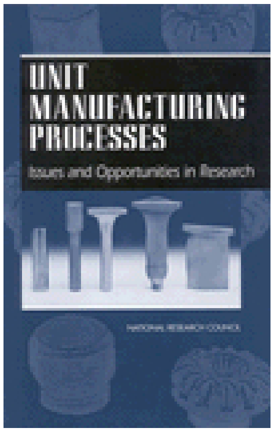

Unit Manufacturing Processes: Issues and Opportunities in Research

Unit Manufacturing Process Research Committee, Commission on Engineering and Technical Systems, National Research Council

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Unit Manufacturing Processes

Issues and Opportunities in Research

Unit Manufacturing Process Research Committee
Manufacturing Studies Board
Commission on Engineering and Technical Systems
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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UNIT MANUFACTURING PROCESS RESEARCH COMMITTEE

IAIN FINNIE, *Chair*, James Fife Professor Emeritus, Department of Mechanical Engineering, University of California, Berkeley

TAYLAN ALTAN, Professor and Director, Engineering, Research Center for Net Shape Manufacturing, Ohio State University, Columbus

DAVID A. DORNFELD, Professor, Department of Mechanical Engineering, and Director, Engineering Systems Research Center, University of California, Berkeley

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MARSHALL G. JONES, Senior Research Engineer and Project Leader, Research and Development Center, General Electric Company, Schenectady, New York

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VERNA J. BOWEN, Staff Assistant
JANICE PRISCO, Senior Project Assistant
THOMAS C. MAHONEY, Director (to April 1994)
ROBERT E. SCHAFRIK, Director (from April 1994)

Consultant

CAROLETTA POWELL, Editorial Concepts, Inc.

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PREFACE

"Why another study of manufacturing processes?" given the host of recent studies concerning manufacturing productivity and national competitiveness. The answer lies in the observation that these previous studies have sought primarily to raise national awareness of problems related to manufacturing and to identify key industries, sectors, or technologies in which the United States has lost, is losing, or may lose its share of the international market. These studies have devoted relatively little attention to the leveraging technologies through which the U.S. industry may regain, maintain, or strengthen its global competitiveness. The need to identify these technologies led the Division of Design and Manufacturing Systems of the National Science Foundation (NSF) to request the Manufacturing Studies Board of the National Research Council to form a committee to conduct the present study.

The overall charge to the committee was to "conduct analyses of key unit processes and determine program areas that NSF, other federal agencies, and members of the industrial base should address." The committee undertook three primary tasks: select a taxonomy for classifying unit processes; develop criteria for determining what makes a unit process technology critical; and conduct an in-depth analysis of specific critical unit processes and provide a prioritized recommendation of future research initiatives.

A committee of fifteen experts was constituted by the National Research Council to conduct the study. The committee met from May 1991 to July 1993. During the process of determining the criteria for selecting critical processes, the committee identified the essential technical components that comprise all unit processes. Consideration of the taxonomy, the essential components, and the various materials handled by unit processes led to the identification of certain key *enabling technologies* which influence all unit processes. The committee's primary finding is that these enabling technologies are critical to the understanding and advancement of all unit processes and hence provide the technical underpinning of manufacturing competitiveness. Thus, this report emphasizes the enabling technologies and the research agenda which must be implemented to advance the unit processes.

For a subject as broad as manufacturing processes it was necessary to set certain limits on the study content. After discussions with the sponsors, the committee excluded from consideration those processes that dealt with the production of raw materials, alloy development, chemical processing of materials, and fabrication of electronic materials. These topics are very important, but lie outside the scope for the present study. Similar considerations apply to *automation* and *assembly* processes that are also important topics in manufacturing but were judged to fall outside the charge to the committee.

This report discusses the crucial and central position which unit processes occupy in the broad areas of manufacturing and industrial competitiveness. It provides specific prioritized recommendations for research on certain enabling technologies. In addition, general recommendations for improving the present level of R&D by government, industry, and university action are presented.

The committee is convinced that the United States can maintain its position as a leading manufacturing nation; and through this, can provide a high standard of living for all of its citizens. However, to do so we must be willing to invest appropriately in the future. Investment in manufacturing is usually measured by the amount of capital equipment purchased in a given period. Two additional key investments must be made for the long range strength of U.S. manufacturing. The first is improvement in the quality of education of the manufacturing workforce that ranges from the professional staff to the production staff. The second is the effective use of existing and new knowledge related to unit processes. Much of our decline in relative productivity growth can be traced to our failure to invest in people, in manufacturing research, and in implementation of research results. More than anything else we do to improve manufacturing productivity, this investment in people, in research, and implementation when coupled with reasonable capital investment, will provide the greatest long-term dividends to our standard of living. Unless, we as a nation consider manufacturing as important as fundamental science, health, social programs, and national security, we will not be able to generate the resources necessary to pay for our investments in these factors which contribute to our standard of living.

Comments or suggestions that readers of this report wish to make can be sent via Internet electronic mail to nmab@nas.edu or by FAX to the Manufacturing Studies Board (202)334-3718.

IAIN FINNIE, CHAIR

UNIT MANUFACTURING PROCESS RESEARCH COMMITTEE

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UNIT MANUFACTURING PROCESSES

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EXECUTIVE SUMMARY

American companies must be able to manufacture products of superior quality at competitive costs to compete effectively in the global economy. Many studies undertaken in recent years to define the most important areas of industrial research have emphasized the need to place manufacturing process development on an equal basis with new product technologies. According to these studies, the United States must establish a preeminent foundation in engineering and science, which is capable of innovating and improving not only products but manufacturing processes.

Investment in manufacturing is commonly measured by the amount of capital equipment that is purchased. This approach does not incorporate the investment in the underlying infrastructure, which includes the development of process technologies and the education and training of a motivated work force. Future economic success will be driven not only by capital spending but by process technologies and the skill base of the work force.

This report suggests key criteria for determining the critical elements of unit processes and applies these criteria to illustrative examples to demonstrate how the criteria can be used to identify opportunities in research and development (R&D) for unit process technologies and the supporting enabling technologies. Generalized conclusions and recommendations regarding process technologies are presented that support a strategy of improving national competitiveness in manufacturing.

FUNDAMENTALS OF UNIT MANUFACTURING PROCESSES

Manufacturing, reduced to its simplest form, involves the controlled application of energy to convert raw materials (typically supplied in simple or shapeless forms) into finished products with defined shape, structure, and properties. Usually manufacturing entails the sequencing of the product-forms through a number of different processes. Each individual step is known as a "unit manufacturing process." For the sake of brevity, the committee will refer to them as "unit processes." These unit processes can be considered as the fundamental building blocks of a nation's manufacturing capability.

There is an extraordinarily large number of unit processes. However, many share common traits that can be used as the basis for organizing them into families. The committee chose a taxonomy for this study based on the physical process by which the configuration or structure of a material is changed. In order to narrow the scope of this study, the committee excluded consideration of the following types of unit processes: production of raw materials, alloy development, chemical synthesis, fabrication of electronic materials, component assembly, and information technology. Taking these exclusions into consideration, five distinct unit process families were rationalized:

1. *mass-change processes*, which remove or add material by mechanical, electrical, or chemical means (included are the traditional processes of machining, grinding, and plating, as well as such nontraditional processes as electrodischarge and electrochemical machining);
2. *phase-change processes*, which produce a solid part from material originally in the liquid or vapor phase (typical examples are the casting of metals, the manufacture of composites by infiltration, and injection molding of polymers);
3. *structure-change processes*, which alter the microstructure of a workpiece, either throughout its bulk or in a localized area such as its surface (heat treatment and surface hardening are typical processes within this family; the family also encompasses phase changes in the solid state, such as precipitation hardening);
4. *deformation processes*, which alter the shape of a solid workpiece without changing its mass or composition (classical bulk-forming metalworking processes of rolling and forging are in this category, as are sheet-forming processes such as deep drawing and ironing); and
5. *consolidation processes*, which combine materials such as particles, filaments, or solid sections to form a solid part or component (powder metallurgy, ceramic molding, and polymer-matrix composite pressing are examples, as are joining processes, such as welding and brazing).

Even though these unit processes are very diverse, they all possess five key process components: the workpiece material, process tooling, a localized workzone within the material, an interface between the tooling and the workzone, and the process equipment that provides the controlled application of energy. Advances in unit process technologies can be targeted at any one, or all, of these components, although usually all five are affected to some extent by a change in any one of the components. Thus, a systems approach is required for improving existing unit manufacturing unit processes and for developing new ones.

This taxonomy of unit processes is independent of the type of material being worked. Specific material considerations are taken into account through understanding the mechanisms that occur in the workzone. The overall organization of unit processes can be conceptualized in three-dimensional space with one axis being the unit process families; the second axis, the unit process components; and the third axis, the types and combinations of materials being processed.

SETTING PRIORITIES FOR UNIT MANUFACTURING PROCESSES

The overall significance of a unit process innovation can be determined from several primary considerations:

Does it offer the potential to be cost-effective? This factor examines, from basic considerations, the ability of a process to provide the required quality level at minimum input cost per unit of output. This would include, for example, the minimization of such factors as energy use, scrap generation, and labor costs. Thus, a single precisely controlled process that combines in essentially one operation what had previously required multiple operations could be highly rated by this criterion.

Does it provide a unique way to cost-effectively exploit the physical properties of an advanced material? Too often, advanced materials with outstanding properties have languished in the laboratory because little, if any, consideration has been given to the methods required to produce them in usable shapes and quantities. Processes that are fundamentally simple, requiring low capital investment, would be highly rated by this criterion.

Can it shorten the time to move a product technology from the research stage to commercialization? This factor includes the capability of providing rapid response to customer needs. Unit processes that are relatively easy to scale-up from the laboratory to the factory due to their inherent flexibility, as well as efforts to develop process technology concurrently with the product technology, would be highly rated.

Does it provide a method of processing that is fundamentally environmentally friendly? Since it is often difficult to attach a firm cost to environmental transgressions a priori, processes that avoid the difficulty in the first place, or that produce environmental effects that can be readily mitigated, would be highly rated.

Is it applicable to a diverse range of materials? This criterion would rate higher those processes that are adaptable to a range of materials, and those that are more specialized would rate lower. However, it should be noted that nearly every unit process requires some amount of adjustment to accommodate different types of materials.

The committee selected several examples of unit processes from each of the five families and developed recommendations for research opportunities by applying the above criteria. These specific recommendations are representative of how priorities in unit process R&D can be established within a defined context, but they are not all inclusive.

The committee determined that the following six areas of applied scientific and technical knowledge are intrinsic to the design and operation of nearly every unit process and therefore may be termed "enabling." These areas, called "enabling technologies" here, provide primary levers of change in unit manufacturing processing.

ENABLING TECHNOLOGIES

Understanding Material Behavior

This technology involves understanding the relevant material properties and microstructure that exist at the start of the process and how they change in response to the processing. The evolution of microstructure, conditions under which fracture occurs, and the role of interface conditions such as friction and heat transfer are among the elements that must be understood. Furthermore, these elements should be known at various levels of scale. For example, shape changes resulting from deformation processes can be readily treated at a macroscopic level, but understanding the origins of crystallographic texture in a highly worked product requires knowledge of properties at a microscopic level. It is often convenient to represent process criteria and mapping of defects and damage in terms of process parameters, in a format known as "process maps." This may entail the development of databases that are useful in characterizing material behavior under extreme conditions (e.g., high temperature, high strain rate).

Use Of Simulation And Modeling

This technology includes the analytical and numerical representation of the five components of a unit process. Simulation and modeling can often eliminate time-consuming and expensive trial-and-error process development and lead to rapid development of processes for new materials and new products. Simulation of unit processes is largely based on computer-aided approaches and includes three main activities: modeling, visualization, and design. The essence of modeling involves solving the classic laws of conservation of mass, momentum, and energy for constitutive formulations of the material behavior during its residency in the unit process. The solution procedure is governed by initial and boundary conditions that represent the process conditions. The complexity of the model may be simplified with first-order assumptions to provide a solution with reasonable accuracy. This methodology goes far beyond the empirical techniques of the past. The most important task in unit process design is selecting the optimum processing conditions that will ensure the required mechanical and physical characteristics of the product at the necessary quality level. Experimental validation must accompany more-sophisticated modeling procedures.

