilities. Research units often help to introduce new fields of activity which are still inadequately represented in Germany.

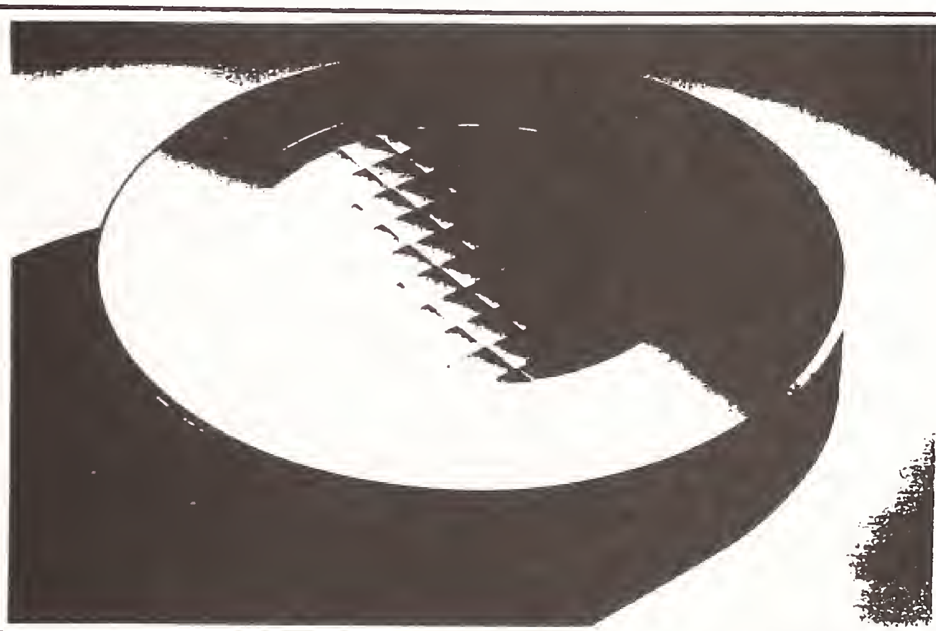
An example for a research unit on precision fabrication is the collaboration of four leading scientists at the university of Aachen. The aim of the group is to effectively apply diamond turning techniques for the fabrication of non-symmetric laser optics. Fig. 11 shows the individual project parts.



<u>Fig. 11:</u> Targets of the research unit "Non-Symmetric Laser Optics"

The requirements on the new resonator and focussing optics come from the institute of laser technology. The fabrication of the optics is done by the scientists from the process technology and the machine tool department. Finally the optics are quality controlled by the department of metrology.

An example of a diamond turned laser optic is shown in Fig. 12.



Source: IPT, Aachen

Br 0043

Fig. 12: Diamond turned integrating laser optic

The special surface pattern was generated in the turning process by using a fast tool servo system, which was developed in one project part.

Central research facilities

Scientific and technical "service facilities" for research are eligible for support by the DFG in the form of "Central research facilities". Centralization of valuable personnel and hardware resources in one place ensures optimum exploitation of scientific and technical experience and rational operation of equipments or technical devices, which tend to be both large and expensive.

Collaborative research centers

Collaborative research centers are research units in universities in which groups of scientists join together, usually for periods of twelve to fifteen years, to co-operate within an interdisciplinary research program. In the question of assistance from the DFG, universities are both applicants and recipients (Fig. 13).

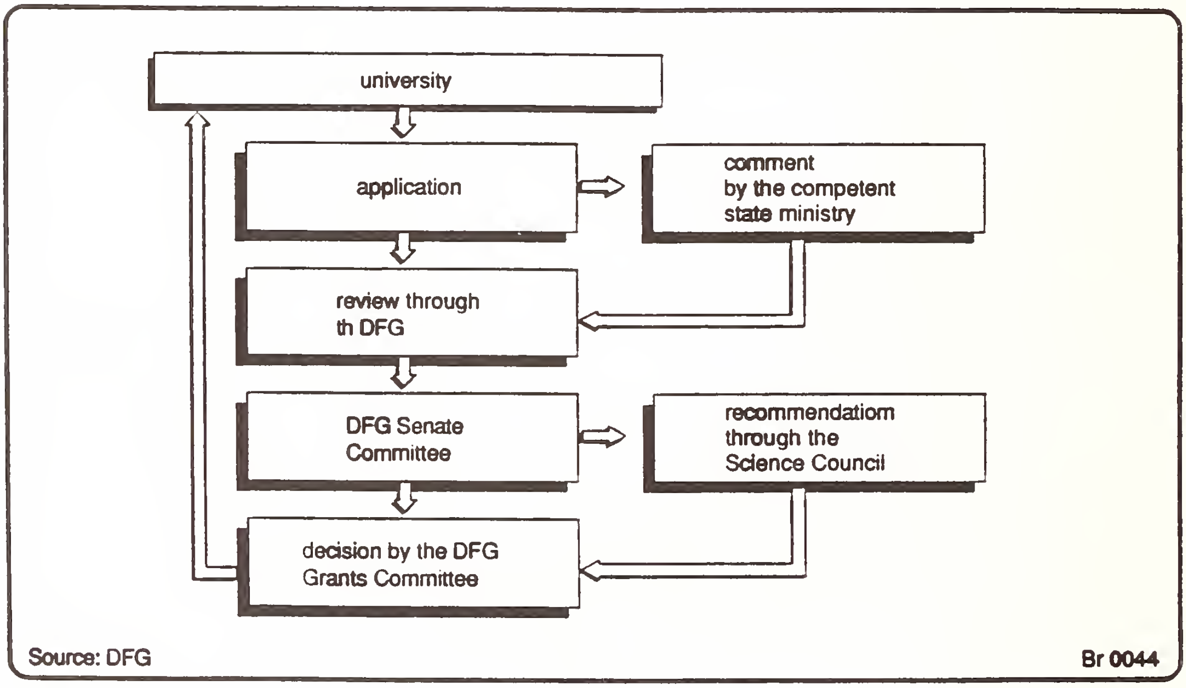


Fig. 13: Procedure for the application of a collaborative research center

The universities, which both submit the proposals and administrate the DFG-funds in this program, supply the staff and basic equipment required. Collaborative research centers enable demanding, expensive and long-term research projects to be accomplished through concentration and co-ordination of resources available to a university.

75 % of the funds employed for collaborative research centers are supplied to the Deutsche Forschungsgemeinschaft by the Federal Government (Federal Ministry of Education and Science), and 25 % by the Federal States.

Decisions relating to assistance for individual collaborative research centers are taken by a special grants committee. This committee consists of 22 academic members as well as representatives from the Federal Government and each of the states. The science council comments on initial applications for support prior to final approval.

Fig. 14 shows a list of collaborative research centers in engineering sciences with relevance to precision fabrication

- Properties of plastic materials (Aachen, 2.0 Mill DM)
- Very large scale integration, VLSI (Kaiserslautern/Saarbrücken, 3.8 Mill DM)
- Methods for saving energy and material (Aachen, 2.7 Mill DM)
- Flexible handling devices in mechanical engineering (Aachen, 2.7 Mill DM)
- Integrated mechanoelectrical systems (Darmstadt, 2.2 Mill DM)
- Tools and tool systems (Hannover, 3.0 Mill DM)
- Metal- and ceramic matrix composites (Dortmund, 3.6 Mill DM)
- Process integrated quality control (Hannover/Braunschweig, 2.1 Mill DM)
- Workpieces made of fibre-reinforced plastics (Aachen, 2.7 Mill DM)

source: DFG Br0045

Fig. 14: Collaborative Research Centers with relevance to precision fabrication

Graduate colleges

Graduate colleges, since 1990 eligible for support by the DFG, are provided by the universities to assist graduates studying for doctor's degrees by enabling them to participate in research. They supplement the traditional system of individual tutoring by university teaching staff, providing the opportunity to conduct research in groups dedicated to specific terms of reference. A long-term aim is also to reduce the time spent at university. The Federal Government and the Federal States have decided to promote the graduate colleges for five years in the first instance. This period will be necessary to check the effectiveness of the program.

Special programs

Since 1977, a series of special programs has created additional possibilities, especially for supporting qualified young scientists. These programs will be supplemented in the next ten years by additional funds. Special emphasis will be laid on the promotion of young female scientists in all programs to increase the number of women professors in science.

3.2. Funding of fundamental research by the Volkswagen Foundation (VW-Stiftung)

The purpose of the Volkswagen Foundation is to support science and technology in research and teaching. The founders are the Federal Republic of Germany and the state of Niedersachsen. The capital of the foundation is approximately 3 Billion DM /3/.

3.2.1. History

After world war II the rights of possession on the Volkswagen GmbH (Limited) were uncertain. Therefore in 1961 the Volkswagen GmbH was changed into a joint-stock-company (Volkswagen AG).

The breakdown of stock shares was:

- 60 % "Volksaktien" (private stock)
- 20 % Federal Republic of Germany
- 20 % State of Niedersachsen

The capital of the foundation results from dividends and realizations of the latter 40 %.

In 1988 the 20 % of the Federal Republic of Germany were denationalized and the proceeds were added to the funds of the foundation.

Funds from 1962 to 1991:	960.5	million DM
Fund in 1991:	66.2	million DM
from this:	6.6	million DM for natural science
	30.2	million DM for engineering science

3.2.2 Concept of support

The Volkswagen Foundation supports thematic and problem-oriented basic research. For this task priority programs are defined. The proposal comes from and is evaluated by the scientific community and the general board of the foundation. Hence this procedure is very similar to the establishing of priority programs of the DFG. Presently two of such programs are of interest for the engineering sciences and also for precision fabrication:

- Overlapping projects from differant fields of natural science and engineering science and

- Microcharacterization of materials and structural elements

A different type of granting is the support of infrastructure in research and teaching and also in scientific communication by

- symposia und summer schools
- research in foreign countries
- new professorships

3.2.3. Procedure of application

Proposals for projects within the present priority programs can be sent to the secretary at any time. External consultants which are members of the scientific community are named by the secretary individually corresponding to the needs of the project. The experts' opinions are confidential. The final decision on the project is made by the truestees who meet several times a year for this purpose. For big projects a decision can take up to 6 month.

In 1991 54 % of all the proposals were accepted.

3.2.4. Priority programs with relevance to precision fabrication

Microcharacterization of materials and structural elements

The scope of this program are the development of methods of microcharacterization and its use in materials research (material science, physics, mineralogy) and to establish cooperation with the purpose of using different kinds of instrumentation (transmission electron microscope, scanning electron microscope, tunneling microscope, ...)

Subjects of the program are

- Evaluation of faults in crystalline material and multiphase material
- Evaluation of early states of segregation
- Evaluation of dynamic processes in atomic scale (reaction kinetecs in mixtures)
- Further development of imaging methods with high lateral resolution
- Computer simulation and image processing
- Development of preparation techniques

Titles of individual projects with relevance to precision fabrication are

- Real-time-scanning-tunneling-microscope and temperature dependence of clean and adsorbated surfaces
- Fluctuations in the near-order and localization of slipping in concentrated copper alloys
- Analysis of adhesive substrate-polymer-connection in microscopic dimensions
- Real imaging microscopy and spectroscopy of surfaces with slow electrons

Overlapping projects from differant fields of natural science and engineering science

The purpose of this program is to tackle new kinds of problems and to find creative solutions by an interdisciplinary collaboration in the engineering and natural sciences.

Examples for projects (1991) are:

- Development of an application-orientated measuring system for three-dimensional analysis of complex mechanical structures
- The dispersion of the velocity of crystallization caused by differant crystal perfections

3.3. Funding of applied research by the Minister of Research and Technology (BMFT)

The German Minister of Research and Technology supports applied research. He defines program corridors in which industrial companies together with a research group from an university may apply for funding of a collaborative project. Normally the output has to be published in general lines. The specific findings which are interesting for the industrial companies more than for the scientific community need not to be published.

Generally, a 50 % funding of the total expenditures of a project is usual.

As universities normally need a 100 % funding of their expenditures in project part, the funding of the collaborating companies will be lower than 50 %. In addition, there is also a funding procedure where individual companies or research laboratories can get support.

Fig. 15 shows the system and the procedure to apply for BMFT funding.

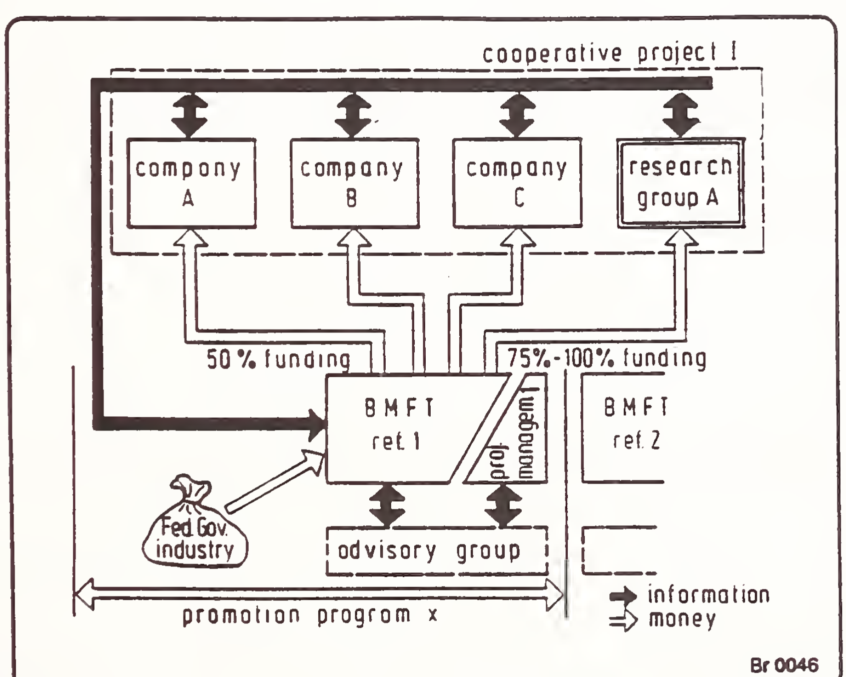


Fig. 15: Collaborative research projects of BMFT

The reviewing procedure for projects is similar to the procedure of other R & D supporting institutions. Usually a funding of a project is only possible within a defined promotion program. Currently there are more than 30 of such programs /4/. The most important of them with relevance to precision fabrication and the funding within the programs are listed up in Fig. 16.

1990	number of projects	funding volume (Mio DM)	industrial companies (Mio DM)	universities (Mio DM)	other R&D laborator. (Mio. DM)
Microsystems Technology inc. Microelectronics and Mikroperipheric	59	64.7	28.1	18.6	18.0
Production Engineering	60	107.0	77.1	14.5	15.4
Advanced Materials	262	125.7	74.4	24.8	26.5
Physical and Chemical Technologies	244	153.3	62.4	50.9	40.0
Quality Assurance (New Program in 1992)					

Source: BMFT

Br 0047

Fig. 16: BMFT promotion programs with relevance to precision fabrication

The largest programs in Fig. 16 are ready to support the development of advanced materials and R & D work on physical and chemical technologies.

A large new program which has just been established is the Quality Assurance program. It has started in 1992. The financial support of the BMFT for this program is given in three different ways:

1. Funding of collaborative research projects (applied research)

2. Funding of co-operating research groups from several universities (basic research)

3. Funding of a priority program of the German Research Foundation DFG (basic research)

The Quality Assurance program is not supposed to support technical measures on the manufacturing process level. Much more has it been established to promote the introduction of quality assurance systems in more general lines with the development of advanced strategies.

In order to give an idea on the type of projects and their budgets within the promotion programs listed in Fig. 16, examples of such projects with relevance to precision fabrication are listed up below in the following /4/.

Examples for collaborative projects within the BMFT promotion program Microsystems Technology incl. Microelectronics and Microperipheric are:

- Integrated optics on glass basis for sensors, sensor systems and signal processing (5 partners, 19.4 Mio. DM total funding)

- Chemical sensor systems (4 partners. 15 Mio DM total funding)

- Micromechanical sensors (5 partners, 3 Mio DM total funding)

- Micromechanical actuators (4 partners, 6.8 Mio DM total funding)

- Thin film-gas sensors (2 partners, 2 Mio DM total funding)

- Integrated optics on silicon (4 partners, 8.5 Mio DM total funding)

- Application of micro sensors (6 partners, 10.6 Mio DM total funding)

- New sensors and actuators for laser beam machining (6 individual industrial projects, 3 Mio DM total funding)

Examples for collaborative projects within the BMFT promotion program Production Engineering

- Quality assurance in flexible manufacturing systems with CMMs
  (12 partners, 10.5 Mio DM total funding)

- High precision metal cutting
  (28 partners, 10 Mio DM total funding)

- Precision metal forming
  (20 partners, 13.5 Mio DM total funding)

- Sheet metal forming
  (22 partners, 11 Mio DM total funding)

- Grinding of advanced ceramics
  (13 partners, 7.2 Mio DM total funding)

Examples for collaborative projects within the BMFT promotion program Advanced Materials

- Wear and material removal mechanisms when cutting with superhard non-metallic tool materials
  (3 partners, 2.6 Mio DM total funding)

- Development of fibre- and particle-re-inforced light metal composites
  (4 partners, 3.7 Mio DM total funding)

- Development of fibre-re-inforced composites of high strength
  (4 partners, 10.2 Mio DM total funding)

- Joining Technologies for high strength Al-Li-alloys
  (5 partners, 1.4 Mio DM total funding)

- Development of short fibre and whisker re-inforced ceramic composites
  (7 partners, 13.6 Mio DM total funding)

- Joining at high workpiece temperatures
  (4 partners, 2.9 Mio DM total funding)

- Molecular re-inforcing of polymers
  (1 company, 2.3 Mio DM total funding)

- Ceramic fibres
  (1 company, 2.6 Mio DM of total funding)

- High temperature resistant materials
  (44 partners, 12.8 Mio DM total funding)

- Ion implantation for tribological applications
  (5 partners, 2 Mio DM total funding)

- Optimized manufacturing for coating processes
  (6 partners, 2.2 Mio DM total funding)

- Fibre re-inforced glass
  (3 partners, 2.8 Mio DM total funding)

- Physical vapour deposition at low temperatures
  (6 partners, 3 Mio DM total funding)

- Development of advanced cermet alloys
  (3 partners, 1.5 Mio DM total funding)

- Coating of fibres with ceramic material
  (2 partners, 1.5 Mio DM total funding)

- Advanced ceramics (individual projects)
  (15 companies and universities, priority program of DFG
  (15 Mio DM), 40 Mio DM total funding)

- Advanced polymers (individual projects)
  (18 companies and universities, 18 Mio DM total funding)

Examples for collaborative projects within the BMFT promotion program Physical and Chemical Technologies

- PVD technologies at low temperature and new layer systems (incl. diamond films) / (12 partners, 13.3 Mio DM)
- Implentation technologies for tribological applications (6 partners, 4.2 Mio DM)
- Diamond coating of components with complex shape (4 partners, 4.8 Mio DM)
- X-ray microscope (2 partners, 1.8 Mio DM)
- New thin film technologies by molecular engineering (6 partners, 11.8 Mio DM)
- Surface modification of plastics by ion implantation (2 partners, 1.8 Mio DM)
- Structuring of surfaces by Laser CVD (3 partners, 3.7 Mio DM)
- Cutting with high performance lasers (10 partners, 8.3 Mio DM)
- 3D-machining with high performance lasers (9 partners, 10.9 Mio DM)
- Surface treatment with CO_2 lasers (19 partners, 10.6 Mio DM)
- Welding with solid state lasers (5 partners, 2.1 Mio DM)
- High power excimer lasers (phase I and II) (11 partners, 27.0 Mio DM)
- Laser workstation for surface treatment (3 partners, 5.5 Mio DM)
- Joining with CO_2 lasers (17 partners, 7.1 Mio DM)
- Micro machining with excimer lasers (11 partners, 9.1 Mio DM)
- Material removal with solid state lasers (7 partners, 4.4 Mio DM)
- Superconducting materials (individual projects) (56 companies and universities, 80 Mio DM)

It may be also of interest how the mentioned programs compare to other programs being funded by the BMFT. A breakdown of expenditures for the sectors with the highest amounts of funding is shown in Fig. 17.

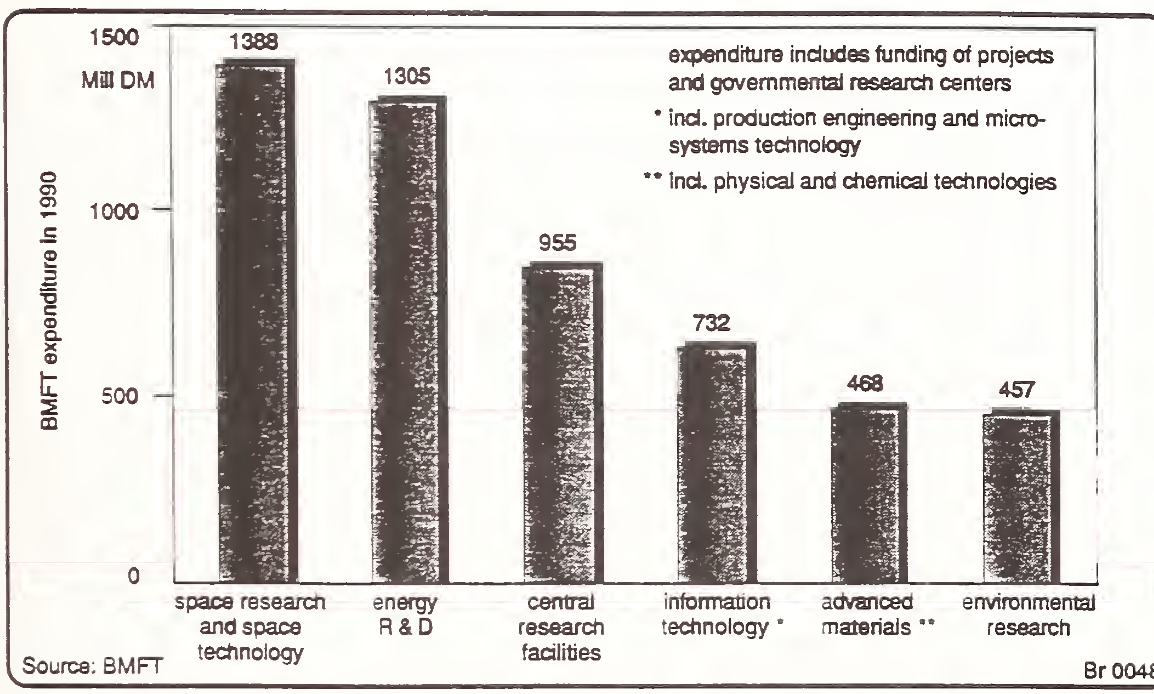


Fig. 17: BMFT expenditures on sectors of funding

It has to be considered that the given numbers do not only stand for the funding of individual projects but do also include the granting of governmental research centers within the listed sectors. Nevertheless it can be seen that the mentioned promotion programs have a relatively high priority within the frame of BMFT funding. Further sectors of support like the funding of R & D in sea technologies, bio-technologies, human health, social scienes, civil construction and aerospace technologies and others have lower budgets and are not mentioned in the figure.

3.4. Funding of applied research by the German Federation of Industrial Cooperative Research Associations AIF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen)

3.4.1. History of the AIF /5/

At the beginning of the 1950'ies German government and industry recognized the neccessity of an effective structural improvement for small and medium sized enterprises (SMEs) in the field of Research and Development (R&D). Due to the well known problems of SMEs to carry out or to finanze R&D on their own, a special instrument was needed to improve the technological standard of SMEs in an efficient way. Taking up the idea of precompetitive "Industrial Cooperative Research" in the year 1954 the so called "Industrielle Gemeinschaftsforschung" was created.

"Industrial Cooperative Research" is not dedicated to a few or single enterprises but to all enterprises related to one or more branches or technical fields. The aim is to improve the technological standard and competitiveness of whole branches with projects being of common interest for all enterprises. Due to the big number of SMEs (nearly 95 % of all European companies are SMEs) the promotion of "Industrial Cooperative Research" is an important element of the governmental R & D policy in Germany and it should play a substantial role in the R & D policy of the European Communities, too.

Nevertheless, "Industrial Cooperative Research" is only one kind of R & D in Germany. Since its creation in 1954 the AIF, the "German Federation of Industrial Cooperative Research Associations" is acting as an agency between the partners in this special field of R&D. Figure 18 shows the AIF between other parts of the R&D organization in Germany.

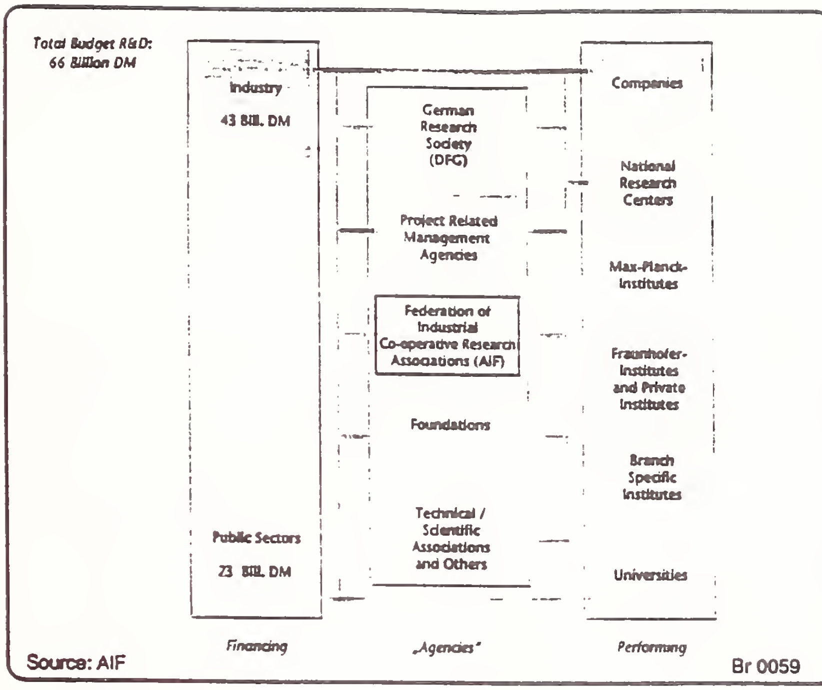


Fig. 18: The AIF in the field of R & D organizations in Germany

3.4.2. Structure

In a lot of branches and technological fields, German SMEs have linked together in industrial research associations. They are working as a frame for their companies, allowing them to act together in the field of industrial cooperative research. Starting with 17 industrial research associations in 1954, today 102 research associations are united under the umbrella of the AIF - the independent German Federation of Industrial Cooperative Research Associations. These research associations have more than 50.000 companies as their members and more than 90 % of these members are SMEs. All these companies are members on a voluntary basis.

Some of the 102 research associations are supporting R&D work also in the area of precision fabrication. Examples are:

- Association of motive power technique (Antriebstechnik)

- Mechanical engineering association (Maschinenbau)

- Machine tool builders' association (Werkzeugmaschinenfabriken)

- Heat treatment and materials' technology (Wärmebehandlung und Werkstoff-Technik)

- Tool- and workpiece materials (Werkzeuge und Werkstoffe)

- Ultraprecision technology (Ultrapräzisionstechnik)

Task of the Research Associations is to find out the research needs of their industry and to create cooperative research projects in order to improve the competitiveness of all their members. This process is industry driven, that means the ideas and proposals for research projects are coming "Bottom up" from the industry. Some research associations have own institutes, others are working together with external establishments like universities or contract research organizations. Cooperative research in Germany is based on the industrial research associations and not on the institutes, anyhow the institutes are acting as performers, and relations between research associations and institutes might be very strong in some cases. Fig. 19 shows levels of "Industrial Cooperative Research" in Germany. It is the process of generating and conducting cooperative research projects which makes the difference to the pure contract research organizations.

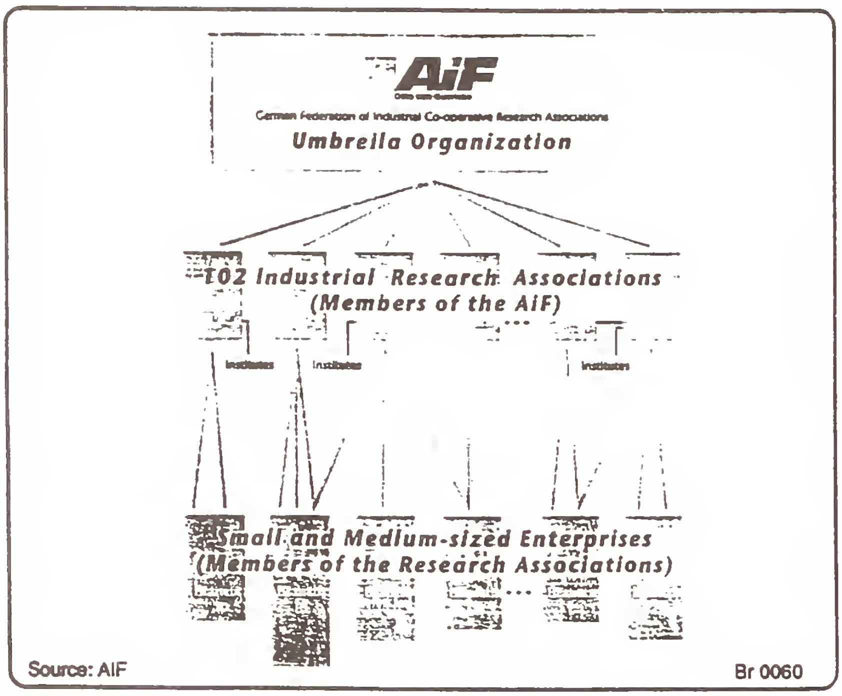


Fig. 19: Levels of industrial cooperative research

It is also essential to this system of R & D that SMEs which are usually competitors are working together in research projects before they enter into competition. Due to this, cooperative research projects must have a precompetitive character. That means at least, not every technical problem can be solved by this kind of R & D. But there are a lot of technological and scientific problems which can only be solved by cooperative research because it is too expensive for individual companies to work on them alone.

3.4.3. Funding procedure

Fig. 20 shows the funding procedure of the AIF.

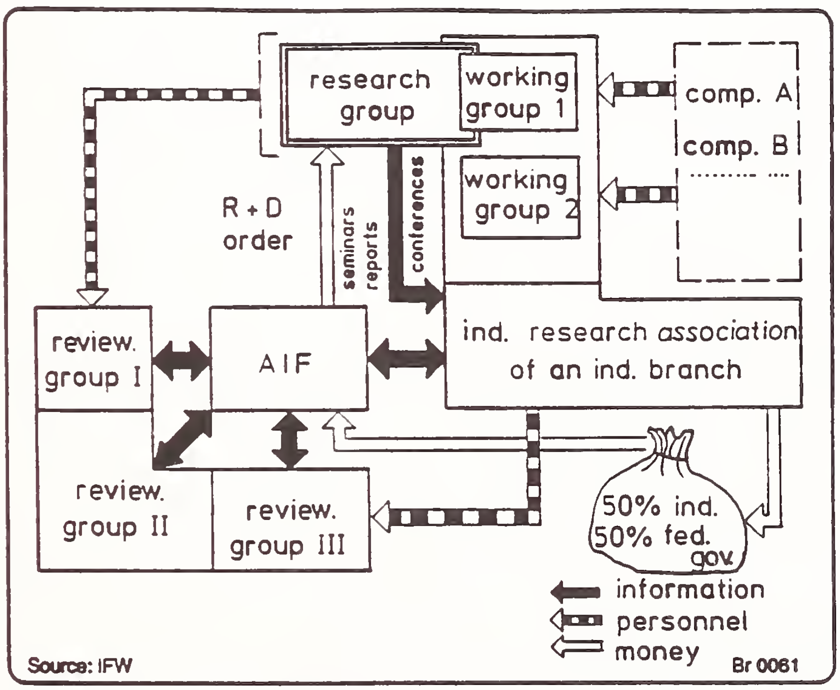


Fig. 20: R & D support by AIF

Different tasks of the Research Associations are:

- discussing ideas, problems and needs coming "Bottom up" from the industry
- evaluating proposals for research projects
- selection of qualified research facilities
- planning and formulation of research projects
- deciding about the financing of the projects

- providing financing mechanisms
- monitoring and controlling of the research work
- evaluating the research results
- transfering and disseminating the research results
- training and advicing for the utilization of the research results

For all these tasks expert groups and committees are acting in each research association constituted by experts from industry, science, authorities and other involved organizations.

If the research associations want to receive public money for cooperative research projects they have to apply for it at the AIF. Eight expert groups of the AIF, constituted by nearly 140 independent experts from industry and science will evaluate the applications of the associations. If these expert groups decide to support an application at least an authorizing committee has to evaluate it again and to recommend it for public funding.

3.4.4. Financing and budget

The possibility to participate in the public support depends on a fundamental precondition which is one of the basic principles of the "Industrial Cooperative Research" system. Those associations which want to receive public support for their research projects have to prove that they have invested at least the same amount out of own funds for cooperative research. In general the AIF evaluates this industrial contributions annually. The availability of public funding for single research association will be fixed every year depending on the governmental budget for cooperative research and on the own contributions of industry spent for this purpose. In general it should be stated that the amount of industrial contributions to cooperative research gives the maximum amount of public fundings for the same purpose.

It is important to this system that the distinction between public funds on one side and funds from industry on the other side is not related to the single research project. That means that cooperative research projects are totally financed either by money from industry or by public money. The research association must decide whether a project is suitable for the more time consuming procedure of public support or whether it should be implemented directly by industries own funds and forces. Fig. 21 shows the relation between public fundings and industrial means for specific branches.

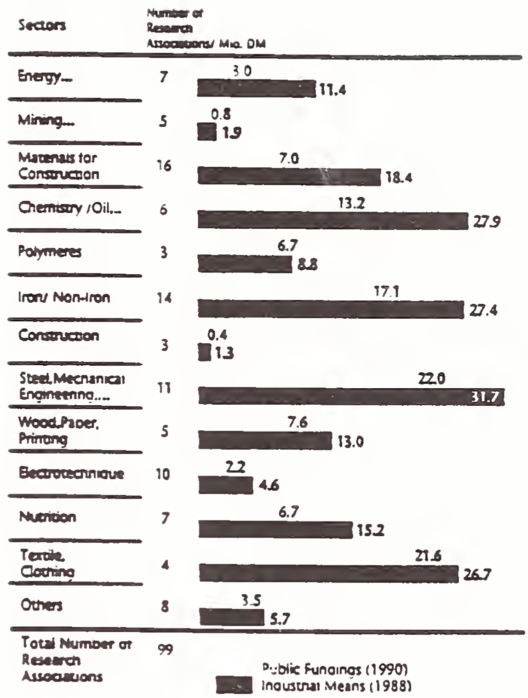


Fig. 21: Public funding for industrial branches

Industries main contributions for cooperative research are the following:

- cash contributions to the work of research associations mainly used for research projects

- specific contributions directly to research institutes on an individual cooperative research project basis

- "in kind" contributions on an individual project basis

- administrative costs covered by industries

More than two third of industries contributions for cooperative research is cash contribution and nearly 20 % is "in kind" contribution for specific research projects.

The average costs for a cooperative research project funded by the AIF is around 400.000,-- DM. Having in mind the public budget of 200 million marks for cooperative research and the number of 50.000 companies which are members of the research associations and which have direct benefit from this budget, at least the funding for each company is around 4.000,-- DM. No other procedure gives the opportunity to contribute more successfully and efficient to the technological progress of small and medium sized enterprises by using so less money.

Due to the precompetitive character of cooperative research it is not easy to demonstrate the benefit of this kind of R & D. It is the task of the single companies to transfer the research results into a success on the market. But the willingness of industry to increase the industrial budget for "Industrial Cooperative Research" is the best evidence for the efficiency of this kind of R & D.

4. Sources of funding in Western Europe

4.1. European Science Foundation ESF

For basic research, scientists can aplly for funding from the European Science Foundation ESF. The ESF is an association of its 56 member research councils and academies in 20 countries. The ESF brings European scientists together to work on topics of common concern, to co-ordinate the use of expensive facilities, and to discover and define new endeavours that will benefit from a cooperative approach /7/.

The scientific work sponsored by ESF includes basic research in the natural sciences, the medical and biosciences, the humanities and the social sciences.

The ESF links scholarship and research supported by its members and adds value by cooperation across national frontiers. Through its function as a co-ordinator, and also by holding workshops and conferences and by enabling researchers to visit and study in laboratories throughout Europe, the ESF works for the advancement of European science.

However until now, ESF has no programs for funding projects in engineering research.

4.2. Funding of research and technical development (RTD) by the European Community (EC)

4.2.1 General information

In EC research programs the results are explicitly requested to be precompetitive. The results are desired to lead directly to products which help the European industry to improve their competitiveness.

Since 1983, the European Community (EC) has coordinated its research and technical development (RTD) activities through multiannual framework programs. These framework programs are implemented through specific RTD programs dealing with selected areas of research - such as the environment or health. So far there have been two framework programs.

On 23 April 1990, the Council adopted the third framework program. This has a duration of 5 years, a budget of 5.7 billion ECU and contains 15 specific RTD programs in the following areas /8/:

- information technologies
- communications technologies
- development of telematics systems in areas of general interest
- industrial and materials technologies (Brite-EuRam II)
- measurement and testing
- environment
- marine science and technology
- biotechnology
- agricultural and agro-industrial research
- biomedical and health research
- life sciences and technologies for developing countries
- non-nuclear energies
- nuclear fission safety
- controlled thermonuclear fusion
- human capital and mobility

For engineering sciences the RTD program Industrial and Materials Technologies Brite-EuRam II is of prior relevance. This program will be carried out through shared-cost research projects. This means that the EC participation in the cost of the research is in principle 50 % of the total project costs. Funding can only be applied for collaborative projects with co-operating companies and universities from differant member states.

The program's main objectives are:

- to increase the competitiveness of European producer and user industries

- to strengthen European economic and social cohesion

- to promote the scientific, technologcial, and economic integrations of European industry

A number of strategic aims complement the general objectives of the program:

- to increase the application of advanced technologies by small and medium sized enterprises (SMEs)
  (An SME is a company which has less than 500 employees, has a net annual turnover of less than 38 million ECU and is not more than one third owned by a parent company or any other organization larger than a SME, although larger shareholdings held by investors such as banks or venture capital firms are permitted)

- to increase the involvement of manufacturing SMEs in European RTD through developing links with other enterprises and promote a better management of their resources

- to reinforce and diversify the training of research workers and engineers for modern Europan industry

- to give full consideration to the social, human and environmental impact of advanced technologies

- to ensure an appropriate dissemination and exploitation of results, especially for development of standards and user specifications.

The EC has defined some general criteria which a research project must fulfill. These criteria are listed in Fig. 22.

- Conformity with the scope and objectives of the program
- Scientific and technical excellence and novelty
- Precompetitive character
- Scientific, technical and economic benefits
- European dimension
- Transnational collaboration
- Ability to provide for a high quality project management
- Technical competence of the partnership
- Environmental aspects

Source: EC

Br 0050

Fig. 22: General criteria for EC projects

Fig. 23 shows the decision procedure for EC projects.

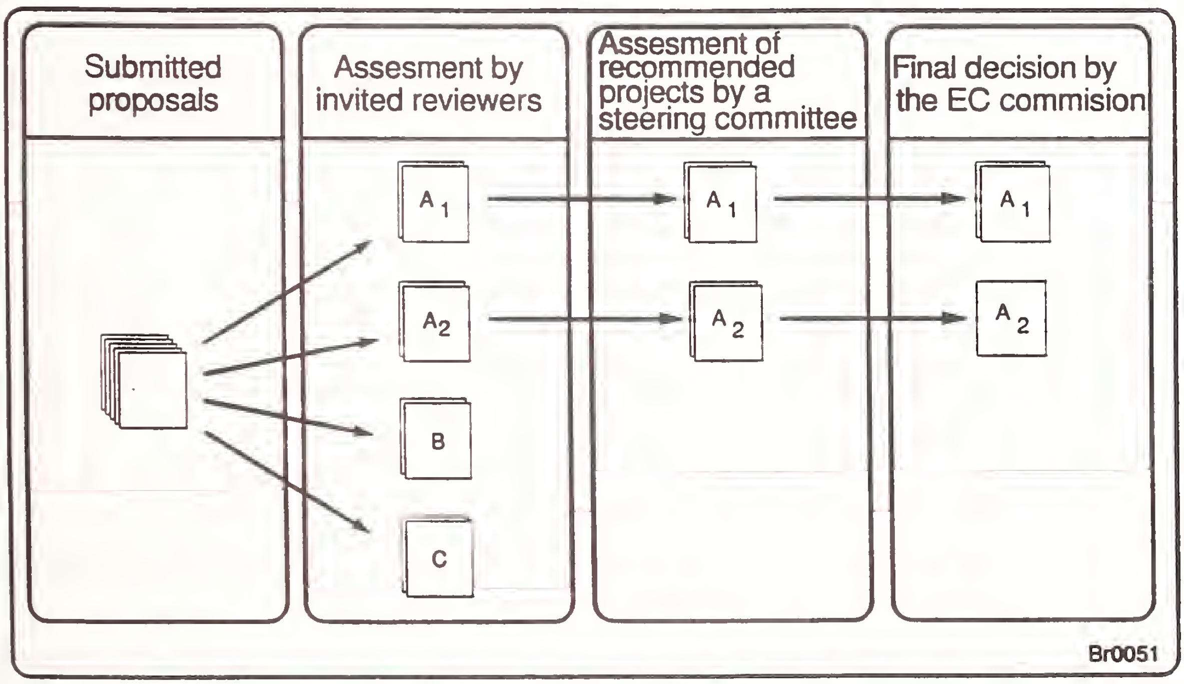


Fig. 23: Decision procedure

4.2.2. Technical areas of Brite-EuRam II

The scope of the technical areas reflects the multisectorial approach of the program and emphasizes the need to bring together, in RTD, partners drawn from suppliers, producers and end-users as well as from basic research intitutes and industrial enterprises (including SMEs) /8/.

For engineering sciences and precision fabrication R & D two areas are of major interest:

Area 1: Materials/Raw Materials

Area 2: Design and Manufacturing

The objectives of the area Materials/Raw Materials are to improve the performance of both advanced and traditional materials at a cost which permits competitive industrial exploitation over a broad range of applications. This extends to improving the technologies to ensure the supply of raw material resources and for recycling, so promoting an integrated approach to the whole life-cycle of materials. It also includes the cost-effective use of new materials in a broad range of products and applications and their diffusion to new application fields. Sub-areas are shown in Fig. 24.

- **Raw Materials:** covering existing processes and new techniques relating to exploration technology, mining technology and mineral processing;
- **Recycling:** covering technologies involved in the recycling and recovery of industrial waste including non ferrous metals and reuse of advanced materials;
- **Structural Materials:** including metals, ceramics, polymers, their corresponding alloys, composites and hybrid combinations, and advanced glasses;
- **Functional Materials for Magnetic, Superconducting, Optical, Electrical and Biomaterial Application:** focusing on synthesis, processing, design and manufacturing within the constraints of optimized performance;
- **Mass Commodity Materials:** covering in particular packaging materials and new construction industry materials.

Source: EC

Br 0052

Fig. 24: Brite-EuRam II
Sub-areas within Materials/Raw Materials

The objectives of the area Design and Manufacturing are to improve the capability of industry to design and manufacture products which take account of functionality, cost-effectiveness, quality, reliability and maintainability, and environmental and social acceptability.

Sub-areas are shown in Fig. 25.

- **Design of Products and Processes:** tools and techniques for innovative design, design methodologies for complex high-technology components, maintainability and reliability;
- **Manufacturing:** tools, techniques and systems for high quality manufacturing, manufacturing techniques for industrial use of advanced materials and integrated approaches to chemical and process engineering;
- **Engineering and Management Strategies for the whole product life cycle:** design integrating strategies, engineering, human factors in engineering, quality and manufacturing management.

Source: EC

Br 0053

Fig. 25: Brite-EuRam II
Sub-areas within Design and Manufacturing

For the interesting area of Design and Manufacturing a more detailed break down of the technical content is given in the following:

Innovative design tools and techniques

Objectives
To develop design tools such as decision support systems to promote more efficient design methods, more economic manufacture, assembly and dismantling, and reliable and ergonomic products.

Design Methodologies for complex components

Objectives
To develop approaches for the incorporation of multifunctional components in product design. To advance the capability of high precision and micro-engineering systems together with design for micro-miniaturisation.

Maintainability and reliability

Objectives
To develop the support tools, including sensor systems, for improved product performance, reliability and maintainbility. To advance the capability and applicability of mathematical modelling to support design, including the integration of modelling techniques with defect and failure mode analysis needed for reliability and predictive maintenance.

Tools, techniques and systems for High Quality Manufacturing

Objectives

To develop skill supporting technologies to make human skills and judgement more effective in the manufacturing process. To develop innovative tools and techniques for high quality and cost effective manufacturing systems to give better process control, higher precision and faster operation and the integrations of new processing technologies with established manufacturing processes.

Manufacturing techniques for industrial use of advanced materials

Objectives

To develop cost-effective and efficient manufacturing techniques for advanced materials to help realise their full potential

Integrated approach to chemical and process engineering

Objectives

To tailor manufacturing technology to the requirements of chemical engineering and to integrate design with process control. To advance the understanding needed to design and control chemical processes with increasing complexity to include avoidance and prevention of pollution.

Design integrating strategies

Objectives

To develop new and more holistic approaches to support the integrations of engineering tasks for the whole product life cycle, such as simultaneous engineering concepts which bring together design, engineering and manufacturing.

Engineering

Objectives

To bring an integrated approach making full use of new materials, new design and manufacturing technologies and process and product control to traditional manufacturing industries, with particular attention to new requirements for environmental control and improved working conditions.

Human factors in engineering and manufacturing management

Objectives

To accelerate the take up of new technology by developing new management techniques which allow identification and reconciliation of potential areas of conflict between new technologies and human resources. To improve methods for the evaluation of the performance of products and processes and their linkage to the overall business.

4.2.3. Implementation of Brite-EuRam II programs

The Brite-EuRam II program is implemented in the following three ways:

1. Shared-cost research
2. Concerted Actions
3. Accompanying Measures

The main actions of the program are carried out through Shared-cost Contracts between the EC and pan-European consortia, made up of partners from industry, research institutes, universities or similar higher education establishments. This type of implementation will cover 96 % of the total budget. Fig. 26 shows the three types of Shard-cost research.

- **Industrial Research** involving industrial enterprises form different member States collaborating in precompetitive research. The research must have the potential for a significant medium-term industrial and economic impact (2 - 3 years after the end of the project).
- **Focused Fundamental Research** for applied research which is up-stream of industrial research but is nevertheless of industrial relevance. The research requires the endorsement of industrial enterprises from different member States.
- **Cooperative Research (CRAFT)** to enable groups of enterprises without research facilities - especially SMEs - to contract with outside research institutes, universities or enterprises to carry out research and development on their behalf (Comparable to the AIF in Germany).

Source: EC Br 0054

Fig. 26: Types of Shared-cost Research in Brite-EuRam II

A summary with the major data of these three types of research can be taken from the Fig. 27 to 29.

INDUSTRIAL RESEARCH PROJECTS

(77 % of total budget for research)

- Conformity with research tasks
- Precompetitive and collaborative
- Subsequent exploitation expected

Size	-	10 man-years minimum
Duration	-	2 - 4 years
Total cost	-	1 - 5 MECU
Funding	-	EC funding: normally not to exceed 50% Industrial funding: minimum $^{2}/_{3}$ of EC funding
Partners	-	at least 2 independent industrial enterprises from different Member States
Calls	-	fixed closing dates: 3 April 1992 26 February 1993 (provisional)

Source: EC

Br 0055

Fig. 27: Industrial Research projects

FOCUSED FUNDAMENTAL RESEARCH PROJECTS

(10 % of total budget for research)

- Basic research upstream of Industrial Research
- Conformity with research tasks
- Precompetitive and collaborative
- Industrial endorsement

Size	-	10 man-years minimum
Duration	-	2 - 4 years
Total cost	-	0.5 - 1.0 MECU
EC Funding	-	up to 50% of full costs up to 100% of additional (marginal) costs
Partners	-	at least 2 organisations from different Member States
Endorsers	-	at least 2 independent industrial enterprises from different Member States
Calls	-	fixed closing dates: see above

Source: EC

Br 0056

Fig. 28: Focused Fundamental Research projects

COOPERATIVE RESEARCH (CRAFT)

(9% of total budget for research)

- Conformity with technical areas
- Research defined by industry (bottom-up approach)
- Precompetitive and cooperative
- Research performed by third parties for a group of proposers
- Exploitation oriented
- 2 step application procedure

Cost	-	0.4 - 1 MECU
Duration	-	1-2 years
EC Funding	-	up to 50 % of full costs
Partners	-	**Step 1** : at least two SMEs from different Member States
		Step 2 : at least four SMEs from at least two Member States
Calls	-	open Call (approximately 2 evaluations/year)

Source: EC Br 0057

Fig. 29: Cooperative Research (CRAFT)

A speciality and new experiment is the introduction of the CRAFT program. The objective is to transfer the good experiences with the AIF in Germany to an European level.

The scheme will provide financial support to a group of industrial companies, mainly SMEs, facing a common industrial or technological research need. CRAFT will enable these SMEs to come together and assign outside organisations (research centers, universities, or other companies) to carry out RTD under contract on their behalf.

4.2.4 Budget of Brite-EuRam II

The program has a total budget of 663.3 M ECU for the period of 1991 - 1994. Fig. 30 shows the breakdown of budget by technical areas and by funding the different types of research.

Breakdown of the budget by technical area:

Area 1:	Raw Materials and Recycling	80 MECU	12 %
	Materials	228.8 MECU	35 %
Area 2:	Design and Manufacturing	301.5 MECU	45 %
Area 3:	Aeronautics Research	53 MECU	8 %

The total indicative funding devoted to research is:

Industrial Research	483.8 MECU	77 %
Focused Fundamental Research	62.8 MECU	10 %
Cooperative Research	56.5 MECU	9 %
Concerted Actions	6.3 MECU	1 %
Feasibility Awards	6.3 MECU	1 %
Specific Training	12.6 MECU	2 %

Source: EC

European Currency:
1 ECU = 2.– DM = 1.3 US $

Br 0058

Fig. 30: Breakdown of budget of Brite-EuRam II

Most of the funding is devoted to industrial research in the area of design and manufacturing.

4.3. Funding of R & D within the EUREKA program JESSI

EUREKA stands for a frame for an increased technological co-operation on innovative research in Europe. EURKEA is neither a promotion program nor is it definded by the governments of European countries. Much more comes the initiative for projects from the European industries and research centers. They have to establish the entire research group with its members and they will determine the way of co-operation. There is also no central EUREKA budget. That means, that all participants have to provide for a financing by using their own resources for R & D support in their home country. So EUREKA is a bottom up approach for an European cooperation. One of the big and successful programs is the Joint European Submicron Semiconductor Industry program JESSI. This will be explained in the following chapter.

4.3.1 Situation of the European microelectronic industry

The recent development of the technology-driven industries in the European community shows, that microelectronics is the key to competitiveness in the areas of data processing and communication systems, electrical engineering, precision mechanics and optics, automotive, and machinery industry. The diffusion of micro-electronics in these fields is a result of its dynamic development in terms of cost, and size reduction and increasing level of comlexity and it affects strongly the performance and costs of the products and systems in which it is used (Fig. 31) /9/. Within the next decade the electronic industry will become one of the largest manufacturing industries in Europe.

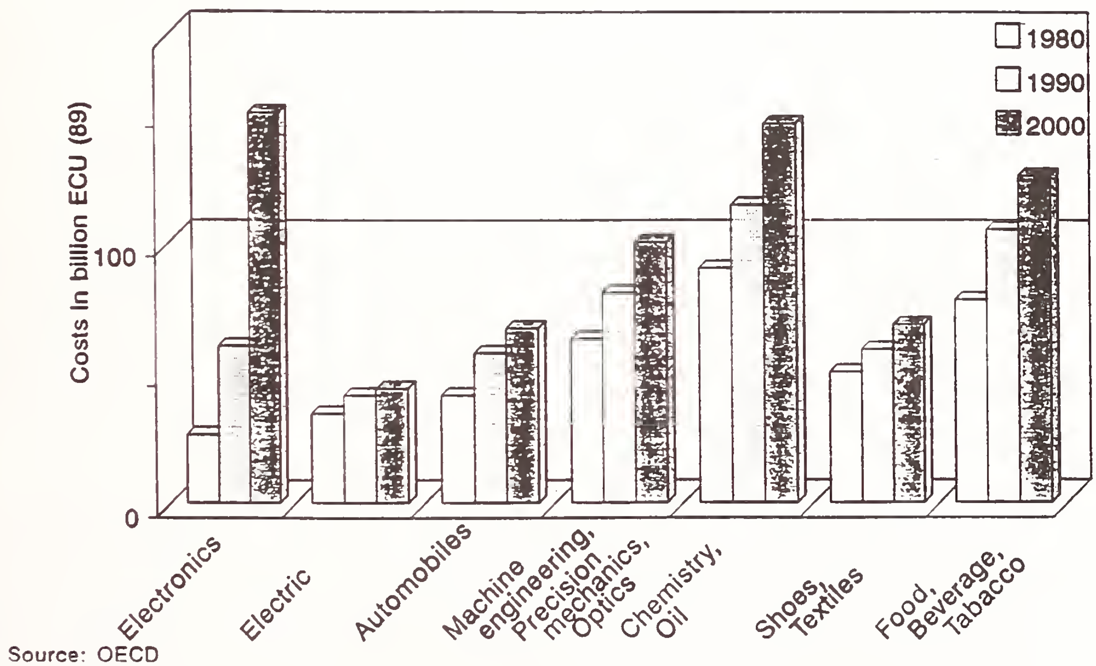
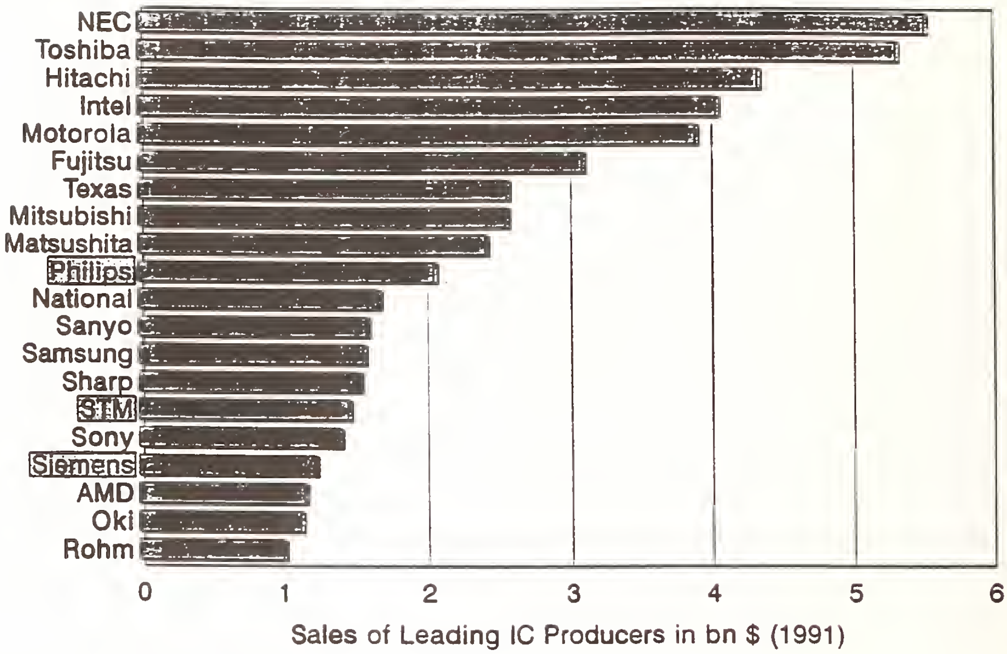


Fig. 31: Comparison of manufacturing industries

Although the European integrated circuit industry by itself is very small. In size, compared to the Japanese companies NEC, Toshiba or Hitachi, the European system houses are comperatively small (Fig. 32).