Application Of Sensors

Sensors are independent devices that can measure process conditions and the response of the material. Sensor technologies play a critical role in the establishment of advanced process control architectures and the production of quality products. There are a wide range of sensor applications that could control the operation of unit processes, monitor and diagnose equipment condition, and inspect and measure the product. They may be remotely located, incorporated in the equipment, contained within the workpiece, or placed in the interface between the workpiece and the tooling. Sensors must not interfere with the process, and they must be robust enough to survive the processing environment. Sensors will be crucial for implementation of intelligent process control and in situ quality technology. Unit processes of the future are expected to be heavily dependent on advances in sensor technology.

Implementation Of Process Control

The incorporation of improved computer software and hardware can make unit processes more flexible and adaptive, while maintaining optimum operation of the process equipment. For example, recent advances in intelligent process control methods make possible self-directed midcycle changes that are based on the response of the material to process variables. This ensures high-quality parts even if the initial and boundary conditions vary. In the past, the predominant control methodology employed the "black box" approach, which used a simple invariant description of the unit process, and advances in control theory were underutilized. Tools to design improved control algorithms and controller hardware are readily available and should be aggressively applied to developing advanced manufacturing process control.

Development Of Process-Related Precision And Measurement Technology

Effective product design and manufacturing hinge, in part, on matching process capabilities to part specifications and on applying real-time measurement methods that support inspection and process control. As activity progresses from initial design to final manufacture, the control of variability becomes the central issue. Variability arises from limitations in the control of the physical processes used to make and assemble parts, as well as from the tolerances inherent in the tooling and workpiece materials used in the processes. In the past, this area has received less attention from researchers than other technologies which, has restrained progress toward producing the highest-quality products cost-effectively.

Design Of Process Equipment

This technology must be a critical focus of any unit process that will be commercialized. Of all the enabling technologies, equipment design is necessarily the broadest, since it draws on all the other enabling technologies. The equipment and associated tooling must be designed to fulfill a specific function in a production environment. Unit process equipment should be viewed as platforms for advanced sensors and control technology. Furthermore, practical factors such as costs associated with the purchase, installation, and maintenance of the equipment must be competitive with alternative processing equipment. Other factors include process cycle time, robustness, maintenance, flexibility of use, production rates, and resultant part quality. This technology can be advanced by innovative designs, as well as by systematic incremental improvements.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. There are hundreds of unit manufacturing processes that exploit a very wide range of material modifying phenomena. Each process has some distinctive characteristics and parameters. Common sets of characteristics can be used to organize these processes into families. If such a taxonomy is constructed according to the physical process by which the configuration or structure of a material is changed, five process families result that specialize in processes that change mass, change phase, change structure, deform, or consolidate.
2. When examined as an isolated entity, the criticality of a particular unit process to overall industrial success cannot be determined. It is only when the unit process is evaluated in the context of manufacturing specific products that an assessment of criticality of the unit process, and improvements that could result from suitable R&D, can be made. However, generic criteria can be developed to make relative assessments and to guide the allocation of R&D resources.
3. The following criteria can be applied to evaluate projects in unit process R&D: How well does the project offer the inherent potential for cost-effective production and shaping of materials? Does it exploit the physical properties of an advanced material cost-effectively and in an unique way? Can it shorten the time needed to move a product technology from the research stage to commercialization? Does it provide a processing method that is inherently environmentally friendly? Is it applicable to a range of materials? Can it produce a variety of parts?
4. There are six critical enabling technologies that serve as the foundation for unit process improvements: characterization of material behavior, simulation and modeling tools and technology, advanced sensor technology advanced process control technology process-related precision technology, and process equipment improvements. Research in these enabling technologies must be connected to the basic physics of processes, and the results must be verified through experiments on specific unit processes.
5. There are opportunities for major and minor improvements across the whole spectrum; these range from advancements in specific unit processes to improvements in the underlying enabling technologies.

6. The links between initial design and final manufacturing are often inadequate. Design engineers typically specify parts and products in terms of nominal shapes, materials properties, and part-mating relations with allowable variations (tolerances). Processes for making parts and products are usually specified by phenomenological parameters, for example, process temperatures, feed rates, and pressures. Thus there is a "mismatch" between the static parameters of design and the dynamic parameters of manufacturing processes.
7. A science has not developed around most of the unit processes. This can be attributed to the fact that in most cases scientific principles from many different disciplines are involved (e.g., physics, chemistry, mechanics, electronics, and materials). No principles unique to unit processing have emerged that could serve as a unifying framework for a new science.
8. Several high-level measures indicate that the United States may be underfunding both unit process R&D and education and training of the workforce. Particular care must be taken to direct available funding to the most promising opportunities and the most pressing educational needs.
9. Even though this report primarily addresses the development of unit process technologies, the committee does not believe that process technologies alone will contribute to overall improvements in manufacturing competitiveness. The nation must possess an educated, motivated workforce, as well as industries committed to making appropriate investments in manufacturing facilities and equipment. Therefore, significant improvements in unit manufacturing process technologies will require, in addition to research in these technologies improvements in workforce education and industrial implementation.

Recommendations

1. Technologies that underpin and enable a wide variety of unit processes are critically important. Research in these enabling technologies must be connected to the underlying physics of processes, and the results verified through experiments on specific unit processes. The following enabling technologies should receive the highest priority:

- *Improved and innovative advanced sensor technologies that could be used to enhance unit process control and increase productivity* . These sensors would be capable of real-time measurements of such quantities as geometric tolerances, material condition, and process conditions.

- *Improved unit process control resulting from extending advanced control theory and concepts, such as self-tuning controllers that employ expert systems and embedded process models*. These controllers would take full advantage of the real-time data provided by advanced sensors.
- *Materials behavior research aimed at providing information usable by process simulation models*. The vast amount of information already available needs to be collected, analyzed, and organized in a form usable by these models. The use of improved descriptions of material behavior in simulation should be validated with experimental data.
- Models for characterizing the *precision of unit processing* in ways useful to design engineers and process planners; methods for assessment in terms of scalability, intrinsic precision, and currently available precision; and the organization and codification of disparate process precision and metrology.

2. Encourage universities to offer suitable courses specializing in the principles of tolerancing, metrology, and process modeling within the engineering and manufacturing disciplines.
3. Encourage and strengthen the framework within which industry, government agencies federal and national laboratories, and universities can collaborate on research to improve the design of process equipment.
4. Government agencies involved in sponsoring R&D in manufacturing processes (e.g., National Science Foundation, Department of Defense, Department of Energy, and National Institute for Standards and Technology) together should carefully evaluate the kinds of manufacturing R&D being supported and the relative funding levels for defense and nondefense R&D. This evaluation could also examine the extent to which other leading industrial countries, notably Germany and Japan, have been effective in commercializing unit process technology, given their investment in research that is related to manufacturing, which is considerably higher (as a proportion of their gross domestic product) than that of the United States.
5. The committee recommends that incentives be found and implemented to increase the number of students majoring in manufacturing-related technology at universities, so that sufficient trained personnel are available to exploit research opportunities in unit processes and to guide their industrial implementation. For example, the National Science Foundation could convene a study group to determine appropriate educational incentives in the context of expected technical opportunities, industry needs, and employment opportunities. One incentive that would quickly attract high caliber students would be an

increase in the number of fellowships available to those specializing in manufacturing.

REPORT ORGANIZATION

This report is divided into four parts. Part I, "Fundamentals of Unit Manufacturing Processes," contains two chapters that discuss the importance of manufacturing and explain the basic definitions used throughout the report. Part II, "Research Opportunities in Illustrative Unit Manufacturing Processes," contains six chapters; each chapter is dedicated to a particular class of unit process. Part III, "Key Unit Manufacturing Process Enabling Technologies," also contains six chapters; each chapter in this section is devoted to a particular enabling technology. And Part IV, "Policy Dimensions," contains three chapters that discuss issues in resource allocation for unit process R&D and education, and an overview of the experience of other industrialized countries in manufacturing-related R&D.

PART I: FUNDAMENTALS OF UNIT MANUFACTURING PROCESSES

To live well, a nation must produce well.
Dertouzos et al., 1989
Productivity isn't everything, but in the long run it is almost everything.
Krugman, 1990

INTRODUCTION

Throughout history a nation's wealth, standard of living, and status in the international community have directly benefitted from the nation's manufacturing capability. Transportation systems, energy generation and distribution, health care, construction, education, banking, and virtually every aspect of the modern way of life depend on the quality and affordability of manufactured products. U.S. manufacturing remains a significant portion of the nation's. economy but has experienced a loss in its global competitive position. One of the key factors contributing to the loss of manufacturing competitiveness and productivity has been a reduction in investment in manufacturing process research and development (R&D; Mettler, 1993).

This section provides an introduction to unit manufacturing processes, the basic building blocks of a nation's manufacturing capability. Manufacturing involves the conversion of raw materials, usually supplied in simple or shapeless forms, into finished products with specific shape, structure, and properties designed to fulfill specific requirements.

Chapter 1 sets the stage for the entire report by highlighting the importance of manufacturing to the nation's economy and providing an overview of the rest of the report.

Chapter 2 develops the technical foundations for the remainder of the report. Every unit process has five key process components: the workpiece material, process tooling, a localized workzone within the material, an interface between the tooling and the workzone, and the process equipment that provides the controlled application of energy. Advances in unit process technologies can be targeted at one or more of these components. The chapter categorizes unit processes in terms of the physical process by which the configuration or structure of a material is changed. This results in five distinct unit process families that are discussed in Part II:

1. *mass-change processes*, which remove or add material by mechanical, electrical, or chemical means;
2. *phase-change processes*, which produce a solid part from material originally in the liquid or vapor phase;
3. *structure change processes*, which alter the microstructure of a workpiece;
4. *deformation processes*, which alter the shape of a solid workpiece without changing its mass or composition; and
5. *consolidation processes*, which combine materials such as particles, filaments, or solid sections to form a solid part or component.

RECOMMENDATIONS

- Even though this report primarily addresses the development of unit process technologies, a national emphasis in manufacturing must address at least three factors: process technologies, workforce education, and implementation. Process technologies will not contribute to overall improvements in manufacturing competitiveness without the nation possessing an educated, motivated workforce and with industries committed to making appropriate investments.
- The following criteria can be applied to evaluate projects in unit process R&D: How well does the project offer the inherent potential for cost-effective production and shaping of materials? Does it exploit the physical properties of an advanced material cost-effectively and in an unique way? Can it shorten the time to move a product technology from the research stage to commercialization? Does it provide a processing method that is inherently environmentally friendly? Is it applicable to a range of materials? Can it produce a variety of parts?

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1

Why Manufacturing Matters

OVERVIEW

A nation that does not produce well may not, in the long run, lose jobs for its citizens, but its citizens will most likely find that the quality of their jobs and their standard of living will deteriorate in comparison to nations that do produce well. Manufacturing matters, because it is a significant component of economy of the United States: nineteen percent of the U.S. gross domestic product is production of durable and nondurable goods;[1] approximately 65 percent of total U.S. exports are manufactured goods; the manufacturing sector accounts for 95 percent of industrial research and development (R&D) spending and more than two-thirds of total R&D activity (Jasinowski, 1992); and manufacturing in 1992 provided roughly 17 percent of total nonfarm payroll employment (Manufacturing Subcouncil, 1993).

U.S. companies must be able to manufacture products of superior quality at competitive prices. Key to the quality of any product is an understanding of the manufacturing process by which it is produced. Many different studies undertaken in recent years to define the most important areas of future industrial research have placed process understanding at or near the top of the list. For instance, the report by the National Research Council, *Materials Science and Engineering in the 1990s: Maintaining Competitiveness in the Age of Materials*, highlights materials synthesis and processing as an important area of expanded emphasis over the next decade (NRC, 1989). Indeed, every nation's success as a global manufacturer requires the development and use of manufacturing

[1] At the end of the third quarter in 1990, manufacturing accounted for 18.9 percent of the gross domestic product in constant 1977 dollars, with 10 percent in durable goods and 8.9 percent in nondurable goods (DoC, 1993).

processes capable of producing high-quality products rapidly and economically in an environmentally acceptable manner.

International competitiveness depends on the timely implementation of new and improved manufacturing processes. Although global integration of product markets and advances in reverse engineering techniques have improved the ability of competitors to determine the components of new products, the ability to clone successful products still depends on competitors' ability to make those components. Excellence in developing and implementing manufacturing processes that provide unique production capabilities with cost and quality advantages can be the determinant of market success and the key to future U.S. competitiveness in manufactured products, since this strategy cannot be easily duplicated.

UNIT MANUFACTURING PROCESSES: THE COGS THAT DRIVE MANUFACTURING PRODUCTIVITY

Any manufacturing system can be decomposed into a series of unit processes that impart both physical shape and structure to the product. Unit processes are intimately linked to one another; the output of one process becomes the input for the next process. The quality of the final product depends not only on the capability of each unit process but also on the proper sequencing of unit processes. Continuous improvement of the manufacturing system involves creation of an understanding of each process by itself, as well as of the influence of each unit process on subsequent unit processes.

The R&D priorities of an industrialized country are key indicators of the emphasis attached to different areas. The United States has tended to invest most heavily in the invention of new products. Other nations have invested more heavily in process technologies. For example, the military R&D spending in the United States allocates 3 percent to process technology and 97 percent to product technology (Thurow, 1987). Overall, current industrial R&D spending in the United States is two-thirds on new products and one-third on new processes. Japanese companies invest at the inverse ratio (i.e., one-third on new products and two-thirds on new processes) and have successfully employed that R&D strategy to become highly competitive in the manufacture of consumer electronic products, such as the video camera, the video recorder, and the facsimile machine. The Japanese have graphically demonstrated that the greatest benefits accrue to those who can cost-effectively manufacture new product technologies.

Some believe that the U.S. focus on products rather than processes has been fueling the relative decline of American manufacturing with respect to other manufacturing nations (Thurow, 1987). It is time to reverse this trend and to emphasize improvements in the most promising manufacturing processes, so that the nation can create products that not only excel in function but also are competitive in both quality and cost in a global market.

Since manufacturing is important to a nation's well-being and it is recognized that creation of the product is dependent upon each unit manufacturing process, both individually and together with other processes as a whole, sufficient resources should be provided to educate the manufacturing work force and to develop and improve key manufacturing processes. The alternative will lead to the decline of the United States as a manufacturing nation.

R&D in unit manufacturing processes can be considered to occur on two levels—proprietary research that is conducted on a confidential basis, since it may have near-term applicability in a competitive market, and precompetitive or generic research that helps establish the foundation for a technology for the benefit of everyone with access to the results. This report primarily deals with the latter case.

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2

What Are Unit Manufacturing Processes?

Manufacturing involves the conversion of raw materials, usually supplied in simple or shapeless forms, into finished products with specific shape, structure, and properties that fulfill given requirements. This conversion into finished products is accomplished using a great variety of processes that apply energy to produce controlled changes in the configuration properties of materials. The energy applied during processing may be mechanical, thermal, electrical, or chemical in nature. The results are meant to satisfy functional requirements that were defined during the product design stage.

In the past, design, materials engineering, and manufacturing were often treated as independent engineering specialties. However, modem manufacturing must be cost-effective and timely. This requires that everyone involved in the entire product life cycle work together concurrently to provide a functional product that can be produced efficiently, can be operated reliably, and is easy to maintain and recycle (Taguchi, 1993). This report identifies a large number of opportunities for improving unit processes. These can be considered as future options for the concurrent engineering teams.

Manufacturing a product or component usually requires the integration of a number of processes. For example, the initial process may involve casting a metal into a mold to produce a desired shape. Next, the casting may be machined with cutting tools to generate surfaces of specified form. Finally, a surface treatment may be employed to improve the durability of the part. Each of these three individual operations—casting, machining, and surface treatment—is a unit manufacturing process. For brevity, in this report they will be referred to as "unit processes." They are the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product.

The information and material flows associated with a typical unit process are shown in Figure 2-1. Raw material or parts from a previous unit process are the input. The output consists of parts, which are one step closer to their final form, and of an influence on the environment, such as particulate or noise pollution. The information input and control to the unit process include product data, process information, and process control methodology. The resource requirements of the unit process are such items as manufacturing equipment, energy, and human resources.

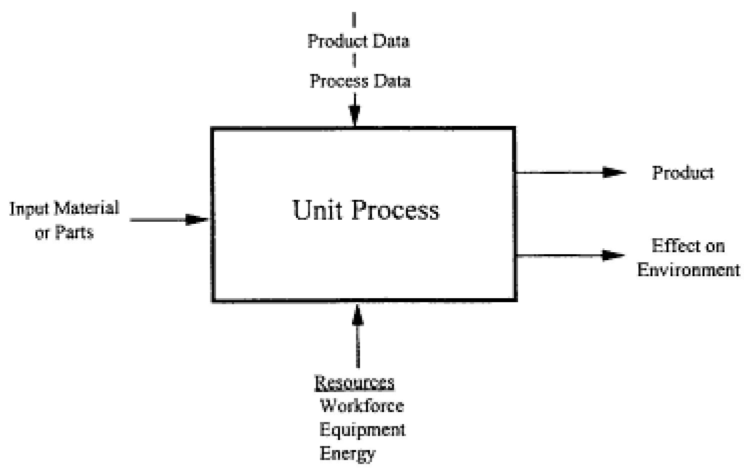

Figure 2-1 Unit process information and materials flow.

A unit process can be considered optimized when the value added in terms of the required configuration and property changes is delivered to the workpiece in the most cost-effective manner from the system as a whole. This involves minimization of factors such as energy use, scrap generation, labor costs, and capital equipment requirements. In addition, rapid response to the needs of customers and a safe working environment are essential. Sequential unit processes, known as process strings, include cost factors that may result from previous unit processes, such as repair operations required by quality lapses of intermediate process steps. Therefore, many factors must be considered in evaluating cost-effectiveness. A general definition is "minimization of input and resource costs per unit of output product value."

A vast number and a great variety of individual classical and novel unit processes exist. Compilations have been prepared that identify several hundred individual processes; for example, the Welding Handbook, Volume I (AWS, 1987). It would be of limited usefulness to discuss each process individually in this report. Instead the Unit Manufacturing Process Research Committee has selected a schematic model that identifies five components common to all unit processes.

In this chapter, the committee presents the rationale for a unit process taxonomy containing five major families. These processes are applicable to the full range of workpiece materials: metals, polymers, ceramics, and composites. The end result is a three-dimensional framework composed of process components, process families, and materials. This scheme provides a concise description of the broad topic of unit processes. Using this framework, the committee determined that there are a few areas of applied scientific and technical knowledge that enable the design and operation of essentially all unit processes. These areas are referred to here as "enabling technologies."

COMPONENTS OF A UNIT PROCESS

A schematic model of a unit process is depicted in Figure 2-2. Energy is delivered to the workpiece material by means of the process equipment and its tooling and is transferred to the workpiece through an interface region between the tooling and the workpiece. Often the interface contains a medium such as a coolant or lubricant. The specific changes in the workpiece configuration and structure usually occur in a localized area of the workpiece, designated as the workzone. For example, a group of metal removal processes, loosely known as

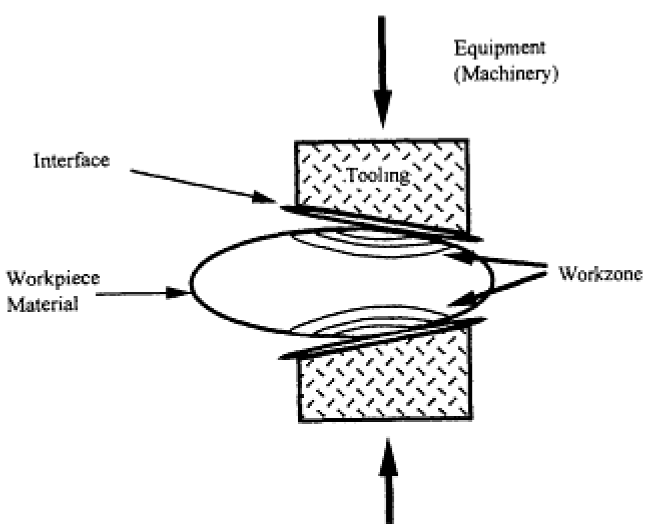

Figure 2-2 Unit manufacturing process model.

machining, includes several operations (e.g., turning, milling, drilling, boring, etc.). Each of these processes is distinguished by the tooling design, the interface (represented by the cutting fluid), and the equipment design and characteristics (i.e., degrees of motional freedom, rate of workpiece or tool feed, and machine rigidity). The workzones of these processes are localized on the workpiece surface and involve shear deformation and fracture as workzone mechanisms, which impart a change in shape to the workpiece.

The wide diversity of unit processes (e.g., machining, forging, casting, and injection molding) incorporate equally diverse groups of equipment, tooling designs, interface materials, and workzone mechanisms. The process equipment may belong to the groups of mechanical, thermal, chemical, photonic, and electrical equipment, as well as to combinations of the groups. Tooling elements include cutting tools, grinding media, dies, molds, forms, patterns, electrodes, and lasers. The array of interface materials typical of unit processes includes lubricants, coolants, insulators, electrolytes, hydraulic fluids, and gases. The operative mechanisms found in the workzones of unit processes include deformation, solidification, fracture, conduction, convection, radiation, diffusion, erosion, vaporization, melting, microstructure change, phase transformations, chemical reactions, and many others. Examples of the five unit process components for six illustrative unit manufacturing processes are presented in Table 2-1.

Each of the five process components—equipment, workpiece, tooling, interface, and workzone—are influenced by the other process components. For example, the interface conditions may govern the rate of energy transfer from the equipment to the workzone and may control the extent of the workzone localization and the uniformity of the changes in the workpiece shape and structure. In the machining process, variation in the thermal behavior or effectiveness of the cutting fluid may impose thermal distortions in the workpiece or equipment and result in a loss of process precision, manifested in products of poor quality.

Most processes involve several competing workzone mechanisms, with one mechanism overriding the others, at any given instant in the process. The design and selection of the process components and operating conditions are usually predicated on the assumption that a prime mechanism will remain dominant during process operation. In some instances, the process conditions may change so that an alternative mechanism becomes dominant, impacting the process operation and the resulting product quality. For example, in hot forging of jet-engine disks from elevated temperature alloys, extended contact time between the heated workpiece material and colder forging dies leads to increased heat flow to the dies. As a result, the workpiece material near the die-workpiece interface cools and does not deform as readily as the hotter zones of the workpiece. This

Table 2-1 Examples of Unit Process Components

Unit Process	Illustrative Equipment	Workpiece Material	Typical Tooling	Typical Interface	Primary Workzone Mechanism
Machining	lathe	bar stock	single point	cutting fluid	deformation, fracture
surface modification	furnace	part	atmosphere	diffusion	phase change
casting	furnace	melt	mold	release agent	solidification
forging	press	preform	die	lubricant	deformation
powder compaction	press	powder	die	lubricant consolidation	deformation
fusion arc welding	power supply	part	arc	plasma	phase change

nonuniformity in deformation affects the microstructure and the properties of the forged disk. The solution to this problem is to control the speed of the forging operation, thus minimizing the contact time of the workpiece and dies and the temperature loss at the workpiece surface. The end result is uniform deformation and uniform microstructure and properties in the forged part.

TAXONOMY OF UNIT MANUFACTURING PROCESSES

The identification of process components provides a useful overview. However, several hundred individual unit manufacturing processes are commercially used in manufacturing operations. In order to discuss these processes in more detail, it is necessary to classify them using some common features. Many such classifications or taxonomies have been presented in the relevant technical literature. The taxonomy chosen for this study emphasizes the physical process by which the configuration or structure of a material is changed. The subsequent discussion of unit processes will be organized according to this taxonomy. Five families of physical processes make up this taxonomy:

- *Mass-change processes* remove or add material by mechanical, electrical, or chemical means. Included in this family are the traditional processes of plating, machining, and grinding, as well as nontraditional removal processes such as electrodischarge and electrochemical machining.
- *Phase-change processes* produce a solid part from material originally in the liquid or vapor phase. The casting of metals, infiltration of composites, and injection molding of polymers represent this family. (Phase changes in the solid state are considered to belong to the structure-change process family.)
- *Structure-change processes* alter the microstructure of a workpiece, either throughout its bulk or in a localized area, such as its surface. Heat treatment and surface hardening are commercial processes representative of this family. Solid-state phase changes are considered part of this family.
- *Deformation processes* alter the shape of a solid workpiece without changing its mass or composition. Classical metalworking processes of rolling and forging fall into this category, as do the sheet-forming processes of deep drawing and ironing.
- *Consolidation processes* combine materials such as particles, filaments, or solid sections to form a part or component. Powder metallurgy, ceramic molding, and polymer-matrix composite pressing are examples of consolidation processes. Joining processes, such as welding and brazing, also belong to this process family.