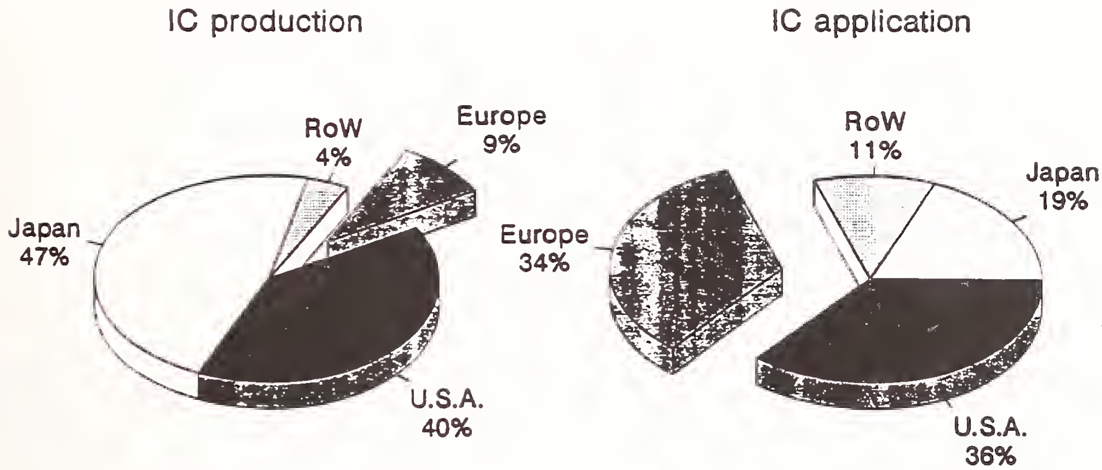


Source: Dataquest, 1992

Fig. 32: Sales of leading IC producing companies

In Japan, microelectronics has been recognized since the late '70s as a key industry for virtually all sectors of the economy and for the country's international competitiveness. Through its long-term, carefully coordinated assignment of research and development resources (particularly by the often-quoted MITI, the Ministry for International Trade and Industry), Japan has been able to capture a dominant market position in many sectors.

Compared with the other highly industrialized regions of Japan and North America, Western Europe still represents a "developing country" in the semiconductor business. The per capita consumption of semiconductor products in North America is double, in Japan six-fold that of Western Europe. In addition, Western Europe is the only region in the triad producing fewer semiconductors per head than it consumes (Fig. 33). At $ 230 compared to $ 17.6, Japan's per capita production volume is 13 times greater than Europe's! This indicates that Europe has large potentials for growth. And the political transformation of Eastern Europe promises additional market potential over the long term /10/.



Source: Dataquest, Elsevier, SIS (1991)

Fig. 33: Comparision of IC production and application

4.3.2 JESSI

4.3.2.1 History

The extremely high R & D effort required for VLSI circuits faces a compatible small turn over in ICs in European companies. To compensate for this disadvantage first a strong cooperation between the IC companies and secondly a financial support for the high R & D expenditures are needed.

This problem has been recognized by the politicians already years ago. Consequently they launched in 1984 the well-known "Mega Project" /11/.

However in the "Mega Project" there was not enough attention paid for the built up of a strong equipment infrastructure that time. Because of the lack of key components in manufacturing the ICs the strong efforts of the Mega Project did not have the desired success for the microelectronics industry. To relief this unsatisfying situation a much stronger cooperation between IC and equipment companies was needed.

In the beginning of '88 a planning group was established to elaborate the technical base for the JESSI Program (Fig. 34). According to the important areas within the JESSI Program the "Planning Team" was divided in four "Section Teams":

- Technology
- Equipment + Materials
- Application
- Basic and Long Term Research

The entire Planning Group was coordinated by the Core Team which entailed under the leadership of the Fraunhofer Gesellschaft an appropriate mix of mainly industrial people from the different sections. The Section Team 2 responsible for the planning in Equipment and Material was structured in a way that beside the core of the Equipment and Materials companies, the influence of the IC manufacturers as well as of the basic and long term research was ensured during the entire planning phase. The results of this planning (description of selected product areas, rough time schedule, manpower alocation etc.) are put down in the so called "Green Books" /11/.

Jan 1988	Start of JESSI Planning Group
Feb 1989	Realease of JESSI Green Book (results of planning phase)
Jun 1989	JESSI declared EUREKA project EU 127
Jul 1989	JESSI organisation starts business
Nov 1989	First JESSI labels assigned
Apr 1990	Agreement on Industrial Property Rights
May 1990	First projects started
Jun 1991	JESSI's main phase (1992 - 1996) approved by EUREKA
Jan 1992	JESSI's main phase started

Fig. 34: JESSI history

In June 89 JESSI was declared to EUREKA Project No. EU 127 by the Commission of the European Communities. Thus in July 89 the JESSI organization started to work in the JESSI office in Munich.

In all the JESSI Board, the highest authority in the JESSI Organization, investigated over 300 individual projects proposals from more than 150 different organisations, and more than 70 entries were allowed to proceed.

In the early phase of the program (April 1990) an important agreement has been achieved on industrial property rights enabling the full exploration of the JESSI results to the mutual benefits of all participants.

Thus far, major individual projects have included the memory project, optical lithography, a frame project for designing chips using Computer Aided Design (CAD), Specific CAD Tools, and a research program to pave the way for future chips with structures of around 0.25 micron.

JESSI has concluded the start-up phase of its European micro-electronics program end of 1991.

Based on the experiences gained during the start-up phase with so many good project proposals, a consolidation of the program has been achieved with respect to the progress reached in projects to date, a thorough evaluation of the situation and orientation towards the main phase /10/.

4.3.2.2 Goals

The main goal of JESSI (Joint European Submicron Silicon) is to secure the availability of world-competitive microelectronics for the European Industry. It is an EUREKA research and development program for the technology of system integration based on silicon (Fig. 35). The program has four main issues /9/:

Technology:

* Development of the basics and proving of a flexible competitive manufacturing technology for advanced system applications, to be available by the mid-90s.

The most advanced technical goal, within the framework of the JESSI Program, is a CMOS-process with minimal structures in the 0.3 µm range. This fine structure range is achieved through intermediate steps at 0.7 µm and 0.5 µm. Each intermediate development involves the overcoming of technical barriers through innovative process steps. Reduction of manufacturing costs will be one of the most important targets. Memories (DRAM/VRAM/SRAM/EPROM) are to be used as the technology drivers.

Application:

* Building up of flexible competitive system-design procedures and tools which are applicable throughout Europe, for the development of highly complex integrated circuits and their integrations into systems, as well as their verification in advanced joint pilot projects in major areas of application.

The European industry has a world-wide leading position in solution-oriented system know-how in a broad range of application fields. The direct knowhow transfer into microelectronic systems realized on silicon is of increasing importance in comparison with the use of standardized integrated circuits. The competitiveness - today and in the future - in standard circuits (e.g. memories) will be determined largely by the smallest structure size, the highest intergration density and production technique. The competitive strength for the development of application-oriented system solutions within this time frame, however, is to the largest extent determined by the availability of flexible process capabilities and design tools.

Within the framework of JESSI, application-oriented system-development tools will be tested in pilot projects (Euro-projects), for example, in information processing, industrial electronics, automobile electronics and in the consumer sphere.

Equipment and Materials:

* Development of manufacturing equipment and materials for microelectronics in selected areas of the European supply industry.

World competitiveness for the European semiconductor industry requires immediate access to the most advanced manufacturing equipment. This can only be achieved by the support of a strong European supply in the areas of manufacturing equipment and semiconductor materials. The earliest availability of equipment and materials according to the technological developments in the semiconductor industry must be secured.

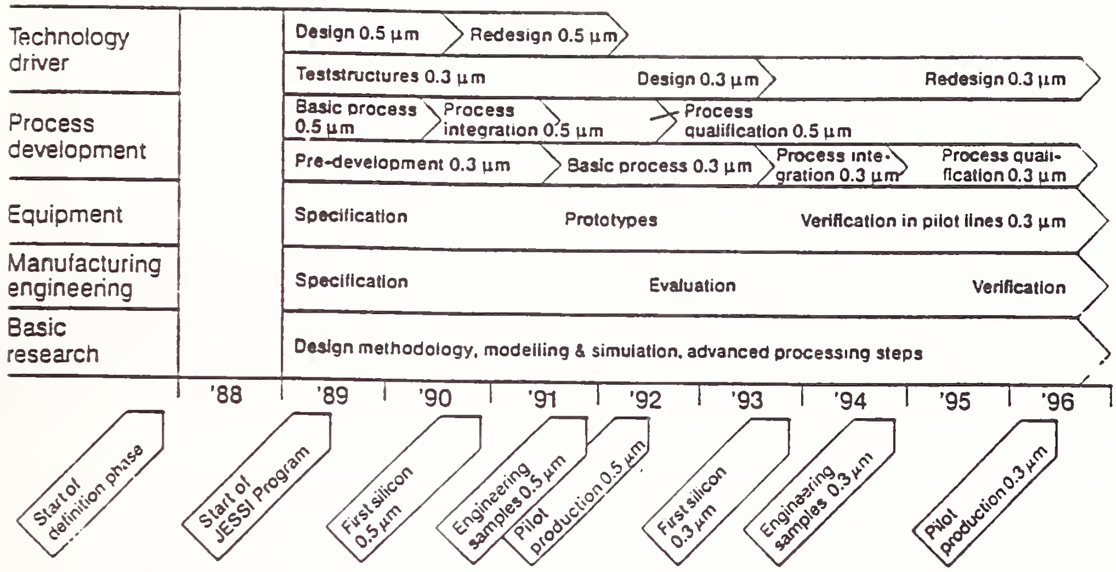


Fig. 35: Milestones of the JESSI Program

Close co-operation between European IC manufacturers and the European equipment/Material suppliers is essential, as the case of Japan shows. Effective forms of co-operation will be developed within the framework of the JESSI Program.

Basic and longterm research:

- Complementary applied research for the long-term future

In order to secure Europe's future economic interests and to capitalize on its current strengths in microelectronics, JESSI's starting point must be a wellorganized interaction between industry and research institutes. Mediumterm goals of the "basic and longterm research" are to support the industrial development of ICs and their application, with feature sizes down to 0.3 µm, and to work out alternative solutions.

The contribution to JESSI may vary by country, depending on industrial and academic infrastructure and on national political and financial strategies. A balance has to be found in Europe between a uniform approach for JESSI for all countries and parties, and a participation according to national and sectorial interests.

4.3.3. Structure

The JESSI Program with more than 140 international participants needs an efficient organization. Because of that there are 4 subprogram management boards (SMB). They represent the major participating industries, take care for industrial monitoring and coordination of subprogram progress, coherence, consistency and adaption. The management boards nominate their representatives for the JESSI board (JB) /9/ (Fig. 36).

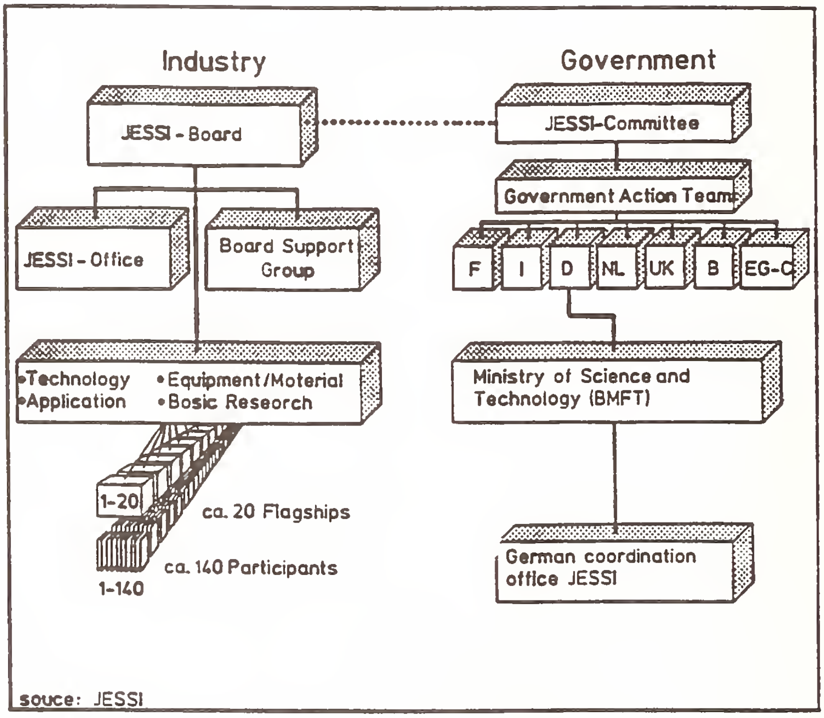


Fig. 36: JESSI Organization

The JB consists of three IC manufacturers (Philips, Siemens, ST) three Application companies (Bosch, Alcatel, Olivetti), one Equipment + Materials company (Electrotech) and one Basic and Long Term Research Institution (STW/Dimes). In addition to these voting members the chairman of the various SMB's are invited to take part in the meeting as non-voting members. The chairman which is full time in charge of the JESSI organization has no vote in the gremium.

The JB is responsible for:

- General strategy
- funding negotiations
- final decisions on proposals
- criteria for project selection
- initiation of progress assessment
- rules for project management etc.

There are at least two meetings a year. The JB has the final decision on the proposals for granting the "JESSI Label". However, the rejection of a project proposal accepted already by the SMB needs 2/3 of votes of the JB /11/.

The board support group supports the JESSI board in the tasks mentioned above. The duties of the JESSI office located in Munich are the organization of meetings, public relations and clerical work /12/.

On the government's side the JESSI Committee works closely together with the JB. They evaluated the proposals and decide on their acceptance. The government action team supports the committee in decision making. Every participating country has a coordination office for their national work /13/.

Based on experiences in the start-up phase, target sectors (clusters) and flagship projects were selected for the main phase of JESSI as significant innovations for implementing the program (Fig. 37).
The goal is to achieve a strengthened and improved focus on central themes of the program /10/.

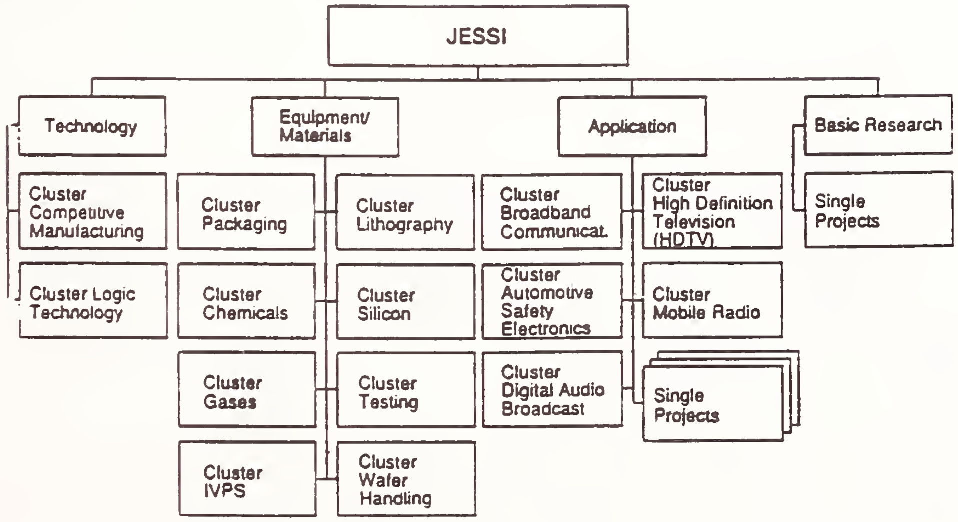


Fig. 37: JESSI Structure and Flagship Projects

Clusters consist of linked projects which share same goals and common technology.

Flagships are greater projects of high importance, aiming at commerical products and emphasizing vertical cooperation.

Linked projects are necessary to reach the flagship goals /10/.

4.3.3.1 Subprogram Technology

Mastering memory technologies and the corresponding manufacturing technologies are the necessary (but not sufficient) ingredients for the competitive manufacturing of logic circuits. The strategic value of logic circuits in general - of ASICs in particular - for the european end users is high and expected to grow /9/. JESSI is essential to increase the necessity towards a closer cooperation of IC manufacturers especially in logic circuit technology. The figures 38 and 39 describe the different categories of logic ICs and their share in the market /14/.

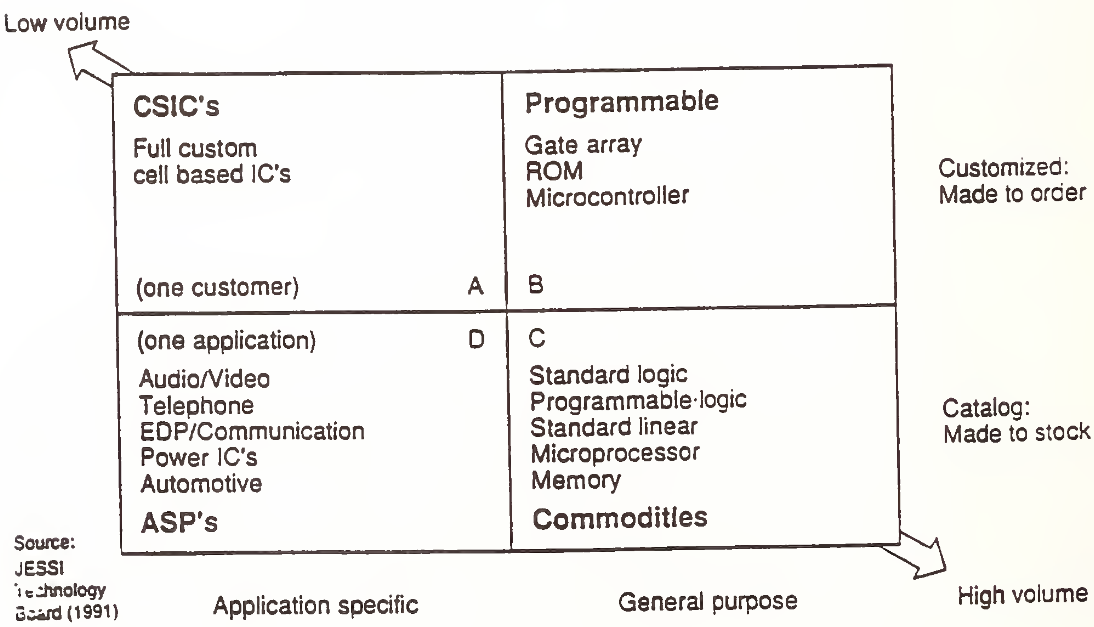


Fig. 38: Different types of logic ICs

There are three major activities in the technology subprogram/9/:

1) Development of submicron (down to 0.3 µm memory generations (DRAM/VRAM, SRAM, EPROM) including the work needed to provide the necessary processing environment.

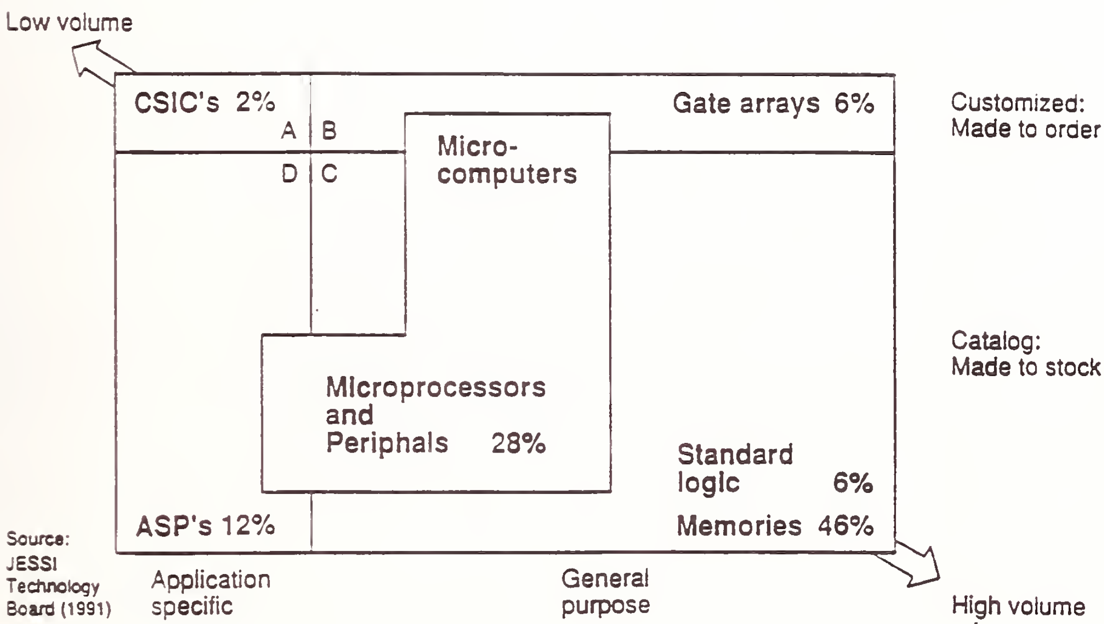


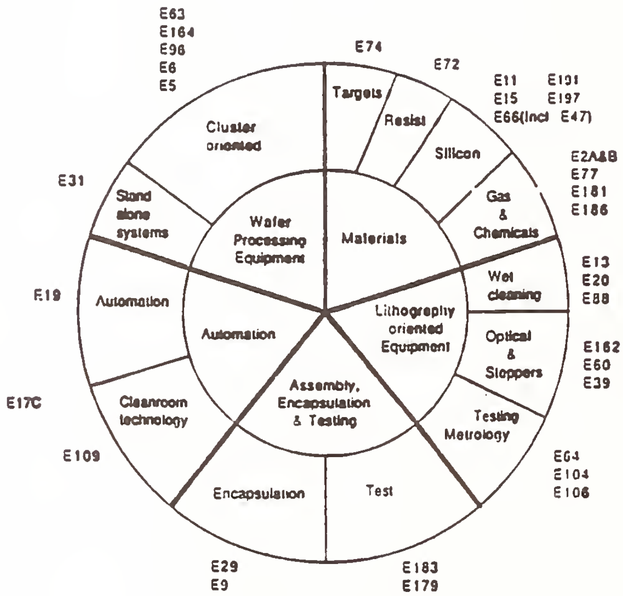
Fig. 39: Market shares of logic ICs

2) Development of logic technologies starting from todays 1 µm technology-base to utilization of submicron technologies that will be provided by the memory projects. This development includes ciruits derived as directly as possible from memory processes (e.g. microprocessors, gate-arrays) and more advanced ciruits that contain process-modules not directly related to a corresponding memory generation (e.g. BICMOS or Logic with E^2PROMs).

3) Development of manfacturing engineering methods that assure timely and cost-efficient production of present and sub-micron circuits on 150 mm and 200 mm wafers.

4.3.3.2 Subprogram Equipment and Materials

The following sectors have been assigned highest priority in the equipment and materials subprogram (Fig. 40) /10, 15/:



<u>Fig. 40:</u> Distribution of labeled projects in the E+M subprogram

- Lithography in the deep-UV range:

This basic process for all IC production involves the development of a suitable wafer stepper, optics (lens) and photoresist for each generation of chips (0.5 microns structural width for 16-Mbit chips, 0.35 microns for 64-Mbit memory chips). Vertical cooperation, i.e. between production equipment and material development and users (i.e. IC manufacturers) is especially important at this stage. Significant advances have already been made in accuracy of positioning and wafer throughput, placing us ahead of worldwide - particularly the Japanese - competition.

- Integrated vacuum processing system and automated wafer handling:

Under extremely pure cleanroom conditions, the integration of various components, standardization of interfaces and development of cluster tools is becoming increasingly important.

- Chemicals and gases:

Ultra-pure chemicals, cleaning fluids and gases largely determine the defect density and ultimately the yield of the entire VLSI production process. Supplying local wafer fabrication with these products opens up additional perspectives and options.

- Silicon wafers:

The basic material must be continually adapted to the requirements of each chip generation with respect to planarity, contamination and other critical factors. The aim is to improve processes and equipment for growing wafer crystals with a diameter of 200 mm and greater.

In the last two points, Europe enjoys a position that is fully competitive on the world market.

4.3.3.3 Subprogram Application

Following the concentration with regard to funding restrictions and having the aspect of vertical integration in mind the following four market sectors are covered by the Application Subprogram when entering the main phase of JESSI:

- Electronics for Automotive Industry
- Consumer Electronics
- Telecom

which are represented by one or two flagship clusters and the sector of:

- Graphics Information Systems

represented by the single project "Digital Controls for High Resolution Display" (Fig. 41) /16/.

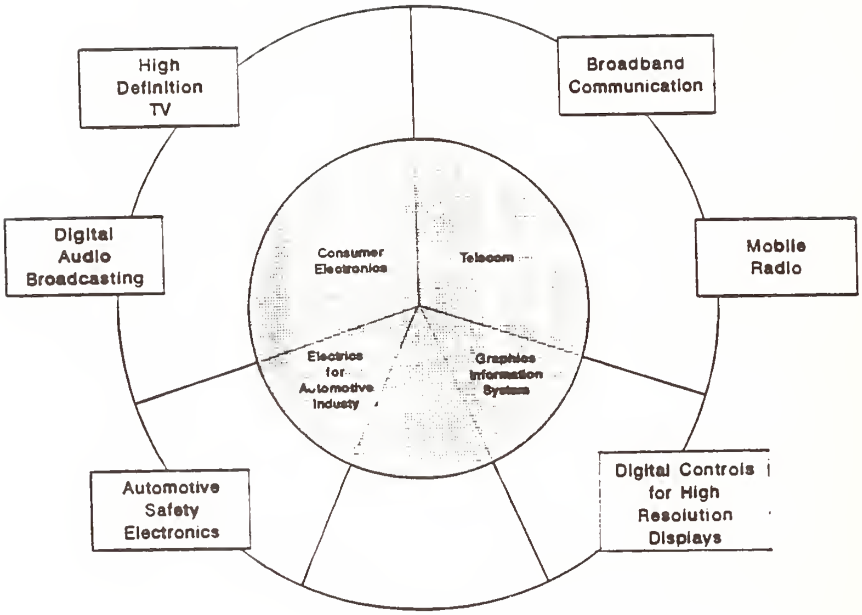


Fig. 41: JESSI's application areas

After the restructuring for the main phase of JESSI the Application subprogram encompasses five flagship clusters covering different market sectors and five single projects not included in flagship clusters.

Cluster: Automotive Safety Electronics
Flagship Project: Ultra Large Scale Integrations of a Control Unit for Safety Critical Systems
Linked CAD Project: Synthesis, Optimization and Analysis

Systems such as ABS, ASR, airbag and electronic fuel injection already heavily rely on electronic control. An increasing number of functions and speical conditions with respect to safety (e.g. fault tolerance), environment conditions (e.g. air pollution), high voltage and electromagnetic compatibility create specific requirements for the operation of microelectronic circuits. Therefore electronics are the critical technology of tomorrow's automotive industry.

Cluster: Digital Audio Broadcasting (DAB)
Flagship Project: Implentation of Prototype Building Blocks for a DAB Standard
Linked CAD Project: Development of an EMC Workbench for Microelectronic Application

The European market for consumer electronics is the largest in the world with the highest growth potential. Worldwide the consumer electronics market is dominated by Japan but there is still a good ranking of some large European companies. To hold this position strong efforts have to be made mainly by implementing new European transmission standards (receivers, recorders, etc.) in advanced CMOS processes.

Cluster: HDTV
Flagship Project: Europroject HDTV
Europroject: Signal Processing for AD/HD VCR
Linked CAD Project: Test Generation and Design for Testability Support

High definition television is to be considered as the most important new market segment in consumer electronics for the late 90ies. All over the world strong efforts are made to develop chipsets with sufficient processing capabilities, enhanced bandwidth and digital control. Europe has chosen a clear approach towards tomorrow by taking into account the situation today. Improved transmission standards (MAC), worldwide agreed new screen format (16:9) and finally HD-MAC is the clear European roadmap towards a new type of vision in the home.

Cluster: Mobile Radio
Flagship Project: Advanced VLSI Components for the GSM Pan European Digital Cellular Radio System
Europroject: Mobile Automatic Cellular Radio
Linked CAD Project: Analog Expert Design System

Within the telecommunication markets of the future digital radio telephony is one of the biggest market segments. With the release of the GSM description end of 1990 by the European Postal Organizations and the industry the Pan European Cellular Digital Radio System is going to become reality. The requirements of the IC development efforts are challenging as portable sets need to be maximally integrated in order ro reduce volume, weight, power consumpition and cost.

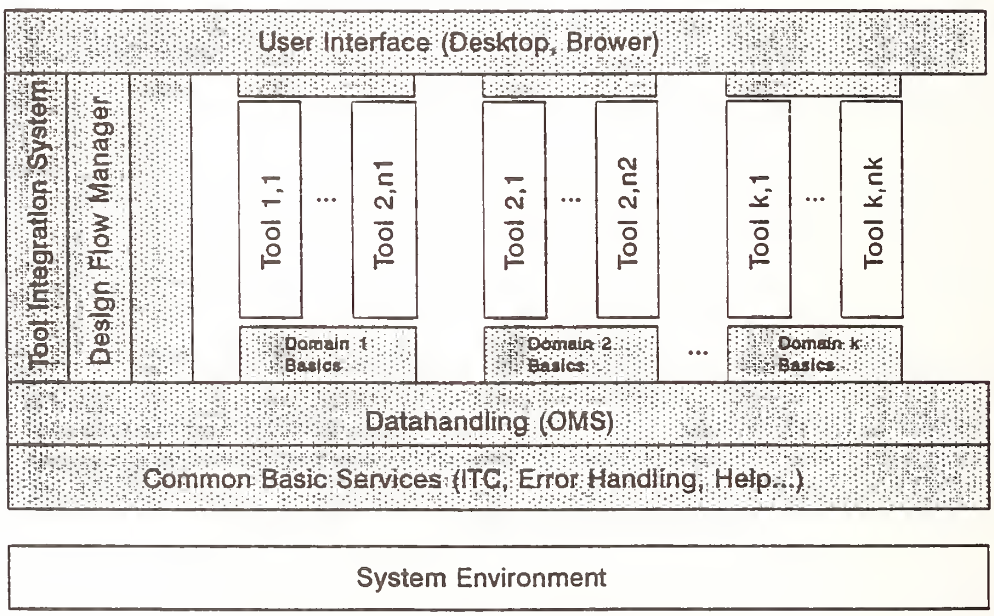
Cluster: Broadband Communication
Flagship Projects: Advanced VLSI Components for B-ISDN ATM Networks, Advanced VLSI Chipset for ISDN Videophones

The integration of all services, which are currently provided on a multitude of networks, on a single ATM (Asynchronous Transfer Mode) broadband communication network will boost both application and equipment provided in the 90ies. In addition high speed data transfer will offer new services like videotelephony, two way TV, HDTV, video library provided via cable to the commerical and private customer.

Integrated JESSI CAD System

The main activities on CAD tools within JESSI are assembled in the different CAD projects linked to the corresponding flagship projects. But this link does not mean that the respective CAD project only follows the demands of that flagship. The goal of all JESSI CAD projects is rather to offer tools which meet the requirements of all applications in the respective desgin field and to make leading edge tools avialable to the benefit of all European microelectronic designers.

To offer all these CAD tools in a common but open environment they will be integrated into the JESSI Common Framework to be developed in the JESSI-COMMON-FRAME project. (Fig. 42). With that integrated system the user gets the powerful JESSI CAD tools under a common design infrastructure which is open to include any other tools needed by the designer for special purposes /16/.



Source: Radelaar

Fig. 42: Architecture of the JESSI-COMMON-FRAME

4.3.3.4 Subprogram Basic and Long-term Research

The Basic and Long-term Research (BLR) subprogram goals could be defined as /9/:

1) Support the European micro-electronics industry with research results to ensure that

   - The IC manufacturers can reach their goals of 0.3 µm structure width, 300 mm² chip area and 10^7 - 10^8 transistor complexity in the pilot production in 1996 and beyond.

   - a growing field of materials and equipment suppliers will reach a strong competitive positon.

2) Broadening of the basis of the microelectronics industry by developing alternatives to improve on and enhance established technologies and to overcome unforeseen future technical and economic bottle-necks.

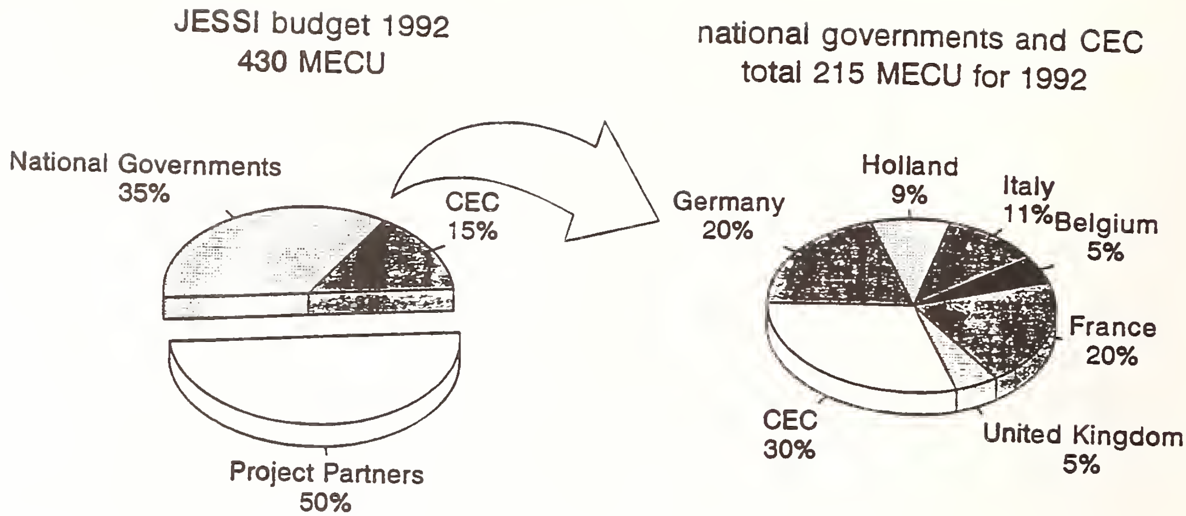
3) Assure long-term continuity for the microelectronics industry by developing new methods and technologies to be exploited economically after 1996.

The BLR-projects are all closely connected with other JESSI-projects. The BLR-projects are partitioned and defined such in order to optimize internal coherance within JESSI.

4.3.4. Budget

The whole JESSI project will comprise almost 22.000 man years of scientific and technical work from 1989 until 1996. This will involve a financial outlay of about 3.8 M ECU. About 50 % of these funds will be supplied by industry and the institutions involved, 40 % by national governments and 10 % by the European Community /13/.

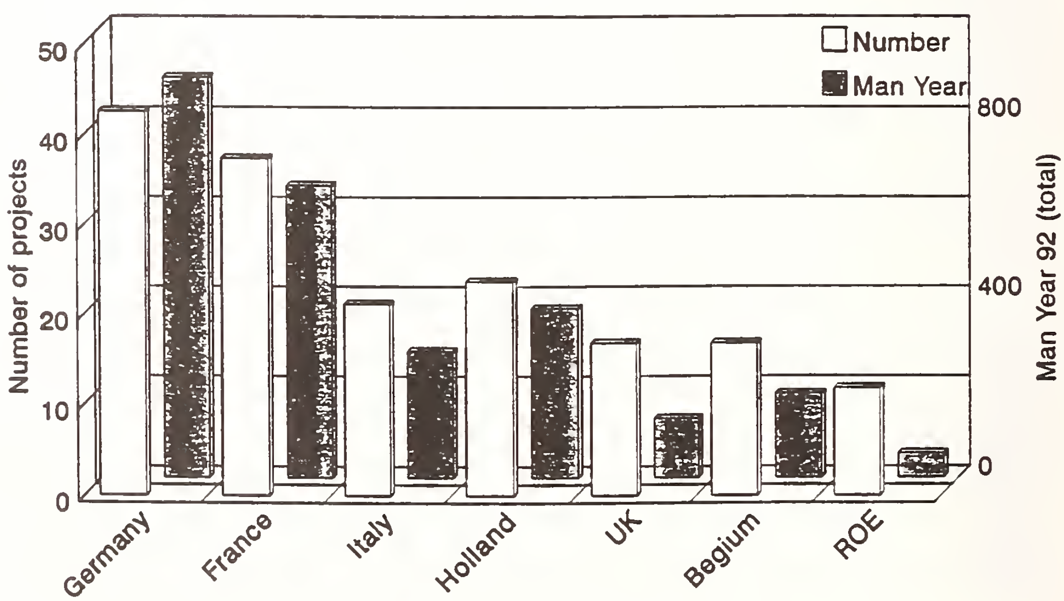
The budget for 1992 has been approved in the common JESSI Board-JESSI Commitee meeting in October 1991. It comprises total project costs of 430 million ECU for 1992. Distribution on individual countries and the European Commission for 1992 and in the start-up phase, is shown in Fig. 43 /17/.



Source: JIL Issue No.10/92

Fig. 43: Financing of the JESSI project

Fig. 44 shows the distribution of the number of projects and the total man years in 1992 to the participating countries.



Source: JIL Issue No.10/92

Fig. 44: Distribution of projects and man years in 1992

4.3.5. Conclusions

The JESSI project has started in the middle of 1990. At that time the project was still at its infancy with a lot of great ideas and proposals but few established working relations and concrete results.

A lot has changed, moved and improved in the meantime /18/:
First, the program has been clearly recognized and established inside the companies and institutes as the European effort towards the highly competitive markets in our business.

Second, the "outside world" and the public authorities are now fully understanding and supporting the program.

Therefore, the major milestone was the approval of the program for the main phase at the Eureka ministerial conference last year. The judgement was based on a thorough evaluation of the program, specifically taking into account the utmost necessity of our program for the whole European information technology industry and the application of advanced microelectronics.

Third, based on these considerations, for the first time in such type of a Eureka project a common understanding between all participants and partners of the program - industry, institutes and public authorities - could be achieved. Esentially the newly adopted structure is a concrete result of these far reaching negotiations.

Fourth, and last but not least considerable resulta could already be achieved in the start-up phase.

4.3.6. Aims for the future

Microelectronics have a high significance for the human race and the technical progress. Because the innovation speed the price for microelectronics decrease up to 100 times per decade. On the other hand the costs for developing and producing microelectronics increase. Fig. 45 shows the cost structure for a high volume fab line. One can see that there is almost a 8 times higher price for a fab by comparing the years 1970 and 1990-. It is difficult for the most political economies to finance such fabs with a maximum lifetime of 4 years. These countries without modern microelectronics will become development countries from the technical point of view in a very short time. Because of that I propose to make worldwide cooperations and exchange of knowledge. The actual trends are of great promise: Siemens, IBM and Toshiba signed the contract (13.07.92) of common developing the 256 Mbit DRAM.

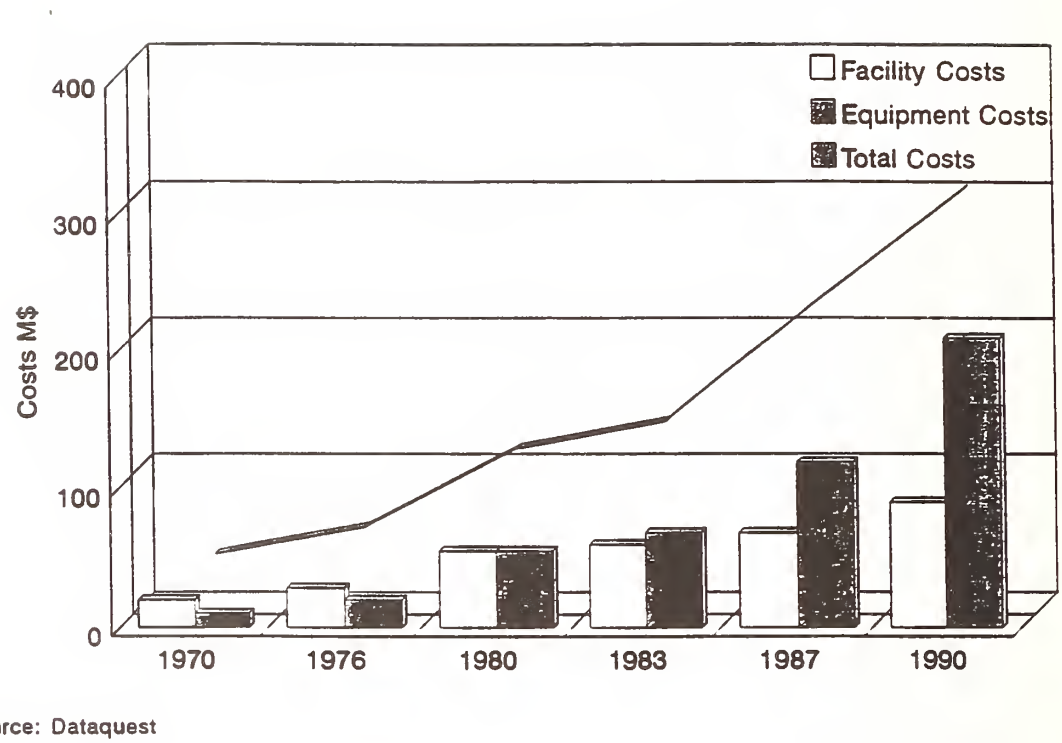


Fig. 45: Costs of a fabrication line

5. Examples for the needs in precision fabrication technology

In this chapter, an example shall be given for the needs in precision fabrication of parts produced by metal cutting. For this task, the design of machine tools and the application of an advanced machining technology are key issues. Therefore the European activities of research in the area of machine tools are introduced. This chapter is taken from a report by Tönshoff, Band and Glöckner /19/ (IFW, University of Hannover) which was written for an EC-commission. It is based on a survey by questionnaire. This chapter is followed by s survey on machine tools designed to machine hard materials by metal cutting. This survey was done for a machine tool builder and was composed also by IFW, Hannover /20/.

5.1. Research in the area of machine tools

5.1.1 Data base of the survey

The data used for this survey were collected in two steps: For a first overview data were collected from national surveys which were made by several CIRP members. In a second step, this was completed by means of a questionnaire.

The CIRP national surveys were avialable for Belgium, the Netherlands, France and Japan. Their information contents mostly comprized the main research topics and the numbers of researchers employed in the individual institutes. So, national profiles, e.g. the french and british focus on machine systems, could already be derived.

The answers gave representative images of the national research and development activities for all addressed countries except for France where only two out of fifteen questionnaires returned. There, an estimation had to be made on the basis of other sources, especially the national CIRP survey. For Ireland, Luxemburg, Portugal and Spain the data base was insufficient to derive any figures about research and development activities.

The domain of machine tool research is divided in 3 categories (Fig. 46):

- machine tool systems
- machine tool oriented processes and
- machine tool components

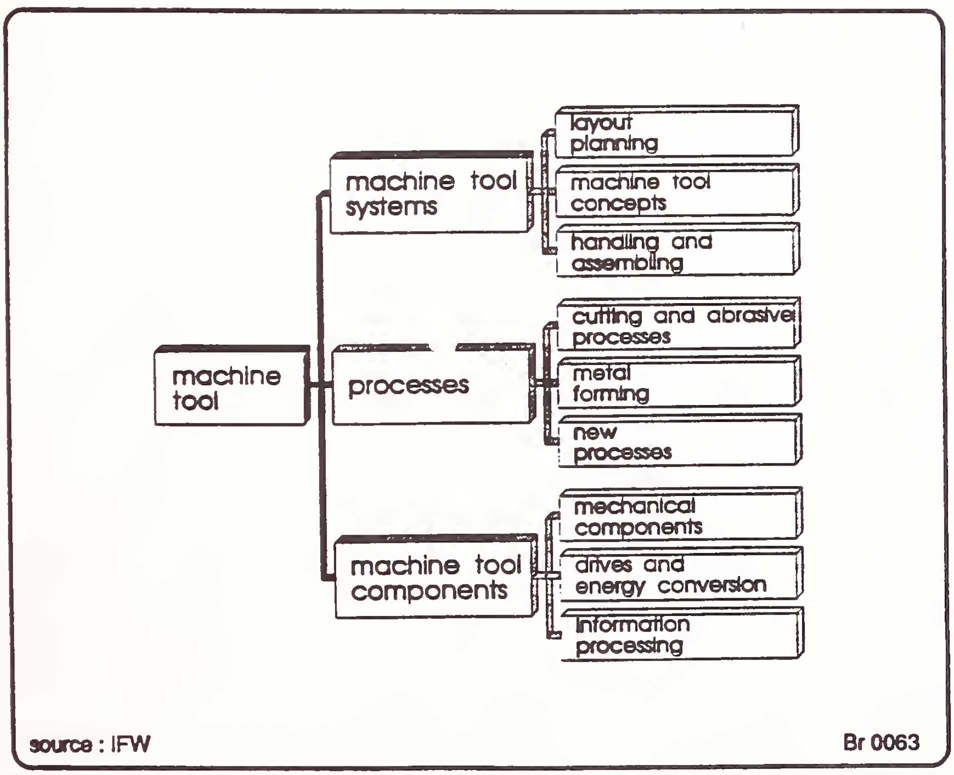


Fig. 46: Fields of machine tool R & D

R & D activities in the category machine tool systems comprize methods to define the production task and the related demands from given manufacturing data such as single workpieces, workpiece families and general boundary conditions. It comprizes the identification of the production problem a machine tool or a production system has to fulfill, and of the requirements towards forms and magnitudes to be manufactured, towards quality, productivity and the adaptation of machine tool systems to the workers and the environment.

The 4 criteria

- Working Space and Generable Forms
- Quality of Workpiece
- Productivity
- Adaptation to Workers and Environment

are equal and have all without exception to be taken into consideration. This is not a new idea. These basic criteria were formulated more than 50 years ago by Otto Kienzle. And it has to be said that human and environmental aspects were already then stated as a mandatory criterium for designing or investing in machine tools far before politicians and the society thought about it. It is of course an other question how and to what extent these demands were followed by the industrial practice.

Machine tool oriented processing is an important field of research and development. And processes of course are of governing effect on the lay- out, the operation and the performance of a machine tool. Therefore, research in this field has to be mentioned, when speaking about machine tools.

A look to scientific journals on production engineering over the last decades shows that in the past works on processes were by far dominant. There were little publications on systems. With the beginning of the 70ies activities about flexible manufacturing systems, about machining cells, workpiece and tool handling and lay out planning of systems came up step by step. In processes today, conventional cutting and abrasive methods are less worked on whereas new processes like laser beam machining, electro-discharge sinking and wirecutting and cutting of hard metals is dealt with increasingly, although from the point of view in the industrial turnover - in machine tool building and in production by machine tools - the conventional processes are by far dominant, are still bread and butter for a majority of companies.

Finally, we name R & D activities on <u>machine tool components</u> that include mechanical components like the mechanical structure of a machine, guide ways, spindle systems, the drives and energy conversion systems and the important field of information processing in the machine and in its neighbourhood.

5.1.2 Research activities outside the EC

Before examining the structure of the EC research activities in detail, we will first look at other members of the triade. Excluding the states of the former Soviet Union, for which there is no reliable data avialable, there remain two countries performing major research effort on machine tools: the USA and Japan. As Fig. 47 shows, the EC can be regarded as the very center of machine tool research in the world with more researchers than the two other domains together.

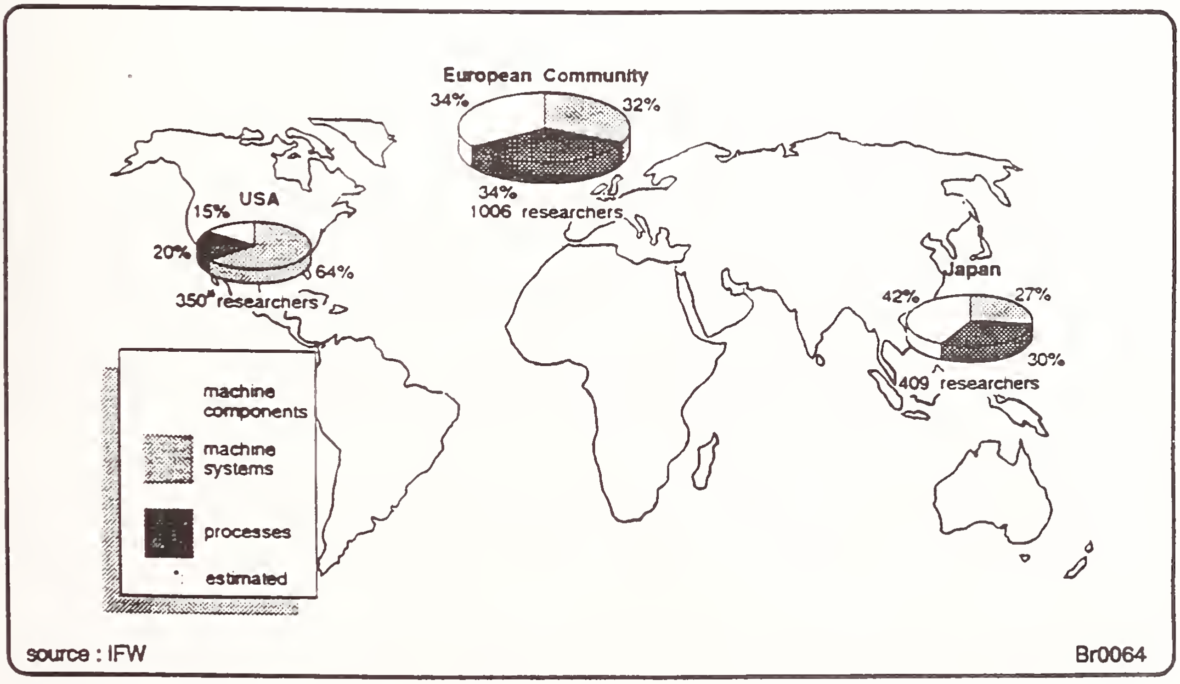


Fig. 47: Global research activities on machine tools

Inside the Western Europe, there are especially two countries outside the EC performing major research on machine tools: Switzerland and Sweden. In Sweden, 62 researchers work in all three topics (machine tool systems, components and processes) with slight focus on components. In Switzerland about 40 researchers work on processes and the other topics. Beside Germany, Switzerland is the only country where funding by a foundation of the national machine tool industry plays a major role.

5.1.3 Research activities inside the EC

After having stressed the dominant role of the EC in world wide machine tool research, the internal structure will be examined in terms of funding and research topics.

Funding

In most countries, the national governments are the most important source of funding (Fig. 48). Only in the United Kingdom their contribution is overweighed by industrial funding. On the other hand, EC funding was not specified by any British research institution. Averaged over all EC countries, EC funding reaches a level of 9 % of overall funding, which means 73 researchers on machine tools (in academic and other research institutions) in total. Also here, there are extreme differences between the nations. The total absence of EC funding in the addressed institutions in the United Kingdom contrasts to the extremely high percentage in Belgium.

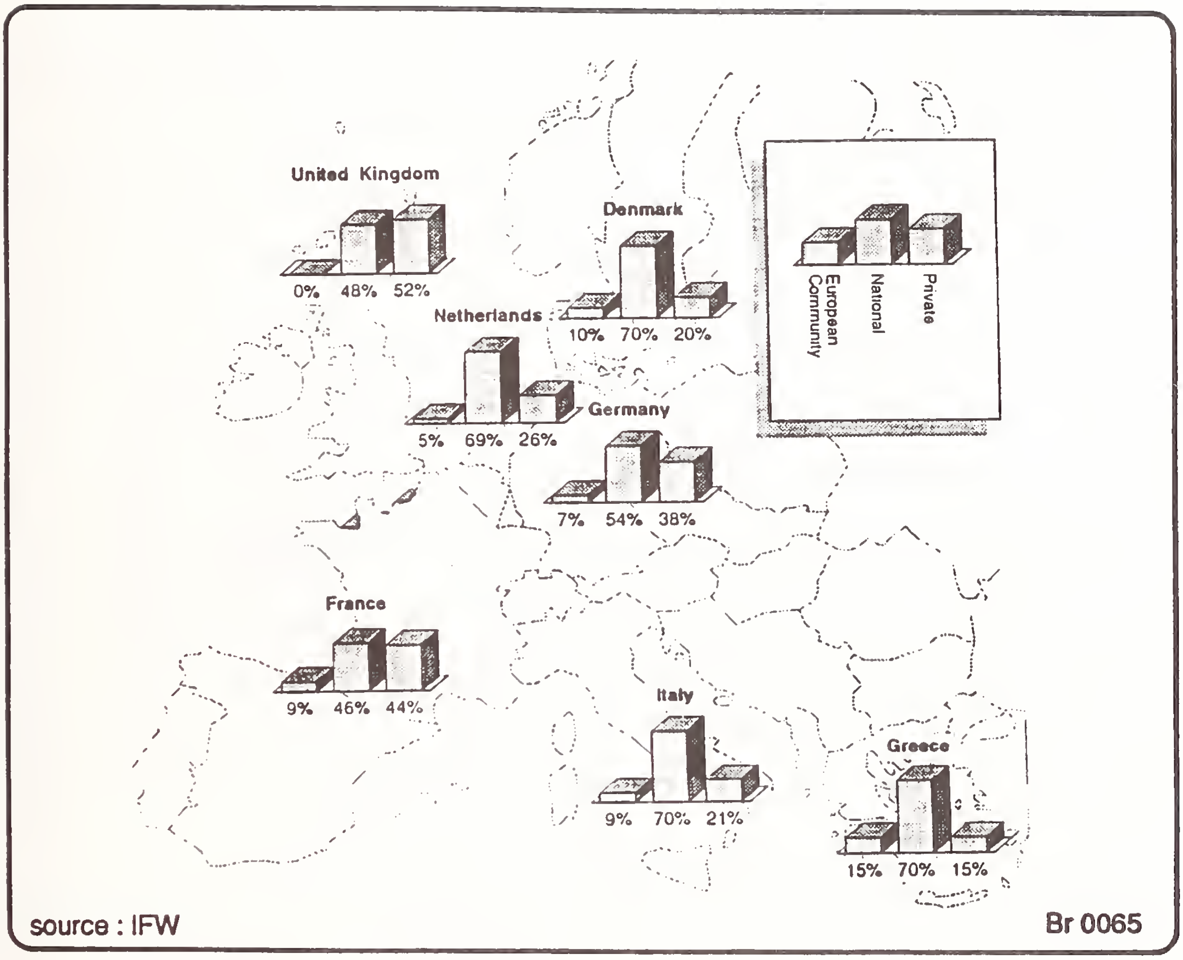


Fig. 48: Funding of European R & D on machine tools

In Germany, for basic research, the German Research Foundation (DFG) is competent. This institution is comparable to the NSF in USA. The German Research Foundation contributes approximately 15 % to 20 % to the budget of an average institute for machine tools.

In EC research programs the results are explicitly requested to be precompetitive. The results are desired to lead directly to products which help the European industry to improve their competitiveness. Foundations closely related to the national industry, e.g. the AIF, close the gap between these programs on one hand and direct industrial R & D on the other hand.

Topics

The evaluation of the questionnaires and several national CIRP surveys revealed a strong heterogenity of the topics tackled with in the different countries (Fig. 49).

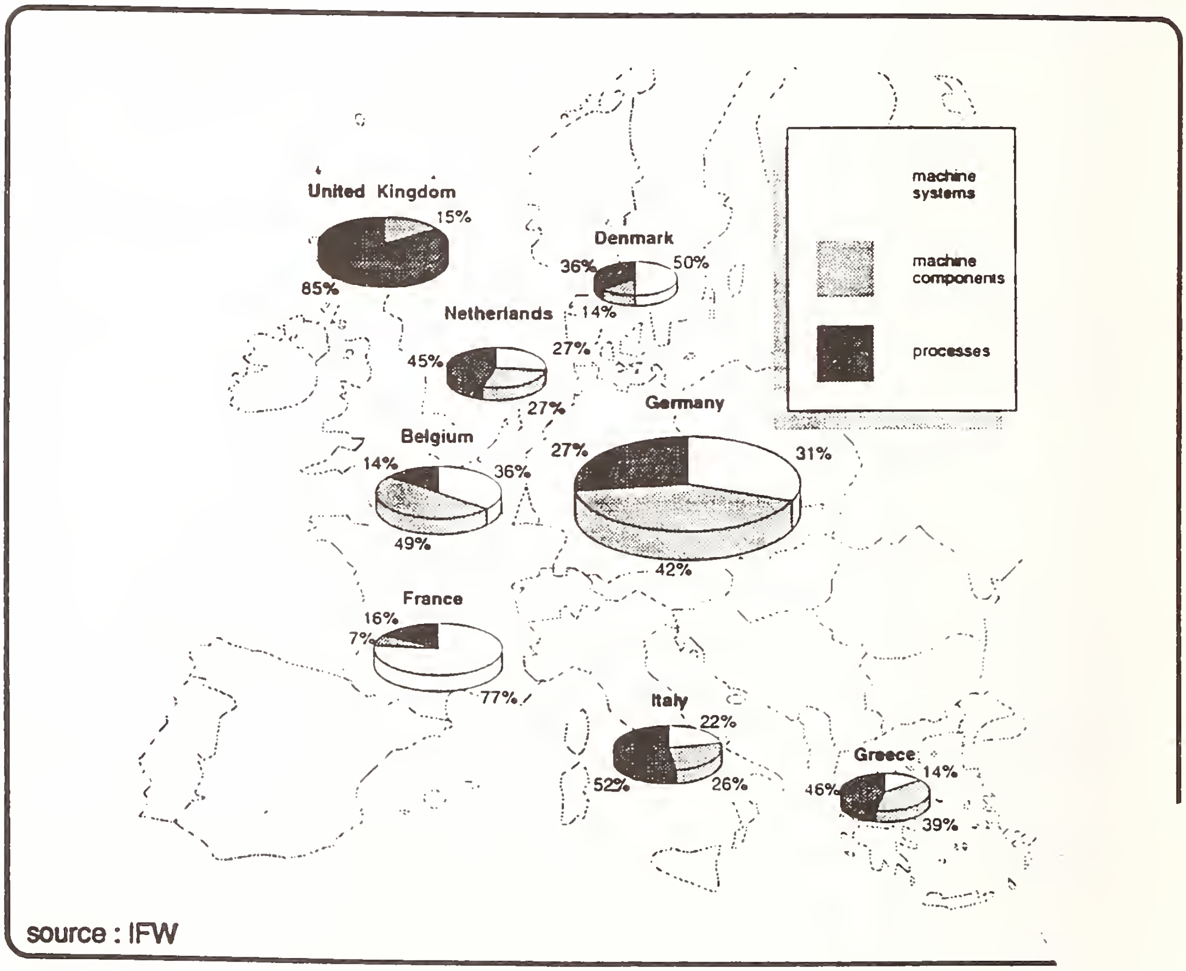


Fig. 49: European research activities on machine tools

Especially, there are two countries with major research effort concentrating strongly on one research field. In the United Kingdom, the focus of research lies on processes with 85 % of all research effort performed there. Research topics mostly named here tackle with the grinding process. In contrast, french research institutions mainly work on the machine tool system as a whole. Topics like FMS software, DNC, automation and CAD-CAM demonstrate the french focus of achieving higher productivity by means of making automation more flexible.

As Fig. 47 shows, these national differences are quite complementary. Summed up, they lead to a distribution comparable to that of the main competitor Japan.

A further differentiation of the research topics led to the result shown in Fig. 50. There, any topic is divided into three subtopics.

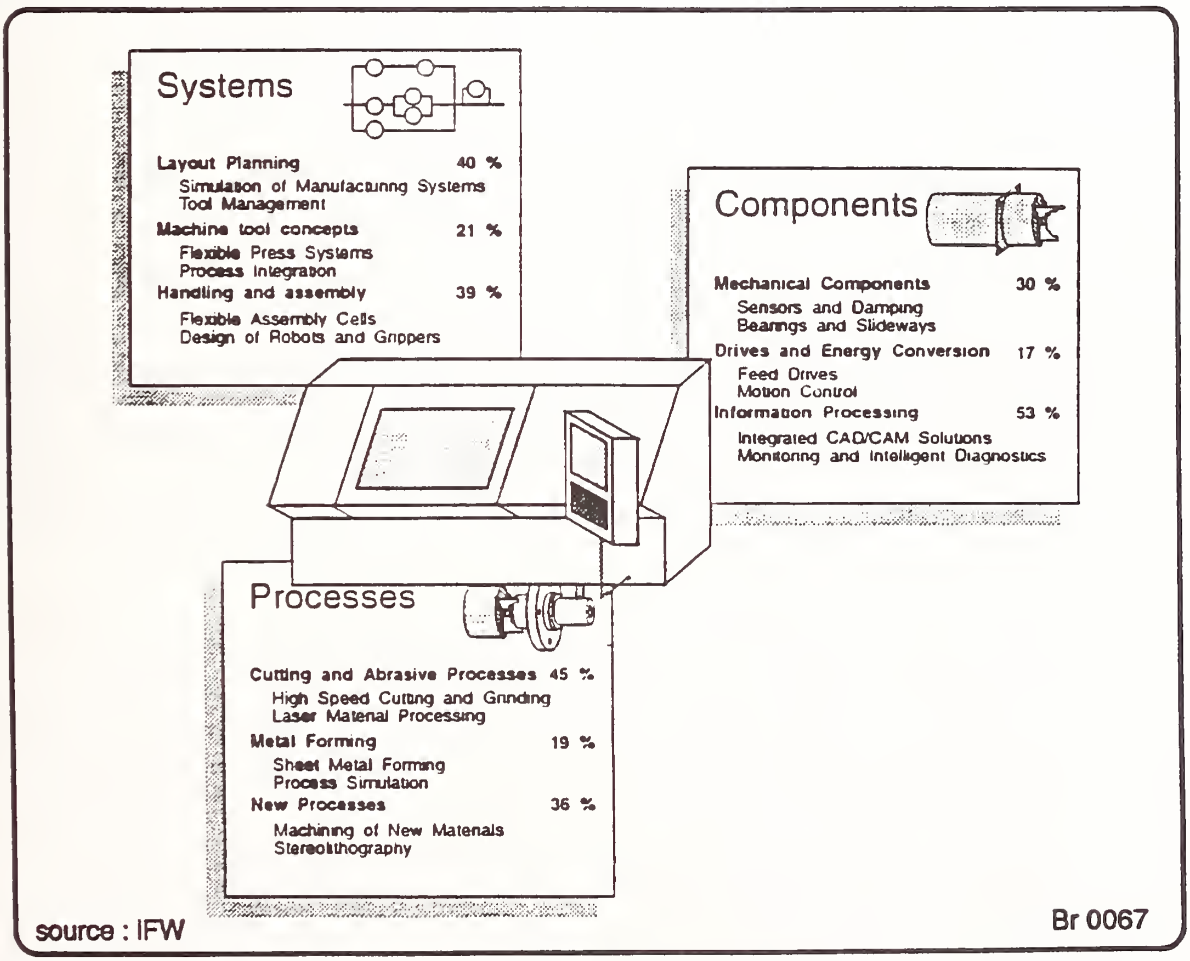


Fig. 50: Research topics on machine tools

A detailed description of individual projects in these areas can be taken from the cited report /19/.

5.1.4 Conclusions

Research and development in Western Europe is widespread over many academic and other public research institutions. The number of researchers exceeds those of the USA and Japan considerably. This variety stimulates creativity and innovation and is an excellent source for young scientific engineers. On the other hand this situation might split the power too. To minimize disadvantages and to intensify the great advantages of Europe's research structure in the field of machine tools, a specific program in this field would help to strengthen the competitiveness of this key technology in manufacturing.

5.2. Requirements on machine tools designed to machine hard materials

5.2.1 Preface

Due to the development of polycrystalline Cubic Boron Nitride tools (CBN) and improvements in the processing of ceramic tool materials (Al_2O_3/TiC), turning instead of grinding of hardened steels has become possible. This new technology has the potential to replace grinding processes and thereby achieve significant reductions in production time and cost. In order to judge the capabilities of these machining processes it is necessary to consider some technological as well as economical aspects of hard turning and drilling.

Machining of hardened rotational components by conventional grinding is substituted more and more by hard turning. Improved cutting tool materials were the most important reasons for this development. Especially the group of reinforced oxide ceramics and cubic boron nitride are suitable for machining of ferrous alloys in their hardened state. CBN tools are preferred for interrupted cutting because of their superior fracture toughness.

The main applications for hard turning obviously are finishing processes with high quality requirements concerning form and size accuracy of the workpiece, surface finish and surface integrity. These attributes are defined not only by the machinging paramaters like feed rate or cutting speed but also by the tool material, the cutting edge geometry, the composition and admission of coolants, the workpiece material and the static and dynamic properties of the machine tool (Fig. 51).

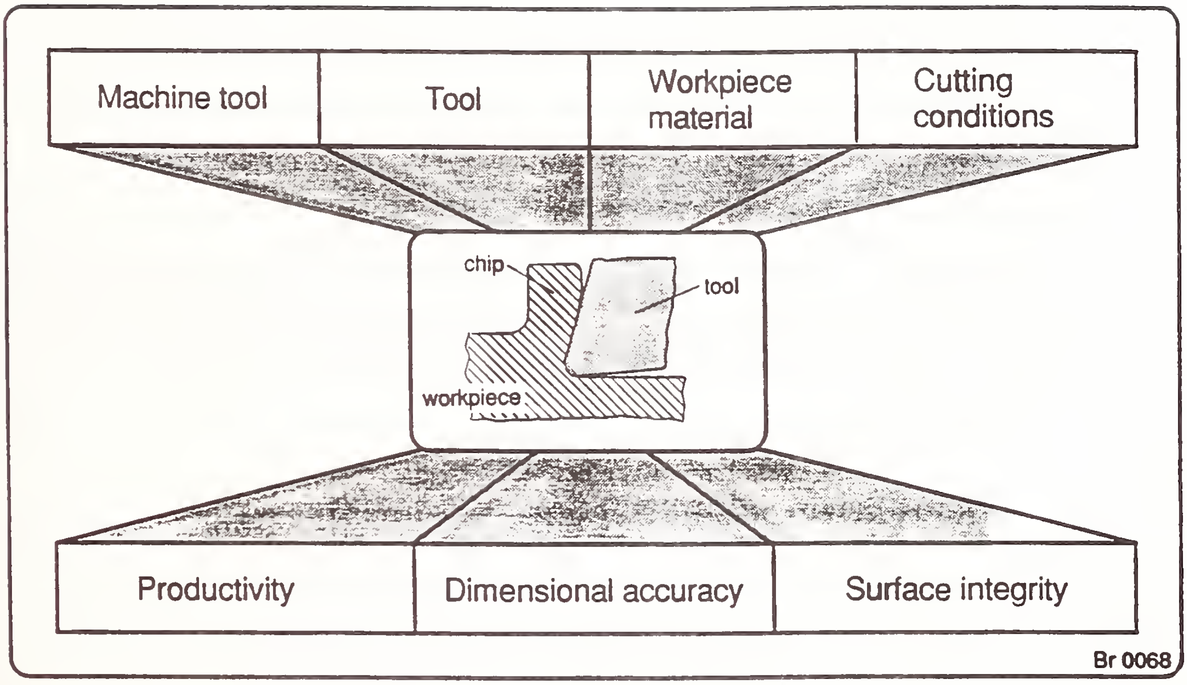


Fig. 51: Influence of input parameters on workpiece quality in hard turning

Usually, higher forces are applied in the grinding wheel contact area on a single-point tool. To avoid dimensional inaccuracy, grinding requires very rigid machine tools. Yet, the dynamic characteristics of the grinding process are different from those of cutting. Expecially vibrations can be suppressed by squeeze-film damping in the comparatively large contact area. So, in general, hard turning requires a dynamically more rigid machine tool than grinding in order to perform the same operation.

5.2.2 Aim of the study

The new technology of hard turning significantly reduces production time, tooling cost and capital investment. However, only a very limited number of applications have been introduced in industry up to today. The rate avialability of lathes specially designed for hard machining is regarded as one reason.

Existing lathes are not adapted to the demands arising from hard turning. Stiffness, accuracy of the control and gauge systems of conventional machines are usually not within the range which may be necessary for precise hard turning operations. Aim of the study therefore was to define the demands on a lathe for hard turning.

5.2.3 Course of action

To judge the situation on the European user market, the IFW selected and interviewed companies involved with the machining of hardened steels and alloys. The selected branches and the number of companies were as follows:

- automobile industry (5)
- bearing system producers (4)
- aerospace/aircraft industry (2)
- gear engineering industry (4)
- others (5)

It turned out that the majority of the enterprises that took part in the study are medium sized, which is typical for German and European metal-working companies. The medium sized enterprises represent the biggest proportion of the market volume for hard machining machine tools and should certainly be addressed with the same intensity as the big enterprises in sale activities.

Form the interviews conducted with leading employees from production departments, information was extracted to characterize the possible demand for hard turning. This was done by examining the scope of components presently produced. A result was that only a fraction of these parts is already produced by hard turning, many are still finished by grinding. Yet, according to the statements of the company representatives, these are the parts that they consider interesting for hard turning in future.

It is important to mention here that the results of the study have to be treated confidental and are thus disclosed. Therefore in the following, only some remarks on the production methods of the involved companies can be given.

5.2.4 Production methods

Grinding, mostly with conventional corundum wheels still by far dominates hard turning (Fig. 52).

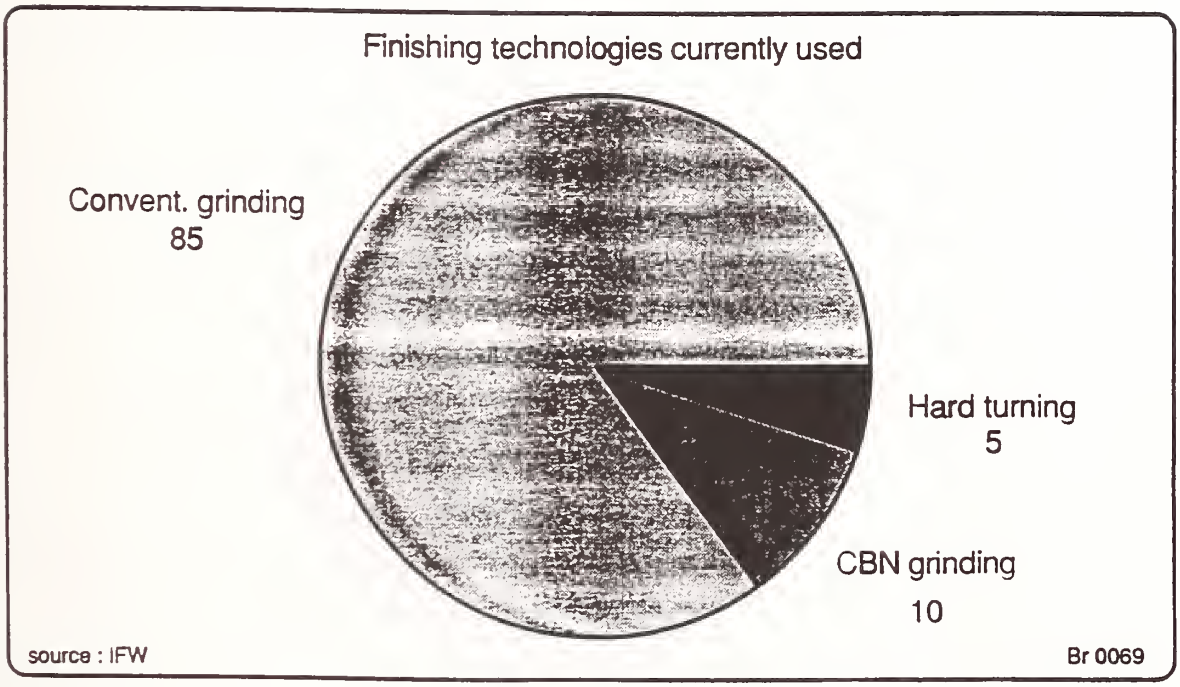


Fig. 52: Methods presently used for finishing of hard steel components

At present, hard turning accounts for no more than 5 p.c. of large scale production. CBN grinding with 10 p.c. has twice the number of applications as hard turning. The technologies of hard turning, grinding with CBN and possibly also with the recently emerging improved grades of sintered alumina are activley competing for overlapping sectors of the finishing market.

Due to the limited experience of most useres with hard turning, considerable dispartiy exits concerning suitable tool materials. The existing uncertainty about the right choise of tools is reflected by a number of publications on machining investigations. Their authors do not present a simple solution. Contradictory in part, differant qualities of CBN as well as alumina-based ceramics are presented as the optimum for the turning of hardened steels. The investigation conducted by the

IFW reveald equally divergent opinions with industrial users who have attempted hard turning. A large group uses ceramics tools only, partly for historical reasons and in part in order to avoid high cost when damaging a tool. (Fig. 53).

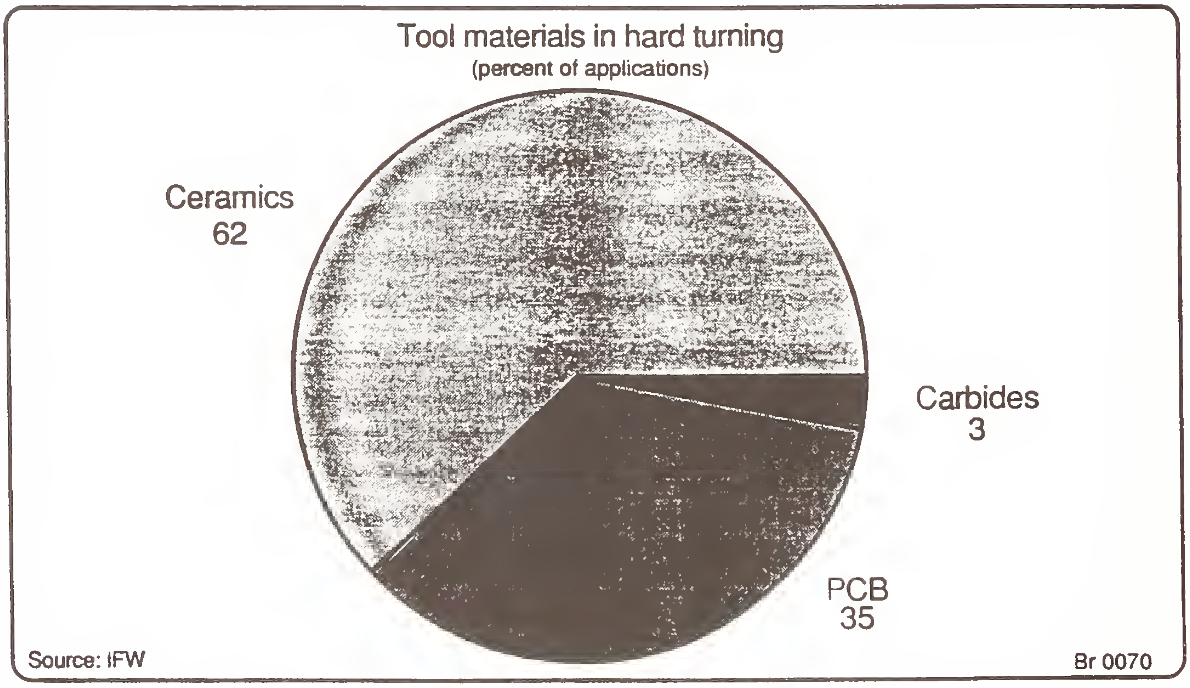


Fig. 53: Tool materials in use for hard turning

Some are convinced of the performance of CBN grades with reduced thermal conductivity, especially in finishing operations with small depths of cut. Others, concerned with surface integrity, propose ordinary CBN. Carbide tools find a very limited use with materials like annealed steel of no more 40-50 HRC. Adequate tooling for the various machining operations will have to be studied in depth to present a convincing overall concept for hard turning.

5.2.5 Requirements for a lathe designed for hard tunring

The design of a lathe must take into consideration the prerequisites imposed by the users who are interested in hard turning. While a considerable degree of uncertainty exits because of lacking technological experience, minimum conditions can be defined as a function of workpieces. Furthermore, users were asked to define requirements from their point of view. Questions were very detailed and aimed at machinable workpiece sizes, speeds, resolutions in programming, accuracy, stiffness of the various axes/spindles, and additional details like automation. Generally, users were not able or willing to give a clear picture of the necessary capabilities of a lathe for hard turning. It was a general opinion that developing a suitable design belonged to the duties of machine tool manufacturer. The detailed results of the study in this area are also disclosed.

5.2.6 Prospects of hard turning in European industry

In today's production, precision finishing of hardened steel components is an upcoming task. The demand arises from the permanent endeavour to increase the specific power of e.g. drive components. Rising stress demands hardened workpiece materials which must be produced at competitive cost. Because of its flexibility, finishing hardened ferrous workpieces by turning offers great savings in time and cost over conventional grinding. At present, the industrial practice of hard machining is still in its experimental or at most in an introductory stage with most European companies. It has not been for long that turning of hardened ferrous workpieces has been feasible at all. The new process of hard turning now has to compete with wellknown and trusted abrasive processes of long standing. These are able to satisfy high quality requirements at a high level of productivity. Hard turning has yet to gain acceptance as being equivalent or even superior for the special applications of a company. Regarding their experiences with and attitudes towards hard turning, the 20 companies interviewed divide into three groups of differant strength (Fig. 54).

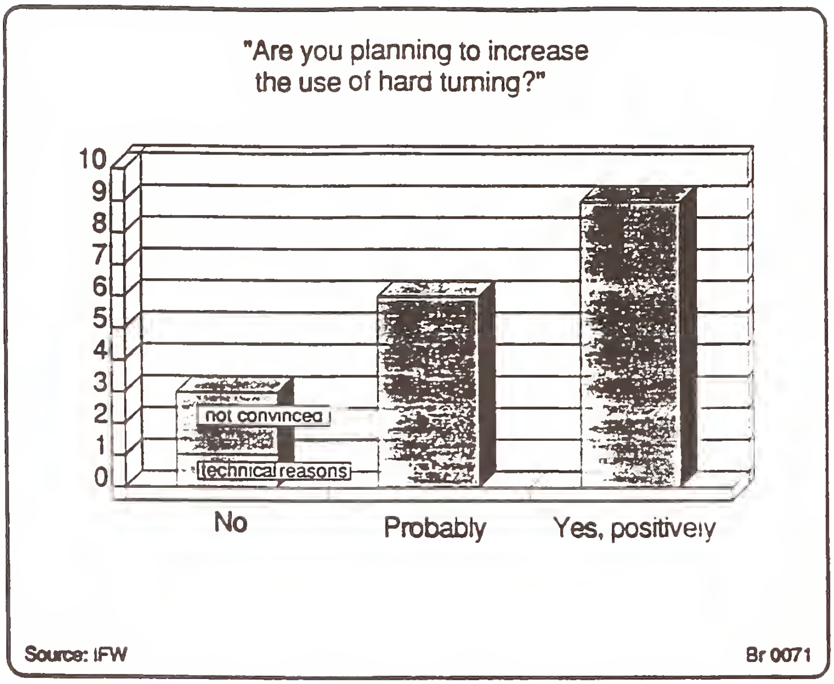


Fig. 54: Attitude of companies towards hard turning

Half of the companies are currently busy testing specific applications and putting them into practice. Some of them use conventional machine tools in close cooperation with the manufacturers, a few are about to buy an ultra-precision lathe. Research activities with EC support are conducted by some companies. Neither of these companies need to be convinced of the benefits of hard turning. Instead, most of them will seriously consider buying an adapted type of lathe from a renowned manufacturer.

At different levels of information and progress, another third of the firms are basically interested in hard turning for some of their parts. These companies haven't yet been able to define a viable machining operation. They are strongly interested in competent support from outside.

The small rest of the enterprises do not think hard turning can be beneficial for them. In one case (bearing industry) the "white layer" problem is considered to rule out hard turning altogether although test are presently conducted at similar companies to check the real significance of this issue. The remaining companies seem to have lack information about hard turning. Companies like these are an untapped market potential as they can possibly be won over by hard facts showing cost and time savings at a constant level of quality.

With any change in production methods such as from grinding to hard turning, doubts have to be dispelled with the responsible production manager. An additional machine earn the money for itself and also for the present equipment. Substitution is easiest when depreciation of the existing machine tools allows a replacement anyway. In any case customers have to be convinced that investing in a lathe rather than a grinder will pay off in terms of quality and productivity.

All the topics involved, technological issues like tool life, surface finish and surface integrity as well as aconomic reasons still wait for thorough investigation. The availability of a suitable lathe with high precision capabilities and superior static and dynamic stiffness is prerequisite to progress in hard turning.

6. References

/1/ - The Deutsche Forschungsgemeinschaft
Organizations and Functions
DFG Report, Bonn 1990

/2/ - Statistics 1991
DFG Report, Bonn 1992

/3/ - Volkswagen-Stiftung
Annual Report 1991

/4/ - BMFT-Förderungskatalog
BMFT Report, Bonn, 1992

/5/ - The German System of Industrial
Cooperative Research
AIF Internal Report 1992, unpublished

/6/ - AIF-Handbuch, Köln 1991

/7/ - European Science Foundation
Annual Report, Strasbourg, 1990

/8/ - Industrial and Materials Technologies
Information Package Brite-EuRam II,
Edition 1991

/9/ - JESSI Program
An Initiative of European Institutions and
Companies
Results of the Planning Phase Itzehoe 1989

/10/ Radelaar, S. JESSI for the Main Phase-European Micro-
electronics on its way
Presentation of the JESSI program
Hannover 16.03.1992, pp. 9 - 33

/11/	Betz, H.	Das Mikroelektronikprogramm für Europa "JESSI" (Geräte) Halbleiterfertigung - Neue Trends bei Produktionsstrukturen und Fertigungsgeräten München 07.,08.11.1989, pp. 221-241
/12/	Knapp, K.H.	Das JESSI-Programm: Ein Wechsel auf die europäische Zukunft Siemens-Zeitschrift (1991)3, pp. 34-38
/13/	Grünewald, M.	JESSI- Europa sucht Anschluß in der Mikroelektronik Spektrum der Wissenschaft (1992)1,pp.16-23
/14/	Dumas, G.	The JESSI Subprogram Technology Presentation of the JESSI program Hannover 16.03.1992, pp. 51 - 77
/15/	Doche, C.	The JESSI Subprogram Equipment & Materials Presentation of the JESSI program Hannover 16.03.1992, pp. 77 - 89
/16/	Sauer, A.	The JESSI Subprogram Application Presentation of the JESSI program Hannover 16.03.1992, pp. 33 - 51
/17/	-	Funding News JESSI-Information-Letter, Issue No. 10 January 1992
/18/	Grünewald, M.	Presentation of the JESSI program Hannover 16.03.1992, pp. 5 - 9
/19/	Tönshoff, H.K. S. Brand M. Glöckner	Research on Machine Tools in Academic and Research Insitutions Report, IFW Hannover, 1992
/20/	Tönshoff, H.K. H.G. Wobker P. Roth	Investigations into the possibilites and limits of a lathe specially designed to machine hard materials Report, IFW Hannover, 1992

Precision Fabrication Technology in the Former Soviet Union and Other East European Countries

Eugene I. Rivin,
Department of Mechanical Engineering
Wayne State University, Detroit, MI 48202

Introduction

Surveying precision fabrication in the former Soviet Union is an especially difficult task because it is "former" and because it was largely a classified area. The industries responsible for precision fabrication (military industries and affiliated industrial establishments) do not exist anymore, at least in the form they did two years ago, and new development has practically stopped. However, the survey, even going back more than one or two years, may be of the significant value, since the infrastructure still exists and, more importantly, the people who were developing precision fabrication technology are still there (or languishing in the West) and are available and eager to transfer the technology.

Two basic premises, formulated earlier in [1] are:

- The inferior products of Soviet industry should not be equated (or confused) with its superior achievements in research and development. The R&D effort was represented by hundreds of research institutes, all very large by Western standards, all employing many talented and well-educated researchers, and many equipped with state-of-the-art facilities.
- The outrageous Soviet system of intra-industrial cooperation resulted in shortages of practically everything, and forced R & D practitioners to come up with simple solutions not requiring complicated supplies and/or imported components; in other words, necessity was the mother of invention.

To these premises, one more can be added: precision fabrication, especially in the last five to ten years, received the special attention (and, thus, resources) of the military due to the strategic importance of precision optical components, computer memory systems, etc. This relates both to manufacturing research institutions in the military-related industrial ministries (at least, twelve huge institutions), and to the civilian research institutions and laboratories of the institutions of higher education which were involved in precision fabrication activities. This presentation is based on information on both activities, with the latter better documented for obvious reasons. The infrastructure associated with development and implementation of precision fabrication technology is not addressed since it has been dramatically changing during the last couple of years. Only basic areas of and development in precision fabrication are being discusse. Information on the old infrastructure (which was essentially stable until recently) can be found in [1].

Modern precision engineering has deep roots in the Soviet fabrication industry. It was understood from the beginning that machine tools are precision fabrication machines and that many issues related to machine tools, machining processes, tooling, and measuring instrumentation must place emphasis on accuracy, and on the design and production factors influencing accuracy. Recent developments in the precision fabrication area in the former Soviet Union cannot be well understood without some excursion into this historical background.

The leading institutions for promoting these efforts were the Experimental Research Institute for Machine Tools (ENIMS) and the Moscow Machine Tool Institute (Stankin, an educational institution), both organized in the early 30's. ENIMS from the very beginning embraced an approach to machine tool accuracy originated by G. Schlesinger, and made the development of standards of machine tool accuracy and means and techniques for its measurement one of its leading activities (V. Dikushin, N. Atcherkan). This activity still continues, and there is now available a most comprehensive set of state standards embracing all basic types of machine tools. The important feature of many of these standards is classification of machine tools by accuracy levels, from general-purpose levels to "enhanced accuracy," "precision," and "ultra precision" levels. In many cases, the accuracy parameters of the higher levels of precision were specified before the machines were built, and then efforts were made under pressure from the military industry customers, to build these machines.

This effort toward continuous development of high precision machine tools and tooling was supported by extensive work at Stankin on the development of a theory of "dimensional chains" which allows us to formulate and assign tolerances on constitutive parts, based on the required output accuracy of the machine or its unit (B. Balakshin). This theory was developed during the 1930's and 40's, and immediately became part of the curriculum for all students in manufacturing technology, machine tool design, measurement, and instrumentation, both at Stankin and at numerous similar institutions around the country.

Recently, this activity has served as the basis for developing a general analytical technique for the assessment of machine tool accuracy at the design stage, and for automatic error correction in CNC machine tools (D. Reshetov and V. Portman [2]). It should be noted that one of the leading Japanese researchers in the area of machine tools and manufacturing, Prof I. Inasaki, considers [2] as "one of the most interesting and informative books relating to machine tool technologies" [17].

All over the country, students in machine tools and manufacturing engineering take intensive two-semester courses on metrology, tolerances, and mechanical measurements, supplemented by a one-semester hands-on laboratory course on metrology and the operation of basic precision measuring instruments. Note that the total length of the machine tool/manufacturing engineering curriculum in the former Soviet Union is five years (with 40-43 weeks a year and 30-40 contact hours a week); see [3].

Some indication of the mode of operation of ENIMS is the fact that in 1982 its library held more than 125,000 volumes directly or tangentially related to the machine tool industry. I would guess that this exceeds the total number of volumes on these topics in all U.S. machine tool companies combined by at least 100 times. The library in Stankin is significantly larger.

Another very important factor which should be considered in assessment of the state of the art of the Soviet fabrication technology, is an excellent information service. World-wide developments are continuously monitored and provided to researchers and designers via comprehensive abstract journals which are published in all important areas of science and engineering. Abstract journal on "Manufacturing Engineering and Technology' contains substantive abstracts on 2,000 - 2,500 publications and patents in each monthly issue. It surveys literature from many languages (English, Russian, Japanese, Polish, French, German,...) on metal cutting, machine tools, assembly, special processes, forming and forging, casting (see Appendix 1). This information, besides alerting researchers and designers to the latest developments, allows to clearly visualize principal directions of development in various areas of manufacturing engineering.

It was understood at a very early stage that accuracy of machine tools does not depend just on geometrical errors in the machining and assembly of their constitutive parts, but is also heavily influenced (especially for precision machines) by deformations of the structural parts and their joints under both cutting and weight forces, and by thermal deformations in the machine tool structure.

Research on contact deformations in joints was pioneered by V. Sokolovsky in the 1930's and 40's. The issue was studied in a very comprehensive way by D. Reshetov and Z. Levina, and now their book [4] is a desk tool for designers of precision machine tools and other precision mechanical devices. A similar comprehensive study was performed on structural deformations of machine tool parts (D. Reshetov, V. Kaminskaya, Z. Levina [5], [6]). Their developed and validated close-form techniques are still useful, notwithstanding available finite element analysis packages.

Research work on the stiffness-related issues was accompanied by wide-scale measurements of stiffness characteristics of machine tools, both general-purpose and precision. As early as in the 1950's, these efforts led to development of industry standards on machine tool stiffness, mostly for factory acceptance checks, supplementing standards on geometrical accuracy. Now there are dozens of standards on machine tool stiffness which might be of use to the Western machine tool makers. Starting in the late 60's and early 70's standards for vibration levels of machine tools at idle running conditions were also developed. These are widely used for acceptance checks.

The importance of thermal deformations in machine tools was recognized at the very early stages of development of precision fabrication techniques. Pioneering work by D. Reshetov and Y. Sokolov in the early 50's ([6], [7]) led to a good understanding of thermal processes, and allowed design predictions and modifications. Now, ENIMS has developed a software package for analyzing thermal deformations of machine tools.

It can be noted that a multi-authored monograph [6] with heavy emphasis on precision machine tools sold 43,000 copies. This monograph essentially summarized the ENIMS results. Besides other topics, it has large chapters on spindle bearings, guideways, vibration control, mechanisms for small precision displacements, and thermal deformations.

Precision Fabrication in the Former USSR (Machine Tool Industry)

The major difficulty in building machine tools in the former Soviet Union, and especially precision machines, was a lack of specialized components such as bearings, guideways, ball screws, drives, controls, etc. This led to many frustrations and failures, but also to many breakthroughs: necessity really was the mother of invention.

With the developing need for high speed/high power/high precision machine tools, special attention was given to machine tool spindles. At the first stage (in the 1950's and 60's) original designs of self-aligning multi-pad hydrodynamic bearings for precision grinding and turning machines were designed and widely implemented [6].

These bearings allow machining of round parts with out-of-roundness within 0.2-0.3 μm. They were incorporated into more than 40,000 machine tools, especially cylindrical grinders, but also boring mills and precision lathes. A heavy-duty lathe was developed which machined fifty-ton parts 1,000 mm in diameter with a roundness of 0.2 μm. Precision boring mills equipped with the self-aligning hydrodynamic spindle bearings machined holes with the overall tolerances within 1.5 μm [9].

Hydrostatic guideways for a rotary table were implemented on a heavy vertical cylindrical grinder (Kolomna Plant). Out-of-roundness for 1,500 mm diameter parts was within 2 μm. Use of hydrostatic guideways and bearings on a horizontal cylindrical grinder (Kharkov Plant) improved surface finish (R_a = 0.125 μm).

The Vilnius Branch of ENIMS (now in Lithuania) specialized in the development of smaller high-precision grinders and gear-cutting machines. In about 1965, this affiliate developed and started production of a cylindrical grinder for diameters of 100-150 mm with out-of-roundness within 0.1-0.15 μm.

A large effort was started in the 60's and is still continuing on the development of precision spindles on ball and roller bearings (A. Figatner, [6]) and on the development of domestic production of spindle bearings with high degrees of precision. Several facilities for manufacturing ultra-precision ball and roller bearings were established at the large ball bearing plants in the 1970's and 80's. This work was characterized by thorough, comprehensive testing and analysis of the best bearings from all major manufacturers worldwide, combined with analytical and experimental studies of the influences of various bearing parameters on spindle performance.

Extensive work on stiffness, thermal deformations, and bearings has recently resulted in a comprehensive software package for analysis of spindles at the design stage.

Extremely high priority was given in the 1960's and 70's to the development of various types of precision gyroscopes. Several research institute/manufacturing plant amalgamations were equipped with state-of-the-art precision machining facilities, and special departments were created at the leading ball bearing plants and research institutes for fabricating ultra-precision miniature bearings.

As early as the late 50's or early 60's S. Sheinberg at ENIMS developed and validated a comprehensive theory of gas lubrication which was immediately employed in designs of high-speed grinding spindles for miniature precision bearings, and for jig-grinders for grinding holes in housings for precision gyroscopes and other instruments [24]. Detailed analytical study of numerous undesirable dynamic phenomena by Sheinberg made ENIMS a leader in the implementation of 60-100,000 rpm grinding spindles in the Soviet ball bearing industry, mostly for military application precision bearings. These spindles, which until recently were produced by the Moscow Plant for High-Speed Precision Electric Drives, comprise three models: 0.8 kW, 15-40,000 rpm; 0.25 kW, 40-100,000 rpm; and 0.08 kW, 120-250,000 rpm [9]. Later a similar spindle (0.25 kW, 20-72,000 rpm) was developed for precision CNC drilling machines for printed circuit boards (manufactured by the same plant), and a heavy duty spindle (7.5-25 kW, 24-48,000 rpm) was also developed and implemented.

Aerostatic bearings were used for circular guideways and a tool carriage guideways of a lathe for machining large precision mirrors.

Other critical units in precision machine tools are motion supporting (bearings, guideways) and motion transforming (lead screws, rack-and-pinion mechanisms, etc.) devices. Some outstanding studies on the behavior of these components have been performed and published (e.g., in [6]). These results are extremely helpful to designers but, unfortunately, are not widely known in the U.S. Obtaining high-precision components was extremely difficult in the Soviet Union, since they were produced by different branches of industry, i.e., by different ministries. This situation provoked the generation of ideas and concepts for the design of motion-supporting and motion-transmitting components which could be produced in-house. As a result, the Soviet machine tool industry (especially its R&D component) was for many years a leader in the development of hydrodynamic, hydrostatic and aerostatic bearings, lead screws, etc.

An extensive effort related to hydrodynamic and then hydrostatic lubrication of bearings and guideways was launched in ENIMS in the late 1950's and early 1960's (G. Levit).

ENIMS developed, together with the machine tool building plants, hydrostatic systems for spindle bearings, rotating tables, lead screws, worm-rack transmissions, etc., mostly for large machine tools. A simple and effective technology was developed for producing high precision hydrostatic linear transmissions (screws, worm-racks) without a need for high precision machining, by using epoxy resin for "printing" counterpart surfaces. Some commercially produced machines in the 1970's included a vertical boring mill with a radial runout of 5μm at 4,000 mm machining diameter, and a 10μm face runout at the same diameter. This machine was manufactured by the Kolomna Heavy Machine Tool Plant for boring submarine propellers. A vertical grinding mill for grinding ball bearing races had a radial runout of 2 μm at 2,000 mm diameter, and 5 μm at 2,500 mm. Practically all machines of these types are now built with hydrostatic guideways. The Kolomna Plant, the largest plant in the former Soviet Union producing heavy machine tools, uses hydrostatic worm transmissions widely. Other heavy machine tools plants, e.g., in Minsk (gantry milling machines), Kramatorsk (large lathes), and Ulyanovsk (gantry milling machines), also use hydrostatic systems extensively, especially for lead screws. A special technology for "printing" long nuts and precision joining of segments of long components of lead screw mechanisms was developed and implemented. Some of the leading participants in this project are now residents of the U.S.

Successful attempts were made at using grease instead of oil in the hydrostatic units of heavy machine tools. In my opinion, in the 1960's and 70's, the Soviet machine tool industry was the world leader in the application of hydrostatic lubrication in heavy precision machine tools.

Hydrostatic spindle bearing technology developed in ENIMS was also utilized in many smaller machines manufactured by its experimental plant, as well as by its Vilnius branch and by the specialized precision machine tool plant Kommunaras in Lithuania. These machines include diamond boring machines using standard boring spindle units with hydrostatic bearings (a line of five models with out-of-roundness within 0.3 μm). Single spindle NC milling machines and a special three-spindle milling machine with spindles in hydrostatic bearings produce surfaces with $R_a = 0.16$ μm.

The critical strategic importance of precision machine tools was well understood in the early 60's. It was clear that building of quiet submarines, of advanced jet and rocket engines, of precision navigation equipment for ballistic missiles, of radar equipment, etc., was not possible without precision fabrication equipment. As a result, a major decision had been made at the highest governmental level to construct large precision manufacturing facilities at about 15 leading machine tool building plants. These units included buildings of 3-10,000 sq. m (30-110,000 sq. ft) floor area with temperature maintained within ± 0.5° C, with smaller areas in some facilities in which the temperature was maintained within ± 0.1° C; state of the art measuring laboratories equipped with the best imported and domestic instrumentation; dozens of large vibration isolated foundations for precision manufacturing machinery and for assembly stations, etc. These units were given the highest funding priority and were constructed within 5-6 years.

An especially advanced "thermo-constant" building was constructed in ENIMS in 1967. Its ground floor had 2,880 sq. m. (32,000 sq. ft) maintained at ±0.5°C, and it was used for the assembly of precision machine tools produced by the Stankokonstruktsia Plant, an experimental facility at ENIMS which also commercially produced machine tools. The 900 sq. m. (10,000 sq. ft.) basement was maintained at ±0.1°C; it also contained several cabins in which the temperature was maintained at ±0.05°C and humidity at 50 ± 5% [9]. This facility was used by ENIMS, sometimes in cooperation with metrology institutes of the State Standards Committee, for the development and calibration of photoelectric and laser comparators, dividing machines, and reference scales. It was also used for other programs. For example, the Astronomy Institute of the USSR Academy of Sciences used the cabins to conduct experiments which allowed the determination of the gravity constant to within the five-decimal-point accuracy; geophysicists used it for tests related to continental drift. Precision components for three-crystal spectrometers and precision magnetometers for an isochronous cyclotron were also built here.

This facility was intended for the development of ultra-high accuracy measuring systems for the machine tool industry. Even before the precision temperature-controlled building was constructed, a highly accurate dividing machine for linear scales was developed. It used an automatic photoelectric microscope and a correction system. The machine had a line accuracy of 0.3 µm and an accumulated pitch error not exceeding 1 µm per 1,000 mm. Calibration of a scale could be performed within 0.2 µm. After the temperature-controlled facilities were constructed, a precision laser interferometer accurate up to 0.02 µm was designed and built. It is interesting to note that during the Soviet era only three precision linear scales were imported (from the SIP Company in Switzerland). Numerous regional and state metrology centers are equipped with high-accuracy reference scales of domestic origin. Thousands of precision linear scales were used in jig-borers and other precision production machines and measuring instruments [9].

A part of the program on construction of precision manufacturing facilities was to develop guidelines on vibration isolation of precision fabrication equipment. Special advanced vibration isolating foundations and their critical components were developed and widely used in the precision manufacturing facilities. In 1962-64, there were also developed advanced vibration isolating mounts, along with guidelines for their application for various groups of machine tools, especially precision tools, and for other production equipment [6], [8]. The high technical effectiveness and ease of use of these mounts led to their rapid acceptance in industry. During the 1970's and 80's 700,000 units per year were produced. Some 150-170,000 units of machinery were installed per year. The most eager users of this installation technique were military industrial plants, which claimed a noticeable improvement in machining accuracy. Later, original self-levelling pneumatic mounts have been developed for ultra-high precision machinery installation.

During the development of the vibration isolating mounts for precision machine tools, it was clear that the Western approach, in which a supplier selects different mount sizes for different mounting points and provides technical consulting services, was absolutely out of the question. This realization, together with thorough research into the principles of vibration isolation, led to the development of a self-adaptive passive vibration isolator which did not require determining the loads on each point, and which combined optimal stiffness and damping characteristics. As a result, *one size* of isolator can be used for a variety of types and sizes of precision and general-purpose machine tools, with performance which is clearly superior to the leading Western models [8].

Simultaneously with the construction of precision fabrication facilities at the machine tool plants, precision fabrication facilities were also erected at the leading military-related manufacturing plants producing critical units for advanced military equipment. I participated in consulting on and designing of vibration isolation systems for the Kirov Mechanical Plant in Leningrad in 1962. Several ultra-precision gear hobbing and gear finishing machines for producing submarine gear reducers were purchased in Germany. I remember the delivery of a Schiess gear hobbing machine capable of producing 5 m diameter gears with a pitch accuracy within one arc second.

Large quantities of state-of-the-art imported equipment and parts were purchased, mostly through third countries, and frequently through fourth countries, to avoid export restrictions. Some American vibration isolators for my research, which was sponsored at a high level of government, were purchased via France and then Austria. However, very heavy emphasis was given to the development of domestic equipment.

For many years, a very significant effort was underway in ENIMS to develop high-precision and high-productivity machine tools for cylindrical and bevel (especially spiral bevel and hypoid) gears. High precision gears are needed in the automotive industry, and especially in the aircraft and missile industries. The Gear Manufacturing Department of ENIMS employed numbers of highly educated and talented researchers and designers who developed novel kinematic solutions for many gear-manufacturing machine tools. Especially worth mentioning are universal gear grinder mod. 5872 for grinding spiral bevel gears up to 800 mm in diameter using a generating method, and mod. MA5A87B for high precision grinding of spiral bevel gears up to 125 mm diameter from a solid blank. High-precision automated gear hobbing machines, mods. 5408A and 5310A, were developed and implemented in commercial production by the Vilnius (Lithuania) branch of ENIMS. This branch also developed a cost-effective technology for manufacturing ultra-high precision curvic couplings using vibratory processes [10], [11].

As early as the 1960's, ENIMS developed and started commercial production of the so-called "master machine" for hobbing ultra-high accuracy worm gears for workpiece drives of high precision gear hobbing machines (mod. 543, pitch accuracy 1.6 arc sec; axial runout of the hob spindle 3 μm; axial and radial runout of indexing worm 2 μm; maximum diameter 1,080 mm). The machine was very simple in design, to improve accuracy; it was at the technical level of the best contemporary Western machines of this type.

This technology was continuously upgraded. Later, a similar "master machine" was designed and fabricated for indexing worm gears with both cyclic and accumulated pitch errors within 1 arc. sec. Similar technology was used to produce "master machines" for globoidal indexing worm gears used in diamond boring machines. These high-accuracy indexing worm gears allowed building diamond boring machines with positioning accuracies for the axes of the machined holes within 0.6-1.0 μm. "Master Gear Grinder" mod. MA5878C was designed and built in the 1970's for high precision grinding of spiral bevel and hypoid gears with diameters up to 1,000 mm. These machines were complemented by a precision measuring machine, Model 5726, for worm and hypoid indexing gears with a maximum diameter of 1,100 mm.

A complete line of general purpose precision balancing machines for rotating parts of various weights (from 10 g to 100 t) has been developed in

ENIMS in the 1960's - 70's. It was supplemented by many special balancing systems, such as one for balancing assembled IC engines. Two examples are commercially produced machines for balancing of rotors up to 1 kg with balancing accuracy 0.3 μm, and for automatic balancing of electric motors with balancing accuracy 1.0 μm.

The ENIMS branch in Erevan (Armenia) developed a novel concept for balancing high-speed gyroscopes at their working speed using exploding wires as generators of the balancing masses. The results satisfied specifications for precision gyroscopes. Working speed balancing was required, since the thin-walled shells of the gyroscope rotors changed their deformations depending on rotational speed. Two leaders of the balancing group emigrated to the U.S. in 1975.

In mid-80's the Soviet Union produced over 40% of the total world output of EDM and ECM equipment [9]. ENIMS has developed numerous pioneering concepts which resulted in dramatic advances of both productivity and accuracy of the so-called "energy ray" machining techniques. High precision/high productivity grinding was facilitated by development of electrochemical /abrasive (especially, diamond) grinding technology. Whirl copying and combination EDM/ECM technologies allowed to produce high accuracy molds and dies with high productivity. Ultrasonic and laser technologies were developed for precision dimensional processing of hard and brittle materials, such as glasses, ceramics, gem-quality stones, and semiconductor materials, such as silicon.

A very strong group of researchers in the area of precision fabrication was organized in Stankin [1]. It concentrated mostly on development and application of high performance hydrostatic and aerostatic lubrication systems, especially (but not only) for small and medium size machines of the highest precision. This group was headed by M. Shimahovich (now living in the U.S.), who calls the area in which he was working, and which is much broader than just machine tools, "contactless mechanics."

The first high precision lathe (16" maximum turning diameter) with a hydrostatic spindle was designed in 1962 for the Krasny Proletary plant in Moscow. Its fabrication was delayed since the plant was overwhelmed by the mass production of general purpose lathes of the same size, at a rate of 1,000 per month. Later, the plant was forced to increase this to 20,000 per year.

As a part of this program, the plant was pressured to make a high-accuracy modification of these lathes. However, in the true spirit of the machine tool industry world-wide, they preferred to avoid the untested but promising concept of hydrostatic bearings for the spindle, and spent time making all the critical parts of the production lathe (bearings, spindles, etc.) to higher accuracy, frequently at immense expense. The result was one lathe producing parts with out-of-roundness below 3 μm.

Two lathes with hydrostatic spindle bearings were finally fabricated in 1967. The machines were thoroughly tested at the plant, with outstanding results. A brass sleeve with 100/50 mm diameters was machined with deviations from roundness and flatness as well as runout within 0.2 μm, and surface finish R_a = 0.16 μm. The lathes have also shown excellent results in diamond turning; diamond burnishing of hardened alloyed steel parts (RC 62) developed a surface finish R_z = 0.08-0.16 μm, and roundness, flatness, and relative runout of the

It is interesting to note that this high accuracy coexisted with absolute dynamic stability. No chatter developed at any regimes, including regimes critical for this type of machine tool, such as 12 mm depth of cut and 0.01 mm/rev feed at 70 m/min cutting speed. Depth of cut was limited only by the strength of the cutting edge or the power of the motor. The high dynamic quality of the lathes allowed cutting thin, uniform steel bands from solid blanks. A chip 0.02 mm thick and 15 mm wide was nearly perfect. Another interesting note is that one of these machines did not live up to expectations when it was installed at the cutting tools lab of the Togliatti Automobile Plant (producing Lada cars). The lathe was used for testing cutting tools for production lines. However, these results were misleading, since all the tools performed three to four times better on this lathe than on any other machine tool in the plant. Notwithstanding this exceptionally good performance, the lathe was not put in production. There were several reasons for this. The lathe was not offered to a customer, but had to be approved by the State Commission appointed by the Ministry. One influential member of this commission was a lathe operator who was also a member of the Supreme Soviet. He asked, "Who needs a lathe with such accuracy?" Another reason was that the Krasny Proletary Plant management was afraid that if they promoted this machine, they would be forced by the State planners to produce huge quantities of them and to sell them at the same price as their regular, less complicated machines.

In 1967, the Department of Boring Machines of ENIMS, together with Stankin, made several diamond boring heads with hydrostatically supported spindles and special driving misalignment-compensating couplings which machined 40mm diameter holes in brass with roundness within 0.04 µm. One of these heads was used at a military electronics R&D center for diamond milling of the faces of large (about 180 mm diameter) polygons made of monocrystallic NaCl for ultrasonic signal delay lines for application in long range radars and color TV systems. These boring heads not only provided a high degree of surface finish, but also greatly reduced damage to the surface layer of the crystal. As a result, energy losses of reflected ultrasonic waves were reduced by an order of magnitude, thus allowing extending the delay time and enhancing the accuracy and range of radar systems, and the picture quality of color TV systems. The percentage of rejects was reduced from 80 percent to 40 percent, the latter number being due to defects in the crystals which were present before diamond milling.

A strong interest in ultra-precision machining by the nine ministries comprising the Soviet military-industrial complex became noticeable in the late 1960's and early 1970's. Initially, it was directed toward memory discs; later, it was predominantly laser optics-related. In the early 1970's there were no commercially available precision lathes for magnetic memory discs, and Soviet computers designed with hard disc memory units were manufactured without hard disc memory, but with space for its future insertion. Meanwhile, the computers used tape memory units.