IDENTIFYING PRIORITY OPPORTUNITIES FOR UNIT PROCESS RESEARCH

The overall significance of a unit process innovation can be determined from several key considerations that are derived from the application context, and which can be structured as criteria. These criteria allow identifiable metrics to be established at the beginning of a development program that can later provide a benchmark to measure progress. These criteria can also be used to organize a "lessons learned" database that future efforts could access to enhance their chance of success.

- *Does it offer the potential to be cost-effective?* This factor examines, from basic considerations, the ability of a process to provide the required quality level at minimum input cost per unit of output. This would include, for example, the minimization of such factors as energy use, scrap generation, and labor costs. Thus, a single precisely controlled process that combines in essentially one operation what had previously required multiple operations could be highly rated by this criterion.
- *Does it provide a unique way to cost-effectively exploit the physical properties of an advanced material?* Too often, advanced materials with outstanding properties have languished in the laboratory because little, if any, consideration had been given to the methods required to produce them in usable shapes and quantities. Processes that are fundamentally simple, requiring low capital investment, would be highly rated by this criterion.
- *Can it shorten the time to transform a product technology from the research stage to commercialization?* This factor includes the capability of providing rapid response to customer needs. Unit processes that are relatively easy to scale-up from the laboratory to the factory due to their inherent flexibility, as well as efforts to develop process technology concurrently with the product technology, would be highly rated.
- *Does it provide a method of processing that is fundamentally environmentally friendly?* Since it is often difficult to attach a firm cost to environmental transgressions a priori, processes that avoid the difficulty in the first place, or that produce environmental effects that can be readily mitigated, would be highly rated.
- *Is it applicable to a diverse range of materials?* This criterion would rate higher those processes that are adaptable to a range of materials, and those that are more specialized would rate lower. However, it should be noted that nearly every unit process requires some amount of adjustment to accommodate different types of materials.

ENABLING TECHNOLOGIES

The processes in each family of the unit manufacturing process taxonomy can be applied to any material—metal, ceramic, polymer—or to the many composite formulations of these materials with polymers, metals, or ceramics as the matrix material. For example, processes in the consolidation family are used in the production of metals (powder compaction), ceramics (hot pressing), and polymer composites (autoclaving). In addition, each combination of process and material requires consideration of the five process components for successful production.

Figure 2-3 illustrates this interaction of process families, materials, and process components. The committee examined the many research opportunities that were identified within each family of unit processes in Part II to determine which were the most important to the advancement of unit process technology. The committee concluded that the efficacy of a new unit process, or process improvement, could only be assessed in the context of a specific application, although criteria could be developed to identify promising research opportunities. This led the committee to synthesize the various research opportunities identified for each family of unit processes. In doing so, it became apparent that a thorough understanding of any unit process with its five process components is dependent on six critical or key technologies that *enable* the correct design and operation of all processes. The committee determined that the six enabling technologies are workpiece material behavior, process simulation and modeling, process sensors, process control, process precision and metrology, and equipment design.

- *Materials behavior* involves an understanding of materials properties and microstructure of the workpiece at the start of the process and during the process as the material is modified. A large database for properties for the extremes of processing conditions (e.g., temperature, strain-rate) may be required. The evolution of microstructure, the conditions under which fracture occurs, and an understanding of interface conditions such as friction are among the factors that must be understood in the context of specific unit processes.
- *Simulation and modeling* involves the analytical and numerical representation of the five components of a unit process, which are depicted in Figure 2-2. This approach can eliminate time-consuming and expensive trial-and-error process development and lead to rapid development of processes for new materials and new types of parts. These models must be experimentally validated.
- *Sensors are* independent devices that can measure process conditions in situ, as well as the response of the workpiece material. They may be remotely located, part of the equipment, contained in the workpiece, or in the interface

between the workpiece and the tooling. The incorporation of innovative sensing devices could greatly enhance the operation and control of unit processes.

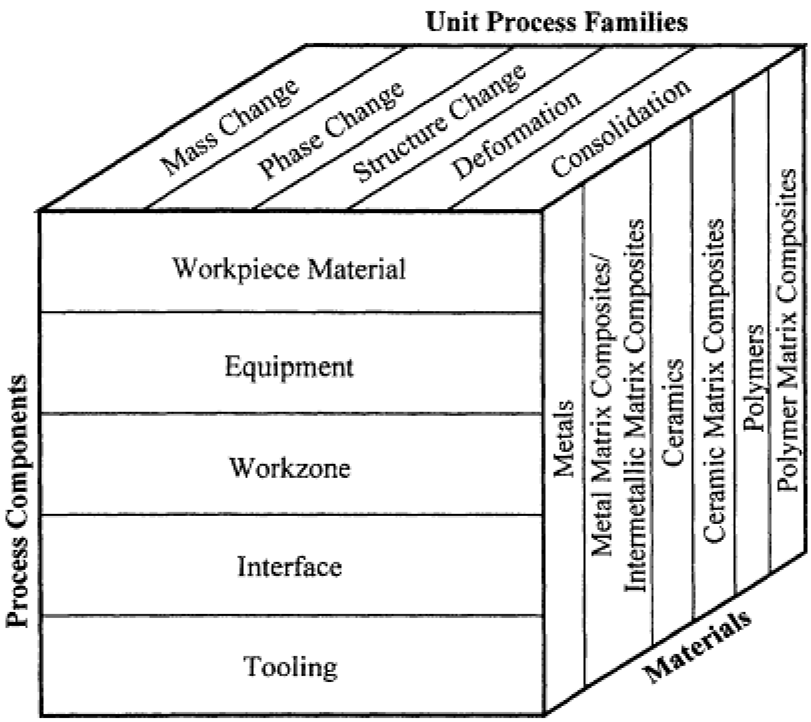

Figure 2-3 Unit manufacturing process families, components, and material classes.

- *Process control* involves the development of improved computer software and hardware to provide the optimum operation of process equipment at the required level of precision. A high-fidelity representation of the unit process, together with the implementation of appropriate process sensors, can contribute to improving process control.
- *Process precision and metrology* technologies directly determine the quality level. In addition to building precision into a process, geometric measurements are required to ensure dimensional control.

- *Equipment design* is the central feature of any unit process. The equipment and associated tooling must be designed to fulfill specific functions in a production environment. In addition, factors such as cost and time of fabrication, maintenance, flexibility of use, production rates, productivity, quality of the parts produced, and environmental friendliness are important aspects. Equipment may involve combinations of mechanical, electrical, chemical, and optical devices. Innovative design concepts can lead to dramatic improvements in unit processes.

The six enabling technologies are not independent of each other. For example, the design of process equipment is highly dependent on an understanding of the process precision and metrology, which are, in turn, integral to the sensor selection and process control methodology. In addition, advanced equipment design efforts often utilize simulation of the equipment operation, including accurate modeling of the workpiece and interface materials behavior during processing. These relationships among the six enabling technologies and the five major process components are depicted schematically in Figure 2-4. The

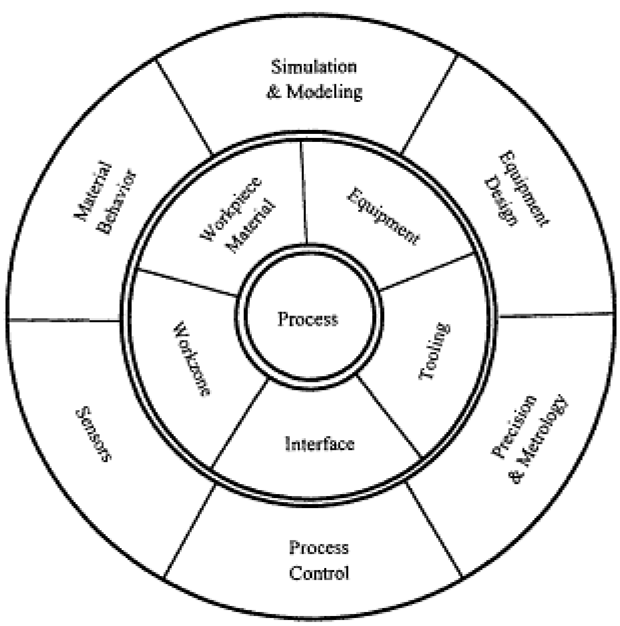

Figure 2-4 Unit process components and enabling technologies.

concentric (hierarchial) structure is shown to emphasize that knowledge flows from the six enabling technologies to the process components, which, in turn, form the unit process.

PROCESS STREAMS AND INTEGRATED PROCESSES

In most cases, product manufacture includes a series of sequential unit processes, referred to as a process stream. Each individual unit process of the stream has the output of the preceding unit process as its input material and is influenced by the characteristics of this material. Each product may then be considered the carrier of the history of the unit processes that preceded it. The final product properties, including microstructure, are the summation of the individual unit process experiences, both positive and negative, and define the final part quality and performance in the application.

The full benefit from an improvement to a particular unit process that is part of a process stream may not be realizable due to limitations in the processes that precede or follow it. The removal of such limitations provides additional opportunities for unit process improvements. The different unit processes can be so directly linked together that they effectively form an integrated system. Such systems are discussed in Chapter 8.

Advanced unit processes would do little good if they were not applied in manufacturing to improve the competitiveness of products by reducing cost and improving quality (IEEE Spectrum, 1993). With proper planning, implementation of these new unit processes can result in continual improvement of manufacturing operations (NAE, 1988; Bakerjian, 1993). While this report necessarily focuses on manufacturing, the important roles of product design engineering, the enterprise's commitment to excellence, participation by the work force, and so on, cannot be neglected in modernizing manufacturing (Clausing, 1994).

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PART II: RESEARCH OPPORTUNITIES IN ILLUSTRATIVE UNIT MANUFACTURING PROCESSES

INTRODUCTION

Any manufacturing system can be decomposed into a series of unit processes that impart both physical shape and structure to the product. Unit processes are intimately linked to one another by the fact that the output of one process becomes the input for the next process. The quality of the final product depends not only on the capability of each unit process but also on the unit processes working together. Continuous improvement of the manufacturing system includes better integration of each process with those that precede or follow, as well as of improvements to the unit processes themselves.

This part describes opportunities for technical advancements in the five unit process families:

- mass-change processes;
- phase-change processes;
- structure-change processes;
- deformation processes; and
- consolidation processes.

The committee selected several examples of unit processes from each of the five families and developed recommendations for research opportunities by applying criteria developed in Chapter 2. These specific recommendations are representative of how priorities in unit process R&D can be established within a defined context.

Chapter 3, "Mass-Change Processes," discusses unit processes that remove or add material by mechanical, electrical, or chemical means. These processes include traditional chip-making processes such as shaping, turning, milling, drilling, sawing, and grinding, as well as nontraditional processes such as laser machining, electrodischarge machining and electrochemical machining.

Chapter 4, "Phase-Change Processes," discusses processes that produce a solid part from material originally in the liquid or vapor phase. These processes include metal casting, infiltration of composites, and injection molding of polymers. They are necessarily specialized to the type of material being processed.

Chapter 5, "Structure-Change Processes," discusses processes that alter the microstructure of a workpiece. The changes are usually achieved through thermal treatments involving heating and cooling under controlled conditions, sometimes in combination with mechanical force. These processes are dependent on the type of material being processed. Surface treatment processes are included within this family, for example, applying very thin highly adherent coatings, surface alloying, and inducing compressive residual stresses.

Chapter 6, "Deformation Processes," discusses processes that alter the shape of a solid workpiece without changing its mass or composition. These processes can be further decomposed into those that are bulk forming (e.g., rolling, extrusion, forging, drawing) and those that are sheet forming (e.g., stretching, flanging, drawing, and contouring).

Chapter 7, "Consolidation Processes," discusses processes that combine materials such as particles, filaments, or solid sections to form a solid part or component. The interaction between the material and the energy that produces the consolidation is a key feature of these processes. The chapter provides an overview of powder processing, polymeric composites, and welding/joining.

Chapter 8, "Integrated Processes," discusses processes that combine more than one specific unit process into a single piece of equipment or into a group of work stations that are operated under unified control. The potential of such integration is beginning to be realized by processes such as those that use directed-beam technologies.

The opportunities for improvements to individual unit processes derive from the need to overcome specific technical limits and barriers to process performance. The resulting set of research recommendations provides the basis for identifying several key enabling technologies that support all unit process families and material classes. These enabling technologies are described in Part III.