In the late 1960's the Stankin group designed and in 1972 Krasny Proletary started production of a diamond-turning lathe with a horizontal spindle. The first machine had hydrostatic spindle bearings and guideways, and machined hard magnetic memeory discs with a surface finish $R_z = 50$ nm. The machine was completely redesigned in 1979, becoming a vertical lathe with aerostatic spindle bearings, contactless pneumo-hydraulic guideways and feed drives, and inertial spindle drive. The spindle is accelerated by the driving motor during the workpiece changing process, but during machining the motor is disconnected and does not transmit any vibrations to the spindle. The driving unit for the cutting tool is designed as a piston separated from the cylinder by a hydrostatic sliding bearing. The lathe was designed for machining memory discs as well as flat and spherical components of laser optics; microasperities on the machined surface are characterized by $R_z = 10$ nm, and macrogeometry (waviness) is within 20 nm for machining magnetic memory discs. Production lathes are available in five models (see Table 1 [12]). A modification of this lathe for turning flat and spherical components up to 500 mm diameter for laser optical systems produced surface finishes of $R_z = 4$-5 nm. More than eighty machines were manufactured. This lathe was exhibited last September at IMTS-92 in Chicago, and attracted some interest because of its exceptional performance and low price ($60,000). Interest would be much greater if the machine had a more decent appearance. When this machine was exhibited in 1975 at the All-Union Industrial Fair, there was an error in the accompanying specifications list; this stated that the spindle was supported in *electrostatic* bearings. The machine excited a lot of interest from foreign visitors, especially the Japanese. M. Shimanovich remembers the Japanese group, fifteen strong, completely surrounding the lathe, looking for "electrostatic bearings." The error was corrected. A similar Japanese lathe (with hydrostatic bearings) was shown in Moscow in 1980.

Some modifications of this lathe were produced, e.g., for machining the internal optical surfaces of an X-ray laser. Designs were developed for larger, ultra-precision lathes for machining optical components. These include machines for huge (several meters in diameter) mirrors, not only flat and spherical, but also cylindrical with an elliptical cross section. Krasny Proletary designed an ultra-precision lathe with contactless mechanisms, such as lead screws. However, only the prototypes were fabricated; production could not begin due to the non-availability of suitable NC controllers.

In 1968, Kolomna Plant also started designing an ultra-precision turning machine for mirrors several meters in diameter.

An obvious question arises: Why were the machine tool plants undertaking such expensive projects, knowing that they could not even start production? The answer is very simple: These were special assignments formulated in decrees by the highest military-industrial/party authorities, who committed all necessary resources for these projects, which were needed for the huge Soviet "Star Wars" program.

One of the most important centers for developing military-related optics was the Lebedev Institute of Physics of the USSR Academy of Sciences. The head of this activity was one of the inventors of the laser, Nobel Prize laureate Academician A. Prokhorov. He had unlimited power, but he did not believe in machine-tool technology, and was firmly against diamond-turning lathes. In the

Institute, he collected the best skilled precision instrument makers, and they manually polished metal optic components for lasers. However, comparison of the machined (turned) and manually polished optical components has shown that the former have 1.5 decimal orders of magnitude better endurance under intense laser radiation. As a result, Prokhorov visited Krasny Proletary and personally ordered the machines.

During the 1970's and 80's, Krasny Proletary Plant manufactured about 1,000 high accuracy general-purpose lathes with spindles in hydrostatic bearings and with digital display. The customers were nine military-industrial ministries, where the lathes were used for machining hard-to-machine and/or non-grindable materials, at both rough and finish regimes. The spindle journal diameter is 100 mm, and cutting forces up to 7,000 N for the radial component and up to 18,000 N for the axial component are allowable.

In the early 1980's, there was a decision at the highest level to start domestic production of consumer video cassette recorders, using the facilities of the military radioelectronics industry. However, there was an acute shortage of high precision machine tools for producting the mechanical parts of VCRs, especially heads. The proposed solution was to retrofit the popular Swiss turning machines produced by the Schaublin Company by changing the existing spindle bearings for hydrostatic and gasostatic bearings. Unfortunately, the only plant with a large inventory of Schaublins was located in the town of Pripyat, just next to Chernobyl, and after the Chernobyl catastrophe the modernization program was scrapped.

In 1988-1989 Krasny Proletary Plant and Ryazan Machine Tool Plant manufactured high-speed, high-accuracy CNC lathes with hydrostatically-supported spindles. The Krasny Proletary lathe has maximum machining diameter of 400 mm, a spindle journal diameter of 110 mm, and a maximum spindle speed of 4,000 rpm. The Ryazan lathe has a maximum diameter of 600 mm, a spindle journal diameter of 160 mm, and a maximum spindle speed of 3,800 rpm. Both machine tools keep the roundness of machined hardened steel parts (RC62) within less than 1 μm [13]. The energy losses at high rpm in these machines are claimed to be no higher than for similar machines whose spindles are supported on antifriction bearings, due to the specifics of the hydrostatic bearing designs.

In 1988, Ryazan Plant manufactured a special high-precision lathe incorporating contactless mechanics for cutting thin precision teflon strips with a wide cutter from a solid teflon bar 600 mm diameter and 300 mm long. The strip, for use in miniature capacitors, is 300 mm wide and 5 ± 0.1 μm thick. Other approaches were tried, but failed to produce a tape within these parameters.

The Stankin group under M. Shimanovich was also involved in the development of high-accuracy grinding machines. In 1969, an effort began in the Moscow Transfer Lines Plant (MTLP) to design grinders with hydrostatics in both the spindle bearings and guideways. Production of centerless grinders with wide grinding wheels (600 mm in diameter, 500 mm wide) and with both grinding and supporting wheels in hydrostatic bearings started in 1970. The use of hydrostatic bearings led to dramatic increases in allowable regimes and power utilization, in wheels life, and in reduction of rejects. Hundreds of piston pins and bearing races were ground per hour with out-of-roundness within 0.1 μm and taper within 0.5 μm. Only one grinder, instead of two or three, was required for the finishing stations in the transfer lines. The machines showed an amazingly low sensitivity to the environment. About one hundred such grinders have been manufactured. One modification, which resulted in a noticeable improvement in maintenance procedures, had a spindle for the wide grinding wheel made as a sleeve rotating on hydrostatic bearings around a stationary axle.

Special cylindrical and internal grinders with hydrostatic spindle bearings and guideways were developed for bearing races. These grinders combined high accuracy with high cutting speed (125 m/s for OD grinding, 80 m/s for ID grinding) and high power (drive motors up to 100 kW). About three hundred such grinders were manufactured and installed at a new ball bearing plant (GPZ-16) in Kazakhstan, where they were operated by hard-core convicts who frequently sabotaged the machines. However, the grinders proved to be extremely reliable and maintained high accuracy and productivity.

Grinding machines with hydrostatic spindle bearings were also used at the completely automated production line for #209 ball bearings at the leading Soviet ball bearing factory, GPZ-1 in Moscow. The internal grinder for grinding the outer race has a high-speed/high-power motor-spindle (30 kW, 30,000 rpm) with hydrostatic bearings. Tests have shown that bearings whose races were machined by the grinders with hydrostatic spindles have dramatically longer useful lives. These grinders were designed by the Moscow Design Bureau for Transfer Lines and Special Machines, and built by MTLP. The Stankin group (M. Shimanovich) developed the spindle bearing designs.

In addition to the 30 kW, 30,000 rpm motor spindle, there were developed other high speed motor-spindles with gydrostatic bearings with the maximum sliding speed 70m/s (dn = 1.4×10^6). The prototype units had been built also for 15 kW/60,000rpm; 3 kW/90,000rpm; and 1.5 kW/120,000rpm. Special design features (especially thrust bearing design) assured relatively low losses, 15-20% of total power at the nominal speed (with the exception of the 1.5/120 spindle which had 0.5 kW losses). These units were intended for internal grinding, but instead have been successfully tested for high speed/high power/high accuracy milling on turning machines. Enhancement of accuracy was due to reduction of cutting forces (in comparison with turning) up to three decimal orders of magnitude and, consequently, reduction of deformations. This concept was also successfully tested for precision contour turning (on the example of an automotive piston). Tool movements for generation of the profile are much easier to accomplish since the workpiece is rotating with a much lower rpm than for turning (150 rpm vs 1,500 rpm for the piston machining). Another test was performed for finish machining of the tapered holes in hardened spindles at the Krasny Proletary plant; both productivity and accuracy were significantly better than for grinding when the spindle was supported in the hydrostatic work rest.

In the 1970's the Kama Truck Plant started full production of heavy trucks, especially for the army. The plant uses numerous American-made machines. A problem developed with machining cylinder liners for the diesel engines which were produced on the American production line. Ground external and face surfaces of the liners were out of specifications most of the time. The Stankin group, together with MTLP, developed a high-precision grinder for OD and face grinding of the liners. The liner being machined was supported by gasostatic bearings and driven by an original drive which did not create undesirable loads on the liner. The grinding spindle and table were supported by hydrostatic bearings/guideways. These bearings and the workpiece drive resulted in the accuracy of the OD being an order of magnitude better than ID. Initially, these machines were installed at the Kama plant, where they completely eliminated rejects and also dramatically increased productivity to 1,400 liners a day, since the power used for the grinding process could be increased from 4 to 26 kW.

Seventy such machines were manufactured for Soviet diesel engine plants, including all tank plants. One such grinder is now being evaluated at a Litton Corporation plant.

About 2,000 cylindrical and internal grinders with hydrostatic bearings designed by M. Shimanovich were manufactured. They were mainly utilized for machining the components of internal combustion engines and antifriction bearings. A large number of big surface grinders of such makes as Matrix and Waldrich Coburg were retrofitted by incorporating hydrostatic bearings for the wheel spindle, while the widely-used Churchill universal grinders were retrofitted by incorporating hydrostatic bearings in the workpiece spindle. Both the accuracy and productivity of these machines were significantly improved.

The Stankin group consulted Moscow Grinding Machines Plant (MGMP) in developing vertical hydrostatic guideways for the rams of gear-grinding machines. More than 2,000 such machines have been produced. Out of this number, about 1,000 gear grinders used modified guideways: a flat + V combination with so-called "mutually-reciprocal choking," which were developed in the early 1980's. Such guideways were exhibited as a novelty by one American company at IMTS-92.

MGMP also made five heavy gear grinders with hydrostatics for gears up to 1.2 m diameter, specifically for helicopter transmissions.

Non-contact hydrostatic fixtures (bearings) were developed for supporting shafts and workpieces with interrupted surfaces during precision machining. Examples include hydrostatic steady-rests for grinding the principal surfaces of spindles for mass-produced lathes at Krasny Proletary plant, and combined hydrostatic/gasostatic supports for tailstock sleeves with a key slot. The latter is used for grinding the Morse taper hole in the sleeve.

Typical results were observed after hydrodynamic spindle bearings were replaced by hydrostatic bearings in a grinder for diamond rollers for trueing the worm-shaped abrasive wheels of Reishauer-like gear grinders. After retrofitting, the accuracy of the rollers and the productivity of the trueing process have improved. The life of the corundum wheels used for grinding and periods between dressings have increased. Also increased are such parameters as the life of the rollers, the trueing rate of the worm wheels, the accuracy of the ground gears, and the life of the worm wheels. All these improvements were very significant, in many cases by two or three times.

The Stankin group developed some other advanced concepts of contactless mechanics which were tested in prototypes in application to machine tools. These concepts include boring spindles with automatic tool retraction from the machined surface during the back stroke, both with rotating and non-rotating spindle; lathes and grinders with oscillating spindles, e.g. for chip breaking; machine tools with asially movable spindle to provide for the feed motion (thus eliminating feed drives and guideways). Use of hydrostatic spindle bearings as guideways for microdisplacements allows to compensate geometric errors as well as thermal and force-induced deformations; they demonstrated resolution of about 10 nm.

Other Efforts Related to Precision Fabrication

Not only the machine tool community was involved in developing Soviet precision fabricating technology.

As reported in [14], the East German concern of Carl Zeiss of Jena, together with unspecified Russian collaborators, developed in the mid-1970's, years ahead of U.S. companies, an advanced electron beam lithographic system, ZRM12, which could print circuit linewidths as narrow as 0.5µm. Within the next few years, steady progress in this equipment was monitored. Models ZBA-10 and ZBA-20 were able to print lines as fine as 0.1 µm and edgewidths on the order of 0.05 µm while handling up to eight 3-inch wafers per hour. Thus equipment capable of fabricating the most advanced microcircuits at the time, such as 256k RAM, was domestically produced, and used a Soviet-built processor to provide the high data rate necessary for the required throughput. This very sophisticated equipment was shipped to a number of Comecon countries, including the Soviet Union, and some units were sold to Japan, one of the world leaders in this technology. There is no reason to believe that the technology did not progress further. Many other breakthroughs in precision fabrication in the micro-electronics area have been described in the open journal *Soviet Microelectronics*, and it can only be guessed what else was available in the numerous classified institutes. Another Nobel Prize laureate for lasers, N. Basov, is reported in [14] as leading the Soviet effort in developing very high density optical processors and data storage systems, which obviously require extremely high precision.

A large research center, "Vibrotekhnika," in Kaunas (now Lithuania), headed by K. Ragulskis, concentrated on developing precision mechanical systems and their units [15]. A large area of activity is precision vibromotors based in novel conceptual approaches. Vibro-motors with positioning accuracy within 1.0 nm (and prototypes with positioning accuracy within fractions of one angstrom), and with positioning speeds from 1 µm/min to 200 mm/s, were claimed to have been developed. Some other specific developments: a wave transformer for continuous or discrete reversible rotation with ω_{max} = 8 rad/s, T_{nom} = 0.015 Nm, positioning accuracy 1.0 arc. sec., dimensions 40 x 35 mm, weight 0.1 kg; a vibratory screw mechanism with minimal axial step 2 nm, force

80 N, dimensions 150 x 120 x 85 mm; a precision vertical vibrodrive with a range of 0.5 mm, minimal step 10 nm, maximum transported mass 5 kg, dimensions 60 x 52 x 24 mm; a linear vibromotor with minimal step 20 nm, force 20N, max velocity 40 mm/s; a thin-film deformable surface (60 mm diameter) employing local displacement at 60 points by electrostatic forces, with a range of deformation of ±3 μm, positioning accuracy 10 nm, and response time 1.0 μs; a precision linear measuring device of a novel ultrasonic type, with a measurement limit of 250 mm and 10 nm resolution, intra-step nonlinearity 0.2 percent, and measurement rate 100 mm/s; and a two-coordinate inclinometer with a resolution of 0.01 arc sec.

Although funding was provided by the military, one gets the impression that the Center (affiliated with Kaunas Polytechnic Institute) was not very eager to move beyond developing working prototypes.

Both reversible and unidirectional precision piezoelectric vibromotors were also developed by the cooperative establishment "Kvant," in Kiev, Ukraine.

Diamond tools, with both discrete cutting edges and abrasive cutting tools, are critically important for precision fabrication. This was clearly understood at the very early stages of industrial development in the former Soviet Union. Concerted efforts were launched to develop domestic sources for industrial-grade diamonds. These efforts resulted in the discovery of very rich resources of natural diamonds, and in the development of a large industry for the production of synthetic diamonds and other superhard materials. Several research institutes are dedicated to R&D in new superhard materials, and their applications to tooling. These include the Institute of Superhard Materials in Kiev, the Institute of Technical Physics in Minsk, and the Institutes for Diamond Tooling and for Abrasives and Grinding in Moscow. Very advanced results in diamond grinding and the design of diamond grinding wheels are described, for example, in [21].

A significant effort was made to develop advanced technologies for fabrication of optical parts, since even before the advent of lasers and "Star Wars" the optical industry represented a large and important component of the military infrastructure. Besides the high precision diamond cutting machine tools described above, original and very effective technologies were developed for fine grinding and polishing of optical parts. One of these technologies is magneto-abrasive machining [21], which allows removal of 0.02-0.5 mm from a metal part in 10-120 sec, while achieving a surface finish of R_a = 10-80 nm and the required geometric shape. This technology was further advanced in the Institute of Heat and Mass Transfer in Minsk by the application of a magnetorheological fluid, recently developed there, with improved characteristics for programmed (CNC) machining of optical (including aspherical lenses) or other critical parts to nanometer tolerances and angstrom surface finish (Table 2, [22]). This technology is being developed in the U.S. under license by Byelocorp Scientific Inc. (New York). Other technologies, such as anodo-mechanical grinding, etc., are described in [23].

Another technology (developed in a mitary industry-related institute) is briefly described in [26] for machining optical surfaces on silicon and silicon carbide by polishing to surface finish within 5 nm.

There was also developed a technology for making precision optical parabolic mirrors which doesnot require precision machinery and thus is the ultimate in cutting the red tape. This technology [27], patented in the former Soviet Union, is using rotating reservoires with fluid whose surface become parabolic due to interaction of forces of gravity and centrifugal forces. Special arrangements provide insensitivity to vibrations and variations of rotational speed and it is claimed that liquid mirrors have accuracy at least on par with the best glass mirrors.

Significant efforts were applied to developing near-net-shape manufacturing techniques, especially precision casting and forming technologies. While precision casting processes were developed mostly in military industry manufacturing technology institutes, precision forming techniques for gears, complex shape shafts, balls, etc., were successfully developed in VNIIMETMASH (Moscow). Precision forming of splines on shafts was performed in ENIMS. A promising "squeeze casting" technology was originally developed in the Soviet Union and was under development for both military and civilian industry applications.

A concentrated effort was also extended towards development of automated assembly technologies, especially for small precision mechanical devices. As early as 1950's - 1960's, transfer eines for machining and assembly of various size watches (including wrist watches) were developed and successfully implemented (NIIChasProm, Moscow). This work resulted in solving many generic problems related to automated production of precision mechanical systems. One has to remember, that watch-producing plants (as well as photographic equipment plants) were, essentially, military plants which were kept "warm" by assigning to them manufacturing of consumer products in times where demand for the military products was not very high.

Metrology and Precision Measuring Instruments

A very significant activity was undertaken in metrology and precision measuring instruments for manufacturing. The common image of the Soviet manufacturing industry as backward in measuring technology is definitely not correct. To begin with, the most common dial indicators used in the Soviet plants (the cheapest, mass-produced, and very affordable) have 0.01 mm divisions, compared to 0.025 mm (0.001 in) in the U.S. Thus, all measurements involving dial indicators are noticeably more accurate. The Soviet dial indicators use a combination link-gear mechanism whose theory was developed in the Soviet Union, instead of gear mechanisms in the U.S.-made indicators. Dial indicators with such mechanisms are much cheaper to produce; they have special compensation components built in, which provide for easy adjustments at the assembly stage.

Gage blocks of all grades of accuracy are domestically produced. There is a very well established infrastructure of regional metrology centers which is a part of the State Committee of Standards and Quality. All measuring instruments must be periodically certified at these centers. Technical guidance for the regional centers is provided by several Research Institutes on metrology, the largest located in St. Petersburg and Moscow.

Very popular in the Soviet metal fabricating industries are high precision mechanical measuring instruments such as microcators and opticators with 0.02 - 1.0 μm divisions. Ya. Tseitlin, former head of the linear measurement laboratory in the St. Petersburg Mendeleev Institute of Metrology (VNIIMS) and now a U.S. resident, estimates that inventory of these instruments is about one million. In the last few years, annual production was about 10,000. The microcator uses a twisted metal strip as a sensitive element; it is a reasonably rugged device. The addition of a simple transducer makes it an electronic transducer with a resolution of 0.03 μm which can be used in automatic systems (Ya. Tseitlin). Production of such instruments never began, despite very successful prototype testing. Microcators and opticators are not manufactured in the U.S.; the only other manufacturer in the world is Johansson in Sweden. In U.S. shops, measuring instruments with resolutions less than 0.00005 in (1.25 μm) are a rarity.

One explanation for the wider use of precision mechanical measuring instruments in the former Soviet Union is the generally poorer quality of the available precision production equipment. Accordingly, tight tolerances are produced manually by extremely skilled toolmakers, with an ensuing need for precision measurements.

High-accuracy measuring instruments are manufactured in large quantities at such huge and well equipped plants as Kalibr (Moscow), Izmeron (St. Petersburg), the Chelyabinsk Plant for Tools and Measuring Instruments, etc. However, the incorporation of electronics and digital systems has progressed very slowly, due to a need for cooperation with other ministries.

Advanced sensors and measuring systems for active control of machining processes, for tool condition monitoring, are developed in several "open" places, not mentioning classified institutes. One of the leaders is Kiev Polytechnic Institute (V. Ostafiev) where some advanced optical (and fiber-optic) systems with resolution of fractions of one μm were developed (e.g., [16]).

Due to lack of commercially produced sensors, many novel and effective sensor concepts have been developed and, usually, disclosed in open publications and certificates of invention. One example is a torsional sensor described in [18] and later perfected at Ford Research laboratories to measure torsional velocity variations less than 0.01% [19].

With the advent of "nanotechnology", role of ultra-precision measurements became even more important. Since only imported precision electronic and opto-electronic instruments were available, the emphasis was on manually operated precision optical metrology instruments, such as interferometers, which are available with the highest degrees of precision, together with highly skilled technicians.

Other East European Countries

Except for the former East Germany, there was not a substantial activity in other East European countries related to ultra-precision fabrication, although Chechoslovakia was producing machine tools of high accuracy. This can be explained by absence of the pressure from the "Military-Industrial Complex" in these countries. East Germany was an exception since its traditional optical and measuring instrument industries were closely cooperating with the Soviet computer electronics and militarized optical industries. On the other hand, Poland was cooperating with heavy military equipment industries (tanks, artillery) and Czechoslovakia-with heavy and light (machine guns, assault weapons) military equipment industries. A high-precision turning laboratory was only recently established in Hungary [20].

Poland, Czechoslovakia, and Bulgaria were producing small quantities of precision mechanical measuring instruments. Poland also has established a synthetic diamond industry producing about 1 mln carats a year [25].

Conclusions

1. The former Soviet Union had numerous developments in the area of precision fabrication technology which, mostly, had only a limited implementation, first of all in the defense industry. A wider implementation was hampered by the bureaucratic system of industry management.

2. These developments even now may be of a significant interest for the U.S. industry. Besides the examples of such developments which were accomplished in the open institutes and industrial plants, there are definitely much more developments which were accomplished in numerous formerly classified institutes, design bureaus, and plants of the military industries.

3. Many leading engineerings and researchers who played key roles in the precision fabrication area are now residing in the U.S. or in Israel and their expertise is frequently under-utilized.

4. Facilities, infrastructure, and expertise, related to precision fabrication technology in the former Soviet Union might be utilized to the benefit of the U.S. machine tool and other companies if a proper cooperation were organized.

5. The continuing publication "Abstract Journal on Manufacturing Engineering and Technology" contains immence world-wide information on latest developments in Manufacturing Engineering, including precision fabrication issues, which is far more comprehensive than any other available data bases.

Acknowledgment

This paper would not be possible without cooperation of many former Soviet engineers now residing in the U.S. Especially helpful was Dr. M. Shimanovich who prepared a memoir reflecting his work in the area of "contactless mechanics" resulted in 5,000+ precision machines with hydrostatic and gasostatic bearings and guideways successfully working all over the former

Soviet Union. Other people whose input has been used are Mr. A. Tabenkin, Dr. Ya. Tseitlin, Dr. I. Churin, and Dr. W. Begell.

References

1. Rivin, E.I., "Soviet R&D: The Benefits for U.S. Industry," Mechanical Engineering, April 1983, Vol. 105, No. 4, pp. 62-71.
2. Reshetov, D.N., Portman, V., "Accuracy of Machine Tools," ASME Press, 1988.
3. Rivin, E.I., "Engineering Education—European Style," The Journal of Applied Manufacturing Systems, Spring 1990, pp. 15-19.
4. Levina, Z. M., Reshetov, D.N., "Contact Stiffness of Machines," Moscow, Mashinostroenie Publish House, 1972 [in Russian].
5. Reshetov, D.N., Kaminshaya, V.V., Levina, Z.M., "Beds and Frame Parts of Machine Tools," Moscow, Mashgiz Publishing House, 1960 [in Russian].
6. Reshetov, D.N., ed., "Components and Mechanisms of Machine Tools," vol. 1-664 pp, vol. 2-520 pp, Moscow, Mashinostroenie, 1972 [in Russian].
7. Sokolov, Yu. N., "Temperature-Induced Deformations of Machine Tools," in Automatizatsiya privoda i upravleniua mashin, Moscow, Nauka Publishing House, 1967 [in Russian].
8. Rivin, E.I., "Principles and Criteria of Vibration Isolation of Production Machinery," Transactions ASME, J. of Mechanical Design, 1979, Vol. 101, No. 4, pp. 682-692.
9. "ENIMS is 50 Years Old," Moscow, 1983, 156 pp.
10. Rivin, E.I., "Trends in Tooling for CNC Machine Tools: Tool-Spindle Interfaces," Manufacturing Review, 1991, Vol. 4, No. 4, pp. 264-274.
11. Galinskas, A.V., Mikuckas, Yu.-R, "Experimental Study of Vibratory Method and Means for Obtaining High Accuracy of Gear Elements of Dividing Devices," Vibrotekhnika, 1988, 60(3), pp. 83-89 (in Russian).
12. "Krasny Proletary," The Catalogue of Production, 44 pp, 1990.
13. Shimanovich, M. "Hydrostatic Spindle Unit of a Large High-Precision CNC Lathe," Stanki i instrument, 1990, No. 1, pp. 16-19 [in Russian].
14. Wohl, R., "Soviet Research and Development", Defense Science & Electronics, September 1983, pp. 11-19.
15. Vibrotechnika-20, Kaunas, 1988, 40 pp.
16. Ostafiev, V.A., et al, "Monitoring of Limiting Conditions of Cutting Tools with Opto-Electronic Analysis", in Proceedings of "Stanki-'91", Kiev, 1991, p. 50-51.
17. Inasaki, I., Private communication.
18. Rivin, E.I., "Measuring of Torsional Vibrations with Asynchronous Tachogenerators," in Antivibratsionnye Elementy Dlya

Technologitcheskogo Oborudovaniya [Anti-Vibration Elements for Machinery], Proceedings of the VNIINMASH, Vol. XYIII, Moscow, 1974, pp. 144-152.

19. Milenkovic, V., Shmuter, S., "Axle in Process Diagnostic Tester: Development of Angular Sensors", Ford Motor Co., 1987.

20. Szabo, O., "Ultra-Precision Lathe", Gepgyartastechnologia, 1991, vol.31, No. 10, pp417-418.

21a. Yascheritsin, P.I., et al, "Diamond-Abrasive Processing and Strengthening of Parts in Magnetic Field", Nauka i tekhnika, Minsk, 1988, 272 pp [in Russian]

21b Skvorchevskii, N.Ya., et al, "Effectiveness of Magneto-Abrasive Machining", Navuka i tekhnika, Minsk, 1991, 215 pp [in Russian]

22. "Electro- and Magnetorheological Technologies", A.V.Lykov Institute of Heat and Mass Transfer, Minsk, 1992, 42 pp [in Russian]

23. Tsesnek, L.S., et al, "Metallic Mirrors", Mashinostroenie, Moscow, 1983, 231 pp [in Russian]

24. Sheinberg, S.A., ed., "Sliding Bearings with Gaseous Lubrication", Mashinostroenie, Moscow, 1979, 290 pp [in Russian]

25. Bakon, A., Bakon, M., "Poland - the Foreseeble Future", Industrial Diamond Review, 1991, vol.51, No.547, pp.299-300

26. "Russian Specialists at the Congress on Surface Processing", Air et cosmos, 1991, vol.29, No.1357, pp.32-33 [in French]

27. Vasiliev, V.P., "Second Birth of Hydrooptic", Khimiya i zhizn, 1980, No.7, pp. 34-36

Table 1. Technical Specifications of Ultra-High Accuracy Lathes

Manufactured by Krasny Proletary Plant [12]

Parameter	Model MK-6501	MK-6502	MK-6504	MK-6516	MK-6562
Max machined diameter, mm	500	500	130; optional 45; 90; 200	500	90-380
Max thickness of workpiece, mm	50	120	45	150	—
Max length of workpiece, mm	—	—	—	—	270-670
Spindle speed, rpm	300-2,805	300-2,805	600-6,000	300-2,800	300-2,500
Working feed, mm/min		20	-	200	
Fast feed rate of transverse support, in/min			2		
Installed power of main motor, kW			4.8		
Dimensions, mm					
Length	2,120	2,120	850	2,500	2,730
Width	1,470	1,170	850	1,860	1,520
Height	1,950	1,950	1,310	2,440	1,360
Weight, t	4.68	7.75	1.5	7.9	4.5

Table 2. Performance Results of Magnetorheological Polishing Unit [22]

Material	Initial Surface Finish R_a, µm	Final Surface Finish R_a, µm	Productivity µm/min
Zink Selenide	$2 \cdot 10^{-2}$	$12.8 \cdot 10^{-4}$	0.08-0.1
Gallium Arsenide	$65 \cdot 10^{-2}$	$10 \cdot 10^{-4}$	0.34
Sapphire	$1.5 \cdot 10^{-2}$	$25 \cdot 10^{-4}$	0.02
Quartz	$30 \cdot 10^{-2}$	$40 \cdot 10^{-4}$	0.15
Carbosital	$25 \cdot 10^{-2}$	$150 \cdot 10^{-4}$	0.15
Si_3N_4 Ceramics	$25 \cdot 10^{-2}$	$35 \cdot 10^{-4}$	0.1
TF-10 Glass	$9 \cdot 10^{-2}$	$12 \cdot 10^{-4}$	0.5

Appendix 1

CONTENTS OF 'REFERATIVNYI ZHURNAL' (ABSTRACT JOURNAL) ON MANUFACTURING ENGINEERING AND TECHNOLOGY

Topic	No. of abstr.per mth
General issues of machine tool industry	30
Metal cutting	
Metal processing by cutting tools	92
Metal processing by abrasive tools	35
Metal-cutting machine tools	
General topics related to machine tools	11
Design and research issues for machine tools	18
Control of machine tools	40
Multipurpose machine tools and machining centers	35
Flexible manufacturing systems and cells	55
Transfer lines	7
Multispindle heads and special machine tools	11
Turning machines	56
Drilling and boring machines	25
Broaching, shaping, and planing machines	3
Milling machines	25
Sawing and filing machines	17
Gear cutting machines	10
Grinding machines	60
EDM and ECM machines	50
Combination and miscellaneous machine tools	5
Components and units of machine tools	36
Auxilliary equipment and fixtures for machine tools	52
Metal-cutting tooling	105
General issues of machine-building technology	17
General topics of manufacturing	
Metal-cutting technology	50
Production process planning	
Design of production processes and fixtures	35
Special and universal fixtures	5
Machining quality	12
Effectiveness of production processes	8
Mechanization and automation of production processes	
General issues	5
Application of FMS	13
Mechanization and automation of part machining	5
Mechanization and automation of auxilliary operations	40
Devices for recycling of lubricants and lubricoolants	5

Fabrication of non-metallic parts		
General topics	5	
Fabrication of plastic parts	6	
Fabrication of parts from hard-to-machine materials		10
Fabrication of parts from miscellaneous materials	5	
Technology and equipment for energy-ray processing		
General issues	3	
Laser, plasma, EB machining	12	
EDM	25	
ECM	8	
Physico-chemical machining	3	
Ultrasonic machining		2
Technology and equipment for thermal and strenthening processing		
General issues	23	
Heat treatment	28	
Thermomechanical processing	5	
Chemico-thermal treatment	37	
Other thermal-strengthening techniques	25	
Surface stengthening by plastic deformation (burnishing and shot blasting)		20
Powder metallurgy	35	
Miscellaneous production processes (balancing, abrasive jet cutting, etc)	20	
Production technology for machine components and units		
Components for vehicles, tractors, construction machinery	10	
Components for metal processing equipment		3
Components for heavy and energy-generating equipment	5	
Components for instruments, electronic, and electrotechnical devices	5	
General purpose mechanical components	18	
Production technology for fixtures, tools, etc.	27	
Miscellaneous components	9	
Technology and equipment for assembly		
General issues	5	
Mechanical joining	9	
Welding	50	
Soldering	8	
Adhesive joining	5	
Process planing for assembly		11
Assembly systems for machines, instruments, and their units	23	
Assembly automation		20
Hand-held machines	33	
Technology and equipment for surface treatment and coating		
General issues	10	
Surface cleaning	27	
Surface preparation	21	
Metallic coatings	22	
Painting and other non-metallic coating processes	24	

Temporary surface protection and part conservation	2
Patterning, engraving, etc.	9
Combination and miscellaneous coatings	7
Installation, maintenance, and repair of machine building equipment	20
General issues of metal forming production	55
Complex (combined) forming processes	10
Forging	10
Die stamping (forging)	
Theory and research of die stamping processes	18
Technology of die stamping	43
Equipment for die stamping	25
Tooling and fixtures for die stamping	10
Rolling of threads, splines, and gear teeth	11
Sheet metal stamping	
Theory and research	15
Technology of sheet metal stamping	22
Equipment for sheet metal stamping	17
Automation	25
Tooling and fixtures	34
Pulse forming techniques	7
Rotary forming	9
Bending and righting of sheets and profiles; spring coiling	
Bending of sheets and profiles	62
Righting of sheets and profiles	9
Spring coiling	9
Cutting of blanks	14
Extrusion	
Theory and research	5
Extrusion technology	12
Equipment	4
Heating	7
Comprehensive automation of metal-forming production	10
General issues of casting production	33
Theory of casting processes	
Crystallization of metals and alloys	6
Solidification and cooling of castings	12

Casting alloys		
Cast iron	18	
Steels	11	
Non-ferrous alloys	6	
Special alloys	2	
Castings		
Casting design	5	
Quality of castings and their cleaning		20
Melting and pouring of metal		
Theory and research	5	
Melting of cast iron	44	
Melting of steel	40	
Melting of non-ferrous alloys		8
Pouring and handling of metal	12	
Quality control instruments	1	
Molding materials		
Basic materials	7	
Molding and core blends	5	
Regeneration of molding materials	3	
Molding paints	2	
Casting into sand molds		
Gating systems	3	
Patterns	3	
Mold and core making	8	
Molding and core making machinery		8
Mold filling	3	
Casting cleaning	1	
Special processes	6	
Special casting processes		
Lost wax process	6	
Injection casting	37	
Low pressure casting	5	
Permanent mold casting	20	
Centrifugal casting	1	
Continuous casting	64	
Miscellaneous processes	17	
Automation of casting processes	12	

Note: Numbers of abstracts are given for 11-1990 issue; they vary significantly between issues.

Precision Fabrication R&D Workshop

29-Oct-92

Precision Fabrication of Japan in 1993

Tomomasa SATO

RCAST,University of Tokyo
(Research Center for Advanced Science and Technologu)

This documant is a collection of the reports by each author shown in corresponding article.

Precision Fabrication of Japan in 1993

5 Projects

Advanced Material-Processing and Machining Technology
Micro Machine Technology
SAKAKI Quantum Wave Project
Quantum Functional Devices Project
Ultimate Manipulation of Atoms and Molecules

26 Indivisual Research Activities

<National Laboratory and Universities>
Mechanical Engineering Lab., AIST, MITI(3)
Sophia University(1)
Tohoku University(1)
University of Tokyo
  Faculty of Engineering(3)
  IIS(2)
  RCAST(3)
<Companies>
Central Research Lab. Mitsubishi Electric Co.(1)
Fuji Electric Co. R&D Ltd.(1)
Kawasaki Heavy Industries(1)
Matsushita Research Institute Tokyo, Inc.(1)
Mechanical Engineering Research La.,Hitachi(2)
MEITEC Co. R&D(1)
Olympus Opt, Co.LTD.(2)
Toshiba Co.(3)
  Manufacturing Engineering Reserch Center
  Energy and Mechanical Eng.ineering Labs. R&D Center
Yokogawa Electric Co.(1)

5 Projects

Advanced Material-Processing and Machining Technology
Micro Machine Technology
SAKAKI Quantum Wave Project
Quantum Functional Devices Project
Ultimate Manipulation of Atoms and Molecules

Advanced Material-Processing and Machining Technology (AIST MITI)

FY1986-1993 $125 Million/ 8 Years

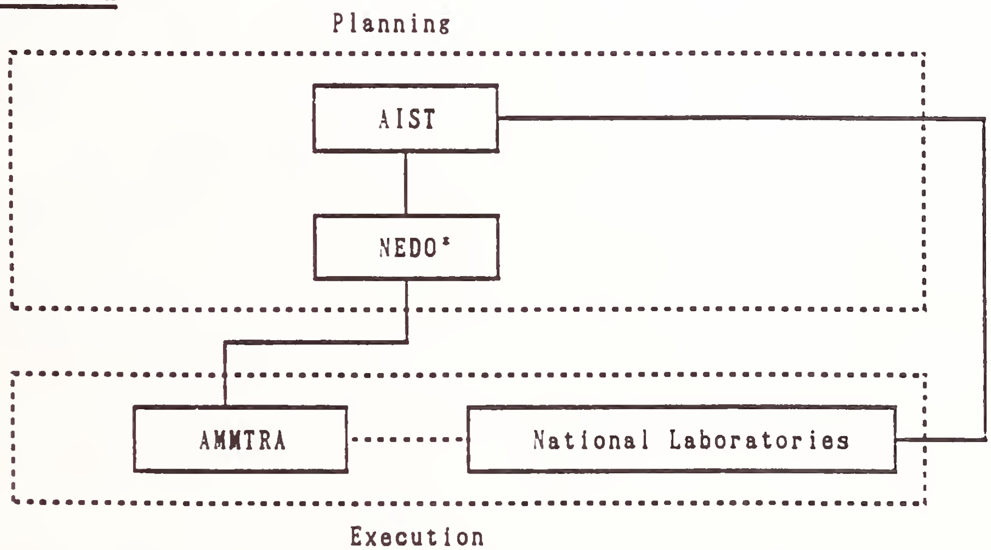
Establishment of Excimer Laser, Ion Beam Technology and Ultra-Precision Machining Technologies, which realize precise and highly-functionated parts, necessary for a variety of advanced industries.

Project Name: Advanced Material-Processing and Machining Technology
--- Large-Scale R & D Programm

Adress: (Planning) Agency of Industrial Science and Technology(AIST), MITI
1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo, 100
Tel. +3-3501-9222, Fax. +3-3501-9229
(Execution) Advanced Material-Processing and Machining Technology Research Association(AMMTRA)
Sumitomo Seimei Shin-Osaka Building South Wing 10F.
5-5-15 Nishi-Nakajima, Yodogawa-ku, Osaka, 532
Tel. +06-390-7021, Fax. +06-390-7061

Period & Budget: Period ; FY 1986 - 1993
Budget ; 15 billion Yen / 8 Years

Organization:



* New Energy and Industrial Technology Development Organization

Research Overview:
Establishment of Excimer Laser and Ion Beam Technologies and Ultra-Precision Machining Technologies, which realize precise and highly-functionated parts, necessary for a variety of advanced industries.

Main R & D Subjects:
A) R & D on Machine and Instrument Technologies
1) Excimer Laser
2) Ion Beam
3) Ultra-Precision Machining, including Grinding and Superfinish
B) Advanced Processing & Machining Technologies
C) Supporting Technologies, including ultra-precision measurement
D) Total System Technology

Background:

It can be said that 20th Century is the era of Quantum Sciense and Technology; the typical development might be seen in Electronics. Many industrial revolutions have been brought about. But,in order to achieve the real utilization of such scientific and technological knowledge, it is inevitable to get new fundamental processing means or tools to meet with needs of 21st Century. To realize such technologies, the programm has been started in 1986, undertaken by AIST, MITI.

Research Issues in Details:

Rather detailed research issues are shown below:

A) Advanced Machine and Equipment Technologies:
   1) Excimer Laser Equipment--High power,high reputation,high quality and short wavelength excimer laser equ.
   2) Ion Beam Equipment------focuced, clustered, and wide-range energy ion beam and large-current, high energy ion·beam eqs.
   3) Ultra-Precision Machine--Cutting, Grinding and Polishing Machines for Complex 3D Parts, with high-accuracy and high-efficiency

B) Advanced Material Processing and Machining Technologies:
   1) Super-precise Form Generation--Machinnig Cnditions etc.
   2) Thin-film Coating----Excimer Laser/Ion Beam Processing Cond. etc.
   3) Modification of Material Properties---Excited Beam Process etc.

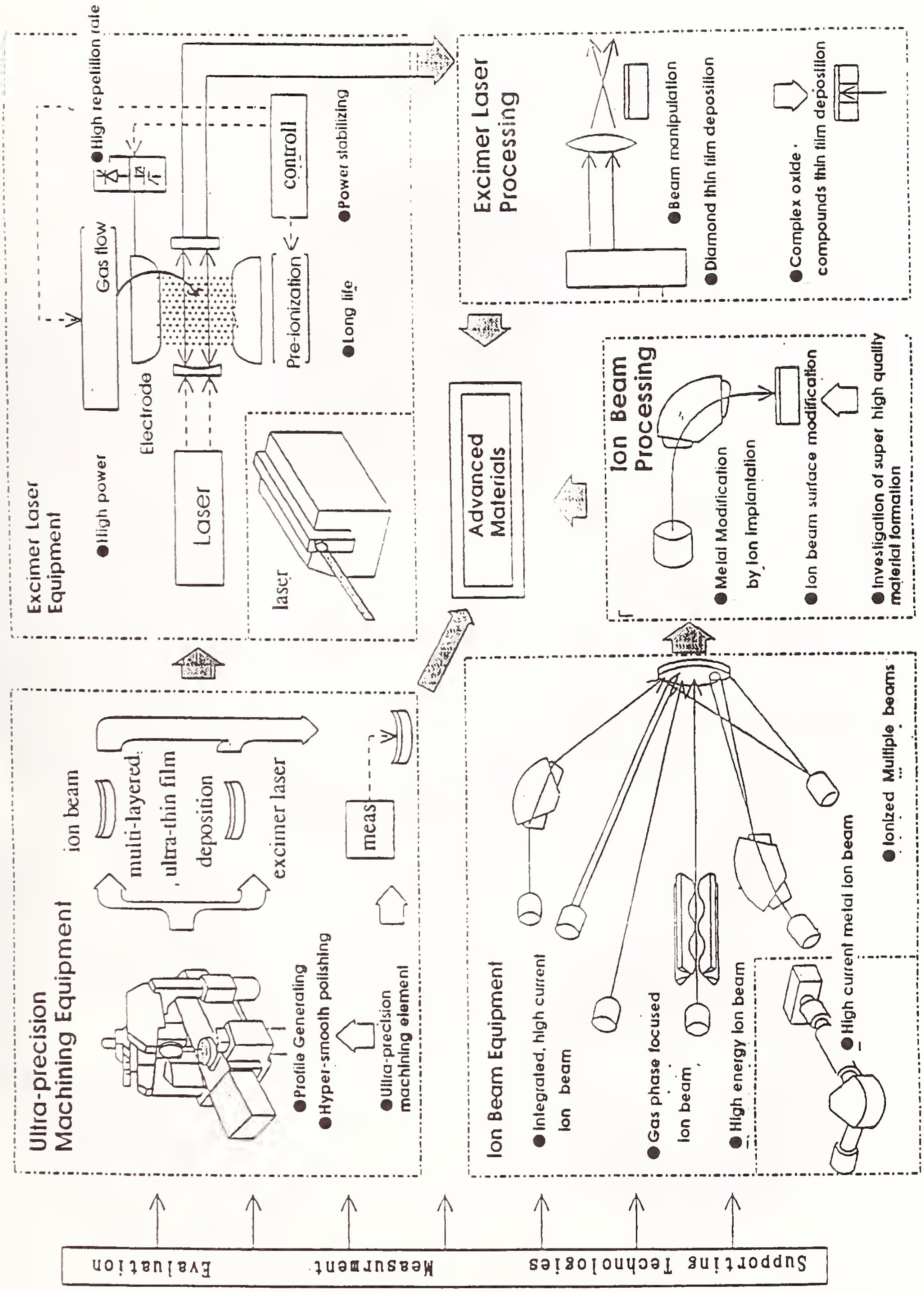
C) Supporting Technologies:
   1) Ultra-precision Measurment--Mechanical, Electrical, Optical, Chemical Properties etc. of Products and Materials
   2) Evaluation Technologies-----Evaluation of devepioped Machines and Processing Technologies (Mainly executed by National Research Laboratories)

D) Total System Technology:
   1) Investigations--------------International & Domestic Move towards AMMT R & D
   2) Corroborative Evidence------Design of Proving Tests in the Program
   3) System Concept--------------Offer of Total System Concept for the practical Advanced Material-Processing and Machining Technologies

The R & D schema is shown in Fig. 1, and Potential Applications for next generation in Fig. 2.

International Cooperation:

1) Annually-held International Symposium by AMMUTRA (Overseas Technology Exchange Programm)
2) General Accademic Presentaitions
3) Information Exchange between each sector



Ultra-precision Machining Equipment
Profile Generating
Hyper-smooth polishing
Ultra-precision machining element
ion beam
multi-layered, ultra-thin film deposition
excimer laser
meas
Excimer Laser Equipment
High power
High repetition rate
Gas flow
Electrode
Laser
Pre-ionization
controll
Long life
Power stabilizing
laser
Excimer Laser Processing
Beam manipulation
Diamond thin film deposition
Complex oxide · compounds thin film deposition
Advanced Materials
Ion Beam Processing
Metal Modification by Ion Implantation
Ion beam surface modification
Investigation of super high quality material formation
Ion Beam Equipment
Integrated, high current ion beam
Gas phase focused ion beam
High energy ion beam
High current metal ion beam
Ionized Multiple beams
Evaluation
Measurement
Supporting Technologies

APPLICATIONS FOR THE 21st CENTURY

X-ray microscope

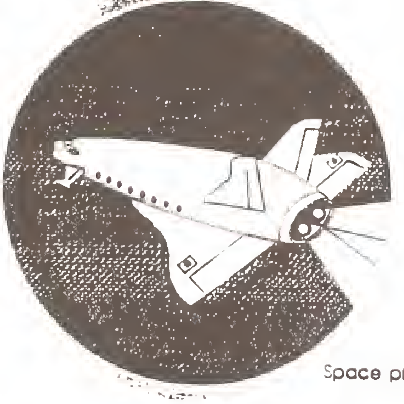
Fusion reactor wall material

<Energy Applications>
Elementary-particle accelerators
Ultra high temperature gas turbines
Deep layer oil digging
Ocean development
Ultra vacuum pumps
Isotope separation

<Ultra-precision Machining and Measurement Applications>
Pressure transducer
X-ray optics
High performance NC machine tool
Micro actuators
Diamond tools
Ultra precise press molds
Ultra-precision three dimensional measuring devices
Micro sensors
Thin film analyzers
Micro analyzers

Ultra super LSI

<Electronics Applications>
Micro-lithography
Quantum device
Light computer
Artificial intelligence robot
Blue-green light emitting semi-conductor laser



Space plane

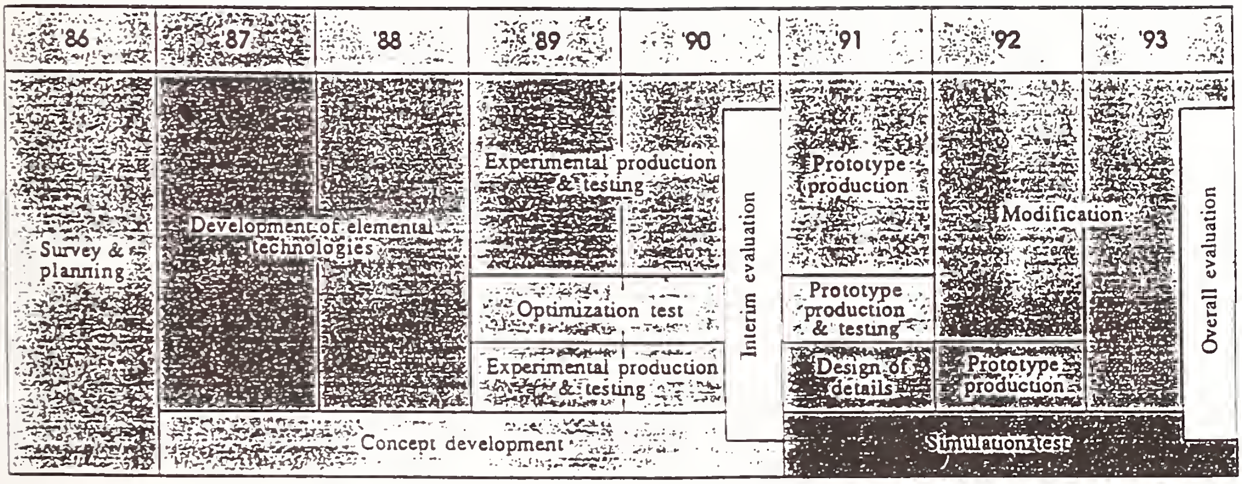
<Aerospace Applications>
Electrical generators to use in space
Rocket turbines
Multi-function graded chemical composition materials
Radiation-resistant materials for space plane
Solar energy driven systems

Mag-lev train

<Medical and New-Materials Creating Applications>
Artificial bones, dental roots, organs
Bio-microscopes
Medical robots
Bio-adopted polymers
Bio-ceramics
Ceramics engines
Artificial gems
New materials with improved surface layers

Research Schedule(Arrow Diagram)

R&D Diagram



Research Resuls in FY 1991-1992

1) "Intermediate Report of Advanced Material-Processing and Machining Technology R & D Programm", 1991-3, AMMTRA, (in Japanese)
2) "Proceeding of the 3rd Simposium on the Advanced Material-Processing and Machining Technology Research Project", 1991-12, AMMTRA
3) "Reports of '92 AMMTRA Overseas Technology Exchange", 1992-6

Micro Machine Technology
(AIST MITI)

FY1991-2000 $210 Million/ 10 Years

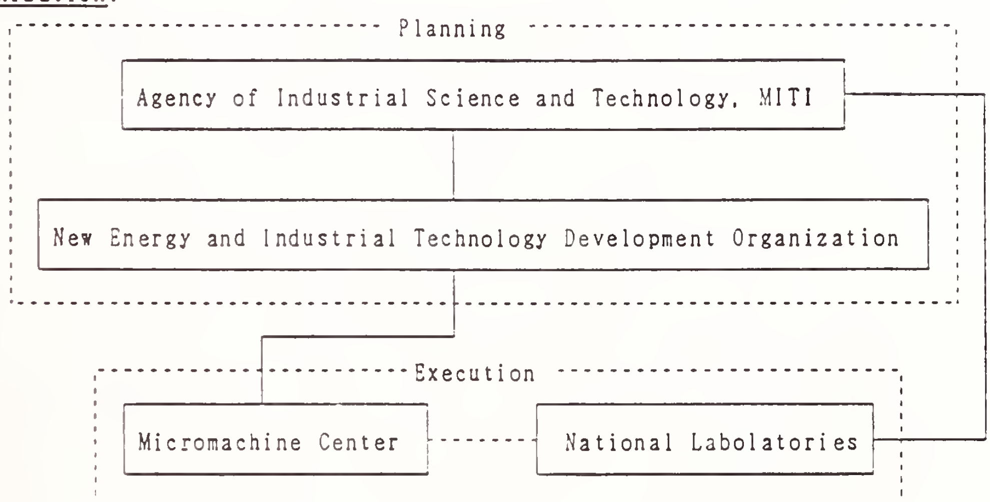
The target of the project is establishment of micro machine technology for micro machine systems which can move in confined spaces, such as inside a pipe in power plant or inside a living organism for autonomous carrying out inspection and repair or treatment.

Project Name: Large-Scale Project "Micro Machine Technology R&D"

Adress: (Planning) Agency of Industrial Science and Technology(AIST), MITI
Kasumigaseki 1-3-1, Chiyoda-ku, Tokyo 100, JAPAN
Tel.+3-3501-9222, Fax.+3-3501-9229
(Execution) Micromachine Center
Sanko Bldg. 3F, Mita 3-12-16, Minato-ku, Tokyo 108, JAPAN
Tel.+3-5443-2971, Fax.+3-5443-2975

Period and Budget: Period 10 years
First phase: Fy1991-1995
Second phase: Fy1996-2000
Budget 25 billion yen/10 years
Fy1991: 30 million yen
Fy1992 800 million yen

Organization:



Research Overview:

The aim of the project is to establish micro machine technology for realizing micro machine systems which can move in confined spaces, such as inside a pipe in power plant or inside a living organism, for automonous carrying out inspection and repair or treatment.

Research Main Subjects:

A] R&D on Advanced Maintenance System for Power Plant
1) Micro-Capsule R&D
2) Mother Ship R&D
3) Inspection Module R&D
4) Repair Module R&D
5) Research into Complete System

B] R&D on Intraluminal Diagnostic and Therapeutic System
1)Sensor device R&D
2)laser device R&D

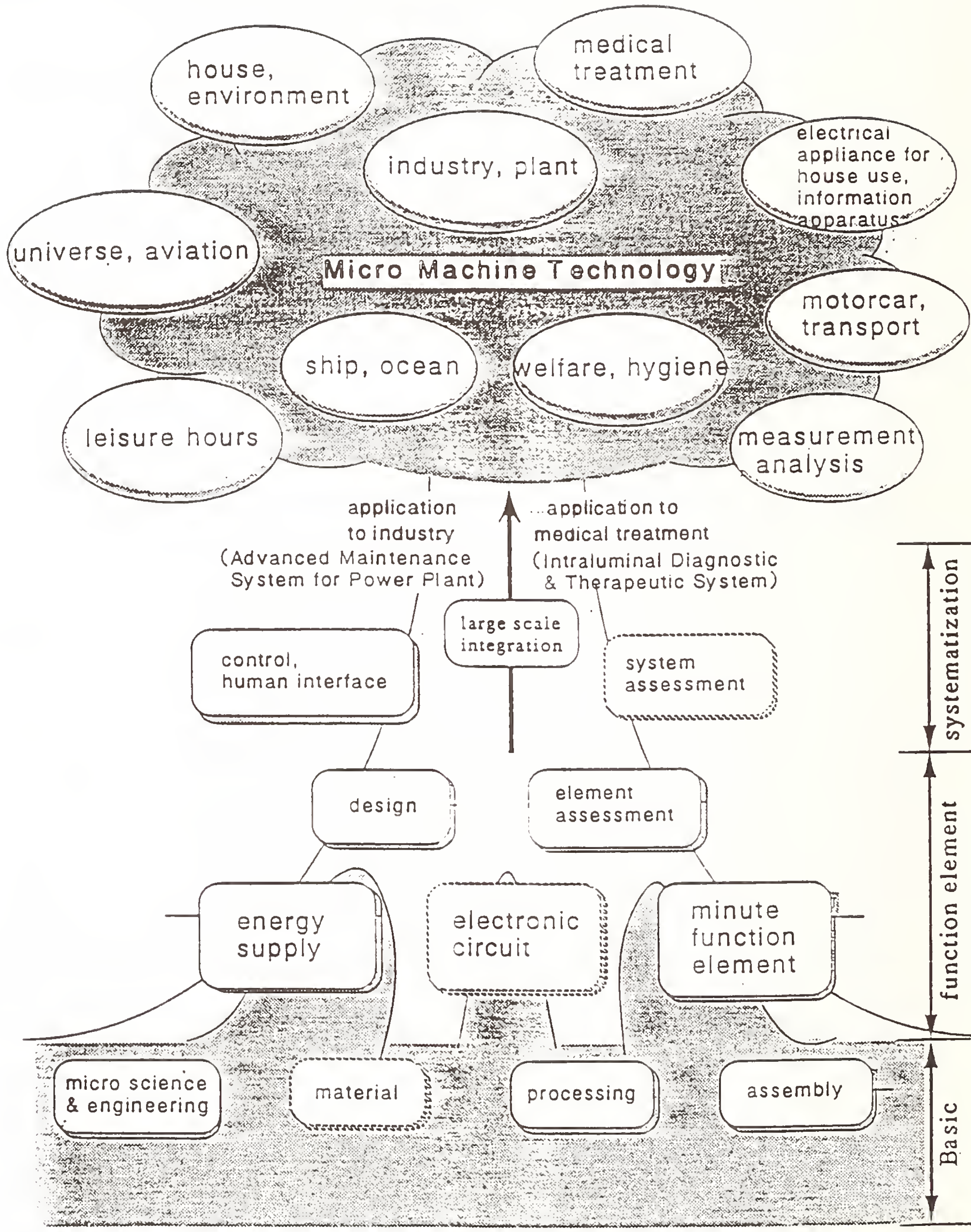


Fig.1 Micro machine technology and its applications

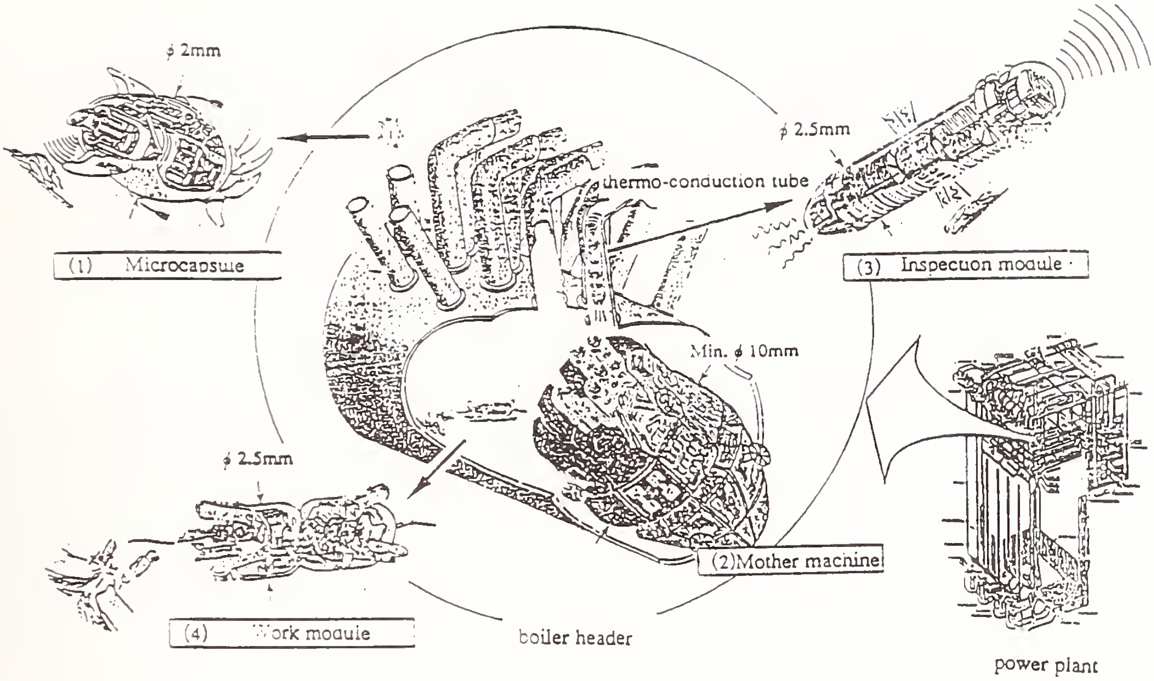


Fig. 2 Image of micro machine system (Advanced maintenance system for power plant). This system consists of the following micro-machines. (1)Micro-Capsule, (2)Mother Ship, (3)Inspection Module, (4)Repair Module

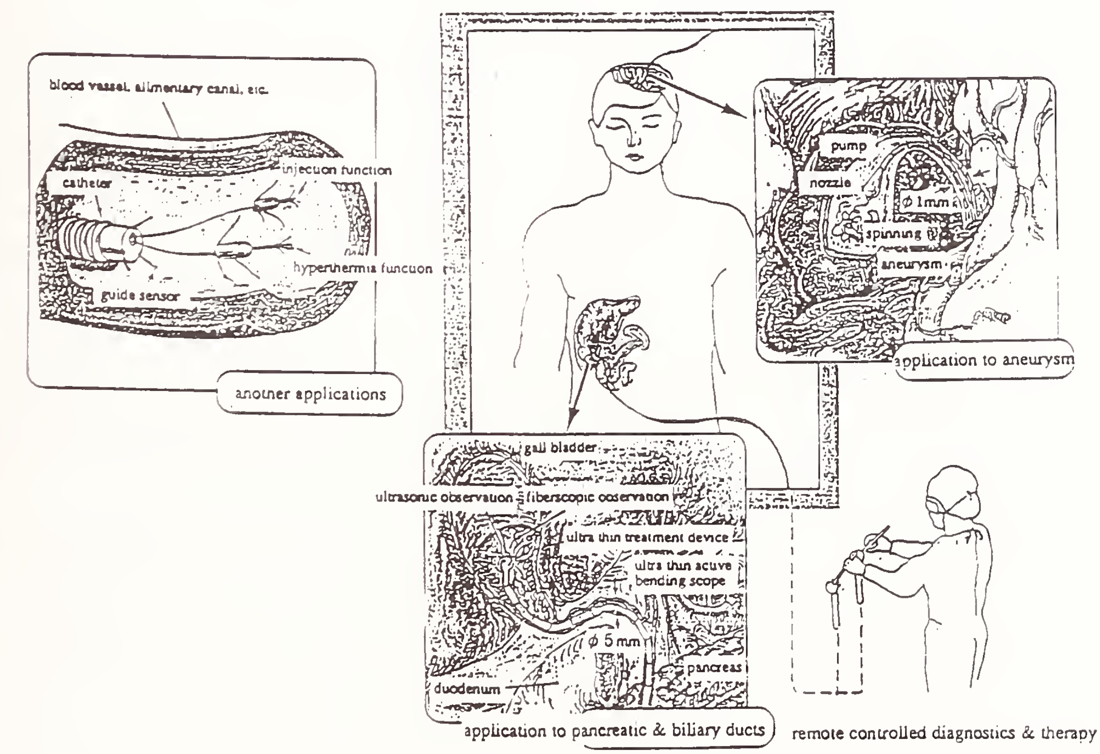


Fig. 3 Image of micro machine system (Intraluminal diagnostic & therapeutic system). This system consists of the following micro-machines. (1)Flexible active catheter, (2)Multi-functional diagnostic device, (3)Multi-functional treatment device

Background:

Micro machine systems composed of a number of small-sized functional elements are expected to produce far-reaching changes in various fields of technology. As micro machine technology is still in its infancy, the establishment of the technology will involve heavy funding, high risk and a long period of time. In view of these circumstance, the Ministry of International Trade and Industry(MITI) embarked on "Micro Machine Technology R&D" as one of the Large-scale Projects in Fy1991.

Research Issues in details:

This project envisions an advanced maintenance system for power plant (Fig.2) and an intraluminal diagnostic and therapeutic system system(Fig.3), and developes verious kinds of functional modules(shown in Table 1) that compose these systems. The R&D in the first phase of the project(Fy1991-1995) is aimed at establishing the basic technologies shown in Table 2. The R&D plan during the second phase(Fy1996-2000) has not been determined in detail yet, but will focus on the advancement and systematization of the micro machine technology through R&D of devices, modules and systems.

Table 1 Functional modules and its components

Module	Main Components
Micro-Capsule	Dynamo, Steering mechanism, Flaw detection device, Position detecting device, Signal oscillation device
Mother Ship	driving mechanism, Optical device, Clamping mechanism, Battery, Group control, Behavior control
Inspection Module	Inching worm driving mechanism, Visual sensing device, Spectrum annalying device, Functional connection, Light energy supply device, Coordination control
Repair Module	Tube type manipulator, Optical driving mechanism, High power source, Photo-cell & boosting device, Environment sensing device
Others	Tactile sensor, Multi-sensor device, Laser irradiation device

Table 2 Basic technologies on micro machine

	Basic Technologies
Functional Micro-Elements	(1)Actuators, Motion transfer Mechanisms, Sensors (2)Micro-Machining & Fabrication, Bonding
Energy Supply	(1)External Energy Supply (2)Internal Energy Supply
System Control	Information Processing, Communication, Cooperative Control,
Evaluation	Measurement and Evaluation for Micro Elements and Devices

International Cooperation:

1)SRI international(U.S.), IS Robotics Inc.(U.S.) and Melbourne Institute of Technology(Australia) have been participating in the project since Fy1992.

2)Micromachine Center Executing the project has some cooperation plans which are the support of international conferences, exchange of reseachers between Japan and abroad, and others related to micro machine technology R&D.

Research Schedule(Arrow Diagram):

Schedule of Large-Scale Project "Micro Machine Technology R&D" is shown in Fig.4.

	1991	First Phase 1992 : 1993 | 1994 | 1995	Second Phase 1996-2000
Advanced Maintenance System for power plant (Micro-capsule, Mother ship, Inspection module, Repair module & System) - - - - - - - - - - Intraluminal Diagnostic & Therapeutic System (Sensor Devices, Laser Device & System)	Survey on Technology	R&D on Basic Technologies & Micro-Devices	(R&D on Devices, Modules, & Systems)

Fig. 4 Schedule of Micro Machine Technology R&D

Research results in Fy 1991-1992:

1)Detailed survey on the present state of micro machine technology
2)Concept design of power plant maintenance system and medical system
3)Feasibility study on the system concepts
4)Reseacn on basic technologies (functional elements, fabrication methods, and others)

References:

"Survey on Micro Machine Technology"(in Japanese). Micromachine Center. 1992-3

Project Name: Large-Scale Project "Micro Machine Technology R&D"

SAKAKI Quantum Wave Project
(ERATO JRDC)

FY1988-1993 $17M / ~~6~~ 5 years

The project is studying quantum wave effects in advanced quantum microstructures of 50-200 Å such as quantum wires and boxes, highly heterogeneous layered structure containing organic materials, metals and/or insulators as well as conventional semiconductors.

SAKAKI Quantum Wave 1988~1993

Project Director:
Dr. Hiroyuki Sakaki

Professor
Research Center for Advanced Science and Technology
University of Tokyo

Sakaki Project Office
Keyaki House 302
3-24 Komaba 4-chome
Meguro-ku, Tokyo 153
Phone: 03-3485-9434
Fax: 03-3460-9026

Background

The evolution of the theory of quantum mechanics has made possible a deep understanding of the characteristics and behavior of electrons, atoms, molecules and crystal structures. Included in quantum mechanics is wave-particle dualism; this phenomenon does not limit applications but, rather, fosters wide-ranging possibilities.

Though electrons in a semiconductor are many times analyzed using quantum mechanics, their behavior in devices with dimensions greater than 1000 angstroms (Å) can be thought of as particles with three-dimensional freedom, since the wavelengths involved are relatively small. Most existing semiconductor devices have sizes greater than 1000Å (= 0.1 μm). The transistor can, thus, be described in terms of current control, just as water flow in a pipe.

By using nano-fabrication techniques, however, there is the possibility to make semiconductor structures with atomic-scale features. Electrons confined at this level lose their particle nature and behave like waves in the confinement direction: quantized with restricted energy levels, depending on their wavelengths, just as sound in an organ pipe is restricted by the pipe length.

Hiroyuki Sakaki has been a pioneer from the early 70's in pursuing low-dimensional solid-state devices that are based on the wave nature of electrons. The types of targets that he set more than ten years ago have become common targets for many materials scientists.

Research Strategy

The Sakaki quantum wave project is studying quantum wave effects in advanced quantum microstructures of 50 - 200Å, which have hitherto been difficult to produce. These include such novel structures as quantum wires and boxes, highly heterogeneous layered structures containing organic materials, metals and/or insulators as well as conventional semiconductors.

Applications are being sought which transcend the usual views of electronics and devices: a novel electronic filter in which electrons of particular wavelength are strongly reflected by periodic arrays of quantum wire and/or boxes. Electrons confined in a quantum wire structure should exhibit an extremely limited change in the propagation direction through scattering and obtain high mobilities. By using quantum-box arrays as a semiconductor laser material, with completely quantized electronic levels, this system should behave as an "artificial atom" with a large lasing efficiency. Such devices may open an entire new field in which the quantum wave nature of electrons could be fully controlled and exploited.

Research Progress

Theoretical works have been made to predict, control, and explain novel transport and optical properties of electrons in quantum structures: they include a novel scheme to suppress phonon scattering in semiconductors, a noise analysis of quantum interferometers, a light modulator and a light source using quantum wires.

To allow the full exploitation of quantum effects, novel methods have been explored to fabricate quantum wire structures with feature sizes of about 100Å.

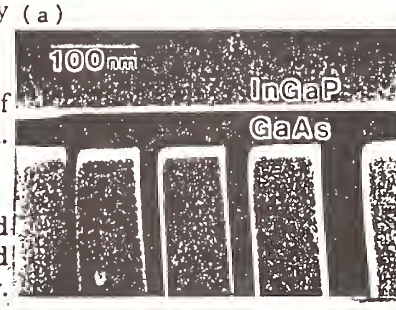
One method is an etch-and-overgrowth approach to form the wire on the edge surface of quantum wells. Here, all processings are carried out in an ultrahigh vacuum (UHV) environment to maintain a clean sample surface. A special multi-chamber system has thus been designed in which molecular beam epitaxy (MBE) is carried out in one chamber and electron beam induced etching in another. After growing an AlGaAs/GaAs layered structure, it is selectively chlorine-gas etched to form V-grooves. This pattern is drawn by electron beam irradiation which enhances or suppresses the local rate of etching. The AlGaAs layer is then regrown over the "V" edge. An etching-regrowth heterointerface has been proven for the first time to be sufficiently clean to make quantum wires.

AlAs/GaAs multilayer facet structure grown by molecular beam epitaxy on a reverse micromesa for the formation of edge quantum wires.

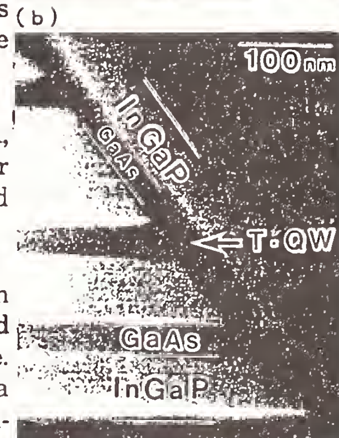
Another method takes advantage of the selective epitaxial growth of GaAs on a pre-patterned substrate, leading to the facet formation. Quantum wires can be fabricated on the surface of such facets.

Yet another method uses the gentle etching of partially-masked multiple GaAs/InGaP wells, the subsequent overgrowth of GaAs and InGaP on the revealed edges of wells by chloride atomic layer epitaxy. The resultant T-shaped wire structure (a crossing of two wells) is expected to confine both electrons and holes at the crossing point, since the cross region is energetically more favorable.

(a)



(b)



T-shaped quantum wire structures formed by atomic layer epitaxy on (a) cleaved and (b) V-groove etched edges of GaAs/InGaP superlattice.

Fabricated quantum wire structures are now being characterized, especially by magnetotransport and optical spectroscopy using far infrared light, which has started to reveal novel properties of confined electron systems.

Novel quantum structure containing organic conjugated π-electron materials, such as alkyl-oligothiophenes and oligoacenes, are expected to show interesting properties, owing to their quantum box-like nature. Well-ordered thin films of these materials have been prepared in a UHV chamber. Their optical and transport properties are being studied, including a relatively high hole mobility in a field effect transistor (FET) of sexithiophene systems.

Quantum Functional Devices Project (AIST,MITI)

FY1991-2000 $40 Million/ 10 years

The purpose of the project is to establish basic technology for developing electronic devices by controlling quantum effects with ultra-high speed and multi-functions essential to industry in the next generation.

Project Name: Jisedai Program "Quantum Functional Devices Project"

Address: (Planning)

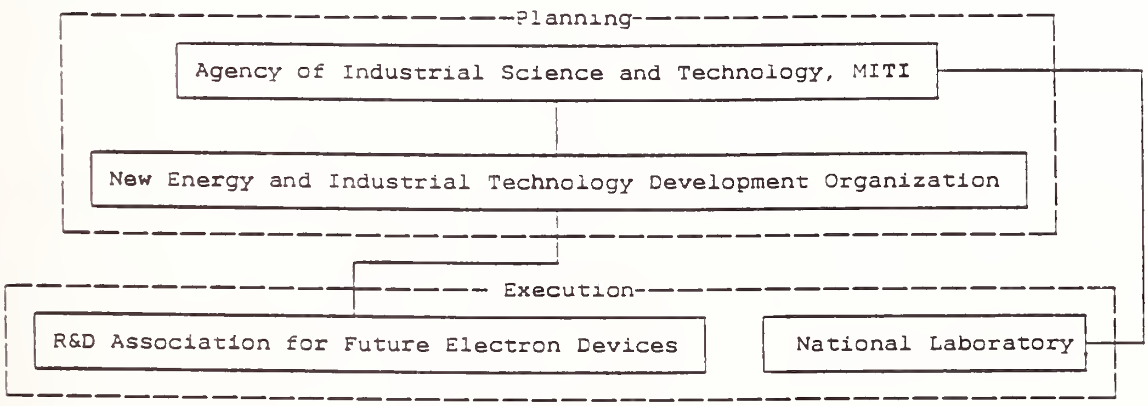
Agency of Industrial Science and Technology (AIST)
Ministry of International Trade and Industry (MITI)
Kasumigaseki 1-3-1, chiyoda-ku, Tokyo 100, Japan
Tel.+81-3-3501-7869, Fax.+81-3-3501-7924

(Execution)

Research & Development Association for Future Electron Devices (FED)
Fukide Building No.2 4-1-21
Toranomon Minatoku, Tokyo 103, Japan
Tel.+81-3-3434-3893, Fax.+81-3-3434-7320

Period and Budget:	Period	10 years	First Phase ; Fy 1991-1994
			Second Phase; Fy 1995-1997
			Third Phase ; Fy 1998-2000
	Budget	5 billion yen/10 years	

Organization:



Research Overview:

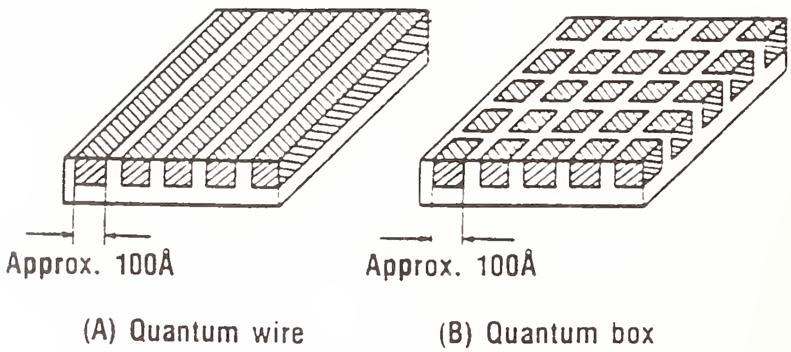
The purpose of this project is to establish basic technology for developing electronic devices by controlling quantum effects with ultra-high speed and multi-functions essential to industry in the next generation.

Research Main Subjects:

A) R&D on basic technologies for establishing quantum functions and R&D on basic technologies for fabricating and evaluating quantum microstructures.

B) R&D on device application technologies for quantum functions, R&D on technologies for fabricating element devices based on quantum functions and R&D on technologies for fabricating integrated systems.

1) Tunneling control functional device R&D
2) Quantized-Band-coupling multi-functional device R&D
3) Resonant electron-transfer functional device R&D
4) Quantized energy level memory device R&D
5) Coupled quantum dots device R&D
6) Quantum-wave structure functional device R&D



• When electrons are confined in a quantum wire or quantum box whose sectional dimension (about 100Å) is similar to the electron wavelength, the quantum effects become conspicuous.

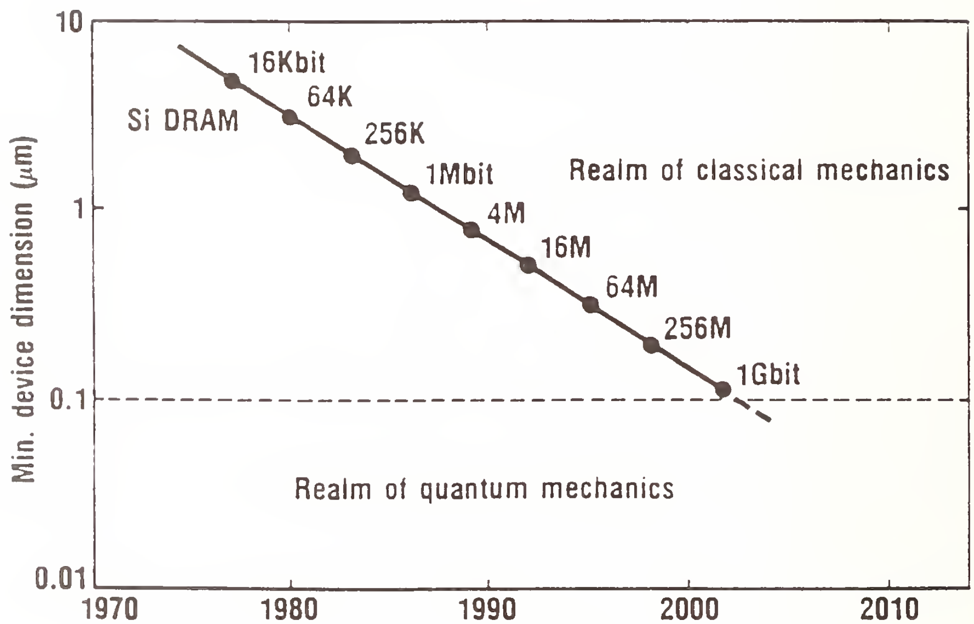
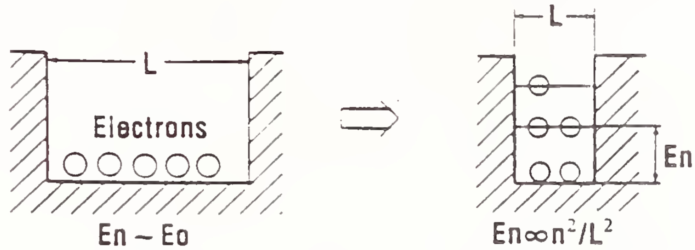


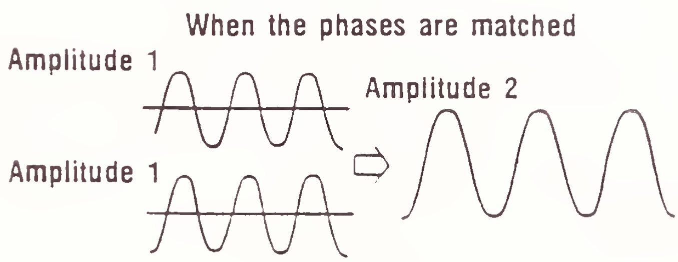
Fig. 1 Basic conceptual diageam of a three-dimensional quantum microstructure and Reducing sizes of devices in DRAM

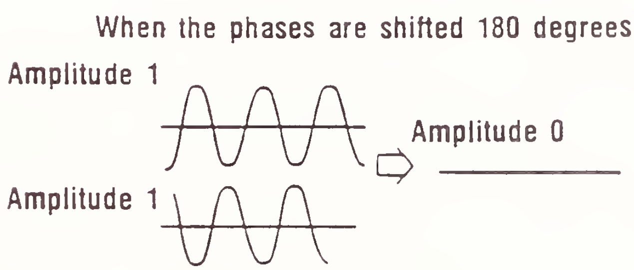
Quantized electron energy in zero-dimensional (quantum-dot) structure → Increased information capacity (Applicable to storage devices)



If "L" is large, then all electrons are at the same energy level, but if "L" is small enough, then the electrons separate into different energy levels as illustrated above.

Predominance of the wave motion of electrons, Increased coherence →
Multiple functions, ultra-high speed, lower power consumption
(Applicable to switching devices)





Electrons have two different characteristics; particle and wave motion. The characteristics of the wave motion appear in the ultrafine structure of a device.

Fig. 2 Quantum effects utilized for quantum functional devices

Background:

Stepping into the mesoscopic realm in fabrication size the operational limit of conventional devices based on classical solid state electronics is going to be encountered due to the appearance of quantum phenomena.

Quantum functional devices which enable us to overcome this limit and to utilize positively quantum effects appearing in ultrafine structures (less than 0.1um) are urgently required to pursue.

In addition, the Quantum Functional Devices Project owes its possible success to the two former Jisedai projects entitled "Superlattice Devices" and "Three Dimensional Integrated Circuits" utilizing their fruitful results.

The Quantum Functional Devices Project started in the 1991 fiscal.

Research Issues in details:

New Energy and Industrial Technology Development Organization (NEDO) has entrusted the promotion of this project with FED. FED has subcontracted with the six private companies (NEC, Motorola Inc., Matsushita Electric Industrial Co.,Ltd., Fujitsu Ltd., Sony Corp., and Hitachi,Ltd.) as research members.

They proposed their own sub themes individually as shown in Table 1.

Table 1. Sub-theme devices and their features

Device	Features
Tunneling-control functional device	· three-terminal tunnel device named surface tunnel transistor (STT) · interband tunnel current between a 2 dimensional electron gas (2DEG) and a p^{+}-region is controlled by a gate voltage
Quantized-band-coupling multi-functional device	· quantum multi-function transistor (QMT) · channels coupled by resonant tunneling effects occurring between their quantum wells · the conductivity of the resonant quantum well is modulated
Resonant electron-transfer functional device	· device unit consists of a silicon quantum wire and a silicon dot · they are coupled each other through tunneling barrier
Quantized energy level memory device	· quantized electron energy levels in quantum boxes are utilized for memory states · quantum boxes are formed at a intersection of two orthogonal interconnections · ultra-high density of a $\sim$10 Gbit/cm^2 is realized
Coupled quantum dots device	· quantum dots arranged in a array are utilized for coupled quantum dots system (CQDS) · patterns of electron distribution in the CQDS · strength of coupling between dots depends on the distances between them
Quantum-wave structure functional device	· quantum wire waveguides are formed in parallel on a substrate · phase modulation of quantum wave in quantum wire is utilized

International Cooperation:

1) Motorola Inc. (USA) has been participating in the project since FY1991 as a sub-contracted member.
2) FED surveys foreign activities of quantum functional devices research. In 1992, Prof. P.M.Petroff (University of California, Santa Barbara) and Prof.Dr. K. v. Klitzing (Max-Planck Institute) will report from USA and Europe respectively.

Research Schedule:

Schedule of Jisedai program "Quantum Functional Devices Project" is shown in Fig. 3.

<table>
<tr><td>1991</td><td>1992</td><td>1993</td><td>1994</td><td>1995</td><td>1996</td><td>1997</td><td>1998</td><td>1999</td><td>2000</td></tr>
<tr><td colspan="4">Phase I</td><td colspan="3">Phase II</td><td colspan="3">Phase III</td></tr>
<tr><td colspan="10">Fabrication and evaluation of quantum structures</td></tr>
<tr><td colspan="10">Basic technology for controling quantum functionity</td></tr>
<tr><td colspan="4">Basic technology for device fabrication

Production of unit device functions</td><td colspan="3">Evaluation of prototype device elements

Production of functional blocks</td><td colspan="3">Evaluation of advanced device elements

Production of integrated systems</td></tr>
</table>

Fig. 3. Schedule of Jisedai program "Quantum Functional Devices Project"

Research results in FY 1991-1992:

1) 2 dimensional analysis in Surface Tunnel Transistor
2) Surface Tunnel Transistor: Gate -Controlled lateral Internal Interband Tunneling Device
3) Quantum Functional Device (with Si material)
4) A New Ⅲ / Ⅴ -Gbit-SRAM Cell Using A Double-Emitter Resonant-Tunneling Hot Electron Transistor Structure
5) 2-electron energy level in a square quantum dot with limited barrier
6) Direct Measurement of Surface Recombination Life-times GaAs Quantum wires by Time Resolved
7) Electromagnetic field profile of excitonic polariton in quantum wire waveguide

Project Name:

Jisedai Program "Quantum Functional Devices Project"

Ultimate Manipulation of Atoms and Molecules
(AIST MITI)

FY1992-2001 $21 Million/ 10 years

The purpose of this project is to develop techniques for probing and manipulating atoms and molecules on solid surface or in three-dimensional space with extreme precision, and their support techniques,as common fundamental technology for such fields as new materials, electronics and biotechnology.

Atom - molecule Space Plan
- Project : Ultimate Manipulation of Atoms and Molecules -

K. Tanaka
Electrotechnical Laboratory
1-1-4 Umezono, Tsukuba-shi, Ibaraki 305, Japan

The Ministry of International Trade and industry has decided to seek budgetary support for a new National R&D Project entitled "Ultimate Manipulation of Atoms and Molecules" with the aim of contributing to the international community through R&D in the field of basic science and technology.

The new project is to be carried out at a new AIST institute named "Interdisciplinary Research Institute for Industrial Science (IRIS)" which will be established on the 1st of January, 1993, in Tsukuba, Japan.

Introduction

On account of recent development in probing and control technology with regard to microscopic objects, larger flexibility has come to be available in developing relevant technologies in such areas as new materials, biotechnology and electronics. New materials bring about new technology and vice versa.

A sort of resonance effect arising in this way has led to such recent developments, and as a result, the technologies in those areas are changing from submicron level to angstrom level in controllable dimensions.

In view of the trend of technological revolution, there is a strong desire for the observation and control technology of microscopic region to be further developed. But there is a serious limitation to the development in a extrapolation of existing technologies.

Therefore, with the objective of realizing a breakthrough over the limitation that is needed to ensure further advance of technological revolution, the project has been worked out that aims to develop, as a generic technology in various fields, new technologies and their support technologies that can allow single atom or molecule either on solid surface or in 3D space to be observed and manipulated with extreme precision.

It has been also decided, in order to attract the best scientists, that the project should run in a new AIST institute with a peer-review granting mechanism and competition by research quality. The new AIST institute is tentatively named as "Interdisciplinary Research Institute for Industrial Science (IRIS)" which will be founded on the 1st of January, 1993, in Tsukuba. An outline of this project is described below (see a cartoon in the figure), although details will be finalized towards the end of 1992.

Description of R&D

(1)Technology for observing atomic and molecular structures of materials.

*Static atomic- and molecular- scale structure probing technology

To develop fundamental tools for probing and identifying (species and electronic states of) atoms and molecules either on solid surfaces, in vacuum or in solutions. The new technology aims to be applicable to a broad spectrum of materials and structures, while the existing technology is mainly applicable to electrically conductive materials.

*Dynamic atomic- and molecular- scale structure probing technology

To develop fundamental tools for high-speed, time-resolved in-situ observation of surface processes at atomic and molecular levels during growth, reaction and etching of the surface.

*DNA structure probing technology

To develop techniques that permit direct observation of DNAs at atomic levels, as a useful tool to unveil the puzzle involved in arrays of particular bases.

(2)Technology for controlling and forming structures at atomic and molecular levels.

*Technology for manipulating atoms and molecules on solid surfaces

To develop techniques that permit atomic layer's at prescribed regions on solid surfaces to pile up or to be peeled off, and particular atoms to be removed, transported or embedded on the surface.

*Technology for manipulating atoms and molecules in 3D space

To develop techniques that permit single ion, atom and molecule to be supplied in a controllable manner, held quiescent, moved, and set into collision and reaction in 3D space, and that furthermore allow softlanding of those atoms and molecules onto the surface of particular materials.

(3)Basic support technology

*Theoretical support

To develop simulation techniques for theoretically predicting possible surface processes through theoretical studies to elucidate the phenomena of surface and interface reactions and of atomic and molecular reactions, that are of fundamental importance for probing and controlling atoms and molecules.

*Ultra-high vacuum technology

To develop fundamental techniques for achieving a ultra-high vacuum that is essentially necessary for probing and manipulating atoms and molecules on solid surfaces or in 3D space, as well as to develop precision ultra-high vacuum gauges.

*Femto-second high-power laser technology

To develop a tunable femto-second high-power laser for probing, manipulation and chemical modification of molecules.

Scale of R&D

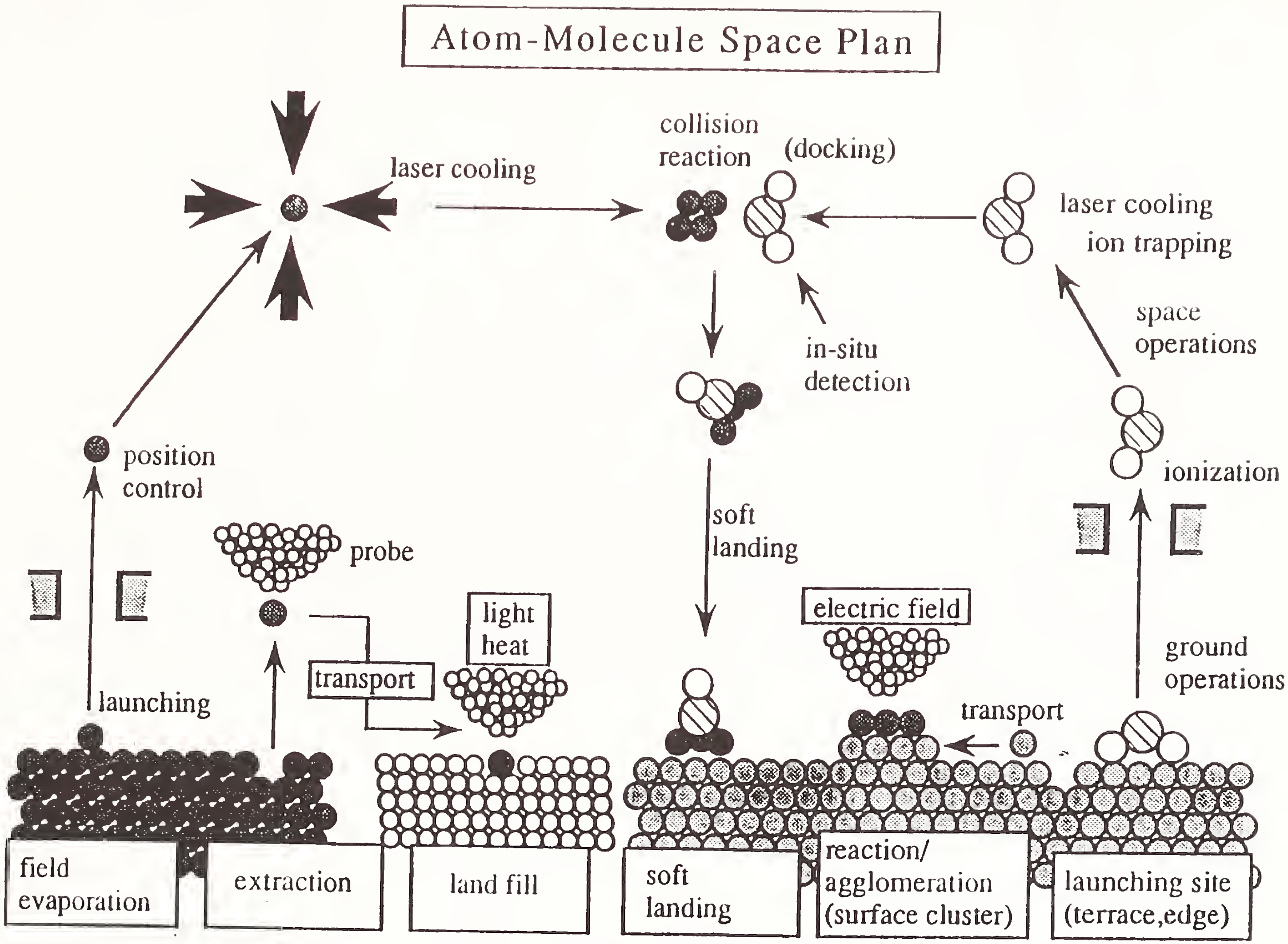
Funding is expected to amount up to around 25 billion Ye.. for 10 years starting 1992, depending on further considerations.

Organization for R&D

To be conducted at a newly planned research institute in Tsukuba, Japan, tentatively named "Interdisciplinary Research Institute for Industrial Science (IRIS)", while encouraging researchers from national research institutes, private sectors, and universities to participate in collaborative work involved in the project at the institute. IRIS is to be established on the 1st of January, 1993, as a new institute attached to the Agency of Industrial Science and Technology (AIST), MITI.

The 1992 plan of R&D

To conduct feasibility study on basic technologies for probing surface structures at atomic and molecular levels, technologies for controlling and forming structures, and support technologies.


Atom-Molecule Space Plan
laser cooling
collision
reaction
(docking)
laser cooling
ion trapping
in-situ
detection
space
operations
position
control
ionization
soft
landing
probe
light
heat
electric field
ground
operations
transport
launching
transport
field
evaporation
extraction
land fill
soft
landing
reaction/
agglomeration
(surface cluster)
launching site
(terrace,edge)

26 Indivisual Research Activities

<National Laboratory and Universities>
Mechanical Engineering Lab., AIST, MITI(3)
Sophia University(1)
Tohoku University(1)
University of Tokyo
  Faculty of Engineering(3)
  IIS(2)
  RCAST(3)
<Companies>
Central Research Lab. Mitsubishi Electric Co.(1)
Fuji Electric Co. R&D Ltd.(1)
Kawasaki Heavy Industries(1)
Matsushita Research Institute Tokyo, Inc.(1)
Mechanical Engineering Research La.,Hitachi(2)
MEITEC Co. R&D(1)
Olympus Opt, Co.LTD.(2)
Toshiba Co.(3)
  Manufacturing Engineering Reserch Center
  Energy and Mechanical Eng.ineering Labs. R&D Center
Yokogawa Electric Co.(1)

Scientist: K.Okano, T.Waida & T.Sutoh

Affiliation: Machining Engineering Div., Mechanical Engineering Labolatory, AIST, MITI

Adress: 1-2, Mamiki, Tsukuba City, Ibaraki-ken, 305 JAPAN
Tel.0298-58-7072

Research Overview:

Micro-grinding by which 3-dimensional micro-parts such as micro turbine-roter & helical gear can be machined has been investigating. The micro-grinding is to be combined with electro-chemical process to improve its micro machining ability.

Research Topics:

1) Characteristics of micro grinding
   a) Smallest part to be machined
   b) Machining Accuracy
2) R&D of forming technique of micro grinding tool
   a) Forming of grinding wheel for micro form grinding
   b) Application of electro-chemical dressing to micro grinding wheel
3) R&D of Electro-Chemical Micro-Grinding(E.M.G.)
   a) Characteristics of E.M.G.
   b) Effect of combination of Grinding and Electro-chemical machining

Research results in fiscal year of 1992:

1)Characteristics of micro grinding

Smallest dimensions of micro part obtainable in grinding was experimentally investigated. A rib with minimum 8 μm thickness and maximum 200 μm hight can be machined on cemented carbide. In cylindrical grinding, minimum diameter of 40 μm with maximum aspect ratio of 50 can be obtained.

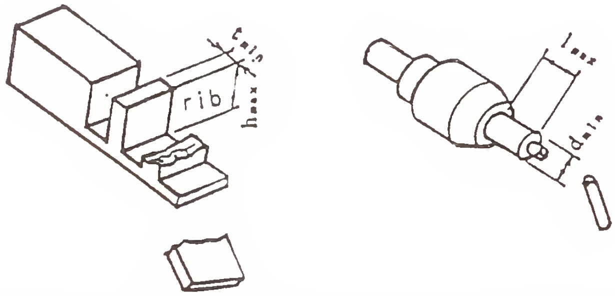
The relation between wear of grinding wheel and work material properties such as hardness, fracture toughness, tensile strength was examined. The wheel wear is influenced considerably by hardness of the material.

References: ————

"Micro-grinding"

K.Okano, T.Waida & T.Sutoh
Mechanical Engineering Labolatory, AIST, MITI

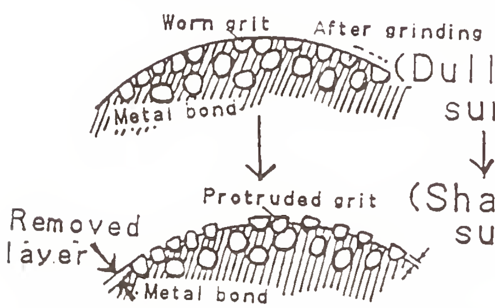
Grinding;



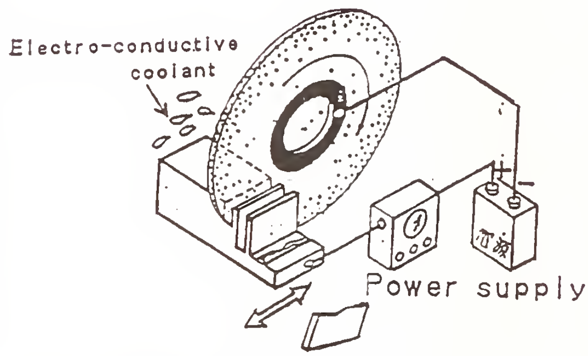
Merit ○ good machining accuracy and good surface roughness

Demerit ● Deformation or rupture of micro-parts by grinding force

Grinding force reduction by assistance of electro-chemical process and/or electro-chemical dressing

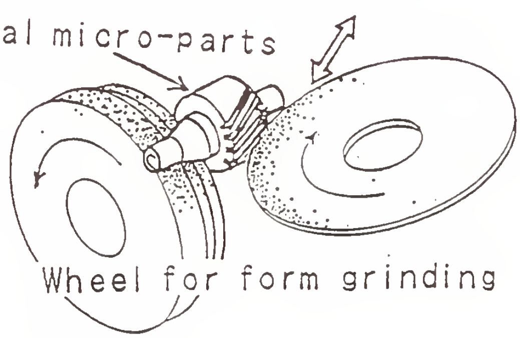


Electro-chemical dressing of grinding wheel



Electro-chemical grinding

New micro-grinding



Target;

Development of high-precision machining for 3-dimensional micro-parts

Primal Scientist : Ryutaro MAEDA
Affiliation: Mechanical Engineering Laboratory /AIST/MITI
Address: 1-2 Namiki Tsukuba Japan 305
Number of staffs:2

Research Overview

Interface activation method, pressure joining under ultra high vacuum condition is studied, by which the joining can be done at low temperature and low deformation of the joint. The method was mainly applied to the joining ceramics to metals and is going to be applied to Silicon to metal joining for micromachine fabrication. The author aims to accomplish the joining for the sample of practical size and the effect of surface conditions such as composition or surface morphology is investigated. Electro-chemical polishing, CVD process, Sputtering deposition are also studied for surface preparation.

Research Topics

1)Ceramics to metals joining by interface activation method
The joining is performed by the method in Ultra high vacuum condition for Al2O3 , ZrO2, and Si3N4 to aluminum alloy
2)Silicon to metal joining by surface activation method for micromachine fabrication
The joining Si to metals is investigated with special emphasis is laid on pressure loading. The pressure load is applied by electrostatic or electromagnetic force in order to attain uniform pressure distribution in the wafer.
3)Surface preparation for joining
Electrochemical polishing, EEM like polishing are studied to obtain flat and defect free surface, and sputtering and chemical vapor deposition process are investigated for surface modification technique for joining.

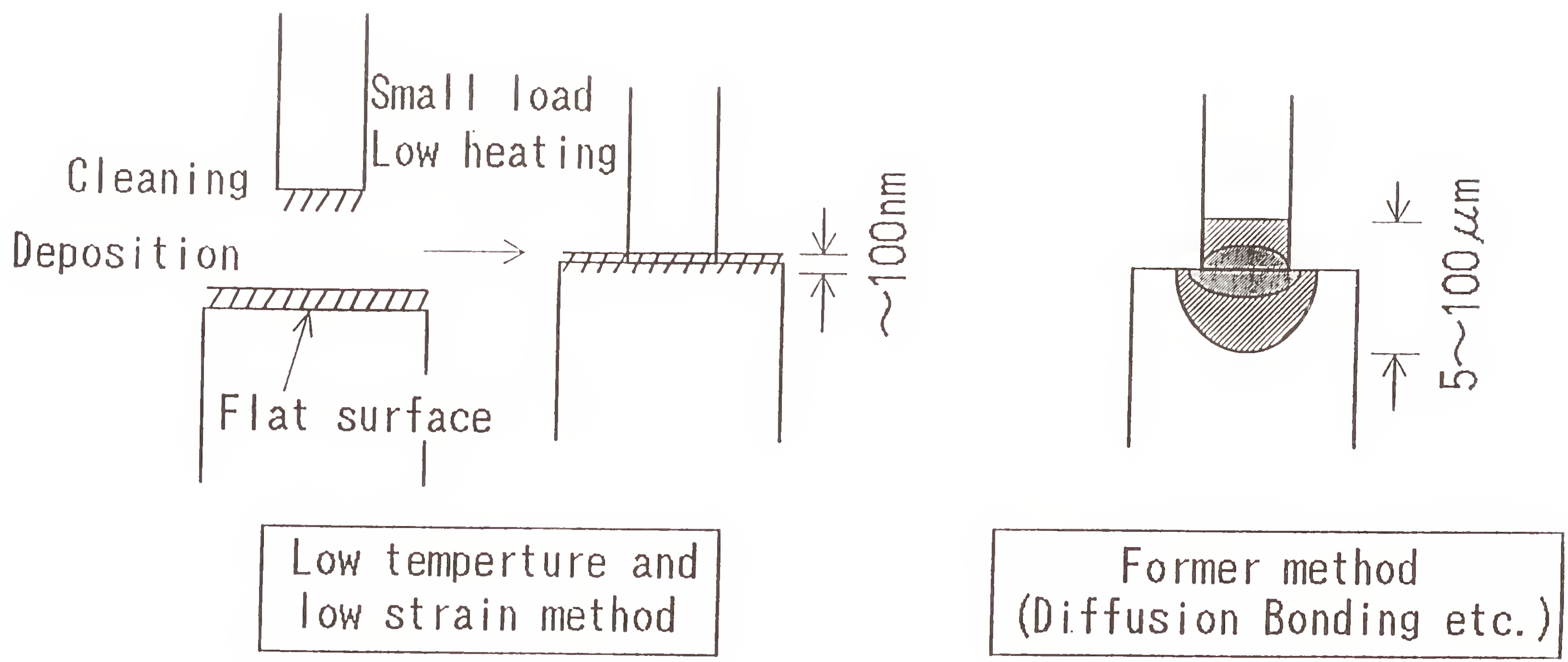
Research results in fiscal year of 1993

1) Joining strength was strongly affected by surface preparation. Clean, flat and defect free surface is suitable for the joining.
2) Utilization of sputter etching and deposition and relative rotational sliding between joining surfaces realized edge to edge joining of Al_2O_3, ZrO_2 and Si_3N_4 to aluminum alloy.
3) Single crystal film of Si was proved to be formed on Silicon or metal by surface activation method.

References

(1) R. MAEDA, H. YAMAMOTO : " Application of friction in vacuum to solid state bonding.", Journal of Japanese Society of Tribologist, vol. 34, 1989, No.12, p860.
(2)R. MAEDA, H. YAMAMOTO :"Low temperature bonding using friction in a vacuum" , MRS Int'l.. Mtg. on Adv. Mats. vol8,p286,1989 Material Research Society
(3) H.Takagi et al.:"High resolution electron microscopy of Al/Si and Al/Si3N4 interfaces prepared by room temperature bonding method", J. Jap. Inst., Metals, vol. 55, No,8(1991)p907

Suraface Activation in Ultra-high Vacuum



Primal Scientist: Shizuka NAKANO
Affiliation: Machinery Department, Advanced Technology Division
Mechanical Engineering laboratory, AIST, MITI
Address: Namiki 1-2, Tsukuba, Ibaraki, Japan 305
Tel. +81-298-58-7163, Fax. +81-298-58-7007
Number ob staff: 2

Research Overview:

"Functional Fabrication" is a new concept of fabrication technique for micro machine elements. Owing to the thin thickness of modified layer and the capability of making small spot of modified area, the high energy ion implantation method becomes one of the effective material modification technique for micro-machine elements. In addition, the combination of the modified materials brings about a new functional effect as a whole.

Research Topics:

Concept: (1) It is better that the function of micro elements is made from material control (design) than form control (design). Because, the material fabrication is more easily than precise forming.

(2) The high energy ion implantation technique is better process to control a material of micro elements. The region it controlled is 0.1 μm order and the and implanted ion are freely selectable.

(3) For examples, the elastic property of ion implanted materials are decreased over the 20%. The fracture toughness of silicone are increased by ion implantation. The electric reactance are decreased by gold ion implantation.

Research results in fiscal year of 1992:

1)Evaluation technique for elastic properties: We have developed the micro three point bending tester. The distance between supporting edges is 400 μm. This system can load from 0.098 to 490mN and measure displacement of loading edge with 10nm resolution. Young's modulus of ion implanted stainless wire was measured to be lower than that un-implanted one.

Referance:

1: S.NAKANO, K.YAMANAKA, H.OGISO, T.KODA, "**Functional Fabrication for Micro-Machine Elements Using High Energy Ion Implantation Technique**" Proc. of 3rd Int. sympo. of Micro Machine and Human science (Oct-1992) Nagoya

2: S. NAKANO, K.YAMANAKA, H.OGAWA, T.KODA, "**Three point bending test for Micro Machine Components**", Proc. of 70th Conf. Vol.B (Sep-1992) Nagano (in japaniese)

"Functional Fubrication"

for micro machine elements using MeV ion implantation

Shizuka NAKANO (Mechanical Engineering Laboratory, AIST, MITI)

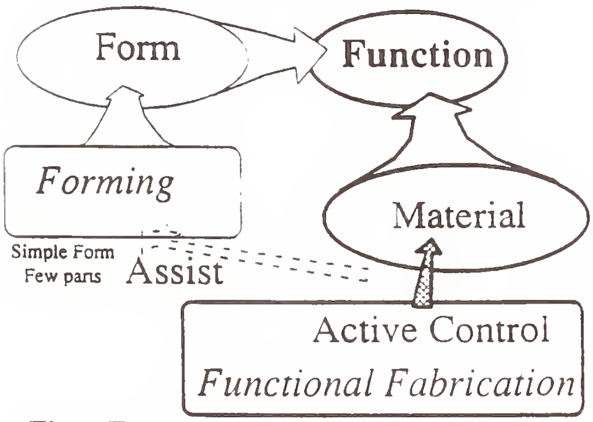


Fig1 Functional Fabrication control the material of elements activlly using high energy ion implantation.

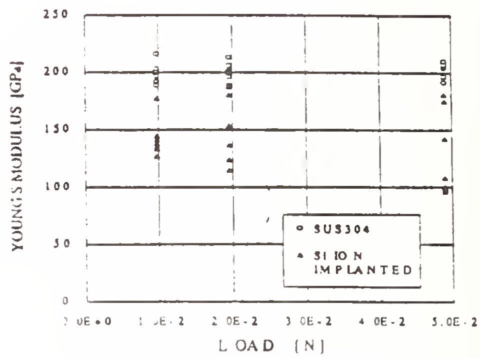


Fig.2 Young's modulus of stainless wire. Si 2.5x1017 /cm2 implanted wires were lower than that of un-implanted.

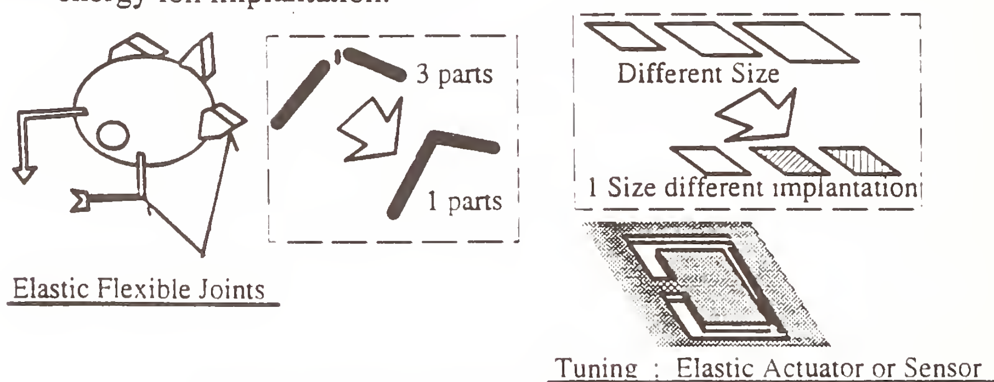


Fig3 Exaples; Changing elastic properties:

1) Elastic Flexible Joints decrease the number of elements and assemble process.

2) Tuning the sensor or actuator corrects it's forming error and decrease the forming pattern.

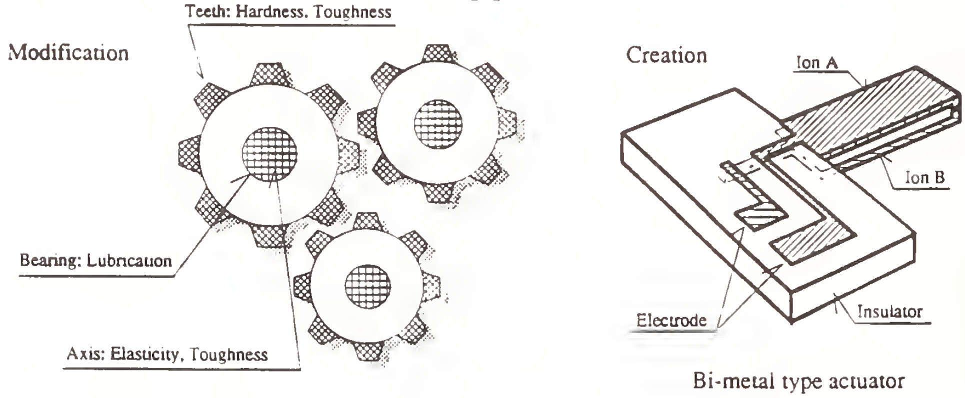


Fig4 Functional Fabrication has 2 Roles: Material modification and creation.

Primal Scientist: Katsufusa SHONO
Affiliation: Sophia University, Faculty of Science and Technology
Adress: Kioichco-7, Chiyoda-ku, Tokyo, Japan 102
Tel.03-3238-3412, Fax.03-3238-4156
Number of staffs: 2(11 students)

Research Overview:
Main target of our research is CMOS integrated circuits. Our tools are Bitmap CAD, EB direct lithography, and other process equipments. By the use of delineation technology and materials, microfabrication of polysilicon sliders and rotors is possible. Observations of micro step motion and combination with CMOS control circuits and solar cell power supply are our way of research on micro-machining on an Si wafer.