WHY CONDUCT R&D ON UNIT PROCESSES?

R&D on unit processes enhance the knowledge level of unit processes and allow the production of better, more cost-effective and competitive products.[1] Over the long run, better understanding of manufacturing processes result in an improved competitive posture for U.S. industry in the global environment.

R&D activities within the enabling technology groups are typically initially focused on a particular process and material. This coupling ensures that the results can eventually be implemented to improve an actual unit process. The understanding developed by such focused activity often may be applied to other materials and processes.

Unit process R&D may involve the processing of traditional or emerging materials by either conventional or novel processes. Significant benefits may also result from the optimization and improvement of traditional processing of high-volume conventional materials. Incremental improvements in quality at reduced costs, although not dramatic, can be significant when applied to large production quantities.

Application of traditional processes to advanced or emerging materials is often cost-effective, because existing equipment and facilities are used. However, the extension of current process practices to these materials requires developing a new understanding of the process requirements specific to the new material.

Novel processes may be required for high-performance materials, such as producing affordable metal-matrix composites. Novel processes may also provide a significant benefit in the processing of traditional materials, for example, near-net-shape casting of steel into structural shapes.

Unit processes should be designed for flexibility, so that variations in starting materials, initial conditions, and so on, can be accommodated without requiring substantial additional process development to produce a quality product.

[1] Unit process R&D will be most effective if conducted in cooperation with industry vitally interested in implementation of the results. Manufacturing companies can readily evaluate the usefulness of the technology and overcome any implementation barriers of a new process.

3

Mass-Change Processes

Mass-change processes are characterized by the removal of material through the use of mechanical, thermal, chemical, or electrical energy.[1] In most instances, the workpiece density is not altered; however, the material microstructure may be modified, particularly at the work surface. Workpiece chemical composition is, in some cases, affected in a small surface region. Mass-change processes are employed in most manufacturing enterprises in intermediate and final processing operations. Workpiece materials span the spectrum of metals, ceramics, polymers, and their composites. High-performance workpiece materials generally are processed by tooling made from higher-strength materials. For example, diamond is used as a tooling coating to process ceramics and ceramic matrix composites.[2]

Processing costs associated with mass-change processes are directly related to the material properties of the workpiece and to the tolerance and surface finish requirements of the final part. Considerations of operation setup time and cost of fixtures and tooling must be included in the evaluation of the process economics.

Mass-change processes can be grouped into traditional (chip-making) and nontraditional processes. Chip-making processes remove unwanted workpiece material by exploiting shear deformation and fracture mechanisms. The basic

[1] Mass-change processes can also add material, such as by laser cladding or a plating operation. However, most of the discussion in this report relates to material removal processes.

[2] Care must be taken in using diamond tools for machining metals that are strong carbide formers, such as steel, since the diamond tends to react with such materials if the interface temperature is above about 500 °F.

chip-making processes include shaping, turning, milling, drilling, sawing, punching, broaching, and grinding (abrasive machining).

Nontraditional processes replace the chip-making mechanisms of material removal with alternative mechanical, electrical, thermal, or chemical removal techniques. These processes usually are used for applications that involve complex shapes or materials that are not easily handled with traditional processes. Typical examples are laser processing, electrodischarge machining (EDM), and electrochemical machining (ECM).

Current research trends have the objective of increasing material removal rates with no loss of part quality or precision. Improved process understanding is guiding advancements, such as the identification of advanced cutting tool and grinding materials for conventional and advanced workpiece materials.

TRADITIONAL CHIP-MAKING PROCESSES

Traditional chip-making processes are mature and have been studied extensively for over a century. Future improvements are projected to be incremental in nature and are expected to be in the areas of:

- machine design and utilization for high-speed operations;
- tooling design and materials;
- precision and high-speed machining; and
- processing of new materials such as ceramics.

The prime productivity goal of machining is increased material removal rates (MRRs), along with improved precision and accuracy levels in the final part. Current material removal rates are attained by using relatively low feed rates, low depths of cut, and high cutting speeds. These conditions result in reduced chip loads and lower machining forces on tooling and ensure precision of part shape and geometry, particularly for advanced materials in which the present abrasive processes have limited removal rates.

Achieving the goal of increased material removal rates requires advances in the process, equipment, and machine control. Specifically, improvements related to increased depth of cut and feed rates, as well as high cutting speeds, are needed. The technical challenges to attaining this goal are in the areas of machine tool stiffness, high-level servo drive control, advanced computer numerical control technology, tool materials and coatings, and thermal management of the process.

TRADITIONAL GRINDING AND FINISHING OPERATIONS

The grinding of steel is a mature commercial process; most of the process conditions are based on empirical experience. State-of-the-art science and technology is often not applied in equipment design, process design, or process control architecture, and the consequence is that cycle times and productivity are not optimized. For example, grinding wheel sharpness greatly influences part surface finish. It demands careful control during production, since grinding wheels can dull and cause surface integrity problems in the workpiece.[3] Advanced grinding materials, such as cubic boron nitride, offer improved performance at an increase in wheel costs. As with machining, the machine stiffness governs the tolerance potential of the process. Also, as is the case for machining fluids, grinding fluids are being categorized as hazardous wastes and may require replacement or elimination in the future.

High-efficiency deep grinding is an example of an advanced grinding process. This technology involves a high-performance surface grinder modified to attain large depths of cut using high traverse speeds. High-efficiency deep grinding achieves material removal rates up to 100 inches^3/minute per inch of width, compared with an upper limit of 5 inches^3/minute per inch of width for traditional high-performance grinding processes.

The grinding of ceramics is becoming a viable commercial process. The operating principles are partially developed, and the understanding of the process properties and performance for these materials is in the early stages of development. Further research will document the mechanisms active in the grinding contact zone and will establish the effect of material removal rate on part precision and quality. High geometric accuracy depends on precise machine tool motions, which are controlled by both the static and dynamic machine stiffness and the grinding wheel design and wear. Part quality is also influenced by material handling and fixturing, since ceramic parts are often brittle and prone to mechanical damage. Advancements in grinding ceramics require combinations of strategies. For example, a cast iron wheel with bonded pieces of diamond, combined with numerical control and in-process electrodischarge dressing of the wheel, can yield improved material removal rates for the production of complex ceramic parts.

[3] Part surface quality can be affected by a dull grinding wheel due to thermal damage or mechanical chatter of the grinding wheel.

NONTRADITIONAL MASS-CHANGE PROCESSES

Traditional mass-change processes remove material by mechanical action. In contrast, nontraditional processes remove material by the individual or combined action of thermal, chemical, and electrical processes. Twenty-one such processes are described in *Nontraditional Manufacturing Processes* (Benedict, 1987). Discussed below are laser machining processes,[4] which are probably the most rapidly developing nontraditional techniques, and EDM and ECM, which are other widely used nontraditional processes.

Laser Machining

Laser machining is a class of processes in which material removal occurs through either phase change (i.e., melting or vaporization) or oxidation reaction with a gas jet. The laser types used most widely in manufacturing are carbon dioxide (10.6-µm wavelength), neodymium-yttrium aluminum garnet (1.06-µm wavelength), and excimer (0.193- to 0.356-µm wavelength) lasers.

There are several advantages of laser machining over mechanical methods. First, since laser processing is principally thermal based, the effectiveness of laser machining depends on the material's thermal properties and its absorption of laser energy rather than on its mechanical properties. Therefore, brittle and hard materials can be machined easily by a laser if their thermal properties (e.g., conductivity, heat of fusion, etc.) are favorable. Second, energy transfer between the laser and material occurs without mechanical contact; therefore, there is no mechanically induced material damage, no tool wear, and no machine vibration effects, and the need for heavy fixturing is eliminated. Third, lasers do not require special processing environments, such as a vacuum.

Along with these advantages, however, there are several disadvantages that inhibit wider adoption of laser processes. First laser systems are currently expensive to purchase and operate. This effectively restricts the use of lasers to the processing high-value parts, high-speed applications, and special applications for which no alternative process exists (e.g., drilling holes with high aspect ratios at high angles of incidence). Second, the reliability of laser systems has not reached the level of traditional machine tools; therefore, maintenance expenses are significantly higher than those for mechanical processes. Finally, laser processing of polymers, composites, and ceramics must be carefully controlled

[4] In addition to machining, lasers are also used in welding and surface modification. These applications are discussed in chapters 5 and 8.

or unacceptable thermally induced bulk material damage can result, such as charring and microcracking.

Although most of the industrial applications to date have emphasized the high-speed aspect of laser processing, an emerging development area exploits the flexible nature of laser machine tools. When combined with a multi-axis workpiece positioning system or robot, the laser beam can perform a variety of unit processes on many classes of engineering materials by changing process parameters (e.g., beam diameter, scanning velocity, beam focus, assist gas, etc.) instead of changing machine tools.

There have been numerous experimental and theoretical studies on laser machining (for example, laser drilling, cutting, and scribing). Laser drilling is usually performed by either impingement of successive laser pulses onto the workpiece surface (i.e., percussion drilling) or cutting a workpiece in a circular beam trajectory (i.e., trepanning). The advantages of laser over mechanical drilling are the ability to drill small-diameter holes (on the order of several millimeters), high achievable drilling rates, and the ability to drill holes at high angles of incidence. For some applications, such as creating cooling holes in superalloy turbine blades and combustor liners, laser drilling is the preferred manufacturing process. In laser drilling of ceramic materials, microcracks develop near the cutting front due to thermally induced stresses but may be controlled through proper selection of parameters.

Laser cutting of two-dimensional shapes can be performed with either a continuous-wave beam or pulsed beam. Beam impingement on the workpiece surface results in material removal by either melting, vaporization, or reaction with a gas jet. Laser cutting allows a great deal of flexibility, since the cutting geometry is set by programming the kinematics of the beam and workpiece instead of the cutter geometry. High processing speeds (up to several meters per second) are also achievable. Laser cutting experiments for metals have been limited mostly to sheets less than 15 mm thick for continuous carbondioxide beams with a power range between 100 watts and 850 watts and scanning velocities between 0.5 and 5 m/minute (Babenko and Tychinskii, 1973; Decker et al., 1983).

The quality of laser-cut surfaces is often a critical consideration. For example, dross formation along the bottom edges of the kerf is a significant issue in surface quality of laser cut stainless steel (Arata et al., 1979). Due to the viscosity of the molten metal, the gas jet can only expel a portion of the molten material out of the kerf. The remaining material resolidifies along the bottom edge, forming dross, which must be removed mechanically after laser processing. Surface quality can be improved by using a *pile cutting* technique to reduce the viscosity of the molten stainless steel through mixing it with molten mild steel (Arata et al., 1979). A second method for improving cut quality uses a rear gas jet in tandem with the laser beam to expel molten material from the kerf. In addition to dross formation, several other surface quality issues exist. Beam divergence effects influence the taper of the kerf edge. Heat conduction into the workpiece causes the formation of a heat-affected zone. These surface quality concerns of dross formation, kerf taper, and heat-affected zone formation also exist for laser cutting of ceramics, plastics, and composites.

Laser grooving and scribing differ from laser cutting in that the laser beam does not penetrate through the entire thickness of the workpiece. Laser grooving and scribing have been used increasingly in applications ranging from marking or engraving identification labels on parts to creating cooling channels for electronics packaging. Laser scribing and grooving processes are used for ceramics, plastics, and composite materials. The issues of resolidified material accumulation, heat-affected zone and microcrack formation, and uniformity in groove depth and profile are of primary concern.

Electrodischarge Machining

EDM relies on material removal by erosion of the workpiece resulting from spark discharge with the tool (i.e., electrode). This process is often used for die sinking and machining. Rates of 480 mm^3/minute have been reported for a 30-amp current. EDM may also be used to produce thin slots in flat or curved surfaces. Traditional EDM used kerosene as the dielectric fluid, which limited its use in unsupervised situations. The development of low-viscosity, highflashpoint fluids has minimized this problem.

There are several key factors that presently limit the extent of application of ECM: the production of precise shapes requires compensation for tool wear; machining rates are typically low; and surface integrity can be an issue, as exemplified by a potential surface layer of residual tensile stress.

A major innovation in the development of electric discharge wire machining (EDWM) was the use of a disposable, continuously moving wire as the electrode. Commercial equipment operates with wires 0.010-0.002 inches in diameter; machines have been modified to use wires with a diameter as small as 0.001 inches. Since deionized water is used as an electrolyte, EDWM can operate for extended periods under computer control without supervision. Surface integrity problems with EDWM or with EDM can be minimized at the expense of decreased cutting rates. With larger diameter wires, cutting rates of 250 mm^2/minute have been reported for EDWM. An advantage of EDM and ECM is that hard materials may be cut as easily as soft ones, but the material being cut must have at least a limited electrical conductivity.

Electrochemical Machining

ECM employs electrolytic dissolution as the material removal process and is typified by machining rates of 2-2.5 cm^3/minute per 1,000-amp current, surface roughness of 0.1-1.2 µm, and accuracy of 10-300 µm. The limiting factor in the ECM process, as with EDM and EDWM, is that materials with low electrical conductivities cannot be processed. In addition, ECM cannot produce sharp radii of less than 0.02 mm.

Tool design, electrolyte processing, and sludge disposal are major technical barriers to wider acceptance and development of ECM. Designing ECM tools is complex and costly, usually employing a trial-and-error approach. And sludge, which may contain toxic and hazardous materials, is a costly environmental problem.

RESEARCH OPPORTUNITIES

High-Speed Machining

Specific research opportunities in the development of high-speed machining include:

- *new tool designs and materials* capable of improved service life at the projected speeds and depth of cut;
- high-speed, high-performance *spindle designs*, including refined bearings and lubrication techniques;.
- enhanced *machine control hardware* (e.g., servo drives and open architecture controllers) that incorporates feed forward compensation[5] to reduce contouring errors during machining that requires high feed and turning speeds and to minimize stiction effects. This enhanced control hardware must also communicate easily with other hardware (e.g., sensors), as well as link to process planning and factory level activities;
- refined *part fixturing for restraint* during the high loading encountered during machining with a high metal removal rate;
- high-capacity *chip removal and flushing systems* to handle the increased material removal rate; and

[5] See Chapter 13 for a discussion of these control methods.

- Improved *machine tool control methods* and alternative equipment and *tooling* designs for machining *thin-walled workpieces* for parts such as gas turbine impellers and ribbed aircraft structures. The technical challenge is overcoming the deflections that are due to the low effective stiffness of the tool[6] or workpiece.

Machining And Drilling Process

Research opportunities for improved efficiency and precision in machining and drilling processes include:

- *New cutting tool materials and wear-resistant coatings for machining and drilling*. Advancements in traditional materials, as well as engineered materials, such as composites, require better cutting tools, including drills, to improve productivity and quality.
- *Tool designs and materials for dry machining and drilling*. Future environmental regulations are restricting and may eliminate the use of traditional metalworking fluids. This requires the development of new tooling capable of dry operation at established productivity rates and quality levels.
- *Intelligent control of drilling and machining*. Application of advanced control methodology (e.g., fuzzy logic, neural networks, and expert systems) with innovative in situ sensors and process models will lead to improved part quality and process productivity by minimizing tool breakage and dulling. Problem-free tooling designs are needed to minimize the need for operator intervention during processing.
- *Understanding the effects of machining process conditions on product integrity*. Part integrity and performance can be compromised by machining operations that produce microstructural damage or residual stress distributions in the finished part. Enhanced understanding of the process conditions related to the occurrence of such situations will lead to better process control methods to minimize integrity problems and enhance product performance.
- *Innovative component fixturing*. Flexible fixturing techniques will provide for rapid changeover from lot to lot, resulting in lower setup times and improved productivity.

[6] This low stiffness is due to the small diameter design of high-speed spindles and long slender tool configurations needed for operations such as die sinking and milling.

- *Improved machine tool accuracy*. Advanced process design, machine design, and process control methods can lead to enhanced process accuracy, resulting in finished parts with tighter tolerances and better performance. For example, eliminating secondary finishing operations for drilled holes offers substantial savings in process costs. On-machine inspection also offers significant opportunities for productivity and quality improvements.

Grinding Operations

Specific research opportunities to improve the economics and precision of grinding operations include:

- *Process understanding*. Simulation of grinding processes, especially newer processes such as ductile regime grinding of "brittle" materials, incorporating appropriate constitutive models of both the grinding media and the workpiece, can be used to develop optimum process conditions. Constitutive models of the grinding media will include the influence of media characteristics (i.e., shape, composition, and size distribution) on finish, geometric tolerance, and surface integrity for a wide range of workpiece materials. In particular, identifying the chip-formation mechanisms in advanced materials, such as structural ceramics, metal matrix composites, and fiber-reinforced composites, is necessary to identify additional influences of the grinding process on material integrity and part performance. This understanding will aid researchers in the development of optimal grinding media.
- *Control of part surface integrity and material damage*. Cracking and other surface defects occur during the grinding of high-strength materials (e.g., M50 steel) and structural ceramics. These problems are exacerbated by efforts to maximize material removal rates. Investigation of the process variables that control such material integrity problems will establish the optimal process conditions for producing defect-free components. This understanding can be incorporated into process control strategies to improve part quality.
- *Real-time control of surface integrity*. Degradation of the grinding wheel during extended, continuous wheel use causes variation in wheel sharpness, which leads to thermal damage and taper and size variations in the workpiece. Process modification based on continuous monitoring of grinding wheel sharpness would reduce such damage and improve productivity.
- *Technology development for superfinishing and honing of advanced materials*. The growing use of structural ceramics will require a commercial capability to finish component surfaces to less than one microinch for applications ranging from fuel injectors to read-write heads in disk storage

devices. Achieving such precision requires improvements in both grinding media and process understanding. Because residual stresses generated during microfinishing of ceramics and metals can lead to part distortion, the development of nondestructive techniques to quantify and determine the distribution of such stresses deserves special attention. Better modeling of the microfinishing process is also needed to establish the processing conditions for minimizing residual stresses.

- *Grinding fluid alternatives*. Grinding fluids are destined to become unavailable due to their hazardous waste classification. Alternative formulations or the development of dry grinding media and techniques will be necessary. Separate techniques may be required to perform the combined lubrication and heat transfer functions of current fluids. Research is required to document the behavior of alternative grinding fluids in terms of tribochemistry, damping effects, lubrication, and heat transfer.
- *Grinding-wheel dressing optimization*. Dressing and truing techniques of used grinding wheels can introduce variation to the grinding process. Aggressive truing produces a sharp wheel, which requires low grinding forces but produces poor surface finishes. Conversely, gentle wheel truing produces a dull wheel, which yields a good surface finish but requires high forces during operation. Development of optimal truing techniques, based on wheel specifications, would lead to refurbished wheels that produce parts with good surface finishes with minimal grinding forces.
- *Real-time process control of grinding*. Control algorithms are needed to achieve reliable, safe, closed-loop control of the grinding process. These algorithms must incorporate reliable process models and define process parameter limits for the production of defect-free parts.
- *Tolerance control for grinding of thin-wall and slender parts*. Deflection during grinding of thin-wall and slender parts increases the difficulty of maintaining high precision and roundness. Accurate simulation models of the grinding process are needed to improve process understanding and to define optimal operating conditions.
- *Finishing technology for superconductors*. Surface finishing is a possible source of defects and detrimental residual stress patterns in high-temperature ceramic superconductors. Development of the process sequence to finish these materials without creating such defects will enhance material performance.

Laser Processes

There are a large number of research opportunities in laser processes:[7]

- *Development of new lasers*. New types of lasers designed specifically for manufacturing applications are needed. The characteristics of these lasers would include shorter pulse duration, smaller focal diameters, compactness, and shorter wavelengths. Promising new laser types include chemical oxygen-iodine, diode-pumped Nd-YAG, crystal-generated harmonics, direct diode, and copper vapor lasers. The benefits of these new lasers include precise control of machining, heat treatment, or welding depth through short pulses; minimization of thermal damage on the material through high energy densities and short pulse duration; smaller wavelengths and focus diameters to create smaller features; and high compactness of the laser. To make these lasers commercially viable, the reliability, size, and cost must all be improved significantly. Precise control of the laser output is also necessary.
- *Rapid prototyping*. A variety of laser-based rapid prototyping techniques have been developed recently, including laminated object manufacturing, stereolithography, and selective laser sintering. In these processes, a part design resident in a computerized database can be translated directly into a three-dimensional part, either through selectively photocuring a polymer, sintering a powder, or laser cutting two-dimensional profiles on thin sheets and then bonding them together. Although these processes show promise as flexible unit manufacturing processes, they are currently limited to selected materials used for geometric prototyping; these processes are only beginning to be extended to the production of structural parts. Also, since the part is created layer-by-layer, processing times up to 24 hours may be needed to fabricate a part. Future directions for research include the use of new laser types for improved dimensional accuracy and tolerances, the ability to process engineering materials such as metals and ceramics, and the design of new machine tools to increase processing speed significantly.
- *Development of laser-assisted processes and machine tools*. A potentially large area of investigation is the application of lasers for novel processing of materials beyond heat treatment, surface modification, welding, and machining. Recently, lasers have been used to perform three-dimensional shaping of workpieces through single-beam vaporization and two-beam grooving and

[7] The majority of the research recommendations also apply to surface treatment and welding applications of lasers, as discussed in chapters 6 and 8, respectively.

subsequent chip removal. The depth of the pocket was determined by the beam power and workpiece velocity. A relationship between the effectiveness of vaporization and the direction of workpiece motion relative to the beam polarization was also studied. A concept for three-dimensional laser machining that uses two laser beams has been demonstrated for applications such as gear making, threading, turning, and die making (Chryssolouris et al., 1986). Commercial equipment is already available to machine cavities for dies and molds.

- Lasers also can be used to *augment a mechanical cutting process*. A technique using a laser to preheat and soften the workpiece material prior to tool contact has been developed in which the laser beam is projected onto the workpiece underneath the flank of the cutting tool. The beam's energy elevates the temperature field and softens the material at the cutting zone, resulting in lower required cutting forces and tool wear (Copley et al., 1983).
- *Other possible applications* for lasers include secondary surface finishing, fabrication of composite parts, direct fabrication of engineered materials and surface layers, and machining micron-size structures in semiconductor materials.
- *Laser process modeling*. Effective development of laser processes requires a comprehensive understanding of the physics of beam-material interaction. Current models of laser processing do not account for the products of these complex interactions, including plasma formation, molten layer flow, chemical reaction with a gas jet, and transient thermal effects due to a pulsed beam. A possible area of investigation is detailed numerical modeling of laser processes with the aid of high-speed computing. Another aspect of modeling is the integration of laser processes with traditional processes in a job shop or factory environment. Process planning tools are needed that can generate sequences of manufacturing processes and operating parameters to exploit the advantages of laser processing and to reduce the trial-and-error calibrations required to find acceptable operating conditions for a given part and material.
- *Sensors and control*. Almost all laser processes currently operate on an open-loop basis. Operating parameters are set through trial and error until satisfactory material removal rates, surface quality, and dimensional accuracy are achieved. Sensing has been limited to beam power and mode monitoring, ultrasonic sensing, and adjustment of the focus head for machining on curved surfaces. However, a controlled beam source does not necessarily result in a controlled heat-affected zone, weld, hole, kerf, or groove. External factors such as gas-jet fluctuations, impurities in the workpiece, and velocity variations contribute to variations in beam-material interaction. One area of investigation may be in developing sensors that monitor the laser process, instead of the beam. Possible approaches include real-time sensing of temperature field fluctuations,

acoustic sensing, and indirect measurement of spark showers. The sensor methods developed must have fast response time (order of one microsecond), high accuracy, and high reliability, and they must be cost-effective for industrial implementation. Using sensor measurements for feedback, closed-loop control systems can be developed that can actuate changes in beam power, workpiece velocity, or gas-jet parameters.