Research Topics:
1) Micro Turn Table: By the use of self-align process technology, a rotor with a shaft and a cap was fabricated as an assembled form. The diameter was 100μm. The rotation speed can be controlled by the frequency of AC supply.
2) Micro Slider: The polysilicon plate (100μm $\times$ 50μm) with bushing (h = 3μm) moves along the polysilicon belts. The step motion mechanisms are analyzed and the movement was controlled by the frequency and voltage of AC supply.

Research results in fiscal year of 1993:
A new step motion of polysilicon sliders and rotors was found. They will be used in electronic consumer products and computer periphery.

References:
1) Terunobu Akiyama and Katsufusa Shono: An Electrostatic Polysilicon Actuator for Micro-motors, Proceeding of Japan-Korea Joint Seminar, Taegu, Korea, pp164-173 (August 1992).
2) Cong-Kha Pham and Katsufusa Shono: CMOS Cell Compiler for a Bit-Mapping CAD System, IEICE Trans., E74 (1991) pp2603-2611.
3) Katsufusa Shono and Ryo-Il Kang: Operation Cell Blocks for Combination CMOS Digital Analog LSI, IEEE Tokyo Chapter Denshi Tokyo, 30 (1991) pp16-20.

Micro slider and rotor fabricated on an Si wafer

Katsufusa Shono (Sophia University)

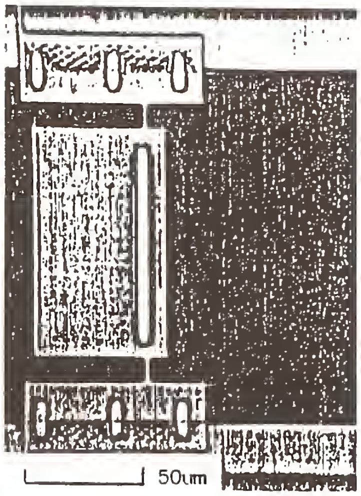


Fig.1 Microphotograph of a polysilicon slider on rails.

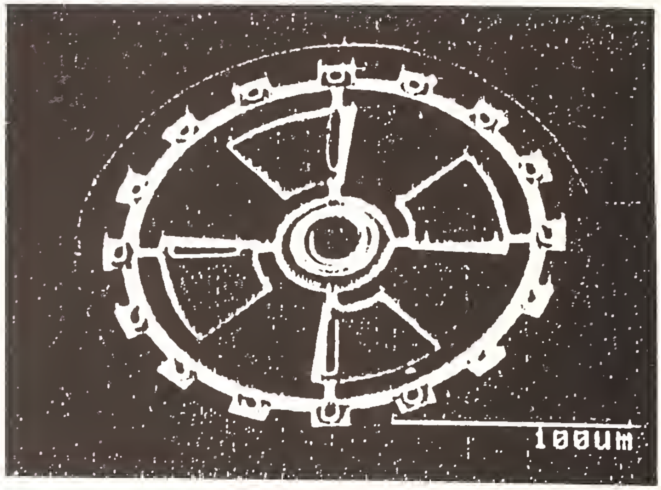


Fig.2 SEM photograph of a polysilicon rotor.

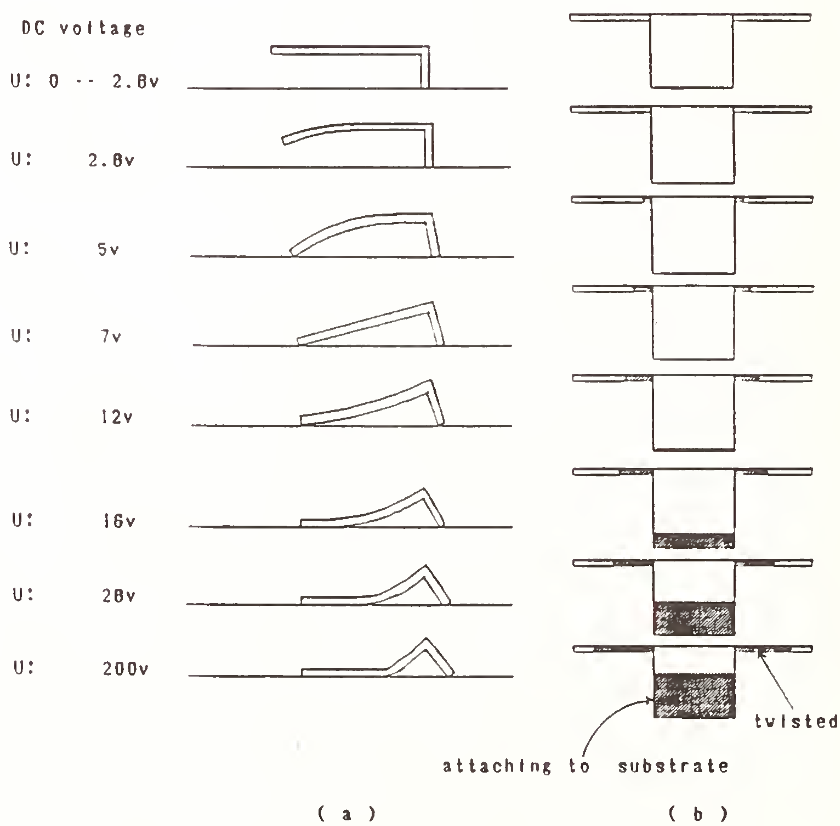


Fig.3 Motion of a microslider. (a)Cross-sectional view. (b)Top view.

Primal Scientist: Masayoshi Esashi
Affiliation: Department of Mechatronics and Precision Engineering
Tohoku University
Address: Aza Aoba, Aramaki, Aoba-ku, Sendai, Japan 980
Tel.+22-222-1800 ext.4207, Fax.+22-215-4845
Number of Staffs: 3(17 students)

Research Overview:
Sophisticated micro actuators and micro sensors by micromachining: Micro actuators, micro sensors, and integrated sensor and actuator systems fabricated by micromachining have been studied. Examples of research projects are as follows: development of electrostatic micro actuators, integrated sensors, micro flow control systems and micro resonant sensors. Micropackaging techniques for micro sensors and three-dimensional micro fabrication techniques are also studied.

Research Topics:
1) Electrostatic micro actuators: A micro actuator consists of many distributed driving units is studied to realize large force and large displacement. Development of a linear micro actuator which has many stepping electrodes is another topic of this project.
2) Accelerometers: Various types of accelerometers are designed and fabricated to achieve high sensitivity and stability. The packaging problems are also studied.
3) Micro flow control systems: Integration of micro flow control devices and micro sensors enables very small flow control systems. Precise gas flow control systems and integrated chemical analysis systems are the topics of this project.
4) Micro resonant sensors: In order to realize high sensitivity and good stability, resonant type vacuum sensors and infrared sensors are studied.
5) Three-dimensional micro fabrication techniques: Selective patterning and deposition by means of excimer laser beam are studied. YAG laser assisted etching techniques are also developed to realizing sophisticated silicon micro structures.

Research results in f scal year of 1993:
1) Electrostatic actuator: Fundamental studies of distributed electrostatic actuator were done. The motion of the actuator was analyzed by finite element model and investigated by the macro model.
2) Integrated accelerometer: An integrated silicon capacitive accelerometer with novel balancing was developed. It has glass-silcon-glass structure realizing a micropackaging. The CMOS capacitance to frequency convertor is integrated and the phase-locked-loop circuit is used for the force balancing system.
3) Micro flow control device: High output pressure micropump was studied and a novel check valve was developed.
4) Packaged resonant sensor: A packaged resonant sensor with high Q-factor was fabricated. The torsional type mono-crystalline silicon resonator was fabricated in glass-silicon-galss structure.

5) High-speed directional dry etching: Low temperature reactive ion etching using SF_6 was studied to realize three-dimensional silicon structure. A maximum etch rate of 2.35 um/min with small undercut ratio of 0.03 was achieved at -120 C.

References:

1) S.Kawamura, K.Minami, M.Esashi,"Fundamental Research of Distributed Electrostatic Micro Actuator", Tech. Dig. of 11th Sensor Symposium, pp27-30, (1992).

2) Y.Matsumoto, M.Esashi,"Integrated Capacitive Accelerometer with Novel Electrostatic Force Balancing", Tech. Dig. of 11th Sensor Symposium, pp47-50 (1992).

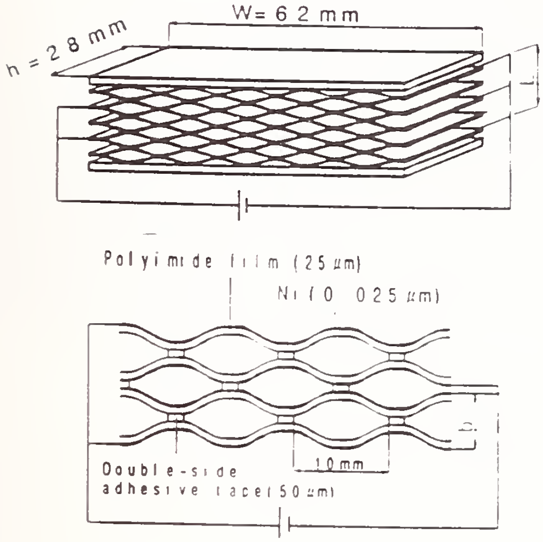
3) S.Shoji, B.van der Schoot, N.F.de Rooij, M.Esashi,"A study of high pressure micropump", Sensors and Actuators, A32, pp335-339, (1992).

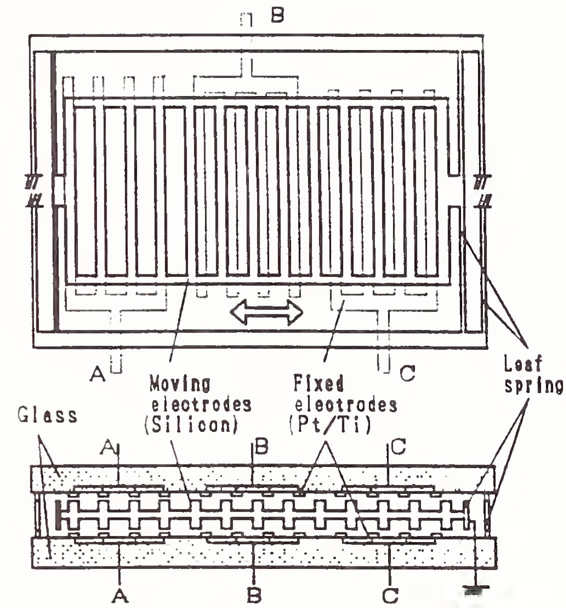
4) K.Yoshimi, K.Minami, Y.Wakabayashi, M.Esashi,"Packaging of Resonant Sensors", Tech. Dig. of 11th Sensor Symposium, pp35-38 (1992).

5) M.Takinami, K.Minami, M.Esashi,"High-speed Directional Low-temperature Dry Etching for Bulk Silicon Micromachining", Tech. Dig. of 11th Sensor Symposium, pp15-18 (1992).

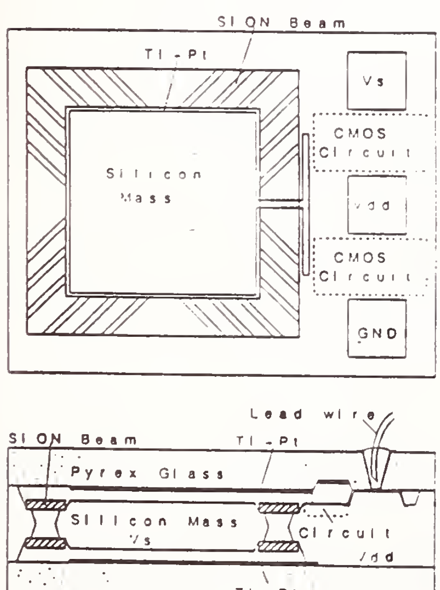
"Sophisticated micro sensors and micro actuators by micromachining"

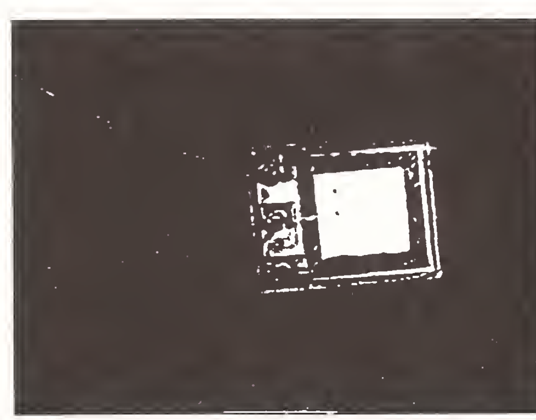
Masayoshi Esashi (Tohoku University)





(a)Distributed Electrostatic Type (b)Stepping Electrostatic Type
Fig.1 Electrostatic micro actuators





(a) Structure of the sensor (b) Photomicrograph of the sensor
Fig.2 Integrated Accelerometer

Primal Scientist: Yotaro HATAMURA, Masayuki NAKAO
Affiliation: The University of Tokyo, Faculty of Engineering
Engineering synthesis
Address: 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113 Japan
TEL +3-3812-2111 ex. 6361 FAX +3-3818-0835
Number of staffs: 4 employees, 13 students, and 5 researchers
(For this project: 2 employees, 6 students, and 1 researcher)

Research Overview:

Nano Manufacturing World is being developed.

Some physicists are trying to go up nanometers scale from angstrom scale by handling atoms through Scanning Tunneling Microscope (STM). We machanical engineers are newly challenging to come down there from macro scale. It supports the human to work in nanometer world as if they were there by using dyanmic, real-time, and 3-dimensional observation/handling instruments. Combination of the two directions makes the human step into an unknown and fruitful world, namely Nano Manufacturing World (Figure 1).

Research Topics:

We have been engaged in developing Nano Manufacturing World for 6 years. Through the development we realized that it needs the following 4 elements.

1) Micro Tools: We are trying various actions with Micro Tools (Figure 2). Blowing off, scraping off, and attracting are useful in nanometer world besides nipping and digging which are widely tried.

2) Nano Manipulator: We have already realized a real-time, 3-dimensional, and ultra-precise nano manipulator in Nano Robot II (Figure 3). It can be operated within 5 nm preciseness through transmission mechanism that is newly designed.

3) Reality Transmission System: We have already realized this system in Nano Robot II. In order to support the operator, stereoview, small sound, and micro force that happen in nanometer world through Scanning Electron Microscope (SEM) are transmitted to the operator.

4) Softwear for Dominant Factors Conversion: We realized through Nano Robot II operation that dominant factors in nanometer world are totally different from those in human-size world. In order to prevent a fatal damage caused by mis-operation and to realize easy operation, a hidden support that automatically converts the dominant factors is indispensable.

Reseach Results in 1992:

The new results in this year are as follows:

1) Micro Tools: Tools for nipping, blowing off and attracting have been developed. Those for dipping and scraping off cannot be realized because their rigidities are too small against the operating force.

2) Nano Manipulator: A new rotation mechanism for the various tools has been developed by using ultra-sonic motor.

3) Reality Transmission System: An ultra-micro force sensor is being developed through semiconductor manufacturing process. Even 1 nano Newton

can be detected with semiconductor strain gauges on parallel thin plates of 0.7 micron thickness.

Reference:

1) Y. Hatamura and H. Morishita: Direct Coupling System Between Nanometer World and Human World, Proc. of MEMS 1990, IEEE, pp203-208 (1990)
2) Y. Hatamura: Micro Manipulation and Reality Transmission, Journal of JSME, 6-1992, pp25-29 (1992), in Japanese
3) Y. Hatamura, M. Nakao et al: A Measurement of Sliding Resistance Forces for Various Heads and Disks by High-Rigid Force Sensor, IEEE Trans. of Magn., Vol. 24, No. 6, pp2638-2640 (1988)
4) Y. Hatamura: A Ring Shape 6-Axis Force Sensor and Its Apprications, Int. Conf. on Advanced Mechatronics, pp647-652, (1989)
5) Y. Hatamura, M. Mitsuishi et al: A Fundamental Structure for Intelligent Manufacturing, Proc. of 6th Annual Conf. ASPE, pp188-191 (1991)

Fig.1 Nano Manufacturing World

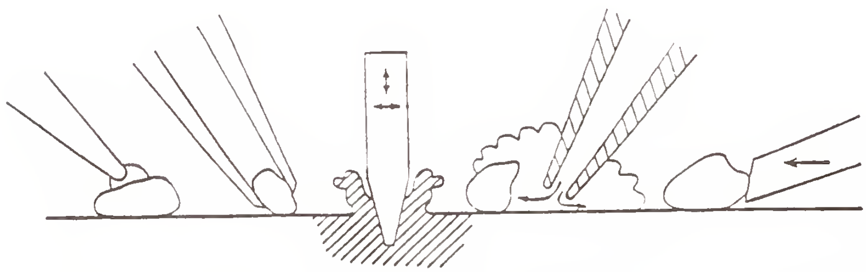


Fig.2 Various Tools Needed in Micro Manipulation

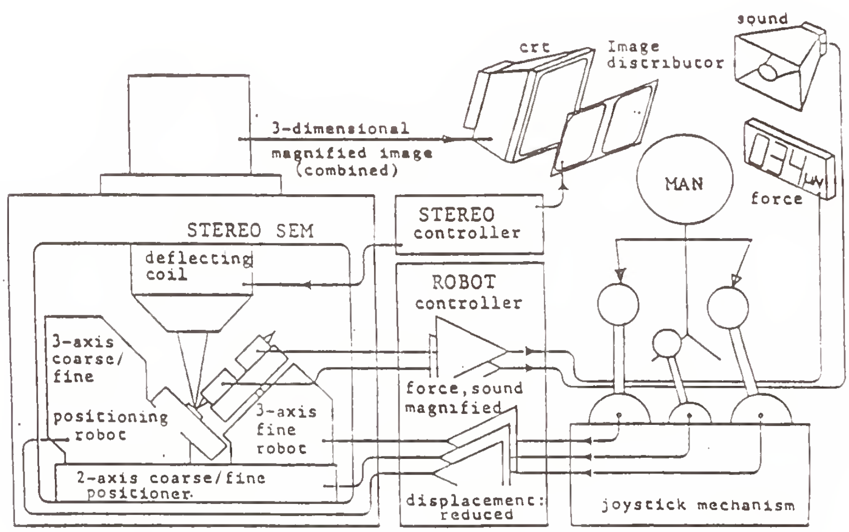
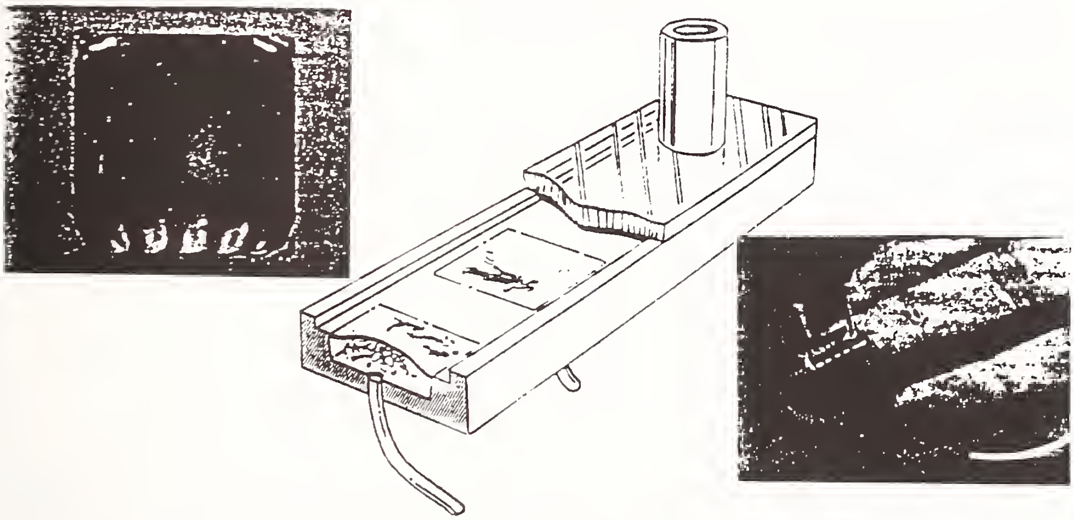


Figure 3 System Diagram of Nanorobot System II

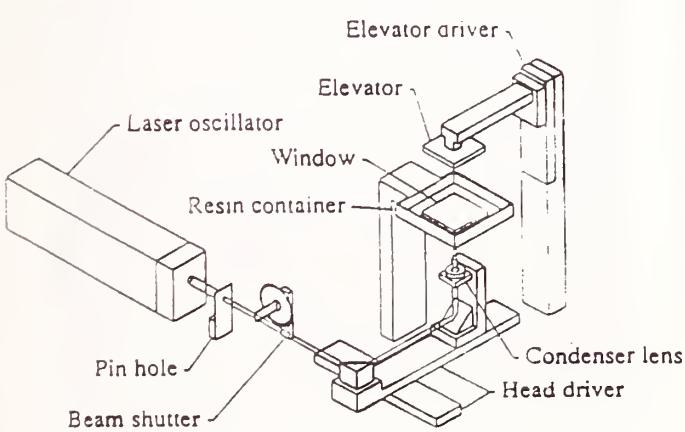
"Micromachine Design & Rapid Manufacturing"

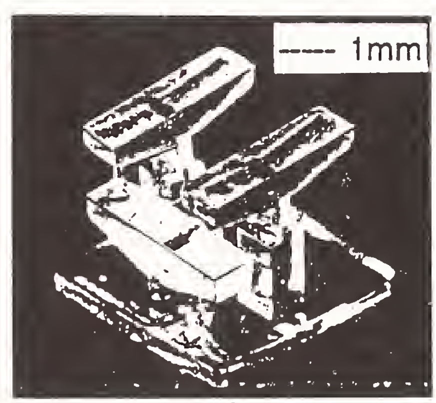
Naomasa NAKAJIMA (Mechanical Engineering for Production. The University of Tokyo)



Pump with five micro-actuators driven by vaporization of fluid, heated by light source through optical fiber

Light Driven Micro-Pump





Three levers model with flexible column

High Resolution Photoforming

Primal Scientists: Hirofumi Miura, Isao Shimoyama
Affiliation: Department of Mechano-Informatics
The University of Tokyo
Address: 7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan
phone (country code 81)-3-3812-2111 x6318
fax (country code 81)-3-3818-0835
Number of Staffs: 2 (23 students)

Research Overview:

We are interested in an approach to micromachines, which makes the most of our background of robotics Our final goal is to build microrobots whose behavior and structures are similar to real insects.

Research Topics:

1) Insect Based Microrobot with an External Skeleton and Elastic Joints[2][3]
2) Analysis of insect motion[1]

Research results in fiscal year of 1992:

1) A flying microrobot is nearly finished.

References:

1] *Isao Shimoyama, Hirofumi Miura, Chiaki Kimura, Manabu Kikuta, "Analyzing the Dynamics of Ants and Application to Microrobots," ASME Symposium on Micromechanical Sensors Actuators and Systems, DSC-Vol.32, pp.279 - 285, 1991.*

2] *Kenji Suzuki, Isao Shimoyama, Hirofumi Miura, Yuichi Ezura, "Creation of an Insect-based Microrobot with an External Skeleton and Elastic Joints," Proceedings of IEEE Workshop on Micro Electro Mechanical Systems, pp.190-195, 1992.*

3] *Isao Shimoyama, Hirofumi Miura, Kenji Suzuki, Yuichi Ezura, "3D Structure of an Insect-based Microrobot with an External Skeleton," IEEE Robotics & Automation, pp.693-698, 1992.*

3D Structure of an Insect-based Microrobot with an External Skeleton

Hirofumi Miura & Isao Shimoyama
Department of Mechano-Informatics
The University of Tokyo

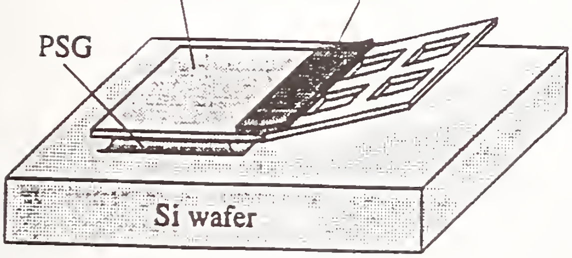


Fig.1. 3D structure with elastic joint.

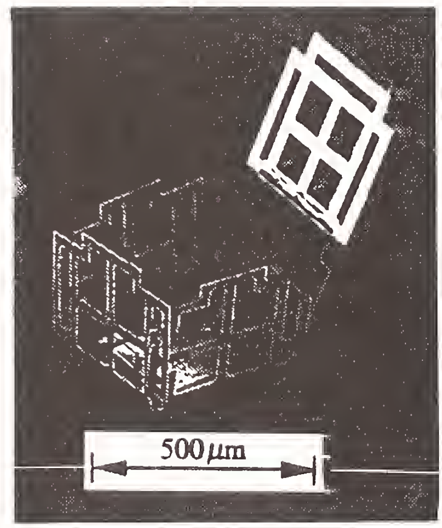


Fig.2. Microcube.

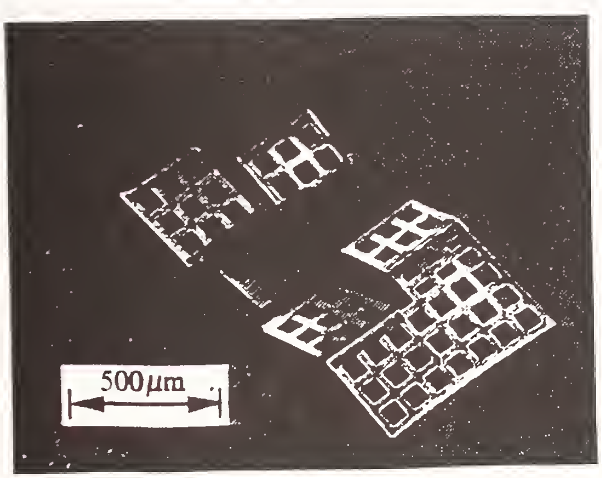


Fig.3. Microsized model of wings.

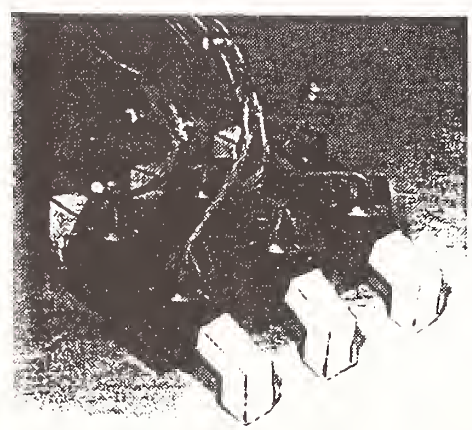


Fig.4. Large scale artificial ant consisting of the leg joint mechanism.

MICROACTUATORS FOR THE CILIARY MOTION SYSTEM

Manabu Ataka. Hiroyuki Fujita (IIS. The Univesity of Tokyo)

The photograph shows a microactuator array for the ciliary motion system[1]. The system mimics the motion of cilia in living organisms. Many cilia vibrate in synchronization to convey objects or fluids. A cilium has two-degree-of-freedom (rotation and bending). Since the micromachined actuator has only simple motion. two actuator element are combined to achieve the two-degree-of-freedom motion. We have fabricated a thermally driven contilever micro actuator[2].

The SEM photograph of cantilever actuators is shown. The basic driving principle is similar to that reported by Riethmüller. et al.[3]. The differences are the material (polyimides) and the simple fabrication process. Two layers of polyimides with different thermal expansion coefficients sandwitches a metal heater. Aluminum was used as a sacrificial material. Since the polyimide used in the upper layer has the larger thermal expansion coefficient than the lower layer the residual tensile stress in that layer curls the cantilever up. (Note that the tensile stress builds up when the polyimide is cured at elevated temperature and cooled down.) When the current flows in the heater and the temperature rises the cantilever bends down. The dimensions of the cantilever are: 500 μm in length, 100 μm in width, 6 μm in thickness. The displacement was 66 μm in the horizontal direction and 123 μm in the vertical direction with 30 mW in the heater. The frequency response without any particular cooling wasmeasured using sinusoidal wave. The cut-off frequency (-3dB) is 10 Hz. We fabricated microactuators in an array. We operated the actuators in coordination to carry an object on the array, although all the control signals were supplied from outside. The object is a silicon chip of $1 \times 1 \times 0.5$ mm^3. The chip was conveyed for the distance of 0.5 mm while 30 cycles of the coordinated motion were repeated.

REFERENCES

[1] N. Takeshima. H Fujita. 'Design and Control of Systems with Microactuator Array', Proc. IEEE Workshop in Advanced Motion Control. Yokohama. Japan. March 1990. pp.219-232.
[2] N. Takeshima. H Fujita. 'Polyimide Bimorph Actuators for a Ciliary Motion System' ASME Winter Annual Meeting, Atlanta. Georgia. Dec 1-6 (1991) DSC-Vol.32 pp.203-209.
[3] W. Riethmüller. W. Benecke. 'Thermally Excited Silicon Microactuators', IEEE Trans on Electron Devices. ED-35. pp.758-763 (1988).

Array of Thermo Bimorph Actuators for Ciliary Motion System.
Each actuator is composed of two layers of polyimides with different thermal expansion coefficients and a micro metallic heater sandwiched between them.
(Fujita Lab., IIS. The University of Tokyo)

Primal Scientist: Takahisa MASUZAWA
Affiliation: I.I.S. (Institute of Industrial Science)
University of Tokyo
Address: 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan
Tel.+81-3-3402-6231, Fax.+81-3-3478-0216
Number of staffs: 2 (3 students)

Research Overview:
The activity in this laboratory is concentrated on the development of technologies relating the production of micro parts. Manufacturing methods for basic components such as microholes, microspindles, micronozzles are the main targets of the research works.

Research Topics:
1) Micromachining: Machining of microspindles or micropins as the application of WEDG (wire electrodischarge grinding), machining of mocroholes by EDM, punching and drilling, machining of microgrooves by milling and machining of micro nozzles by combination of WEDG, ECM and electroplating, etc.

2) Measuring technology for micro parts: Measurement of inner dimensions of microholes by a newly developed method 'vibroscanning'.

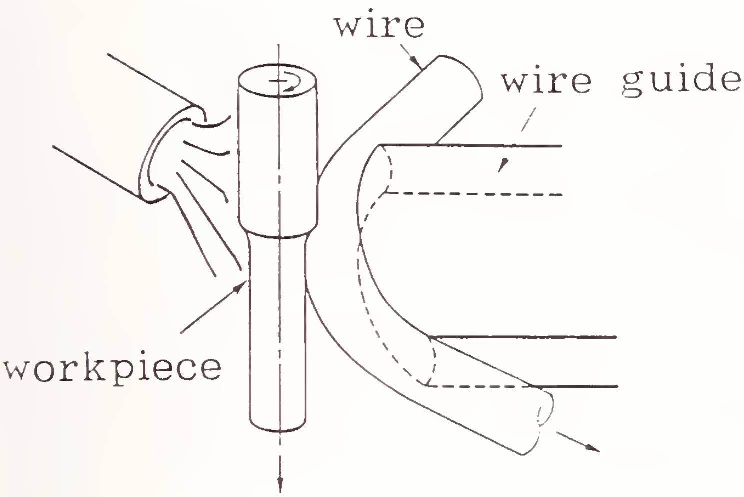
3) Micro assembly: On-machine assembly system for microparts by using WEDG, EDM and ulstrasonic assembly.

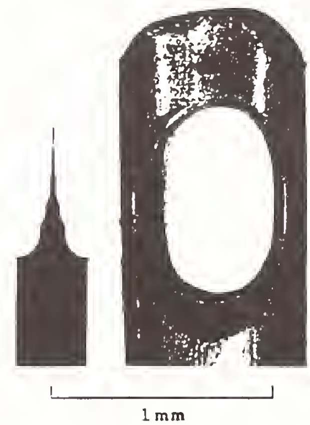
Research results in fiscal year of 1992:
1) Inner dimension of a $\phi 200\mu m$, $700\mu m$ deep hole was successfully measured by vibroscanning method.
2) Machining and assembly of a micropart for Liquid Metal Ion-beam emitter was achieved.

References:
1) C.-L. Kuo, T.Masuzawa, M.Fujino, "High-Precision Micronozzle Fabrication", Proc. of IEEE MEMS '92 (Feb-1992)
2) T.Masuzawa, C.-L.Kuo, M.Fujino, "Drilling of Deep Microholes by EDM using Additional Capacity", Bull., JSPE, 24, 4 (Dec-1990)
3) T.Masuzawa, M.Yamamoto, M.Fujino, "A Micropunching System using Wire-EDG", Proc. of ISEM-9 (Apr-1989)
4) T.Masuzawa, M.Fujino, K.Kobayashi, T.Suzuki, "Wire Electro-Discharge grinding for Micro-Machining", Annals of the CIRP, 34, 1 (Aug-1985)
5) T.Masuzawa, I.Tsuchiya, "Low-Energy High-Current Ion Source for Ion-Milling Equipment", Annals of the CIRP, 33, 1 (Aug-1984)

Microfabrication Technologies

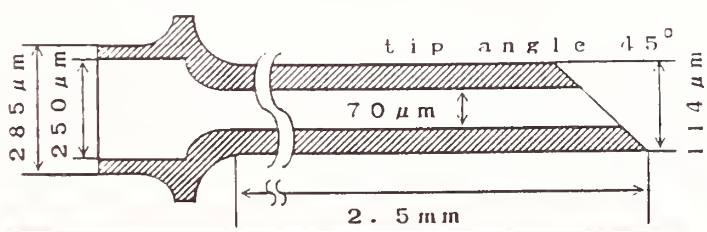
Takahisa MASUZAWA (I.I.S., University of Tokyo)





A $\phi 5\mu m$ tungsten micropin (compared with a sewing needle head).

Fig.1. Wire electrodischarge grinding method for producing micropins, microspindles and microtools.



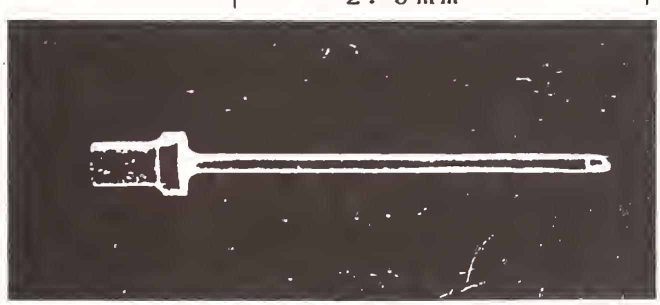


fig.2. A micro injection needle produced by a combined process with WEDG, ECM (electrochemical machining) and electroplating.

Primal Scientist: Isao KARUBE
Affiliation: RCAST(Research Center for Advanced Science and Technology) University of Tokyo
Address: 4-6-1, Komaba, Meguro-ku, Tokyo, Japan 153
Tel. +3-3481-4470, Fax. +3-3481-4581
Number of staffs: 7 (32 students, 13 research fellows, 3 postdoctoral fellows)

Research Overview:

Miniaturization of biosensing system using micromachining techniques is now under investigating. Enzymatic flow injection system is mainly studied. Electrochemical detector, photochemical detector, and enzyme reactor have been fabricated, and also integrated each other. Further research will focus on micropump, which makes it possible to fabricate handy-type flow injection system for clinical, industrial process and environmental monitoring.

Research Topics and Research results in fiscal year of 1991:

1)Glucose sensing system with electrochemical detector:

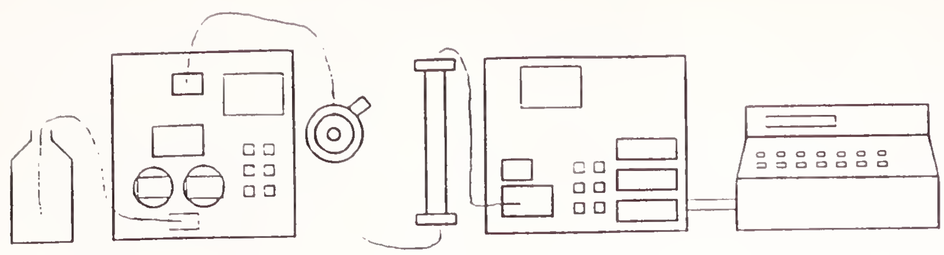
Silicone capillary of 0.1mm width and 1m long was fabricated, and glucose oxidase was covalently immobilized on inner surface of the capillary. And thin film gold electrodes were integrated to detect hydrogen peroxide which is product of enzyme reaction.

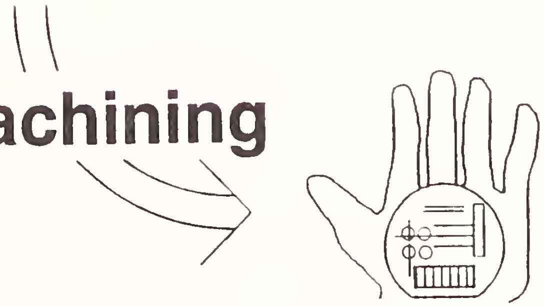
2)Glucose sensing system with photochemical detector:

Glucose oxidase immobilized glass beads were packed into the chamber of device which has the other chamber to mix product of enzyme reaction and reagents to get chimiluminescence detected by photodiode connected on the device

References:

1) Y.Murakami. et al. "Flow type biosensing system using micromachining techniques", proc. of annual meeting of Japan Chem. Soc. I pp.370, (Oct.-1992)
2) T.Takeuchi, et al. "Enzyme FIA system using micromachining techniques", Kagaku, Vol.47, No.6, pp.434 (Jun.-1992)
3) M.Suda, et al. "Micromachined Biosensors", proc. of Biosensors, pp.400 (May-1992)

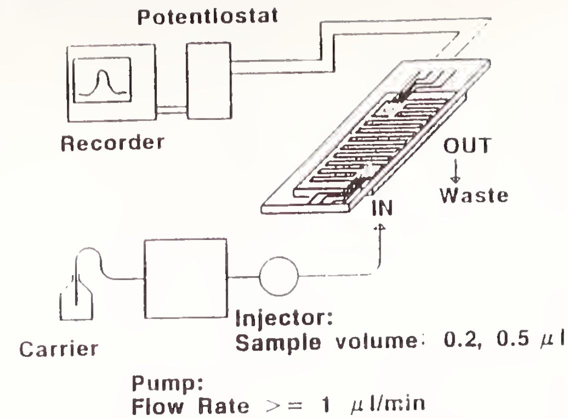




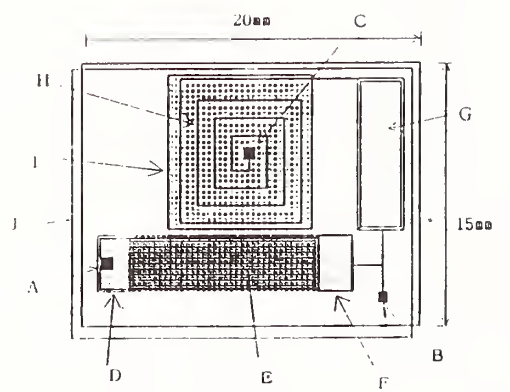
Micromachining

Merits of the System

- Small Amount of Sample
- High Resolution
- High Speed
- Low Cost



Glucose Detection System



A sample inlet
B reagent inlet
C outlet
D enzyme reactor
E glass beads
F stopper
G Mixing chamber
H spiral cell
I photodiode
J pyrex glass

Chemiluminescence detector

22-Sep-92

Primal Scientist: Tomomasa SATO
Affiliation: RCAST(Research Center for Advanced Science and Technology) University of Tokyo
Adress: 4-6-1, Komaba, Meguro-ku, Tokyo, Japan 153
Tel.+3-3481-4479, Fax.+3-3481-4584
Number of staffs: 2 (7 students)

Research Overview:

Intelligent robot to handle very small objects has been investigating. The following are the examples of tasks: assembly of micro machines, repair ofVLSI's, micro surgery, physical measurement of very small biological organs such as years and cells, physical handling of genes. We have been conducting the research systematically from mechanism and control to intelligence for task execution and friendly human robot interraction.

Research Topics:

1) *Micro and nano object handling robot*: A manipulator mechanism and its control, vision and force sensor fusion, model based realtime task oriented intelligence are studied to realize an autonomous hand-eye system consists of optical microscopy or SEM (scanning electron microscopy) and micro handling manipulator with sensitive force sensor.

2) *Micro and nano tereoperation*: The research topics includes such robot support function for human operator as damage prevention, perception enhancemant, knowledge augmentation, shared skillful task execution and learning of the task.

3) *Multirobot for human support*: An automatic behavior understanding of a)robot action, b)human operator and c)surrounding robot behavior is the base of the co-peration between multirotbots as well as human operator and robots.

Reseasrch results in fyscal year of 1993:

1) *Micro object handling robot*: A "vision/motion/operation co-focused manipulator system" suitable for micro handling task was realized. In this system a work space locates inside the manipulator because the handling object is far smaller than the manipulator, while a work space exisits around the manipulator and the task is performed by extending its manipulator in conventional industrial robot.

References:

1]T.SATO,"Teleopcraton Technology in MITI Advanced Robot Technology Project", IEEE Int. Conf. on Robotics and Automation (May-1992)
2]Sakane、Sato、" Automatic Planning of Light Source and Camera Placement for an Active Photometric Stereo System" 、IEEE Robotics and Automation (May-1991)
3]S.Sakane, T.SATO, M.KAKIKURA,"Setup Planning of Active Sensing for Autonomous Robots", J. of Robotics and Mechatronics, Vol.3,No.3,pp196-200(1991)
4]S.HIRAI, T.SATO, T.MATSUI,"Intelligent and Cooperative Control of Telerobot Tasks", IEEE Control Systems, Vol.12, No.1,pp51-56 (Feb-1992)
5]Sato、Hiari、Matusi : " A Telerobot System MEISTER: An Integration of Task Knowledge Base and Cooperative Maneuvaring System" 11th Int. Conf. on Structural Mechanics in Reactor Technology (Aug-1991)

"Intelligent Robot to Handle Very Small Object"

Tomomasa SATO (RCAST, University of Tokyo)

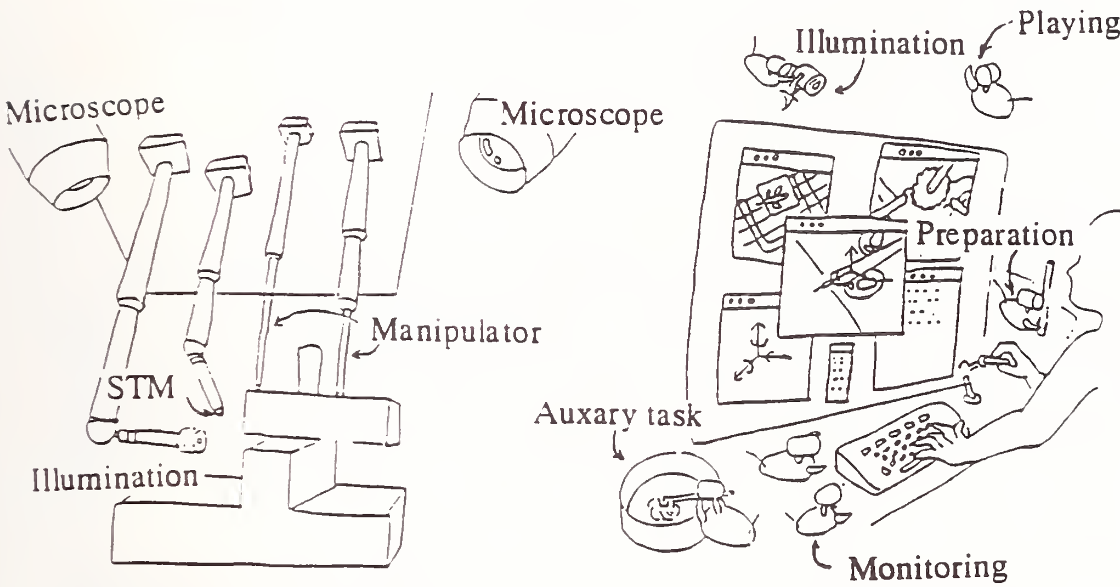


Fig.1 Image of intelligent robot system to handle very small object
The system consists of the following tree components;
1) micro object handling manipulator system,
2) intelligent teleoperation system,
3) multirobot system to support human operator.

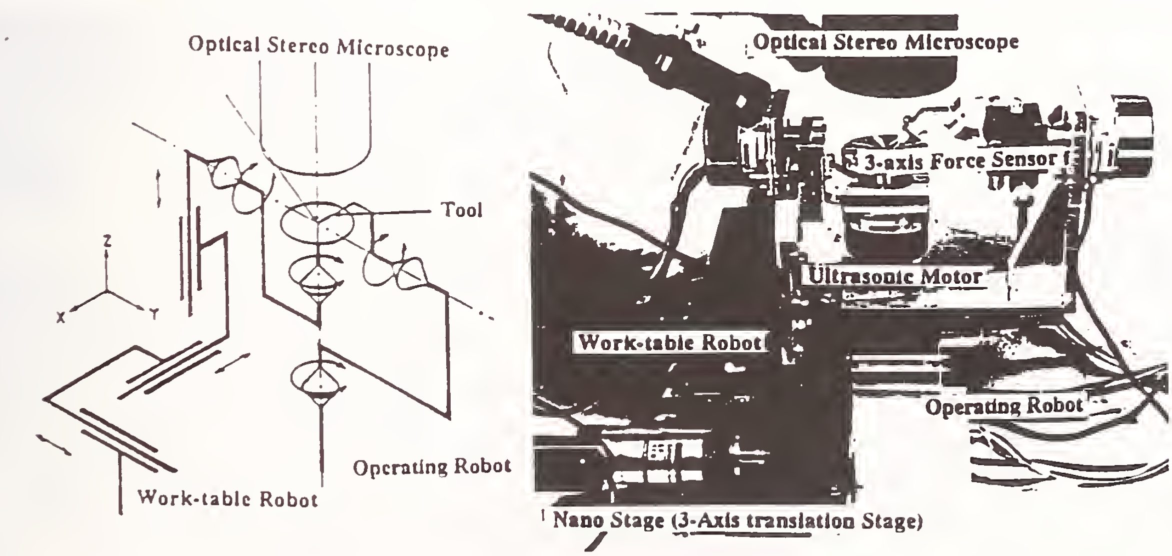


Fig.2 Realized micro object handling manipulator system
The main feature of this manipulator system is that the work space is located inside the manipulator while the work space is spread around the manipulator in case of conventional industrial robot. This new configulation makes the robot suitable for very small object handling.

Primal Scientist: Tadatomo SUGA
Affiliation: RCAST(Research Center for Advanced Science and Technology)
The University of Tokyo
Address: 4-6-1, Komaba, Meguro-ku, Tokyo, Japan 153
Tel./Fax. 03-3481-4488
Number of staffs:3(10 students)

Research Overviews:

We are developing noble techniques for assembling micro-components such as sensors, actuators, processors and structural components in micron-scale, and for constructing integrated micro-robot systems. The basic technologies for the micro-assembly include the development of the micro-machining process for silicon, direct bonding of silicon and piezo-electric ceramics, micro-bonding of LSI circuits, and micro-manipulation of the in scanning electron microscope, as well as fundamental understanding of the mechanism of adhesion and bonding.

Reasearch Topics:

1)Development of the surface activated bonding (SAB) method for room temperature joining; a) development of the SAB process, b) investigation and optimization of the process parameters in the SAB method.
2)Characterization of the microstructure of SAB joined interfaces by high resolusion electron microscopy.
3)Development of a bonding apparatus for manipulation and assembly of micro-components in UHV; a)development of the micro-manipulation and precise allignment system.
4)Development of a micro-force sensor and it application to the atomic force microscopy(AFM).
5)Analysis of adhesion and bonding process by means of the molecular-dynamic simulation and finite element method.

Research results in fiscal year of 1992:

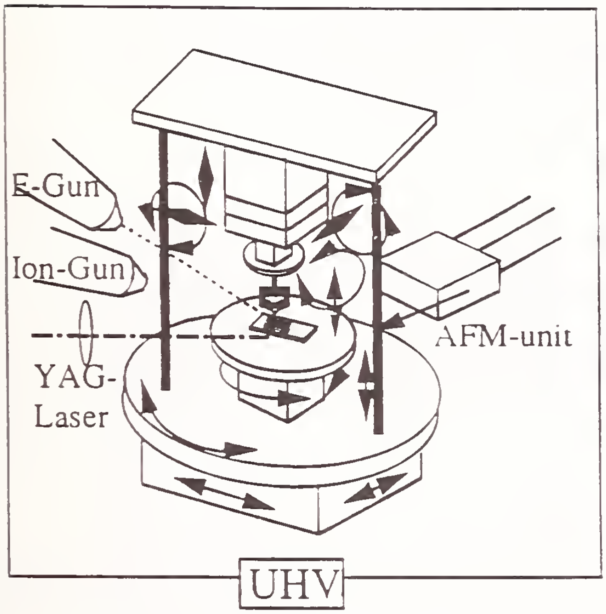
1) We have succeeded in microbonding of LSI and microelectronic components such as LSI flip chip by SAB method at room temperature.
2) We have developed the new SAB process using the radical beam source or the fast atom beam source in UHV($<10^{-8}$Pa).
3) The force sensor using piezoelectric cantilever for the noncontact AFM has been developed.

References:

1]Yutaka TAKAHASHI, Eiichi HOSOMI and Tadatomo SUGA, "Low-Resistivity Contact of YBa2Cu3O7-x/Al Joint Bonded at Room Temperature", Jpn J. Appl. Physics, 30,12A(1991) L2028-
3]Hideki TAKAGI, Yutaka TAKAHASHI, Tadatomo SUGA and Yoshio BANDO, "High Resolution Electron Microscopy of Al/Si and Al/Si3N4 Interfaces Prepared by Room Temperature Bonding Method(Japanese)", J. Japan Inst. Metals, 55(1991) 907-908
4]Yutaka TAKAHASHI, Hideki TAKAGI, Tadatomo SUGA, Borris GIBBESCH, Gerhard ELSSNER and Yoshio BANDO, "Enviromental EFFects on Structural, Mechanical and Electrical Properties of Al/Al Interfaces Joined at Room Temperature(Japanese)", J. Japan Inst. Metals, 55(1991) 1002-1010

"Micro-assembly and Interconnection"

Tadatomo SUGA (RCAST. The University of Tokyo)



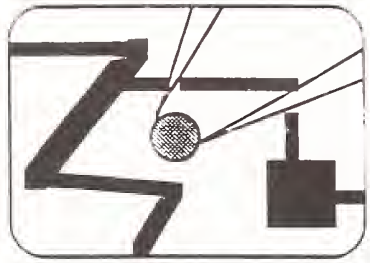


Fig.1 Schematic illustration of micro-assembly system in UHV. The system possesses the following functions: (1) surface activated bonding at room temperature, (2) manipulation and assembly of micro-components in SEM, (3) characterization of the surface topography by atomic force microscope.

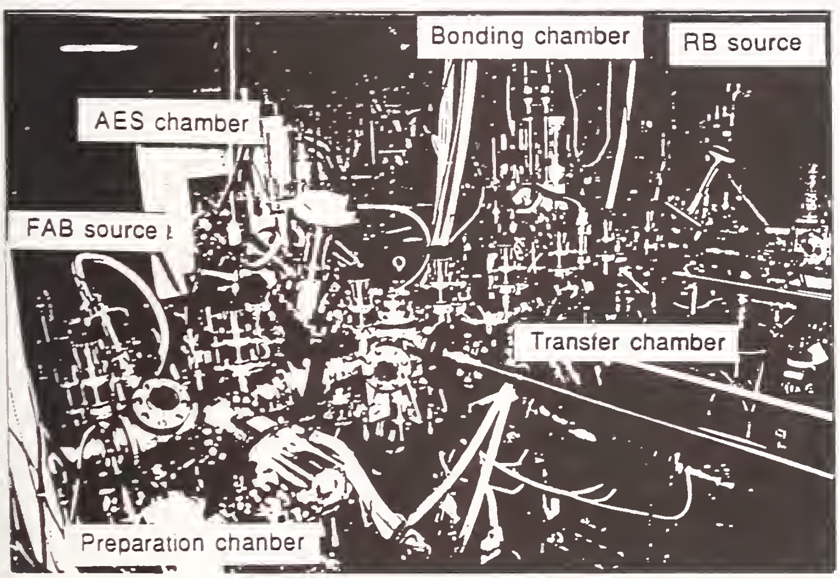


Fig.2 Apparatus for the surface activated bonding (SAB)method. The apparatus consists of UHV bonding chamber, transfer chamber and two preparation chambers with the radical beam source or the fast atom beam source.

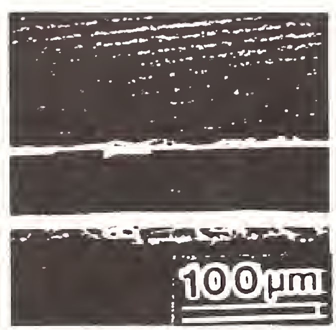


Fig.3 SEM micrograph of LSI flip chip bonded by SAB method at room temperature.

Primary Scientist: Hideharu TANAKA
Affiliation: Advanced Mechanical System Dept.
Central Research Laboratory,Mitsubishi Electric Corp.
Address: 1-1,Tsukaguchi-Honmachi, 8-chome,Amagasaki,Hyogo,661
Japan ,Tel.+6-497-7165,Fax.+6-497-7291

Number of staffs: 15

Research Overview:

R&D of 3D micro magnetic structures and its appliances has been conducting. Targets of R&D are establishment of 3D material processing ,rising power density(output power /volume),size reduction to microscopic, and application to micro-magnetic devices.

Research Topics :

1) *Energy product(coercivity · residual flux density) upgrading of thin-film permanent magnet* : Main technical subjects are formation of uniform composition ,homogenization of crystal structure, anisotropic crystal orientation along the direction of magnetic flux .

2) *Wire-wound microscopic structure*: A structure consists of thin-film core stack and 3D coil. Material processing is investigated to realize a stereoscopic and complicated structure such like this.

3)*Micro-electric power generating device* : This consists of turbine , speed-up gears and AC electric generator to converse water flow energy to electric power energy. This R&D was planned to participate in National Large-Scale Project " Micromachine Technology".

Research Results in fiscal year of 1992

1) Fundamental approach to establish the uniform formations of composition and film thickness was experimentally carried out in the study of thin-film permanent magnet.

2) Several approaches to the material processing for 3D wiring were examined.

3) To extract technical subjects on rising power density , a electric generator of 7 mm in diameter and 9.5 mm in length ,and also speed-up planetary gears of 4.6 mm in diameter and 3 mm in length were manufactured on a trial basis. Output power of approximately 2 W was obtained at the rotor speed of 0.15 million rpm.