Edm, Edwm, And Ecm

Specific research opportunities for EDM, EDWM, and ECM include:

- *EDM and EDWM for electrically conducting ceramics and composites* that offer a potential benefit in producing complex shapes.
- The use of *water-based dielectrics for EDM* to increase the MRR and decrease fire hazard to facilitate unmanned operation.
- *Investigations, monitoring, and control of debris density at the electrode/workpiece gap*. For instance, advanced flushing and suction techniques should be improved to reduce debris and increase process efficiency.
- *Understanding the fundamentals of parameters governing the surface properties of EDM and EDWM machined parts*. Most operations rely on manufacturers' literature for setting controls for rough or fine cutting, but the physics of the removal process, the prediction or measurement of residual stress, and the nature of the recast layer are still incompletely understood.
- *Incorporating EDM and particularly EDWM into computer-aided design and manufacturing programs*. Such automation offers the benefit of off-line wire path programming and debugging without the cost of machine utilization. Process monitoring and control will maximize part quality, minimize wire breakage, and improve equipment productivity.
- *Developing new electrode materials and coating combinations for optimizing EDM performance*. Better electrodes can potentially improve the process economics and thus facilitate the use of EDM for a wider range materials. Component surface integrity, finish, and tolerances should be monitored to identify successful candidate electrode materials.
- *Expanding current ECM process capability by the incorporation of pulsed current and the implementation of rotating tool electrodes* . An additional improvement is the adoption of three-dimensional numerical control of the ECM electrode to produce complex surfaces.
- *Numerical simulation and modeling of the ECM process*. This approach offers the advantage of process design without the costs associated with ECM equipment. Models of the process dynamics and workpiece materials

behavior would be integrated to provide a simulation of the process. Investigation of process parameter effects will lead to an optimized process definition for specific workpiece configuration and materials.

- *Reclamation techniques* for ECM process electrolytes and sludge. The ECM process currently uses potentially toxic electrolytic solutions that often produce sludge containing metallic ions that may be considered toxic waste. Environmentally benign ECM production processes are required.

Other Nontraditional Processes

Other nontraditional processes offer the potential for improved processing performance through the development and understanding of process mechanisms and material behavior. Process simulation based on this understanding and process control, using advanced in-process sensors, will be key technologies. Such processes include electrolyte jet machining, electrolyte abrasive jet machining, three-dimensionalcomputer-numeral-controlelectrochemical grinding, electrochemical discharge machining, electrochemical arc machining with rotating tools, and electrochemical spark machining.

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4

Phase-Change Processes

Phase-change processes produce a solid part from liquid material. They include the commercial processes of metal casting, infiltration of composites, and injection molding of polymers. These processes may reside early in the process stream (e.g., ingot casting of wrought metallic products) or produce a finished component (e.g., a molded polymeric beverage container). Control of the part shape and workpiece microstructure to specific levels is a high priority in these processes and often establishes the economics of the manufacturing process.

This chapter discusses the phase-change processes used to process metals, polymers, and metal-matrix composites.

METALS

Manufacturing processes that change the phase of metals by melting and subsequently resolidifying materials into finished or semifinished products are categorized as molding and casting processes. Primary metal industries use melting, casting, and solidification processes to produce semifinished products. Molten metals and alloys are cast by continuous methods or into individual ingot molds. Subsequently, these primary castings are rolled into semifinished products such as sheet, plate, rod, and bar, or they are forged into semifinished shapes (Weidmann, 1990).

In contrast to the primary metals industry, the foundry industry uses a wide variety of molding and casting processes to produce discrete, shaped products. These products range in size from steel castings of several hundred tons that are used in power generation plants to small, precision castings, such as delicate jewelry produced in investment molds. These processes are typically characterized by their molding process or by the casting process itself. For example, in sand casting, large volumes of castings are poured into sand molds.

Alternative molding methods, such as shell molding, investment casting (also known as the "lost wax" process), and expendable pattern (or "lost foam") casting, provide improved dimensional control and often more intricate shapes.

Major production systems are based on metal mold processes, such as die, or permanent mold casting, which use either pressure or gravity feed in the casting process. Another metal mold process is centrifugal casting, which takes advantage of radial forces on the solidifying product to reduce casting porosity; it is, for example, used to produce pipes. More recently, technologies involving squeeze casting have taken advantage of mechanical forces on the solidifying metal. Rheocasting (or thixocasting) is based on thixotropy, a physical state wherein a liquid/solid mixture or semisolid materials flow more easily when shear stresses are applied.

Casting of single crystal materials is a critical new technology. The molding and casting methods used include crystal growing by techniques such as crystal pulling, zone melting, and vapor deposition. Applications range from gas turbine blades to semiconductor materials.

Manufacturing entities involved in basic primary metals operations are large energy consumers and require significant environmental controls. Consequently, primary metals producers benefit from advances in energy conservation and pollution control.

Continuous or direct casting processes produce a cast sheet or thin slab close to the final hot-rolled dimensions, thereby eliminating hot rolling as a processing step with a corresponding reduction in investment and operating costs. Direct casting has been used in commercial production in the nonferrous industries for more than 70 years. However, the difficulty of controlling liquid steel prevented serious consideration of continuous casting until recently. Nucor Steel has led the implementation of thin-slab steel technology, breaking ground for the first U.S. plant in Crawfordsville, Indiana, in September 1987. Strip casting, a variation of thin-slab casting, eliminates the need for the hot strip mill operation, using small, inexpensive, and cost-efficient equipment (Schwaha et al., 1987).

This further integration of the casting and rolling processes offers additional substantial energy savings in the manufacture of primary metals. Recent reports have described the evolution of technologies that have made this possible and the quality assurance requirements necessary to gain wide adoption (Tsubakihara, 1987), as well as the corresponding operating considerations (Harabuchi and Pehlke, 1988). Future improvements, including direct charging of the hot casting to the reheat furnaces for rolling or for directing-line rolling of cast slabs, can be expected in the areas of equipment design and process development, with anticipated improvements in productivity and energy savings.

Recently, integrated and networked computer control systems have been installed in a number of major slab-casting installations for steel. These systems involve a computer architecture composed of mainframe computers with backup; several minicomputers; and a number of programmed logic controllers, digital controllers, and microprocessor-based controlled operator stations. This computer hardware provides for a distributed control system hierarchy and a database that supports the entire production system. Management of the melting function and its correlation with caster scheduling is implemented at a low control level, along with data collection and reporting and tracking of the slabs in the system. Workstations for operator guidance and the implementation of supervisory set-point control have been installed at the low control level, along with data acquisition/reduction and reporting functions. This control level also supports variable monitoring with alarm systems and local control, such as for mold level, and certain control and sequencing functions, such as tundish movement and ladle turret rotation.

This control structure has provided a dramatic improvement in plant productivity and quality. The productivity gain has been achieved through improved scheduling and extended sequence casting. Product quality has been improved through process optimization; process control; and a substantial upgrade of overall product flow, monitoring, and integrated supervision of downstream functions including slab cutting, marking, and direct charging to the reheat furnace at the hot strip mill. Many sensors now monitor the quality of the continuous casting process. Further upgrading of continuous casting productivity and quality depends to a large extent on the development of improved sensors for monitoring and control functions.

Direct linking of continuous steel casting and hot rolling, either by direct charging or in-line rolling, will be widely adopted in the twenty-first century. Wider acceptance of this technology will depend on assured product quality and maximum productivity and will require the development and implementation of a number of technology areas, including improved overall control of steel-making operations, manufacturing a defect-free strand, ensuring rollable temperatures when delivered for hot rolling, and flexibility of on-line width changing of slabs.

A variation of direct casting is spray forming. It uses atomization onto a substrate to produce near-net shape castings and eliminates traditional hot working processes. Spray forming has been used in the manufacture of rings, tubes, small billets, and pipes for both ferrous and nonferrous metals (Rickinson et al., 1981; Evans et al., 1985).

Of these direct casting processes, *strip casting* appears to have the greatest potential for commercialization in the longer term. The concept has been successful in the production of *steel sheet* (Preston, 1991a,b). This process could replace costly ingot casting and hot-rolling facilities, resulting in significant overall cost savings. The limitations in direct strip casting for manufacturing sheet metal products lie in the ability to identify, monitor, and control relevant process parameters. A suitable process control strategy must be developed that will allow production of high-quality strip on a reproducible basis and within narrow product specifications. Such a control strategy requires improved understanding of process dynamics, so that available computing capabilities can be used to interpret sensory inputs and to apply the resulting information to control the casting process in real time.

Shaped castings are the product of the metal casting industry, which is composed of 3,100 foundries in the United States. Since 1980, the number of foundries in the nation has decreased by over 26 percent. The U.S. industry has identified several key factors that have affected its competitiveness (AFS, 1994). A primary factor is market loss due to the development of new materials and the downsizing of end products (e.g., plastic pipe is replacing iron pipe, the average weight of automobiles is 30 percent less than fifteen years ago, etc.). Another key factor is the fact that the industry is primarily composed of small companies, with 80 percent of U.S. foundries having 100 or fewer employees. This makes research support, research program identification, and education and training difficult.

The American Foundrymen's Society is the major technical organization representing the entire industry. The society is composed of over 850 individuals from the North American metal casting and supplier industry. The society has developed a research and technology plan for the U.S. metal casting industry with four specific objectives, which are summarized in Table 4-1 (AFS, 1994).

A specific research agenda for the cast-metals industry has been set recently by an Advisory Board to the Department of Energy in their effort to respond to the Metal Casting Competitiveness Research Act of 1990. Their recommended research agenda is summarized in Table 4-2.

POLYMERS

The use of polymeric materials as viable structural materials has grown steadily because of their lower cost and weight. Consequently, research efforts have focused on the development of new materials and product applications, rather than on the processes required for their manufacture. The following discussion primarily addresses thermomechanical or thermochemical processes used for batch manufacturing of discrete parts. Technical areas related to processing (such as: melt rheology, microstructure development, sensors, and process control issues) are also considered.

Table 4-1 Objectives of the American Foundrymen's Society Research and Technology Plan

MARKETS
Research that expands cast component markets and applications that will serve to further diversify and stabilize the metal-casting industry
PRODUCTIVITY
Research that maximizes the production efficiency of a foundry. Programs that improve total metal yield and reduce casting rework are of major importance.
ENVIRONMENTAL
Research that reduces or eliminates the environmental risks affecting foundries and their employees.
TECHNOLOGY TRANSFER (EDUCATION)
Research that includes plans to transfer technology and effectively educate the segment(s) of industry that the results address.

There are two basic families of polymeric materials: (1) thermoplastics consisting of a linear chain structure that exhibits reversibility during phase-change processes and (2) thermosetting polymers for which the phase-change process is irreversible because chemical reactions and chain cross-linking take place. Some unit processes can produce components of both materials, while others can only process either thermoplastics or thermosets (Table 4-3).

Two factors are critical in the process science of polymeric materials: the material behavior during processing and process dynamics (Isayev, 1987; Tucker, 1989; Hieber and Shen, 1980; Wang et al., 1986; and Chiang et al., 1991). A thorough understanding of each is essential in the prediction of product characteristics and in the precise control of the process. The current R&D emphasis has centered around these factors and has included the following areas:

- melt rheology during processing;
- modeling and simulation of process dynamics;
- polymerization and kinetics in reactive processing;
- structural changes under processing conditions;
- material properties characterization;
- unit processes for composites; and
- process control and sensor technologies.

Table 4-2 Recommended Metal-Casting Research Priorities

PRIMARY RESEARCH PRIORITIES:
• Solidification and Casting Technologies
Dimensional Control of Castings
Clean Cast-Metal Technology
• Computational Modeling and Design
Computer Integrated Processing Methods for Productivity and Quality Improvements
• Processing Technologies and Design for Energy Efficiency, Material Conservation, Environmental Protection, or Industrial Productivity
Aluminum Furnace Optimization
Process Improvements for Lightweight Components of Aluminum Magnesium and Thin-Wall Metal Castings
Sand Reclamation
Characterization of Waste Streams
SECONDARY RESEARCH PRIORITIES:
• Solidification and Casting Technologies
Expendable Pattern Casting Technology
• Emerging Areas Needing Research
On-Line Process Controls and Sensors for Molding Melting and Coremaking
Plasma Melting
• Processing Technologies and Design for Energy Efficiency, Material Conservation, Environmental Protection, or Industrial Productivity
Cupola Furnace Optimization
Gating System Removal and Finishing Operation Technologies

The payoff to the polymer processing industry that results from the R&D effort in the polymer unit processes is becoming more noticeable. For example, according to a recent survey, computer-aided engineering technology for injection molding has been gaining acceptance in the industry (Naitove and DeGaspari, 1992). Many users of mold analysis software tools are reporting better product quality and shorter lead time and, in some cases, are eliminating the need for prototyping. Recent developments in processes for resin transfer molding and structural reaction injection molding have shown great potential for mass producing low-cost structural parts made from composite materials. Effective use of gas-assisted injection molding could significantly increase the flexibility of plastic part design.