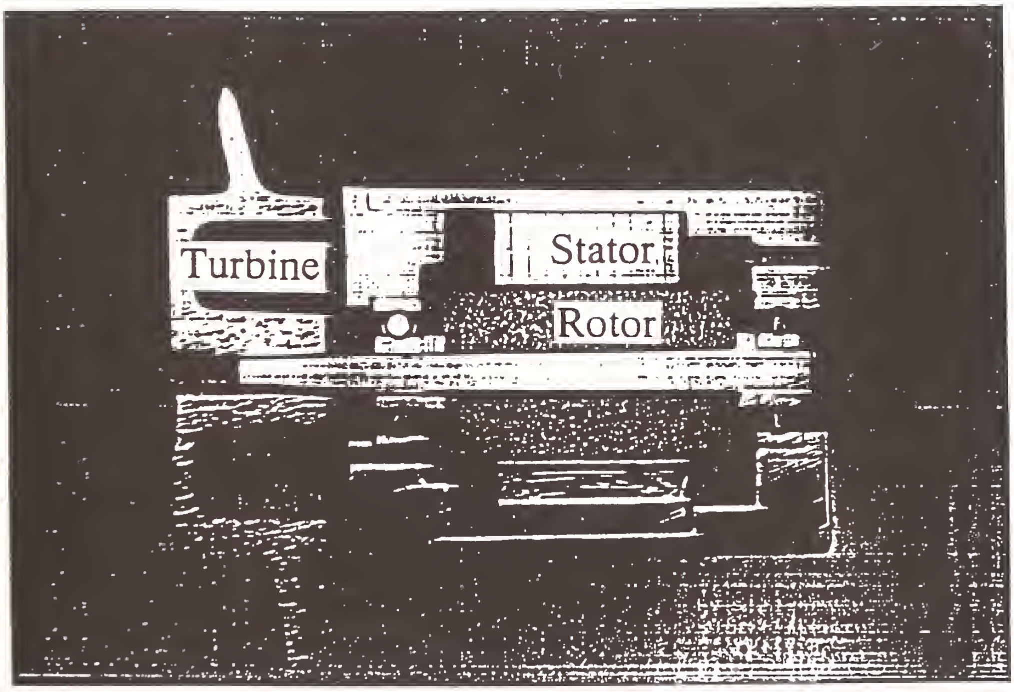


Fig. 1 Electric Generator Driven by Air Turbine

The structure is as following;

1)Stacked cores(silicon steel) of a stator were processed by focused Ion Beam.

2)Winding (30 μm wire in diameter) was performed by hand work using a microscope.

3)Rotor was made of rare-earth plastic permanent magnet.

Primal Scientist: Shinobu SAGISAWA
Affiliation: Fuji Electric Corporate Research and Development, Ltd.
Adress: 2-2-1, Nagasaka, Yokosuka city, Kanagawa, Japan 240-01
Tel. +468-57-6734, Fax. +468-56-2751
Number of staffs: 10

Research Overview:

Silicon based sensors such as tactile sensor, pressure sensor and acceleration sensor have been investigating.

Tactile image recognition system using the data from 3 axis tactile sensor array have been also investigating. "3" axis means a pressure and 2 shear forces

Micro actuators based on the principle of magnetic and electrostatic force have been investigating.

Research Topics:

1)Tactile sensor and image recognition system: 3 types of tactile sensors, which are 3 axis-3mm, 3 axis-1mm and 1 axis-2mm, had been developed. Low-cost and size-extensible sensor array for commercial needs has been developping.

Tactile image recognition system, which can recongnize the force pattern, moment, force centroid, sliding and hardness of grasped object, had been investigating.

2)Micro Actuator: Sizing down the magnetic actuator and enlarging the force and displacement of electrostatic actuator have been promoting.

Research results in fiscal year of 1991:

1)Tactile sensor and image recognition system: Size-extensible tactile sensor array was realized. The array has 16(4×4) sensing elements and a scanner IC. The arrays can be connected each other easily by soldering the pads and thus can meet various size demands. Tactile image recognition system, which has above menti-oned faculties, was realized.

2)Micro Actuator: A 4 mm dia. stepping motor(actuator), which has good speed-cotrolability, was develoed. A 2 mm dia. actuator have been fabricated. A proto type mm-sized electrostatic actuator for the proof of new principle has been tested.

Refereces:

1]S.Sgisawa et al., "Three Direction Sensing Tactile Sensor" Proc. IEEE, Intern. Workshop on Intelligent Robot and Systems, pp.47-51 (Nov. 1988).
2]S.Sgisawa et al., "Accurate Tactile Sensor Array for Robot Fingertip" Proc. Intern. Symposium on Industrial Robots, pp.243-248 (Oct. 1990).
3]M.Ooka et al.: "Tactile Expert System Using a Parallel Finger Hand with Three-Axis Tactile Sensors" Trans. JSME, Vol.C-57, No.544, pp.3855-3862, (Dec. 1991) (Japanese).
4]K.Ueyanagi et al., "Extensible Tactile Sensor Array and its Application" Proc. Symposium on Robotics and Mechatoronics '92, Vol.A, pp.781-784, (June 1992) (Japanese).
5]H.Nakazawa et al., "Parmanent Magnet Type Stepping Motor which have Magnetic Cercuits Adapted Small Diameter" Proc. Symposium on Robotics and Mechatoronics '92, Vol.A, pp.1003-1004, (June 1992) (Japanese).

"Tactile Sensor Array and Micro Actuator"

Shinobu SAGISAWA (Fuji Electric C.R.&D. Ltd.)

Table 1 Specifications of 3 Types of Tactile Sensors

	3D3M	3D1M	1D2M
Means of Force Detection	Piezoresistive Effect	Piezoresistive Effect	Piezoresistive Effect
Detectable Components of Force	3 Components	3 Components	1 Component
Maximum Detectable Force per Element	Fx : ±6 N Fy : ±6 N Fz : 20 N	Fx : ±0.7N Fy : ±0.7N Fz : 2 N	Fz : 10N
Sensitivity	Fx : 8mV/N Fy : 6mV/N Fz : 2.7mV/N	Fx : 107mV/N Fy : 107mV/N Fz : 100mV/N	Fz : 6mV/N
Size of an Element	3mm Square	1mm Long of Beam	1mm Square
Number of Elements	8×15	4×4, 4×12	14, 8, 7
Arrangement of Elements	Matrix	Matrix.	Curved Surface
Number of Electric Wires	8	7	7

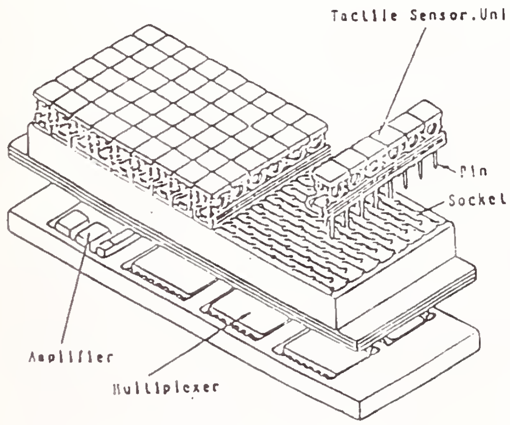


Fig.1 Construction of 3D3M Sensor

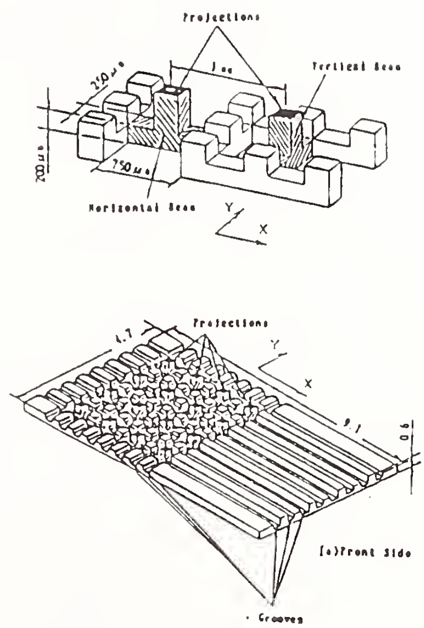


Fig.2 Construction of 3D1M Sensor

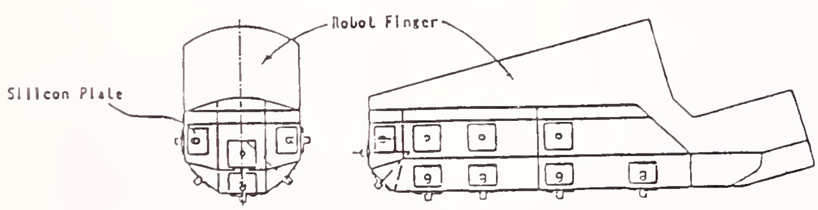


Fig.3 Construction of 1D2M Sensor

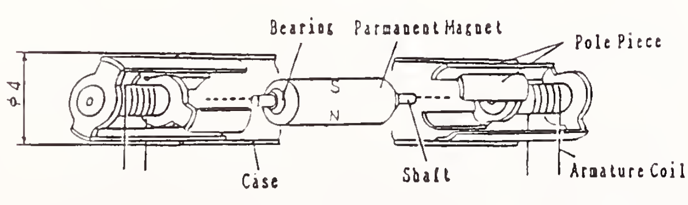


Fig.4 Construction of Magnetic Micro Actuator

Primal Scientist: Yoshimitsu KUROSAKI
Affiliation: KAWASAKI HEAVY INDUSTRIES,LTD.(KHI)
System Technology Development Center
Address: 1-1,Kawasaki-cho.Akashi.673 Japan
Tel.+81(Japan)-78-921-1643,Fax.+81-78-921-1610
Number of staffs: 8

Research Overview:

A ultra-precision servo control system has being investigated. The following are the examples of tasks;a nanometer alignment system the future linear collider,fine motion stage for precision machining and laser mirror alignment. We have constructed a test facility to study the position control system with multiple degrees of freedom .

Research Topics:

1)Ultra-precision alignment for the future linear collider : It is commonly recognized that a nanometer alignment system for will be required for the final focusing magnets of the future e+e- collider. A alignment contorl system for a massive load is to cancel the effect of thermal deformation due to the local temperature difference ,ground motion and the vibration due to the cooling water pulsation .

2)fine motion mechanism and motion stage using parallel spring: We study (a)position control method and (b)control system configuration for the six-degrees of freedom fine motion mechanism. We are also building a new fine motion stage using parallel spring for precision machining.

3)Nanotechology in metrology: The iodine-stabilized HeNe laser is currently the best practical realization of the unit of length. We study anew measurement of the transverse displacement using a laser beam and a pair of position sensors. We will be to study length scales that have a large dynamic range up to a meter, but will allow tenth nanometer measurements with high bandwidth.

Research results in fiscal year of 1993:

1)Position control table for FFTB final lenses: A position control table supports three final lenses of a final focus test beam line (FFTB). The table position is controlled with the accuracy of 50 nm (rms) in vertical and horizontal directions in order to keep the beam position stable as 60 nm (rms) for the iron table and three magnets that are twenty-five tons in weight.

References:

1)N.Ishihara et al., "A Position Feedback Control System for the Test Facility of JLC"in Proceedings of the International Conference on Accelerator and Large Experiment Physics Control Systems, KEK, Nov.11-15, 1991

2)T.Kubota et al.,"A Test Facility for the Position Control System of JLC"in Proceedings of the 2nd International Workshop on Accelerator Alignment, DESY, JUL.10-13, 1990

3)K.Miyashita et al.,"Transverse Displacement Measurement using Sprit Laser Beam"in proceedings of XVTH International Conference on High Energy Accelerators, Hamburg, JUN.20-24, 1992

"Ultra-Precision Servo Control System"
Yoshimitsu KUROSAKI(Kawasaki Heavy Industries.Ltd.)

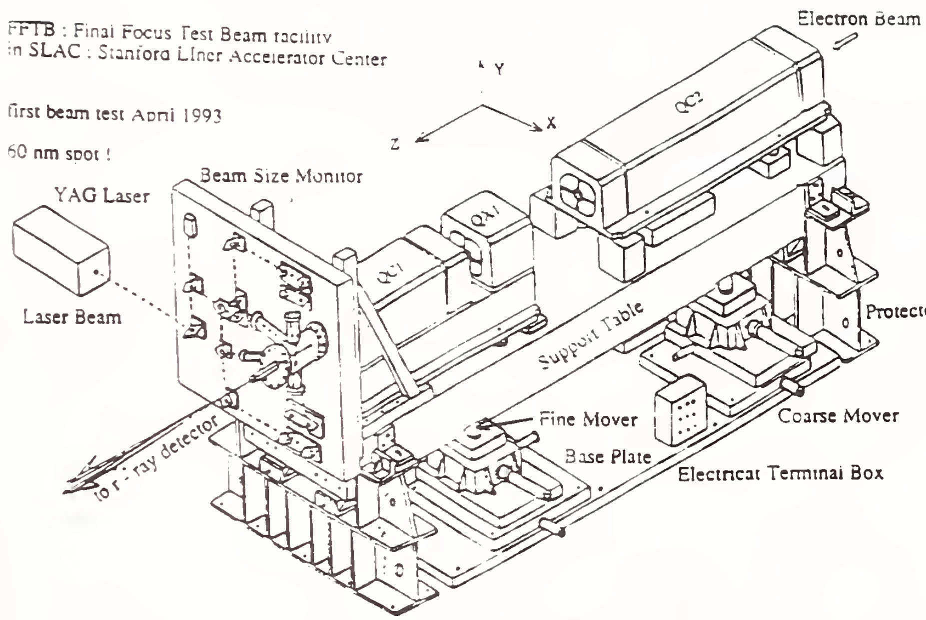


Fig.1 Illustration of the position control table and the final lenses

The system consists of the following components:

1)the table is supported by four movable legs consisting of screw jacks as coarse movers and piezoelectric actuators as fine movers .

2)control system consists of actuators ,laser interferometer and high-speed controller using VME modules.

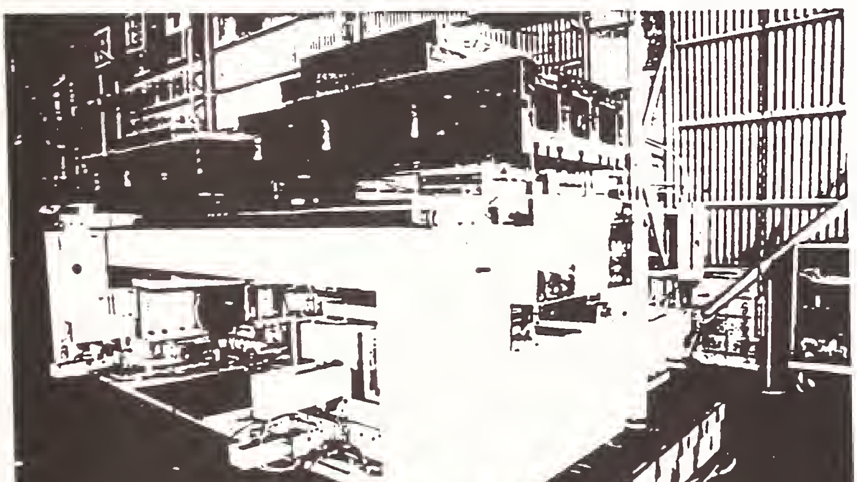


Fig.2 Position control table loaded with dummy weights

Main parameters of the control tables

Table	Load capacity	8 t			
	Size	1000(W)	4530(L)	×	450(H) mm
	Empty weight	16 t			
	Natural frequency	90 Hz			
Mover	Dynamic range	10 mm			
	Time response	>10 nm/s			
	Tolerance	50 nm(Y-axis)			
		500 nm(X-axis)			

Primal Scientist : Tsutomu YANO
Affiliation : Opto-electro Mechanics Research Laboratory
Matsushita Research Institute Tokyo,Inc.
Address : 3-10-1 Higashimita, Tama-ku, Kawasaki 214, Japan
Number of staffs : 8

Research Overview :

We have been developing the micro electro-discharge machines for the micro machining. The capability of machining a micro hole and a micro shaft as small as 5μm in diameter have been achieved. We are now studying the technologies of the micro EDM for the production of the micro mechanical parts which will be required in the fields of the micro electro mechanical systems.

Research Topics :

1) Three dimensional micro machining

Three dimensional micro machining as well as a simple micro boring has been achieved by minimizing the discharging energy to 10^{-7}J level and by realizing a precise mechanism providing submicron accuracy.[1) 2)]

2) Silicon EDM

Boring a micro through-hole and forming a three dimensional micro structure in a silicon wafer which is very difficult by the silicon process has been done by the micro EDM technologies.[3)]

3) Micro air-turbine

A prototype micro air turbine, which can be inserted into a catheter of 2.2mm in external diameter, has been built by micro EDM and rotated at the speed of approx.1000rpm.[3)]

Research results in 1992 :

1) Mold for the micro-gear

Technologies to reduce the wear of electrode for forming a high precision complex shape has been developing, and a micro mold for the injection plastic micro-gear which has 9 involute curved teeth in 0.3mm pitch circle diameter has been machined. [4)]

References :

1) T.Sato, T.Mizutani, K.Kawata ; "Electro-Discharge Machine for Micro hole Boring", National Technical Report,Vol.81 No.5 p105-113,Oct. 1985
2) T.Masaki, K.Kawata, T.Mizutani, K.Yonemoti, A.Shibuya, T.Masuzawa ; "Micro Electro-Discharge Machining", Proceedings of International Symposium for Electro-Machining,p26-29.1989
3) T.Masaki, K.Kawata, T.Masuzawa ; "Micro Electro-Discharge machining and its applications",Proceeding IEEE Micro Electro Mechanical Systems, Napa Valley, CA, Feb. 1990, p21-26
4) K.Nakamura, K.Amemiya, K.Sato, T.Masaki, R.Toyoda ; "The research for the micro-sinking with micro EDM", Proceeding Precision Engineering Oct. 1992, p679-680 (in Japanese)

Micro EDMed Examples

Photo 1. Pyramid on 2mm dia. ball
Pyramid dimension :
150μm base square.H50μm

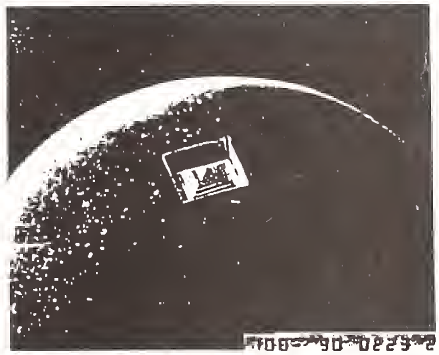


Photo 2. Vertical beam in Silicon
Beam dimension :
W15μm L50μm H50μm
Silicon : P-type,<1,1,1>
10~100Ωcm

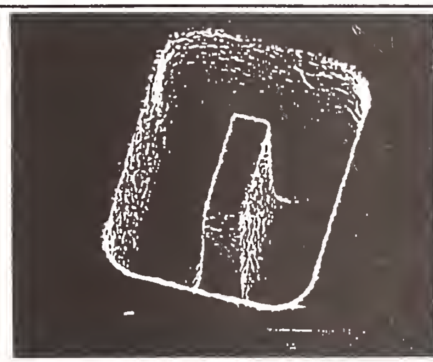
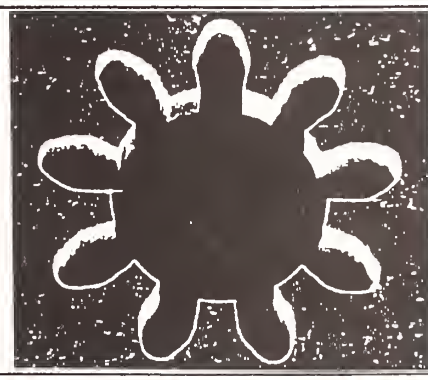


Photo 3. Micro Air tubine/rotor
Rotor outer diameter:0.95mm
Shaft diameter : 0.3mm

Photo 4. Micro-gear mold
0.3mm p.c.d.
Stainless steel 304
0.1mm thickness



Primal Scientist: Akiomi KOHNO
Affiliation: Mechanical Engineering Research Lab.,Hitachi,Ltd.
Address: 502 Kandatsu, Tsuchiura, Ibaraki 300, Japan
Phone: +81.298.32.4111, Fax: +81.32.8251

Research Overview:

Micro-joining has emerged as a major element of the micro-assembly and micro-mechanics technologies receiving significant interest today.

Attention has been paid to low temperature bonding by means of Argon atom bombardment, because the process is expected to apply to heat sensitive materials and delicate micro-devices and mechanics.The method is based on the fact that when two clean surfaces are brought into contact, strong adhesive bond forces can develop at the interface between the solids. This project aims to develope techniques to overcome the process assembly problems including a general reduction in process tolerances, surface contamination and distortion of components due to heating and pressure during bonding.

Research Topics:

1) Surface activation technology

The standard joining (mainly solid phase bonding or soldering) require clean surfaces to be able to achieve high integrity adhesion. With micro-components decreasing in size, contamination problems are more critical. Sputter-cleaned technique by Argon atom bombardment has been developed as the surface activation method for low temperature joining.

2) Surface analytical technique for defining surface condition and to quantify its effect on bondability.

The UHV bonding apparatus has been developed, in which surfaces of specimens to be bonded can be analyzed in-situ by AES and SIMS.

3) Flip chip bonding process with fluxless

Argon beam cleaning and heating is shown to be well suited for reflowing solder pads for subsequent joining of circuit chips to substrates.The process can eliminate the need for chemical flux in obtaining high quality solder joints.

4) Silicon bonding

Interest is now being directed towards silicon to silicon, metals and glass bonding for which processes have not yet been demonstrated. A number of techniques offer potential for this materials, and trials will be carried out using electrostatic bonding, diffusion bonding, eutectic bonding and adhesives. Work will be directed towards developing low temperature bonding procedures.

Reference:

1) M.HORINO,A.KOHNO,"Low temperature bonding with an interlayer of In-Sn alloy", Preprints of the national meeting of Japan Institute of Metals, p.265 (1987)

2) M.HORINO,A.KOHNO,K.TAGUCHI,"Effect of bonding circumstances in low temperature bonding ", Preprints of the national meeting of Japan Institute of Metals, p399 (1991)

3) M.HORINO,A.KOHNO,K.SAHARA," Activation process for surface of solder bumps on LSI chip" Preprints of the national meeting of Japan Welding Society, p396 (1991)

Primal Scientist: Kazuo SATO
Affiliation: Mechanical Engineering Research Laboratory, Hitachi, Ltd.
Address: 502 Kandatsu, Tsuchiura, Ibaraki 300, Japan
Phone: +81.298.32.4111 Fax: +81.32.8251

Research overview:
Silicon micromachining technology and its applications are investigated. Activities on anisotropic chemical etching technology is outstanding. Orientation dependence of the etch rate has been first measured to the complete orientations[1]. Based on this results, etch profile simulation system has been developed[1]. Novel micromechanical devices has been developed using bulk micromachining technologies including anisotropic[2][3] and isotropic[4] etching processes. Recently, a new type of electrostatic actuator to be applied to gas valve system has been invented[5].

Research topics:
1) Anisotropic etching simulation system[1]:
This system is developed to predict etch profiles of single crystal silicon using an etchant of KOH water solution. The system contains a data base of the etch rate related to the crystallographic orientations. Arbitrary masked area, initial wafer shape, and etching temperature can be considered in the analysis.
2) Silicon capacitive acceleration sensor[2]:
A complicated 3-D structure of the sensor gage has been fabricated by applying multiple steps of anisotropic etching processes, instead of conventional process carried out by a single step. Developed gage structure has minimized cross-sensitivity of the sensor.
3) One-to-one biological cell fusion apparatus[3]:
Micromechanical silicon devices has been successfully applied to biological cell operations. The apparatus has 1584 fusion chambers made on a silicon wafer. A cell pair from different species becomes a hybrid in the chamber.
4) Silicon lens for Scanning Acoustic Microscope[4]:
Single crystal silicon lens has been newly developed to be used in a frequency range of GHz. Controlled isotropic etching system has enabled to fabricate a small concave surface whose radius is less than 50 microns.
5) Electrostatic actuator[5]
Novel electrostatic actuator having a moving film element which is elastically bent in an S-shape has been proposed. The actuator is designed to be applied to rarefied gas valve system. Contrary to the conventional micro valve actuator, it allows a large conductance of rarefied gas flow.

References: [1] Koide, A. et al.: Proc. of MEMS'91, 1991, 216-220. [2] Koide, A. et al.: Tech. Digest of the 11th Sensor Symposium, 1992, 23-26. [3] Sato, K. et al.:Sensors and Actuators, A21-A23, 1990, 948-953. [4] Hashimoto, H. et al.:Tech. Digest of Transducers'91, 1991, 853-856. [5] Sato, K. and Shikida, M.: Proc of MEMS'92, 1992, 1-5.

Silicon micromechanical devices developed by Hitachi, ltd.

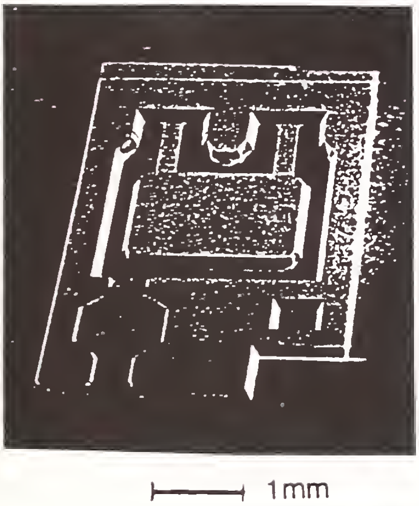


Fig.1 Silicon acceleration sensor chip.

Fig.2 Microchamber array on a silicon wafer applied to biological cell fusion operation.

Fig.3 Silicon lens for scanning acoustic microscopy. Lens body (top) and an enlarged view of the tip(bottom).

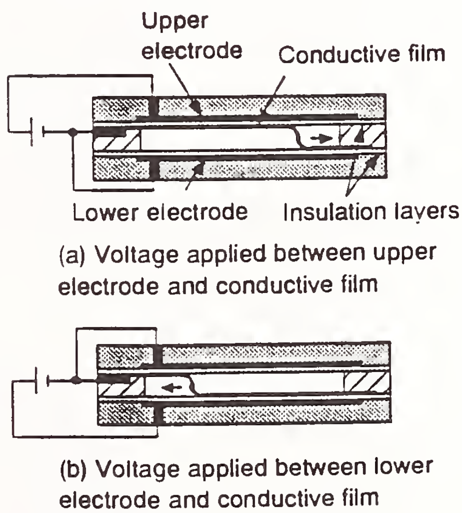


Fig.4 Principle of the S-shaped electrostatic film actuator.

Primal:Teruyuki MATSUI
Affiliation:MEITEC Corp.R&D
Adress:2-20-1 Kohsei-dori, Nishi-ku, Nagoya 451
Number of staffs:4(Hiroshi SHIONO, Hitomi YAMADA, Tomoyasu TAGUSAGAWA, Hiroshi FUKUSHIMA)

Research Overviews

Developments of high accurate x-ray mask to be necessary to fabricate the submicron patern on either planar or non-planar surfaces, such as the cylindrical and irregular structure have been performed. X-ray mask consists of 3-um thick Si menbrane as an x-ray transmitting material and submicron patterned metakkic film on Si menbrane as an x-ray absorbing material. For the high accurate x-ray mask, it has been aimed to form an x-ray absorbing metallic film with the stress free by controlling the film composites and their formation conditions. The micropattern formation technology on non-planar surface has been developed by using plasma polymerization technique which can photochemically react in dry-developable process under UV irradiation. At present, the application of this technology to microactuator formation is under investigation.

Researce Topics

(1)High accurate x-ray mask

It is aimed to form the mettalic film with the stress free on 3-um thick Si membrane by investigating the metallic material, formation process and their formation conditions.

(2)Fabrication technology on non-planar surface

Fabrication technology of precise micropattern on cylindrical or irregular structure have been investigated by the development of the plasma polymerized film technique which can photochemically react under UV irradiation.

(3)Fabrication of flexible microactuator

Developments of flexibly movable microactuator to be applicable to handle the micromechanical parts and that of assemblized technology to drive the microactuater with the resolution of micro-order are under investigation.

Research results in fiscal year of 1993

(1)Fabrication of flexible microactuator

Cantilever type flexible microactuator based on the sandwitched structure of polyimide/metallic film heater/polyimide was fabricated by thin film process. As the driving mechanism, the bending motion induced by the difference of thermal expansion coefficients between polyimides during charging process of the metallic film with electricity was used. It was observed that the each cantilever could be driven by applying 1 V with the frequency range from 1 to 10 Hz.

References

(1)H.Fukushima, et.al.,"X-ray absorbing and mechanical properties of Au-C film for x-ray lithography", SPIE(7-8 March 1990)

(2)H.Yamada,et.al.,patent application, No.200894

(3)T.Tagusagawa,et.al.,"Fabrication of the flexible cantilever type microgripper by thin film process ",'94 MEMS abstract(in preparation)

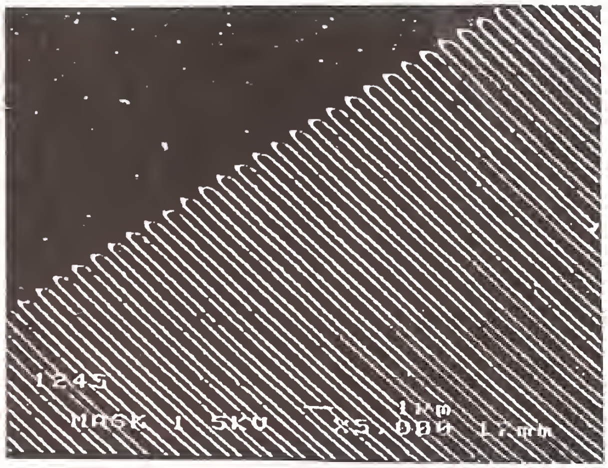


Fig.1 Submicron pattern of x-ray absorbing metallic film

Fig.2 Micropattern formed by non-planar dry-developable fabrication process

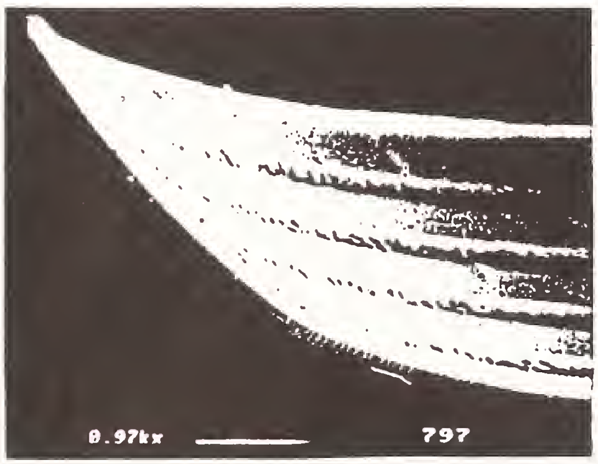


Fig.3 The tip of cantilever type microactuator fabricated by thin film process

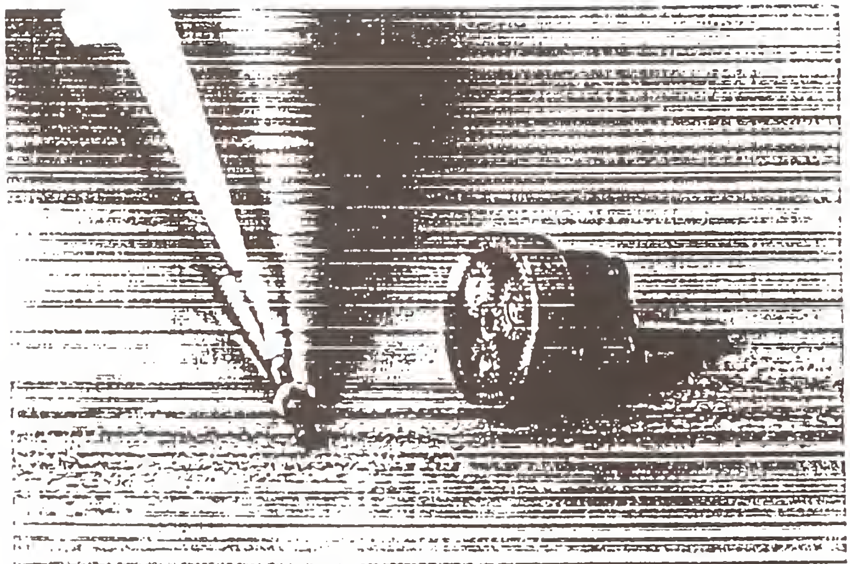


Fig. 2 Speed-Up Planetary Gears

The specification is as following;

1) Diameter of sun gear : 0.96 mm
2) Diameter of planetary gear :1.62 mm
3) Gear ratio : 31
4) Maximum output speed : 0.25 million rpm
5) Processing of gears : Electrical discharge machining

Primal Scientist: Tomoki FUNAKUBO

Affiliation: Production Engineering Dept. of OLYMPUS OPTICAL CO.,LTD.

Address: 2951,Ishikawa-cho,Hachioji-shi,Tokyo,Japan 192
Tel.0426-42-2111 Fax.0426-42-2109

Number of staffs: 7

Research Overview:

Study of Ultrasonic Motors and Piezoelectric Actuators.

We have been studying ultrasonic motors and actuators which are driven by piezoelectric effect. Based upon our study,we have been developing X-Y Stages to which the above motors and actuators were applied.

Research Topics:

(1)Two-dimensional drive ultrasonic motor
(2)Linear drive ultrasonic motor
(3)Rotary drive ultrasonic motor
(4)Multilayered piezoelectric actuator
(5)X-Y Stage using two-dimensional drive ultrasonic motor[1)]
(6)X-Y Stage using multilayered piezoelectric actuator[2)]

Research Result in fiscal year of 1992:

High-resolution X-Y Stage using two-dimensional drive ultrasonic motor :

We have developed an ultrasonic motor which is capable of driving a slider two dimensionally. And we have made a X-Y Stage which is directly driven by the ultrasonic motor. The dimensions of the X-Y Stage is $40 \times 40 \times 53$ (mm). The stroke of X-Y Stage is 8×8 (mm). The following results of X-Y Stage characteristics were known: Resolution of displacement is 5 (nm); Response time is 1 (msec); Maximum speed is 50 (mm/sec).

References:

1)T.Funakubo,T.Tsubata,T.Fujimura,"High-resolution X-Y Stage using two-dimensional drive ultrasonic motor" the 1992 Spring Meeting of the Japan Society for Precision Engineering (1992) 341
2)H.Adachi,T.Funakubo,"Detecting Instrument for detailed surface form" , ELECTRONIC CERAMICS 22 No.10 (1991) 41

"High-resolution X-Y Stage

using two-dimensional drive ultrasonic motor"

Tomoki FUNAKUBO(OLYMPUS OPTICAL CO.,LTD.)

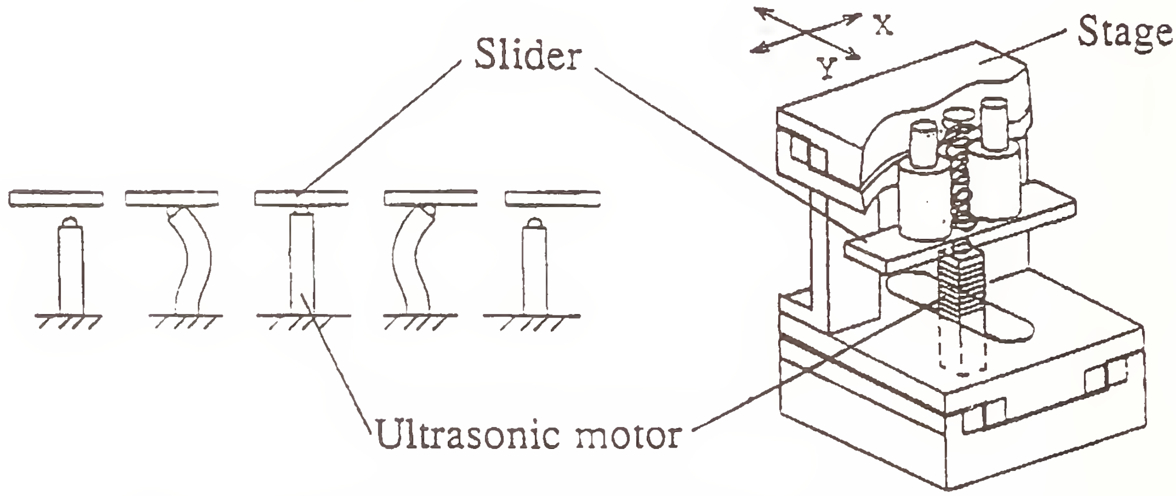


Fig.1 Principle of drive and Outline of X-Y Stage

A slider is driven to any direction on X-Y plane by rotating ultasonic elliptic vibration plane of ultrasonic motor. The stage connected to the slider can be driven to any direction on X-Y plane.

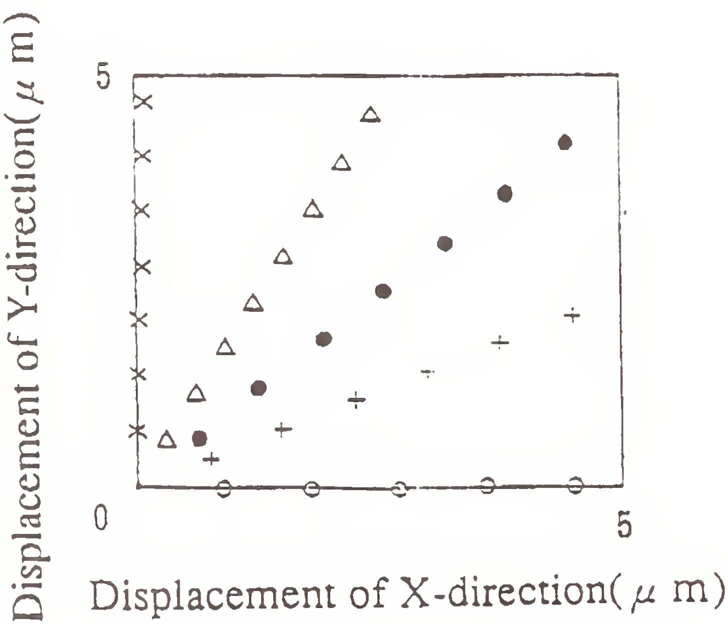


Fig.2 Traces of displacement when X-Y Stage is driven two-dimensionally.

Primal Scientist: Akitoshi Toda
Affiliation: R&D dept. OLYMPUS Opt.Co.LTD.
Address: 2-3 Kuboyamacho Hachioji Tokyo, Japan 192
Tel:+426-91-7111, Fax:+426-91-5709
Number of staffs: 6

Research Overview:
Microfabrication technology applicable for Scanning Probe Microscopy (SPM) have been investigated. *Microfabricated silicon nitride cantilevers* have been studied as a main theme in early days of our study. Combining with a study of *sensors and actuators*, we aim at *new types of SPMs and device* which are able to *use easily in several different environments*. We take "*practical use* " in seriously so that our microfabricated cantilevers have already been applied in our SPM equipments, which have been developed by another group in our laboratry.

Research Topics:
1)Fabrication of the cantilevers with sharp tips:
Sharp tip is essensial in SPM to reveal the sample surface in atomic size resoltion. Tip sharpening methods which make batch fabrication possible, have been studied.

2)Study of interaction between the tip and sample surface:
Surface modification tip is designed for the study. Understanding and Controlling the tip surface is one of our interests.

3)Sensors and actuators:
Sensor and/or actuator included device may change the style of the SPM drastically and widely open up novel applications.

Research results in fyscal year of 1992:
1)Sharpened pyramidal tip; tip radius 15nm, tip vertex angle 50 degree, are successfully obtained by applying *Low Temperature Oxidation process in furnace* into *Micro casting method*
2)Specially *inclined tips* are fabricated. The inclined tips obtain the ideal position towards the sample surface to normal, in usual tilted holding of cantilever tip in SPM equipment

Reference:
1] A.TODA et.al: The Extended Abstructs (The 52th Autumn Meeting 1991); The Japan Society of Applied Physics
2] K.MATSUYAMA et.al: The Extended Abstructs (The 53th Autumn Meeting 1992); The Japan Society of Applied Physics

"Microfabricated cantilever with sharpened tip for SPM"

Akitoshi Toda (R&D dept., OLYMPUS)

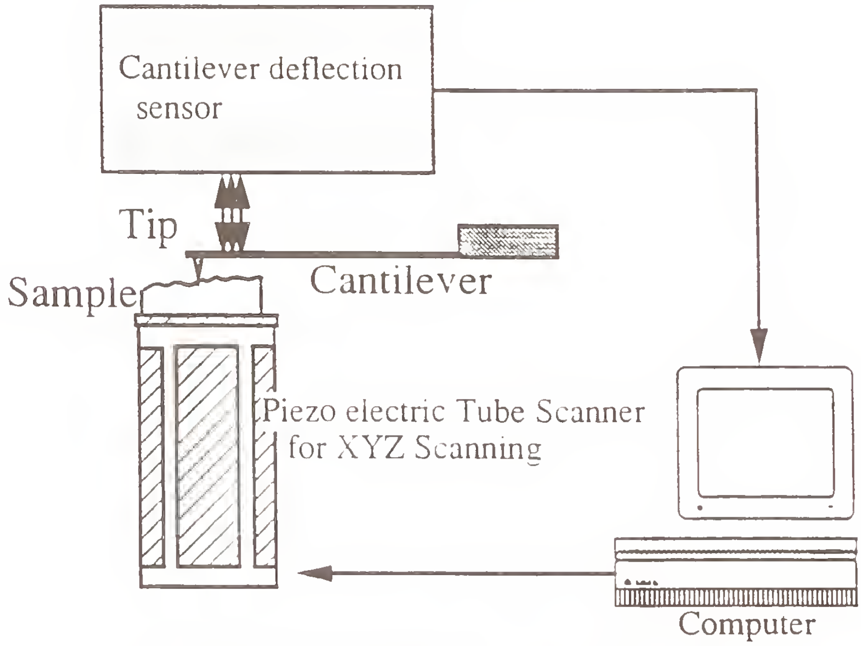
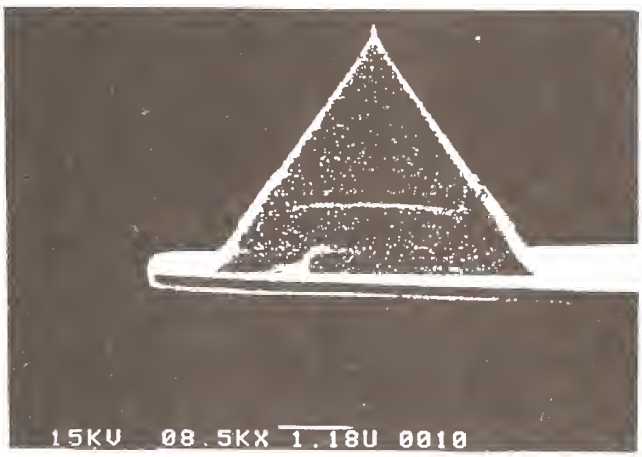


Fig.1 Schematic diagram of SPM



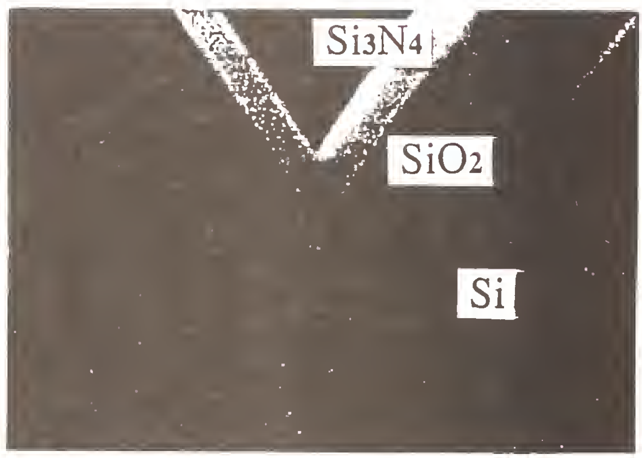


Fig.2 Sharpened pyramidal tip on the end of the cantilever

Cantilever is made by Micro casting method.
Sharpened part of the cantilever tip is presented on from the top about 1 μ m down.

tip radius $\leqq$ 20 nm
vertex angle $\leqq$ 50 degree

Fig.3 Deformed pyramidal etch pit as a micro cast of silicon

Etch pit on the silicon wafer is deformed by Low Temperature Oxidation in furnace. Silicon nitride is deposited on it. Sharpened silicon nitride tip is obtained after whole etching of silicon and oxide layer.

Primal Scientist: Kohei HORI
Affiliation: Energy and Mechanical Research Labs, R&D Center, Toshiba Corporation
Address: 4-1, Ukishima-cho, Kawasaki-ku, Kawasaki-shi, 210, Japan
Tel.+44-288-8087, Fax. +44-288-8214
Number of Staffs: 2

Research Overview:
A micro planetary reduction gearing has been developed for micro-mechanisms. In spite of a simple configuration with only six gears, the gearing has a higher gear ratio than 40:1. These microgears were machined by a wire electric discharge machining (WEDM) which is able to cut hardened steel with a high aspect ratio, and they were assembled. The gearing was driven by a DC motor and functioned to drive certain load successfully. We plan to make a smaller one.

Research Topics:
1) Gearing: A 4.25mm in diameter gearing with Mechanical Paradox was developed.(see Fig.1)
2) Gear design: The gearing has external and internal involute profile shifted spur gear of 0.08 module. Each gear has a fine tooth profile which was designed correctly to avoid all kinds of interference for each meshing.
3) Microgear machning: Using fine wire electrode of 0.025mm in diameter, all the external and internal gears were machined by the WEDM. The smallest gear has a tooth tip circle diameter of 1mm.(see Fig.2)
4) Microgear inspection and assembly:

Research results in fiscal year of 1992:
1) Micro machining: The miniaturization of the gearing depends on that of the six gears. We have been trying to make smaller one, and have achieved a involute gear of 0.04 module which has a half size of the former one.(see Fig.3)

Reference:
1] K.HORI, A.SATO, "Development of micro planetary reduction gear", Proc. of '90 Autumn Meeting, JSPE, pp.67(Oct-1990)(in Japanese)
2] K.HORI, A.SATO, "Micro planetary reduction gear", Proc. of 2nd Int'l Symposium on Micro Machine Science, pp.53(1991)
3] K.HORI, "Development of micro planetary reduction gearing (Wire Electric Discharge Machining of Micro Gears)", Proc. of '92 Symposium on Robotics and Mechanical-electronics system, JSME (1992)(in Japanese)

"Micro Planetary Reduction Gearing" (1)

Kohei HORI (R&D Center, Toshiba Corporation)

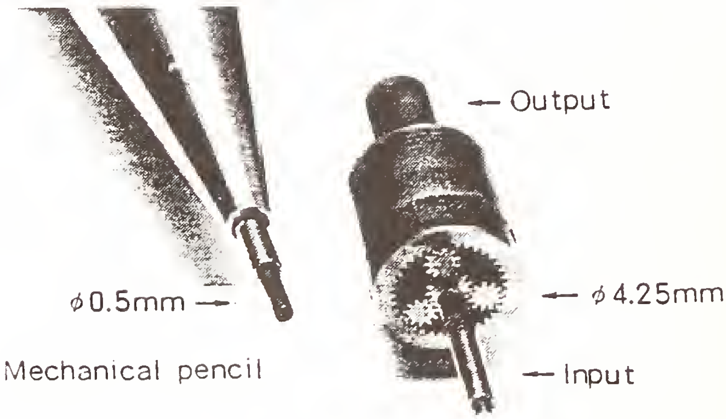


Fig.1 Micro Planetary Reduction Gearing (without gear case)

The gearing has a high gear ratio of 44.2:1. This is suitable to connect to a motor and load because both the input and output are coaxial.

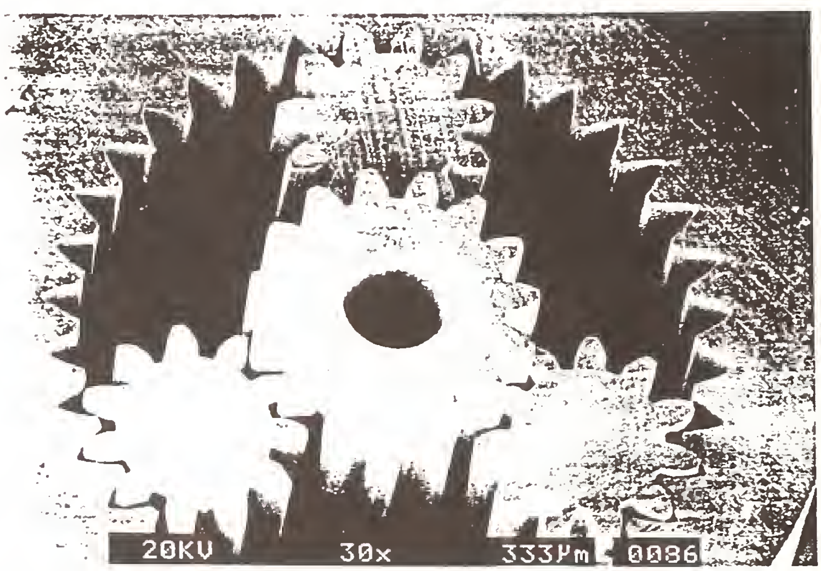


Fig.2 Detail of Micro Planetary Gearing

These micro external and internal gears of 0.08 module were machined by WEDM. This is also suitable for miniaturization because of a simple configuration without a carrier and bearing to support planet gears.

"Micro Planetary Reduction Gearing" (2)

Kohei HORI (R&D Center, Toshiba Corporation)

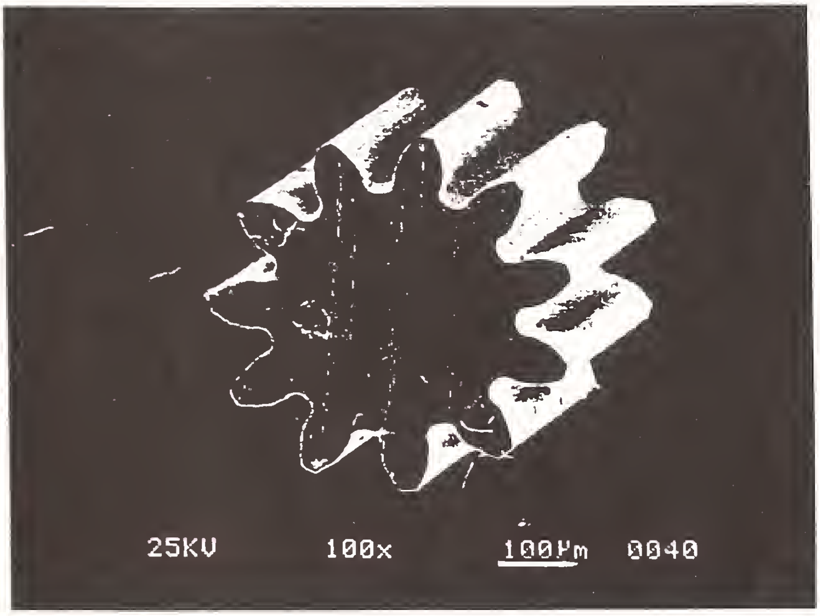


Fig.3 Result of trial gear cutting by WEDM
We plan to make smaller gearing, and tried to cut a gear of 0.04 module, 0.5mm in diameter and 1mm long.

Primal Scientist: Manabu Okamura

Affiliation: Small Motor Developement Center
Manufacturing Engineering Research Center
Toshiba Corporation

Adress: 4–21 Yoshihara–cho,Nishi–ku,Nagoya 451,Japan
Tel.+81–52–532–6389, Fax.+81–52–524–0920

Number of staffs:

Research Overview:

Electromagnetic small motors used in various fields have been developing.

Research Topics:

1) Research of Motor speed control system
2) Manufacturing of Miniaturized motor

Research results in fiscal year of 1992:

1) Electromagnetically actuated ultra small DC motor
Axial gap type motor 0.8mm in external diameter

References:

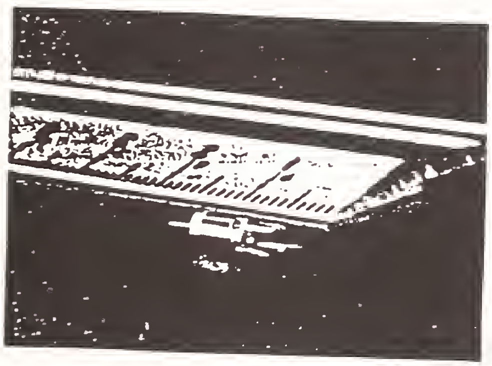
1] H.Izawa, et al.," Slow Speed Brushless DC Motor Control System With Linear Voltage Drive" , SPC–92–35, presented in the IEEJ, Okayama, Japan

2] T.Itoh, M.Okamura," Development Of Ultra Small DC Motor" , 3rd International Symposium on Micromachine and Human Science, pp.27–33, 1992

" Ultra Small DC Motor"

–Electromagnetic motor–

Manabu Okamura (SMC, Toshiba Corporation)



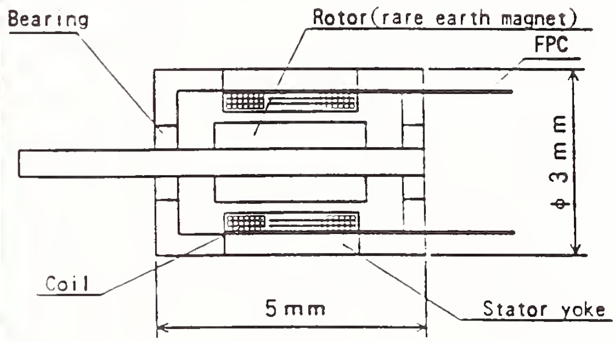
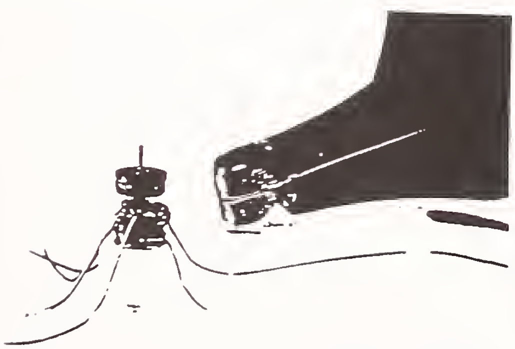


Fig.1 Cylindrical motor(3mm x 5mm)



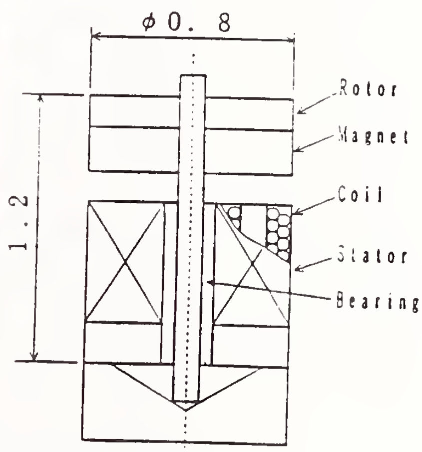


Fig.2 Axial gap motor (0.8mm x 1.2mm)

Primal Scientist: Koichi SUZUMORI
Affiliation: Energy and Mechanical Research Labs, R&D Center, Toshiba Corporation
Address: 4-1, Ukishima-cho, Kawasaki-ku, Kawasaki-shi, 210, Japan
Tel.+44-288-8087, Fax. +44-288-8214
Number of Staffs: 2

Research Overview:
A new type of pneumatic actuator, named Flexible Microactuator or FMA, for miniature robots[1] has been developed. FMA has so simple structure that it is easily miniaturized. FMAs have been applied to several miniature robot mechanisms such as fingers, arms, and legs. The robots consisting of FMAs are suitable for inspection tasks in a narrow space and gentle handling of fragile work.

Research Topics:
1) Miniature robot arm[2]: A 4mm-diameter arm with a mini-gripper was developed. It has seven degrees of freedom including the gripper. (see Fig.2)
2) Robot hand[2]: Multi-fingered robot hand with simple mechanism was developed. It can handle fragile and complicate shaped works with ease.
3) Miniature walking robot[3]: The actuator, FMA, can easily achieve leg motions. A prototype shown in Fig.3 is 15mm long and weighs 1 gram.
4) Pipeline inspection robot[4]: The actuator is also applied to inspection robots in a small pipeline. A prototype was made of serially connected two FMAs and its snake-like movements drive the robot in 1mm internal diameter pipelines.

Research results in fiscal year of 1992:
1) Pipeline inspection robot[4].

Reference:
1] K.SUZUMORI, et al., "Flexible Microactuator for Miniature Robots", IEEE Workshop on Micro Elector Mechanical Systems, pp.204-209 (Jan.-1991)
2] K.SUZUMORI, et al., "Applying a Flexible Microactuator to Robotic Mechanisms", IEEE Control Systems, Vol.12, No.1, pp.21-27 (Feb.-1991)
3] K.SUZUMORI, et al., "Miniature Walking Robot Using Flexible Microactuators", 2nd Int. Symp. on Micro Machine and Human Sciences, pp.29-36 (Oct.-1991)
4] K.SUZUMORI, et al., "Applying Flexible Microactuators to Pipeline Inspection Robots", IMACS/SICE Int. Symp. on Robotics, Mechanics, and Manufacturing Systems, pp.631-636 (Sep.-1992)

"Flexible Microactuator (FMA)" (1)

Koichi SUZUMORI (R&D Center, Toshiba Corporation)

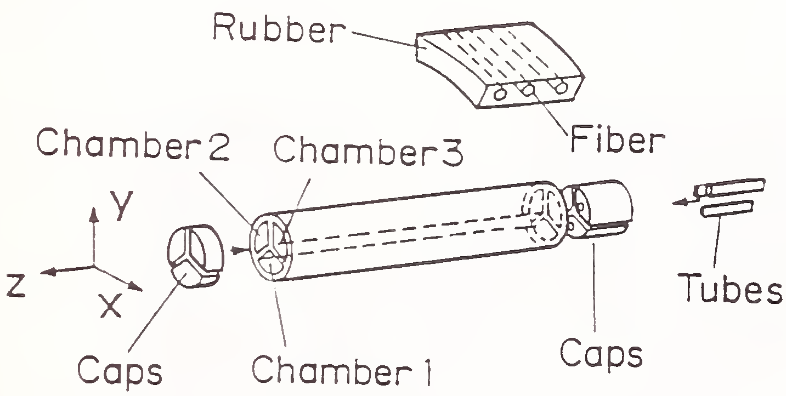


Fig.1 Structure of Flexible Microactuator (FMA)
The actuator is made of fiber-reinforced rubber and is driven pneumatically or hydraulically. Independent pressure control in each chamber causes FMA to move smoothly and easily in all directions.

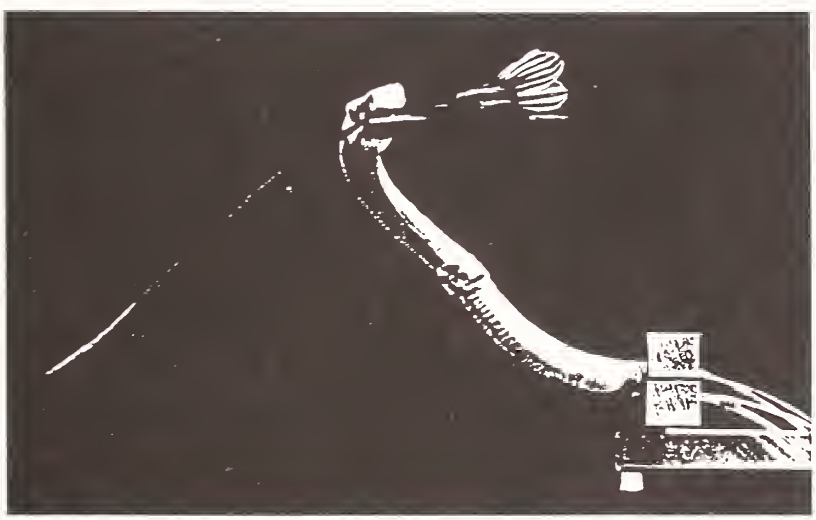
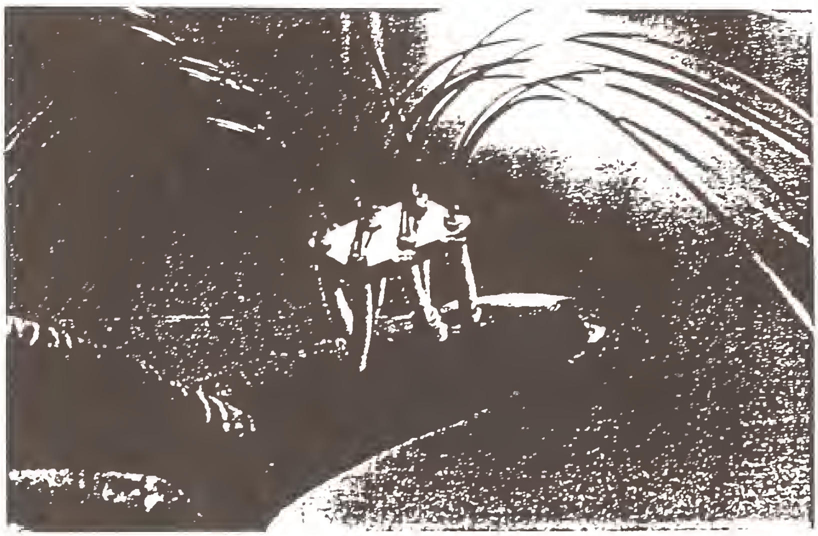


Fig.2 Miniature robot arm, 4mm in diameter
By connecting the actuators serially, we get an arm with many degrees of freedom and snake-like movements. This prototype consisits of two FMAs and a mini-gripper. It can accomplish delicate tasks.

"Flexible Microactuator (FMA)" (2)

Koichi SUZUMORI (R&D Center, Toshiba Corporation)



<u>Fig.3 Miniature walking robot</u>
It is 15mm long and weighs only one gram. Each leg is just 2mm in diameter.
It can walk omni-directionally.

アンケートの回答

１９９２．１０．２０
横河電機株式会社
デバイス研究所マイクロマシンＧｒ
山岸秀章

1. Affiliation
横河電機株式会社
技術開発部門デバイス研究所
マイクロマシンＧｒ

2. Adress
〒１８０東京都武蔵野市中町２－９－３２
ＴＥＬ：０４２２－５２－５５５１
ＦＡＸ：０４２２－５２－４８９２

3. Research Overview
シリコンを中心としたマイクロマシニング技術によるセンサ、アクチュエータの研究開発

4. Research Topics
１）通産省の大型プロジェクト「マイクロマシン技術」に参画し、超小型の光分析システムの要素技術開発に取り組んでいる。
２）水晶のマイクロマシニングによるセンサ、アクチュエータの開発。
３）シリコンダイアフラム上に形成した歪センサによる圧力センサの開発。

5. References

１）T.Ueda,F.kohsaka,D.Yamazaki,T.Iino：Quartz Crystal Micromechanica Devices, Transducers'85　［ﾏｲｸﾛﾘｿｸﾞﾗﾌｨ］
２）K.Ikeda, H.Kuwayama, T.Kobayashi, T.Wtanabe, T.Nishikawa, T.Yoshida：Three Dimensional Micromachining of Silicon Resonant Strain Gage, 7th Sensor Symposium,1988.　［３次元加工］
３）K.Ikeda, H.Kuwayama, T.Kobayashi, T.Wtanabe, T.Nishikawa, T.Yoshida, K.Harada：Silicon Pressure Sensor Integrates Resonant Strain Gauge on Diaphragm,Sensor and Actuators,A21-A23,1990　［３次元加工］
４）S.Miyazaki,T.Kawai,M.Araragi："A Piezo-Electric Pump Driven by a Flexurai Progressive Wave", CH2957-9/91,1991 IEEE ［傾斜機能材料］
５）K.Ishii,N.Tawaragi,I.Inamura,Y.Suzuki,M.Araragi,"High-Temperature Pressure Sensor Using ZMR-SOI Structure",Technical Digest of"The 11th Sensor Symposium,pp.131-134,1992.

Worldwide Microfabrication Research and Development

Robert O. Warrington
Director

Institute for Micromanufacturing
Louisiana Tech University
Ruston, Louisiana 71272
(318) 257-2357
FAX -2562
e-mail row@engr.latech.edu

INTRODUCTION

Often defined as an "emerging" technology, the microelectromechanical systems (MEMS) technologies have their roots in research activities back to the early 60s, as the first micro pressure sensors were fabricated using the anisotropic etching method [1]. Since then, the fabrication techniques developed in microelectronics have begun to directly impact the progress in micromechanics. During these years, pioneer research work in electrostatically-driven microstructures has been performed [2] which a decade later found its further development in surface micromachining for sensor formation [5].

During the 1970s, numerous industrial companies were involved in the efforts to commercialize the existing microfabrication technologies for a new generation of products featuring light weight, small volume and high efficiency. Among those pioneers, Texas Instruments succeeded in marketing micro printing elements in computer accessories and terminal products [3]. At the end of the 70s, the controlled anisotropic undercut etching technique was further developed which resulted in microcantilever beams and similar micromechanical structures.

The continuing exploitation of VLSI processing methods in the 1980s has opened considerable opportunities for the further invention of unique silicon-based micromechanical devices as well as the creation of new markets [4]. In response to the growing need for application specific integrated circuit chips (ASICs), custom design and fabrication facilities have been implemented. The concept of the "IC Foundry" quickly found its expression as the "Silicon Micromechanics Foundry" in the development and production of micromechanical structures [6]. Also during this time, based on a combination of deep-etch lithography and subsequent high-precision replication, a new micromachining technique, known as the "LIGA" process, was introduced in Germany for producing three dimensional microstructures [7]. Innovative improvement and modification to this process have subsequently been made by researchers at the University of Wisconsin [17]. Besides conventional electromagnetic actuators, various types of electrostatic motors and actuators featuring simple structure, micro size and high force/volume ratio were developed worldwide [8] - [11]. Also, different materials were investigated for possible applications in the micro robot domain, such as the shape memory alloy (SMA) [12].

Parallel to the endeavors of pushing ahead the micromanufacturing technique down to the order of submicron and nanometer scales, there have been numerous activities reported which focus on applying different micromachining technologies to fabricate end products which are mainly mini with microcomponents, such as the microcompact heat exchangers produced with diamond bit cutting [13]. To meet the increasing need for metrology and products inspection in the submicron and nano scale, atomic-force microscopes are under further development [14]. Also, micro EDM, molding, plating and many other new techniques are emerging to augment the microsensor and actuator fabrication [16]. It is evident that micromanufacturing technologies will lead to commercialization of revolutionary devices which will dramatically change our lives in the 21st century.

The rest of this paper will describe recent worldwide activities in MEMS, including the Louisiana initiatives in MEMS through the newly formed Institute for Micromanufacturing at Louisiana Tech University and their collaboration with the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University.

MEMS ACTIVITIES IN THE UNITED STATES

The Institute for Micromanufacturing (IfM) and the Center for Advanced Microstructures and Devices (CAMD)

The Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University was established in 1987 by a grant from the Department of Energy. The facility currently consists of an electron storage ring with a linac injector, two beam-lines which are under construction, and ancillary equipment. The Institute for Micromanufacturing (IfM) at Louisiana Tech University was established in 1991 by grants from the Department of Energy. This institute consists of a research building for multiple process micromachining, cleanrooms, process equipment, and state-of-the-art metrology and testing equipment. Additional equipment and line item funding for personnel, operating and supplies, for both facilities has been provided by the state of Louisiana. CAMD synchrotron is very close to being operational with the first beamlines due to be installed shortly. The institute building is currently under architectural design and construction should start by late 1992 or early 1993. Staffing for both facilities is underway. A more complete description of CAMD and IfM are given below.

The Institute for Micromanufacturing is composed of three components. The focal point for the Institute for Micromanufacturing will be the component for research and development located on the Louisiana Tech University campus in Ruston. A second component will be associated with the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University in Baton Rouge. This component will perform research associated with the X-ray lithography micromachining capability at CAMD. The third and final component of the Institute is Technology Transfer. This component will be located in Shreveport/Bossier in order to take advantage of the unique opportunities and resources offered in this region. There will be a strong interaction among the three components of the proposed Institute and each of the components will interact, to varying degrees, with universities, industries and research centers within the state and region.

A major strength of the institute will be the complete integration of multiple process microtechnologies which will span the spectrum from nano to macro. Macro, mini, micro and nano are all a part of MEMS or micromanufacturing. An important component of the institute will be the development of minidevices with microcomponents requiring nanomeasurements with connections to the macroworld. These minidevices could very well become the economic drivers of the technology well into the next century.

The research and development component will consist of a new 43,000 sq. ft. building which will accommodate institute faculty, graduate students, visiting scientists and engineers. Almost 20,000 sq. ft. of laboratory space will include space for metrology and testing (2,700 sq. ft.), lithography (initially over 3,000 sq. ft. of class 1000/100 cleanroom space will be available, expandable to 5,500 sq. ft.), and alternative micromachining technologies such as energy beams and EDM. The entire floor of the laboratory area will be isolated from the structure and, in addition, many areas within the laboratory space will be isolated from the main floor pad. The laboratory bay will be kept at 68 ± 1 °F and 45 ± 5% relative humidity. Four areas of concentration will be developed within the facility at Louisiana Tech University. They are:

* The design and fabrication of microdevices, such as micro-motors, actuators, sensors, pumps, valves, and connectors.

* The design and fabrication of microstructures, such as micro-heat exchangers, filters, distillation columns and supports for micro-devices and systems.

* Research related directly to the manufacturing processes, including fabrication, metrology assembly and testing of the microproducts mentioned above.

* Microsystem research involving the integration of these microdevices/structures and interfacing of these systems with the macroworld.

Several technologies will be developed and used for the fabrication of these micro devices and structures. First, the existing capabilities in diamond bit machining at Louisiana Tech University will be enhanced. Micro electrical discharge machining capabilities are being acquired along with micro drilling and power beam micromachining (excimer laser and focused ion beam) will be developed. Second, conventional photo lithography and chemical etch will be developed and used for the fabrication of low aspect ratio devices and structures. Third, as X-ray lithography technology becomes available at CAMD, Louisiana Tech and LSU researchers will utilize a dedicated beam line to fabricate high aspect ratio devices and structures. Finally, research and development will be performed on small machines techniques that can build and assemble these microproducts.

The x-ray lithography component for high aspect ratio structures and devices consists of a dedicated beam line (off of the electron storage ring at CAMD and associated equipment specifically for the fabrication of high aspect ratio structures and devices. Researchers from Louisiana Tech and Louisiana State University will work at CAMD on research directly related to the fabrication of microdevices and structures using selective etch techniques and the X-ray depth lithography available at CAMD. Direct communication with the component of the Institute in Ruston, will facilitate the design and fabrication of the structures and devices at the CAMD facility. This type of machining is currently available at only KfK in Karlsrhue, Germany and the University of Wisconsin.

Of course, one of the key components of the institute will be the synchrotron light source. This electron storage ring has been optimized for soft X-ray lithography [15]. The CAMD storage ring has an energy of 1.2 GeV with 400 Ma circulating current. The ring can operate at 1.4 GeV with a decrease in circulating current to 200 Ma. The mean radius of the ring is 8.78 m with a circumference of 55.2 m. The ring has been designed with four straight sections, one of which is used for the 200 MeV low energy injection for the linac. The other three sections will be used for insertion devices such as undulators and wigglers.

The beamline for the micromachining application is currently being designed. Preliminary specifications for the line are that the line must transmit photons of 2 - 8.5 KeV and the high energy transmission must be less than 15% at 10 KeV. The photons must be incident vertically over a field of view of 50 mm horizontally with a uniformity of ± 3% and with a beam spot of less than 3 mm height. The beamline must be capable of exposing 100 micron thick 50 mm x 25 mm PMMA resists to a minimum of 4 kj/cc and a maximum of 20 kj/cc in less than 120 seconds with the CAMD storage ring being operated at nominal conditions. The beamline will have a calorimeter and beam position sensor which has a resolution of better than .05 mm for the vertical direction. The beryllium window must be of variable thickness and the transverse window size must be 10 mm x 50 mm. The beamline must be compatible for operation with a superconducting wiggler insertion device.

In addition to micromachining the following uses are anticipated for the facility:

* X-ray lithography for sub - .05 micron featured integrated circuits (the ring was optimized for this application).

* Electronic structure, surface science, etc.

* Geometrical structure, crystallography, etc.

* Imaging, microscopy, tomography, etc.

* Medical technology.

* Education of engineers, scientists and technicians.

Technology transfer is intended to help existing manufacturers obtain and use new and existing technologies to modernize their manufacturing processes and improve their productivity. Existence of such a facility should be helpful in attracting new industry as well. Staff members would conduct training at the facility or off-site, as needed, as well as using computer and video linkages to efficiently serve industry. In addition, they would seek to develop markets for existing products, look for new products to be developed.

Two facilities will be available for this activity. Space and limited conferencing facilities will be available at the research and development building on the Louisiana Tech University campus. A larger facility is being planned for Shreveport, Louisiana. This proposed facility of 30,000 sq. ft. will be used for conferencing, technology transfer and for close interaction with the Louisiana State University-Shreveport Biomedical Research Center.

The Institute for Micromanufacturing is currently involved in the integration of different technologies with direct applications. Several examples of this will be detailed. These applications include micro heat exchangers and heat and mass transport at the micro level, smart bearings with self-diagnostic capabilities, advanced ultra-precision air bearings, surface-driven electrostatic micro positioners and shape memory alloy propulsion for micro robots. The following examples are presented to show the breadth of MEMS and its relation to precision engineering.

Micro Heat Exchangers

There are applications of micromanufacturing where the final device is in the "mini" region but has elements in the micro domain. Such a device is a micro heat exchanger. A micro heat exchanger is hereby defined as a device with a heat transfer surface density (heat transfer surface area divided by active heat transfer volume) above 5000. Typical compact heat exchangers have a surface density of only 1000 to 3000. With such a high surface density, micro heat exchangers have a very high volumetric heat transfer coefficient.

The micro heat exchangers currently under development are based on high conductivity copper and precision diamond machining. For the plate-type cross flow heat exchanger, thin foils of oxygen free (SAE alloy CA122) or electronic grade (SAE alloy CA110) are used to form the plates. These foils are typically 125 micrometers thick. In the surface of these foils, micro flow channels are machined with specially contoured diamond tools. This machining is performed on an air bearing spindle to reduce vibration and improve channel surface finish. The size of the channels can be variable but are typically 85 micrometers deep and 100 micrometers wide at the bottom [4]. A machined foil is shown in Figure 1 and a single folw channel is shown in Figure 2. After machining, the foils are stacked such that each layer has its channels running perpendicular to the adjacent layers, thus forming the cross flow device. The stack is then vacuum diffusion bonded and the faces are diamond machined flat. The device is then ready for use.

The current design is very conservative so that the fabrication and operating variables may be more easily identified. Current testing is with a device composed of a total of 80 layers. Thus each fluid side has 1440 flow passages and the total active volume is 1.64 square centimeters. The surface density for this particular device is 6876 square meters/cubic meter. Filtered water at 20° C and 70° C were used as the working fluids. The mass flow rate was typically 0.02 to 0.04 kilograms/second. These operating parameters gave a 2 to 5 atmosphere pressure drop through the core and a volumetric heat transfer coefficient of 45 megawatts/cubic meter-K (log-mean temperature difference). A design model predicts that a device with a volumetric coefficient over 300 mega-watts/cubic meter-K is easily attainable [5].

Smart Bearings with Self-diagnostic Capabilities

Bearings are the fundamental mechanical components widely used in manufacturing and other industrial branches. Though small in volume, they are highly complex in construction, featuring different parts like rolling-elements, raceways and cages. Depending on the type of applications, bearings are mostly sealed up after machine assembly and often used under extreme conditions such as in cryogenic regions or high temperature, corrosive media or ultra high speeds. In case of overloading or overheating, bearing failure will occur and manufacturing precision will suffer greatly or a critical component may fail endangering human life.

An effective way of preventing such critical situations and thus helping to maintain the manufacturing precision and improve the machine operation security is the on-line, real time supervision of bearing operating environment [6]. The environment mainly consists of the bearing load and operating temperature. This can be achieved by equipping the bearings with self-checking and error reporting functions through integration of sensors and microelectronics into the bearing environment. This concept is shown in Figure 3.

The sensors embedded in the "smart bearings" generate real time electronic signals which correspond to the force and temperature variations in the bearing components. The operating signals will be continuously monitored by microelectronic circuitry located in the bearing housing. The operating signals will be compared with pre-determined "threshold" values which represent a critical loading or temperature condition. Should a critical condition exist, a signal indicating potential damage will be sent from an embedded high frequency data transmitter to the machine control system which then can make corresponding adjustments. In using only an overload signal, the control system is not burdened with a continual stream of data. However, to generate critical "signatures", the real-time data can be monitored and stored for subsequent evaluation which will also be beneficial to improving the existing machine control algorithm. A novel feature of the smart bearing is that for data transmission, no direct cable connection will be needed. This wireless method is especially suitable for applications where the accessibility of the measurand is not easily available. Similarly, the power supply for the embedded transducer will be provided through non-contact voltage induction.

In contrast to traditional methods of manufacturing precision controls which focus on post-error adjustment and compensation, instrumented smart bearings will allow on-line error source location and pre-failure adjustment. This method can be very well applied to the high-tech areas like aerospace and the military or automotive industry, where high precision, reliability and accuracy of manufacturing and operation are required.

Herring Bone Air Bearings for Ultra-Precision Spindles

Air bearings of all types (including linear guides, x-y tables, and spindles) have been widely employed in the ultra-precision engineering field to ensure the extremely high precision requirements of machinery such as in diamond-tool machining. The design optimization of the journal air bearing for precision and high performance applications is currently in progress. Among various self-acting air bearings, the herring bone type shown in Figure 4 has been considered as one of the best bearings for high speed spindles due to its high efficiency and high stability. For the best possible bearing design, the relationship between the design specifications and the bearing characteristics, such as load capacity and stability, must be known. However, the design information available in the literature only give a limited number of design specification sets. This information is, in most cases, insufficient for design optimization. Therefore, the design of herring bone bearings, especially when high speed and stability are required, still depends mainly on testing and the experience of the designer. Because of this, the design of herring bone air bearings is still very challenging.

The Reynolds equation, which governs the performance of the air bearing, has been numerically solved by specially developed finite element method programs. Once the solution, that is the pressure distribution over the bearing surface, is obtained, the bearing performance may be simulated in the computer.

The groove pump-in angle β affects the bearing load capacity W, as well as the stability indirectly through the bearing attitude angle Θ, (which is a divergent angle between the eccentricity and the direction of load), as shown in Figure 5. The eccentricity ratio in the figure is defined as a ratio of eccentricity to average bearing clearance ($\varepsilon = e/h_0$), while Λ is a nondimensional parameter used to express the rotational speed and n is the number of grooves. Through such figures, the influence of the design specifications on the performance of the herring bone bearing over the most common ranges have been discussed. Consequently, the design optimization of the bearing has been made possible [7].

Surface-driven Micro Electrostatic Positioner

In the past several years, there has become a growing need for micro-sized motors and actuators for applications in micromanufacturing and other microelectromechanical systems domain (MEMS). Among other topics, the design and fabrication of micro electrostatic motors have found widespread interests. Compared to conventional electromagnetic motors commonly used in the large-scale motion world, electrostatic equivalents promise numerous advantages like simple structure, small size, high force-to-volume ratio and fine motion/step control.

Among different types of electrostatic motors (side-driven, surface-driven and cylindrical harmonic or wobble), the surface-driven version effectively utilizes the whole stator/slider overlapping area so that its force density is the highest. The basic motion principle is that a sequence controlled multiphase excitation voltage pattern (positive, negative and ground) is applied on the electrodes which are either evenly or unevenly pitched on the stator board. This voltage pattern will induce electrical charges in the slider film which is laid on the top of the stator surface. The interaction between the induced electrical charges in the slider film and the applied charges on the stator electrodes results in three types of forces: an upward levitational force which reduces the contact friction between the slider and the stator, a repulsive force between electrical charges of the same polarity and an attractive force between opposite charges. The combined effects of these forces is that each time the voltage pattern is applied, the slider will move a certain length (step), which corresponds to the electrode pitch width, in a certain direction and at a certain speed, depending on the configuration of the excitation voltage pattern. The slider motion will continue when the voltage pattern cycle applied on the electrodes is shifted and repeated. To enable easy modifications and flexible changes of the excitation voltage pattern for any desired slider motion behavior, the electronic circuits are software controlled by a computer. The excitation voltage generation part of the circuits was built with power bipolar and MOSFET transistors. For control unit protection and isolation, opto-couplers were used. In Figure 6, the principle of an electrostatic motor is schematically shown.

The arrangement of the stator electrodes (linear or radial) determines, whether the slider will perform a linear or a rotary motion. The resolution of the motion steps is mainly dependent on the dimensions and manufacturing precision of the electrodes. By appropriate connection of the slider to further mechanism, it can be well expected that high precision positioners, micro conveyors, micro feeders or micro drive systems can be realized which will find wide applications in conventional and micro manufacturing, medical, biochemical, aerospace or other relevant fields.

Biomechanical Micro Swimming Robots Using Smart Materials

The objective of this research is to design and fabricate microrobots with a simple method of propulsion using smart materials instead of electric motors. Such devices can be fabricated at a very small scale and will have a high strength to weight ratio for special applications.

In this study, two types of micro robots will be designed and fabricated with smart materials based on biomechanical similarity principles. The first type, as shown in Figure 7a, is a jellyfish-like robot with an umbrella made of shape memory alloy (SMA) which has the capability of remembering and reproducing its original shape when exposed to a change in temperature. The second type, as shown in Figure 7b, is a tadpole-like device with muscles made of either SMA or piezoelectric materials, which can change dimensions upon electrical stimulation.

The muscles within the umbrella of the jellyfish will be activated by heat generated from an electric current flowing in the SMA, while cooling will come from the liquid through which the robot is swimming. As the umbrella is heated, it will contract and will result in forward movement of the device. As the umbrella cools, it will return to its original position. With proper design, this impulse will provide a forward propulsion. The muscles on the sides of the tadpole will differentially expand and contract causing the tail to move in a sidewise direction. This reversing process will cause the tail to provide a forward propulsion similar to a fish. The main advantage of this robot is that it is easy to fabricate at small dimensions due to its simplicity of design, it should have high reliability due to the simple movement, and it has high efficiency because no mechanical mechanisms are used.

Designs using SMA materials, and the control systems required for the robots, are often complex and difficult to perform because of the lack of appropriate models. In addition, the hysteresis of the material causes added complexity to the design and fabrication and the hysteresis is not properly understood. A dynamic model of the SMA material has been developed to aid the design and control of the robots. The shape memory effect is the result of a crystalline transformation between two phases of the material and so the model is based upon that phenomenon. From this, the physical properties and behavior of the SMA may be computed for a specific configuration and set of parameters. The SMA is divided into the martensitic and austenitic phases, and the behavior of each is computed for variations in the stress and temperature fields.

To confirm the applicability of the model, a comparison between the model and experimentation was made. In the experiment, TiNi50 wire of 0.1mm diameter and 20mm length was loaded with a 360g mass, and then heated. The heating power was supplied as a square pulse and the wire was allowed to cool by natural convection and radiation into the room at 18 °C. Using heat transfer theory for the heating and cooling process, the simulation was developed for the two phase material. Excellent agreement was found between the simulation and experimental results.

Focused ion beam micromachining

Energy beam micromachining represents a true bridge between lithographic micromachining technologies and the more traditional precision engineering technologies. Shown in Figure [8] is an example of ion beam micromachining. The needle structure is made of tungsten and is 13 microns long and has .7 micron wide vertical members. This technique could be used to micromachine resist to use as a mold for the "back end" of the LIGA process.

Other MEMS Research in the United States

The description of the research activities in MEMS at other locations in the United States will be much briefer and, because of space and time limitations, not all activities will be mentioned below. It has been estimated that the US research expenditures for MEMS is 10-15 million $/yr.

The Berkeley Sensor and Actuator Center (BSAC) at the University of California, Berkeley, is undoubtedly one of the world leaders in MEMS research. They developed the concept of the sacrificial layer and have made many pioneering developments in surface micromachining of silicon. Significant advances in bulk micromachining have been made by the Center for Integrated Sensors and Circuits at the University of Michigan, Ann Arbor. Other focus areas for MEMS in the United States include the University of Wisconsin (LIGA), MIT (robotics, motors,etc.), the National Nanofabrication Facility, MCNC, the Center for Engineering Design (also bridges MEMS and precision engineering), and other university research groups. Several national laboratories have ongoing programs such as Lawrence Livermoore, JPL, and Los Alamos. Industrial players include Lucas Nova Sensors, IC Sensors, Analog Devices, GM Research, Texas Instruments, Delco Electronics, Honeywell and others.

MEMS Activities in Germany

Germany is certainly a leader in Microsystems Technology (MST)- both in research and in educational programs. The talk will outline the level of effort of several of the research groups and will outline the extensive technology transfer efforts and educational programs. Estimates of research expenditures for MST in Germany range from 70 to 100 million $/yr.

MEMS Activities in The Netherlands, Switzerland and Russia

The Netherlands has identified MEMS as a key technology for their future. The focal point for their research is Delft University. Estimates of research expenditures in MEMS run as high as 100 million $/yr. Switzerland has several areas of research in MEMS and includes their watch maker skills in this technology. Research expenditures range from 5 to 10 million $/yr. Russian research expenditures in this area would be impossible to estimate at this time.

A United States-Russia forum on manufacturing, factories of the future, and productivity enhancement was held in St. Petersburg, Russia from 18 to 21 May, 1992. The first author presented a paper on micromanufacturing [18] and interacted with researchers interested in MEMS. In addition to this interaction, several universities and companies were visited in the St. Petersburg area. A follow-on trip to Moscow resulted in a visit and presentation to the recently formed Russian Academy of Sciences (includes engineering and everything else). Several general observations from this visit listed are: 1) the status of MEMS in the United States is not well known in Russia (the reverse is also true); 2) the status of MEMS research in Russia does not seem to be well known by researchers in Russia, particularly what is being done in defense related industries - this is just now becoming available and it appears that everything is opening up; 3) the Russian researchers are eager to collaborate and have initiated some collaborations, particularly with Europe; 4) until the economy stabilizes, their resources (for travel, operating, etc.) appear to be very limited; 5) their higher educational system and structure is currently undergoing major review and it appears that the revisions which will be implemented will incorporate both the US and European (particularly German) systems; and 6) the Russian Academy of Sciences is extremely sensitive and worried about the movement of scientists and bright students from Russia to other parts of the world.

There appears to be considerable activities in MEMS throughout Russia, however, several scientists felt that this was a small field of activity. MEMS interest appeared to be mostly focused on sensors, optics, acoustics, and materials. None of the researchers that were contacted knew of research in micro gears, motors, or systems, however most were interested in extending their work into these areas. Several robotics researchers attended the workshop and indicated that they were interested in microrobots, although none knew of any current research activities in this area. Listed below are a few current MEMS activities from one large microelectronics firm and one university research center.

* Avangard (microelectronics company outside of St. Petersburg)

    - Ion sensor (ion-sensitive field effect transistor), chip size 5 x 1 mm.
    - Multiple gas sensor on chip (up to three) with local calorimetric control and heater temperature control.
    - Acoustoelectronic devices with reflector arrays.
    - Approximately 35,000 sq. ft. of class 1000 (?) cleanroom space.

* Scientific-Educational Center of Microtechnology and Testing (St. Petersburg Electrical Engineering Institute)

    - Bio crystals of phospholipid analogues for sensors and molecular electronics micro actuators.
    - Starting to investigate micromechanical device fabrication.

These facilities were in relatively good shape. Processing equipment used 2-3 inch wafer technology and most of the equipment was of Russian origin. The laboratories were well maintained. however, the cleanrooms were not of high quality. It appears that the many Russian microelectronic industries are not competitive for VLSI but could be very competitive in MEMS.

MEMS activities in Japan and Taiwan

Japan is clearly the leader in research expenditures in MEMS. Estimates run as high as 200 million $/yr. The Minsitry for International Trade and Industry has taken a lead role in the development of MEMS technology and have designated micromachines, particularly microrobots, as their focus. The level of effort in Taiwan appears to be very small, however they have a tremendous amount of capital, good microfabication capabilities, and some interest in developing a program.

Summary

The key to future technological applications will be the ability to rapidly and effectively integrate, as necessary, the macro-, mini-, micro-, and nano-world. Basic science is driving the scale down to, and beyond, the nano-domain. These investigations are necessary to understand material properties and behavior at the fundamental level. These studies are also necessary to understand the fundamental interactions between materials and outside influences such as electrical and magnetic fields, gravity, light, and electromechanical driving forces. Although the science learned at this level will greatly aid in the design and control of micro and nano devices, these devices must still adapt to the macro world.

The Institute for Micromanufacturing is dedicated to the integration of these various domains. Total integration will not be possible at the process level because of the large difference in the dimensional orders of magnitude within the domain. Therefore it is necessary to design and fabricate assist-devices so that either humans or their kinematic extensions can grasp, manipulate, position, adjust, and assemble nano-components or attach/integrate nano-components into a macro- or mini-device. In addition, it will be necessary to develop the speed, sensitivity, reliability, and inspection aspects of micromanufacturing so that these curiosities may move from the laboratory to a production environment.

References

[1] O.N. Tufte, P.W. Chapman and D. Long, "Silicon Diffused-Element Piezoresistive Diaphragms", *J. Appl. Physics*, vol. 33, pp. 3322-3329, 1962.

[2] H.C. Nathanson, W.E. Newell, R.A. Wickstrom and J.R. Davis, "The Resonant-Gate Transistor", *IEEE Trans. ED*, vol. 14, 117-133, 1967.

[3] Texas Instruments Thermal Character Print Head, EPN3620, *Bulletin DL-S7712505*, 1977.

[4] H. Guckel and D.W. Burns, "A Technology for Integrated Transducers", *Transducers '85. IEEE Int'l Conf. on Solid-State Sensors and Actuators, 90-92*, Philadelphia, PA, 1985.

[5] R.T. Howe and R.S. Muller, "Resonant-Microbridge Vapor Sensor", *IEEE Trans. Electron Devices*, vol. 33, pp. 499-506, 1986.

[6] K. Petersen, "The Silicon Micromechanics Foundry", *IEEE*, 87TH0204-8, 1987.

[7] W. Ehrfeld, P. Bley, F. Götz, P. Hagman, A. Maner, J. Mohr, H.O. Moser, D. Münchmeyer, W. Schelb, D. Schmidt and E.W. Becker, "Fabrication of Microstructures Using the LIGA Precess", *IEEE*, 87TH0204-8, 1987.

[8] S.D. Senturia, "Microfabricated Structures for the Measurement of Mechanical Properties and Adhesion of Thin Films", in *Proc. 4th Int. Conf. Solid-State and Sensors and Actuators (Transducers '87)*, pp. 11-16, Tokyo, 1987.

[9] W.S. Trimmer and K.J. Gabriel, "Design Consideration for a Practical Electrostatic Micromotor", *Sensors and Actuators*, vol. 11, pp. 189-206, 1987.

[10] H. Fujita and A. Omodaka, "The Fabrication of an Electrostatic Linear Actuator by Silicon Micromachining", IEEE Trans. Electron Devices, vol. 35, pp. 731- 734, 1988.

[11] S.C. Jacobsen, R.H. Price, J.E. Wood, T.H. Rytting and M. Rafaelof, "The Wobble Motor: An Electrostatic Planetry-Armature Microactuator", in *Proc. IEEE Micro Electro Mechanical Systems*, Salt Lake City, Utah, 1989.

[12] K. Kuribayashi, "Milimeter Size Joint Actuator Using Shape Memory Alloy", *1989 IEEE Micro Electro Mechanical Systems Workshop*, pp. 139-144, Salt Lake City, Utah, 1989.

[13] C.R. Friedrich and R.O. Warrington, "Machining of Metal Foils for Use in Microcompact Heat Exchangers", in *Proc. Micro System Technologies 90*, pp. 509-514, Berlin, Germany, 1990.

[14] L.C. Kong, B.G. Orr and K.D. Wise, "A Micromachined Silicon Scan Tip for an Atomic Force Microscope", *Digest IEEE Solid-State Sensor Workshop*, Hilton Head, S.C. pp. 28-31, 1990.

[15] R.L. Stockbauer, et al, "Center for Advanced Microstructures and Devices at Louisiana State University", Physica Scripta, vol. 41, pp. 788-792, 1990.

[16] J. Simon, G. Engelmann, O. Ehrmann and H. Reichl, "Plating of Microstrutures for Sensors", in *Proc. Micro System Technologies 91*, pp. 315-321, Berlin, Germany, 1991.

[17] H. Guckel, K. Skrobis, T. Christenson, J. Klein, S. Han, B. Choi and E. Lovell, "Fabrication of Assembled Micromechanical Components via Deep X-Ray Lithography", in *Proc. IEEE Micro Electro Mechanical Systems*, pp. 74-79, Nara, Japan, 1991.

[18] R.O. Warrington, C.R. Friedrich, R.X. Gao and G. Lin, "Micromanufacturing, An Emerging Technology", presented at the *1992 US-Russia Forum on Manufacturing, Factories of the Future and Productivity Enhancement*, St. Petersburg, Russia, 1992.

[19] E.W. Becker, H. Betz, W. Ehrfeld, W. Glashauser, A. Heuberger, H.J. Michael, D. Münchmeyer, S. Pongratz and R.v. Siemens, "Production of Separation Nozzle Systems for Uranium Enrichment by a Combination of X-Ray Lithography and Galvano-plastics, *Naturwissenschaften*, 69, 520-523, 1982.

[20] C.R. Friedrich and S.W. Kang, "Performance of High Flux Heat Exchangers Fabricated by Diamond Machining", submitted to *Precision Engineering*, 1992.

[21] R.X. Gao, M. Bhandiwad and R.O. Warrington, "Smart Grinding Balls and Smart Bearings for On-line Process Supervision", to be presented at *7th ASPE Annual Meeting* in Orlando, Fl, October 1992.

[22] G. Lin and T. Satomi, "Characteristics and Optimization of the Spiral Grooved Thrust Air Bearings", *Trans. JSME*, Ser. C, No. 541, vol. 57, pp. 2971-2977, (in Japanese), 1991.

Useful References

1. "Integrated Circuit Fabrication Technology," David J. Elliott, McGraw-Hill, Second Edition, 1989
2. "Semiconductor Lithography - Principles, Practices and Materials," Wayne M. Moreau, Plenum, 1987
3. "VLSI Technology," S. M. Sze, McGraw-Hill, 1983
4. "The Physics of Microfabrication," Brodie and Muray, Plenum, 1987
5. "ESD Program Management," Danglemayer, Van Nostrand Reinhold, 1990
6. "Cleanroom Practices," Kozicki, Hoenig and Robinson, Van Nostrand Reinhold, 1991
7. "Handbook on Synchrotron Radiation," Koch, Volumes 1a, 1b and 2, Elsevier, 1983
8. "Electronic Materials," Warnes, Van Nostrand Reinhold, 1990
9. "Proligh/2 User's Manual," Finle Technologies, 1992
10. "Excimer Laser Lithography," Jain, SPIE Press, 1990
11. "Introduction to Microelectronic Fabrication," Volume 5, Richard C. Jaeger, Addison-Wesley

Useful Journals/Proceedings

1. Journal of Microelectromechanical Systems, IEEE/ASME
2. Sensors and Actuators, Elsevier Sequoia
3. Journal of Micromechanics and Microengineering, Institute of Physics
4. Nanotechnology, Institute of Physics
5. Precision Engineering, Butterworth-Heinemann
6. Transducers — Biannual Conference Proceedings
7. MEMS — Annual Conference Proceedings
8. Symposium on Microlithography — Annual Conference Proceedings
9. Solid State Sensors and Actuators — Biannual Conference Proceedings
10. Micro Systems Technologies — Annual Conference Proceedings

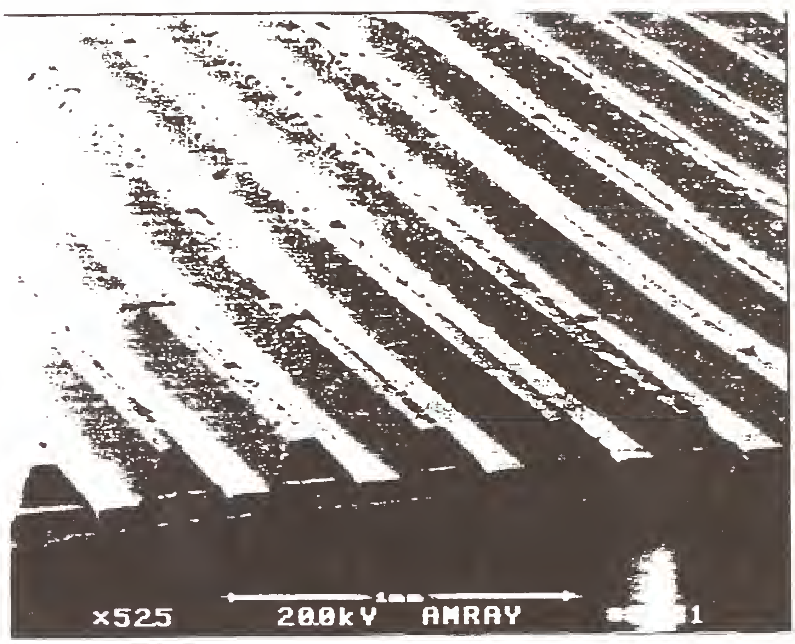


Figure 1. Micrograph of machined flow channels

Figure 2. Micrograph of single flow channel (rms roughness 39 nm)

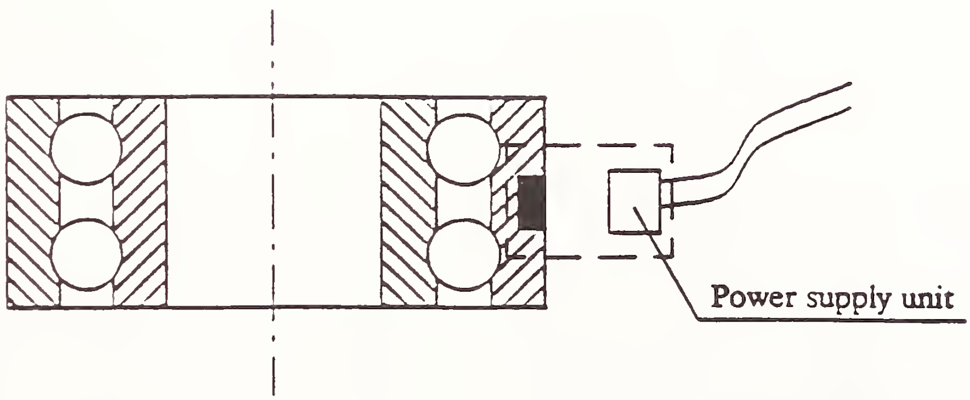


Figure 3. Sensor located in smart bearing

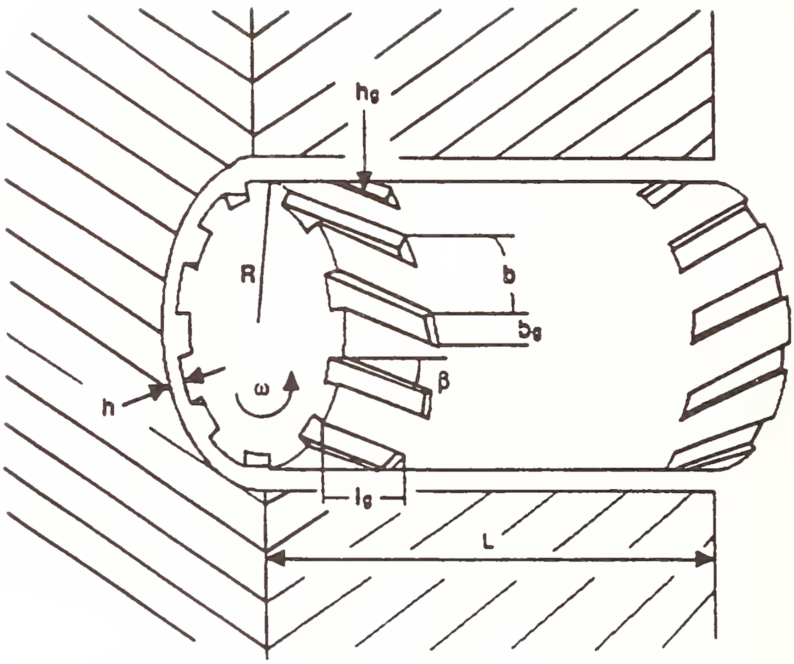


Figure 4. Configuration of a herring bone air bearing

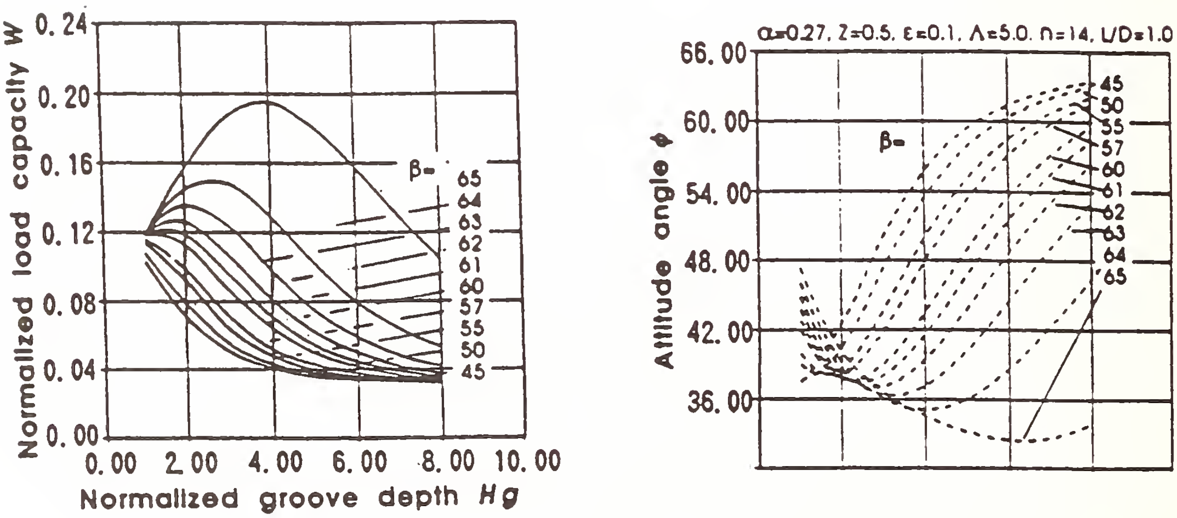


Figure 5. Influence of the groove pump-in angle

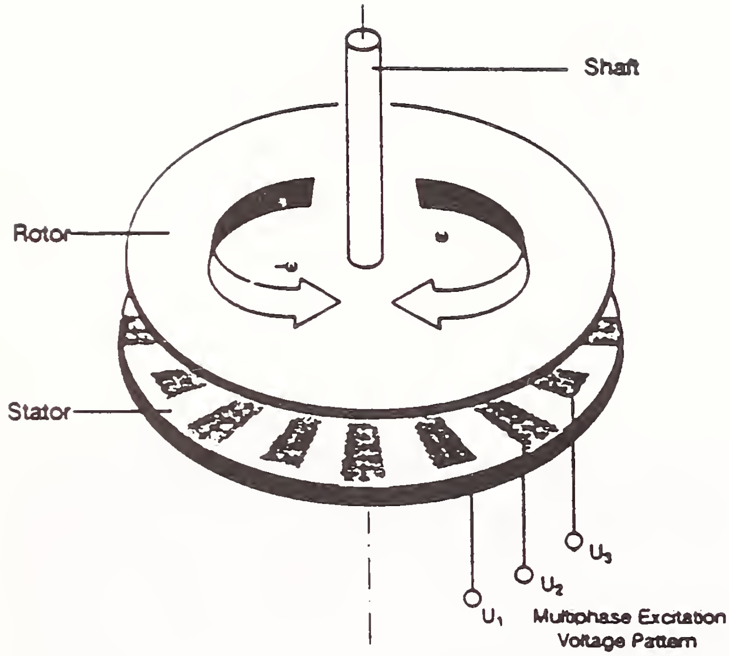
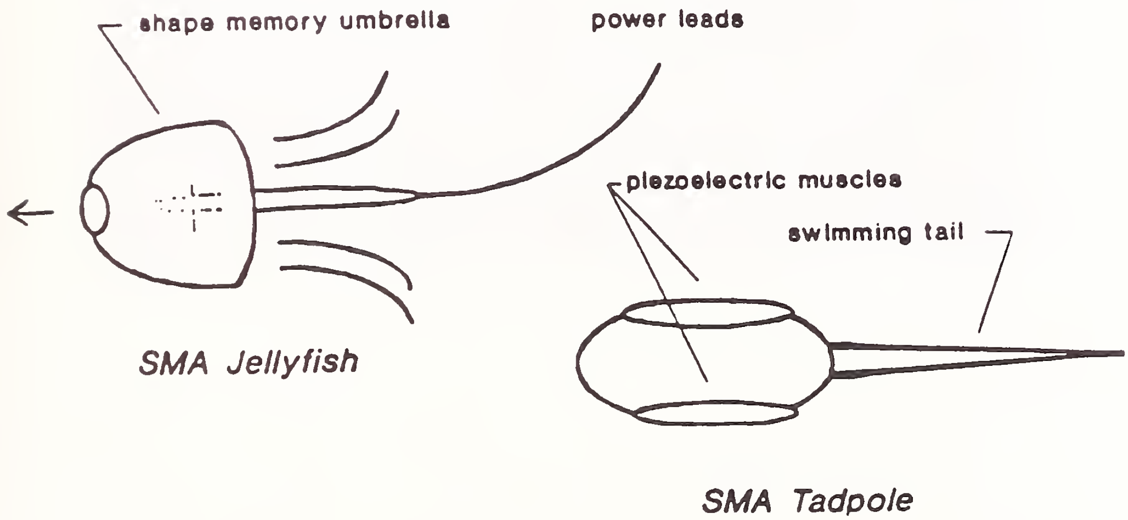


Figure 6. Layout of electrostatic motor



7a. Jelly-fish like robot

7b. Tadpole-like robot

Figure 7. Shape memory alloy robots

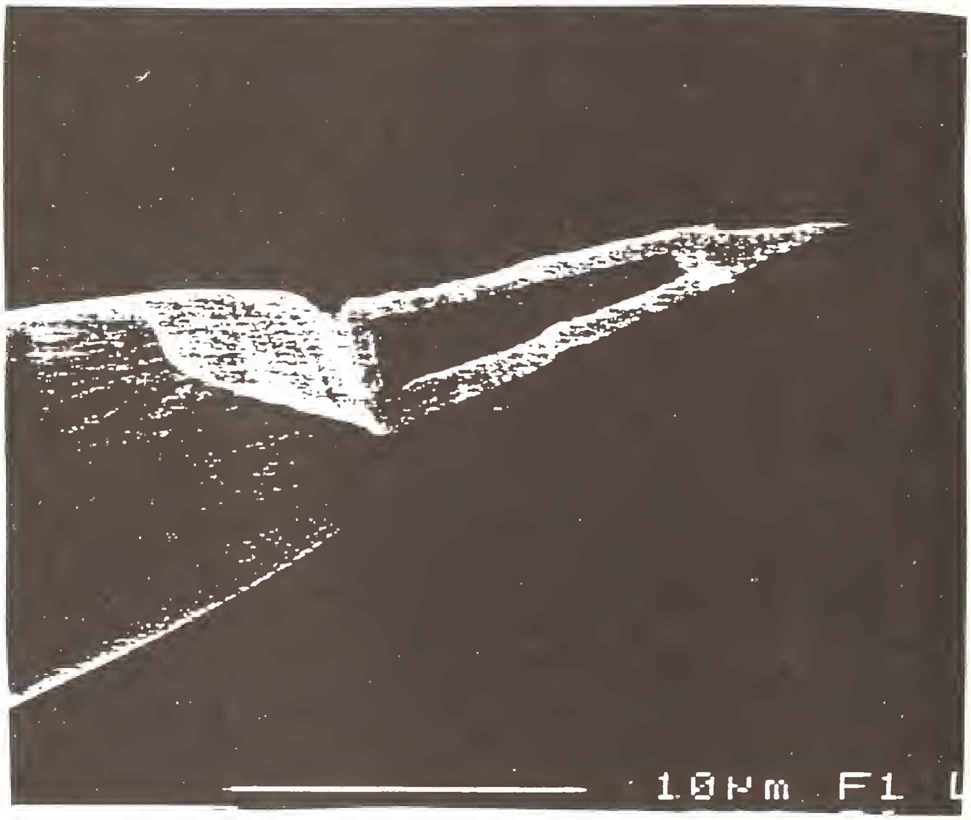


Figure 8. Example of Focused Ion Beam Micromachining

☆ U.S. GOVERNMENT PRINTING OFFICE: 1993—341-932/83025

NIST *Technical Publications*

Periodical

Journal of Research of the National Institute of Standards and Technology—Reports NIST research and development in those disciplines of the physical and engineering sciences in which the Institute is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Institute's technical and scientific programs. Issued six times a year.

Nonperiodicals

Monographs—Major contributions to the technical literature on various subjects related to the Institute's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NIST, NIST annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NIST under the authority of the National Standard Data Act (Public Law 90-396). NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published bimonthly for NIST by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements are available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Institute on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NIST under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NIST administers this program in support of the efforts of private-sector standardizing organizations.

Consumer Information Series—Practical information, based on NIST research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order the **above** *NIST publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

Order the **following** *NIST publications—FIPS and NISTIRs—from the National Technical Information Service, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NIST pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NIST Interagency Reports (NISTIR)—A special series of interim or final reports on work performed by NIST for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service, Springfield, VA 22161, in paper copy or microfiche form.

U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899

Official Business
Penalty for Private Use $300