Table 4-3 Polymer Phase-Change Processes

Materials Processes	**Thermoplastics**	**Thermosets**
Injection Molding	X	X
Compression Molding	X	X
Polymer Casting	X	X
Rotational Molding	X	X
Co-Injection Molding	X	
Gas-Assisted Injection Molding	X	
Foam Molding	X	
Calendering	X	
Cold Forming	X	
Extrusion	X	
Blow Molding	X	
Themoforming	X	
Transfer Molding		X
Reaction Injection Molding		X
Liquid Injection Molding		X
Rubber Injection Molding		X
Reinforced Injection Molding		X

METAL-MATRIX COMPOSITES

Metal-matrix composite (MMC) materials are reinforced with continuous fibers, discontinuous whiskers, or particulates that exhibit properties that are widely different from the matrix. These reinforcements are made from nonmetallic materials, such as carbon, alumina, silicon carbide, or organic materials such as polyaramid or polyethylene. Reinforcement orientation can range from highly aligned to random. The resultant properties of the composite material are the result of the reinforcement composition, amount, distribution, orientation, and interaction with the matrix.

Continuous-fiber MMCs are expensive and thus have found use principally in defense and space applications that demand high-performance materials. For example, carbon fiber-reinforced aluminum costs more than ten times the cost of its constituents (carbon fiber itself is much more expensive than aluminum) due to the highly labor intensive nature of its manufacturing process: First liquid-metal, infiltrated-fiber tows must be made; these are laid-up on a platen press and interlaid with aluminum sheets. Finally the laminate is consolidated by diffusion bonding.

Discrete parts of discontinuously reinforced MMCs are being produced much more cost-effectively using phase-change processes, such as aluminum with discontinuous particles of Al_2O_3 or SiC. Casting technology for discontinuously reinforced MMCs experienced a development spurt roughly fifteen years ago. Cast composite technology then suffered from the stigma of castings having highly segregated microconstituents that resulted in nonuniform and variable product properties. The demonstration of rheocasting and thixocasting (i.e., the processing of a semisolid slurry) has led to processes and process design methodology that are geared to optimizing of cast structure and properties (Sawtell, 1990). The technology itself is apparently well developed, as is exemplified by the thixocasting, investment-casting, and pressure-casting technologies. These types of composites are relatively isotropic compared with the continuous fiber types. With the proper selection of matrix and reinforcements materials, they do not exhibit many of the problems associated with fiber interaction during service and fiber degradation during processing. Also, these composites can typically be easily joined; for example, some can be welded. Their primary drawback is their inferior mechanical properties compared with the properties of the continuous fiber composites in the principal axis direction.

Cast MMC parts with discontinuous reinforcement are potentially economically acceptable for a wide range of applications. For example, thixocastbased processes will likely find wide use in automotive, defense/ aerospace, and heavy applications in which weight savings translate to increased fuel efficiently and, therefore, cost savings. MMCs processed by thixocasting are lighter than cast iron, exhibit better wear resistance and higher thermal conductivity and are thus excellent candidates for disc brake rotors. Similarly, investment-cast MMCs are being employed in microelectronic packaging and in stiffness-driven structures, while pressure-cast MMCs, with their superior surface finish and good dimensional tolerances, are increasingly used for machine tools and products requiring high thermal conductivity.

Several new matrix alloys and materials are currently under consideration. Probable applications include large structural components such as aircraft frames, surgical implants, and structures for transatmospheric hypersonic vehicles, as well as smaller applications such as constraining cores for printed circuit boards. Matrix materials include beryllium and titanium. For aerospace propulsion systems with lighter engines and reduced cooling requirements, reinforced intermetallics are being investigated. Those such as Ti_3Al, NiAl, FeAl, and $NbAl_3$ offer improvements in weight, stiffness, and corrosion resistance but suffer from low toughness at low temperatures and strength degradation at high temperatures. These limitations can be overcome by reinforcing the matrix with high-strength discontinuous fibers and particulates. When these considerations are coupled with the technical challenge of incorporating reinforcing fibers into the aluminide matrix without adverse interfacial reactions, another major barrier to MMC application becomes evident.

The need for high-temperature performance led to the use of MMCs in automotive pistons, as demonstrated by Toyota's ceramic fiber-reinforced aluminum alloy pistons in diesel engines in the early 1980s. The development program for the National Aerospace Plane in the 1990s has furthered the challenge of integrating and optimizing the manufacturing steps for composite material processing. To date, highly controlled processing techniques such as powder metallurgy, thermal spraying, and diffusion bonding have not been found to be cost-effective.

Although extensive effort has been devoted to manufacturing processes that emphasize techniques to optimize structure and properties of the MMC, the lag in the development of such techniques that are also cost-effective represents one major barrier to the widespread use of MMCs. Another major barrier prohibiting more-extensive use of cast MMCs is the development of matrix/reinforcement systems that can be readily produced in the foundry. These systems would have castable matrices with reinforcing agents that are nonreactive during the high temperatures encountered during processing. Thus, control or elimination of interfacial reactions is another serious consideration in the selection of composite constituents.

In summary, much additional fundamental research will be necessary before the full potential of MMCs is realized in commercial products. Many design engineers have the incorrect perception that casting processes yield parts and products with properties that are inconsistent and inferior to those of wrought processes. Part of this stigma reflects the lack of a unified focus on optimal processing techniques. A well-characterized composite system produced under strictly controlled processes would help to remove this perception.

RESEARCH OPPORTUNITIES

Metal-Casting Processes

Specific research opportunities in metal-casting processes can be summarized as the following:

Advanced or emerging technologies. A number of new processes have shown considerable promise and are in various stages of commercialization. These processes include near-net shape casting, pressure die casting, rheocasting, rapid solidification, metal-matrix composites, powder process technologies, and vapor/solid processes for films and coatings (Flemings and Brown, 1988). Potential benefits for these processes include lower costs and safe, environmentally clean processing.

Modeling and design. Modeling and design is the key to advancement of process understanding and optimization for molding, melting, and casting processes. Computer modeling of fluid flow, heat transfer, and solidification mechanisms is a consistent need for every casting process. For instance, improved models of materials behavior would result in prediction of residual stresses and the resulting geometric distortions of castings. Developing such models requires additional mechanical property data (e.g., elastic and plastic) for the casting material from room temperature to the melting point and specific volume data over this temperature range, as well as accurate multicomponent phase diagrams. Modeling also requires the development of pertinent thermal property data for the mold and casting materials, as well as models of the heat transfer situation at the mold-casting interfaces. For instance, there is a need for modeling the thixotropic process, including the flow of the material into the mold coupled with cooling gradients and solidification rates. Particular opportunities may exist in processes such as magnesium alloy die casting.

Automation control and sensors. Process automation, control, and the development of required supporting sensor technologies are key aspects in the future advancement of the casting industries.

Energy conservation and environmental protection. Significant R&D needs relate to energy conservation, waste reduction, and environmental control for the casting industries. The molding, melting, and casting industries are energy intensive and environmentally sensitive. As these industries evolve and undergo modifications, improvements, and advances in technology, productivity, and quality, R&D efforts must be directed toward energy conservation and environmental control. The competitiveness and viability of these industries depends on success in addressing these basic issues.

Advanced Polymeric Unit Processes

There are many research opportunities for advanced polymeric unit processes despite the considerable progress that has been made to date. The following generic research areas support the further development of polymers:

Material characterization and testing techniques. Methodologies and instruments for accurate measurement of dynamic properties of polymer materials under processing conditions are required. In addition, accurate mathematical representations of the measured properties (i.e., viscosity, specific heat, thermal conductivity, thermodynamic behavior, and constitutive relationships) are needed to support process simulation development. For instance, in order to predict and control the shrinkage and warpage of injection-molded parts, improvements in the characterization of the viscoelastic and thermodynamic properties of the material during processing are required. In addition, improved processing of crystalline thermoplastics and reactive polymers depends on the determination of the crystallization and chemical reaction kinetics, respectively. In processing polymer composite materials, the basic knowledge of the influence of fiber orientation on injection or compression molding of short-fiber-reinforced polymers at high fiber concentration requires further development. Similarly, the flow behavior of polymers through preformed fiber mats during the process of resin transfer molding requires substantial characterization. Expansion of the characterization to include commercial production materials is critical to the realization of enhanced manufacturing productivity in the polymer processing industries.

Process modeling and simulation. Improvements in numerical techniques for three-dimensional simulations of anisotropic material behavior are required for process design of polymer composite parts. Expanded simulation of solidification events in polymer processing, detailed predictions of component thermal shrinkage, and thermomechanical modeling of part distortion are also key future needs for improved part quality and process productivity. In addition, three-dimensional simulation capability will extend the level of complexity of accurate part design.

Innovative unit processes and equipment. For economical production of quality components, processes and equipment designed from a basic understanding of the behavior of materials is necessary. New and emerging advanced polymeric materials (e.g., supermicrocellular foams, long-fiber-filled polymers, or liquid-crystal polymers) are particularly sensitive to this issue. In addition, innovative processes of increased capability in component precision and geometric complexity offer added opportunities in the flexibility of part design. For example, a novel injection molding process, gas-injection molding, allows the manufacture of parts with increased structural stiffness and improved surface finish and tolerances; it is one of the most promising types of polymer injection molding.

Development of advanced process-control methodologies. Increased process productivity can result from better process control that is enabled by improved sensors and process control software. Improved part quality is projected to be an added benefit.

Application of traditional polymeric processing to advanced composites . Dramatic reductions in production costs are feasible with the adaptation of commercially available equipment to the processing of high-performance advanced composites. Process design methodologies offer the potential for both high-volume and low-volume products at lower cost.

Recycling techniques and considerations. Recycling is a major issue in using plastics for the decades to come. Considerations of recycling during materials development and in product-process design are high priorities. Future efforts should also include the development of recycling technologies for emerging materials.

Mmcs

Research opportunities for unit processes in support of producing discrete parts made from MMCs include the following:

More emphasis on characterizing MMC behavior during realistic processing conditions. Such characterization should occur during the early stage of development.

Improved product consistency using existing unit processes. This process development must include consideration of the influence of process conditions on the property levels and durability of the MMC components. Realistic *modeling* and *simulation* approaches to identify optimal processing conditions are required. The development of *criteria functions* for the production of sound-cast MMC products using unit manufacturing processes would improve the efficiency and the economics of MMC commercialization.

Development of adaptive-control techniques for the processing of cast composites. The success of this endeavor depends a great deal on the accuracy of the control's software knowledge of the behavior of the unit process and the MMC workpiece. The material must be accurately characterized on microscopic and macroscopic bases, and the property changes as functions of the process and the accompanying mechanical responses must be predictable. Accordingly, enhanced measurement techniques and process modeling capabilities are also required.

Development of fiber coatings and fiber preforms for in-mold liquid metal infiltration techniques of continuous-fiber MMC. Research on improving the manufacture of continuous fiber MMCs requires an integration of process technologies, sensors, controls, and materials characterization. Studies of suitable coatings that inhibit interfacial reactions and, at the same time, improve wetting are necessary to advance this technology, together with the development of processes to efficiently apply these coatings. In the long term, development of new fiber materials that are nonreactive in the matrix would be highly desirable. Research and analytical modeling of liquid-metal infiltration processes are also needed. Processes utilizing liquid-metal infiltration of fiber preforms with suitable fiber coatings offer a promising route to reducing the cost of continuous-fiber MMC materials.

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5

Structure-Change Processes

Microstructural changes can be induced in almost all engineering materials to alter their mechanical properties. This is usually achieved through thermal treatments involving heating and cooling under controlled conditions. The treatment temperatures and processing conditions vary according to the nature and composition of the material. Combinations of mechanical and thermal treatments are sometimes used (i.e., thermomechanical treatments) to produce properties that cannot be obtained in any other way. In some cases, different properties are desired in the bulk than in the surface of a part. In these instances, specialized thermal treatments involving surface diffusion or surface (differential) heating are used.

This chapter discusses the main categories of structure-change processes used for metals, ceramics, and polymeric materials and for coating and laser processes that produce desirable structural change.

MATERIALS

Metals And Alloys

Iron-base alloys, particularly the carbon and low-alloy steels, are among the most widely used structural materials in industry. Structure change can be achieved easily in iron-carbon alloys using straightforward thermal treatments that rely on the change in solubility for carbon and alloying elements that accompany iron's allotropic transformations. As expected, mechanical properties vary with the structure. Furnace-cooled (i.e., slow cooling rate) materials exhibit low strengths and high ductilities, since they are fully annealed, while rapidly cooled materials (water-, oil-, or air-quenched, depending on the alloy content) exhibit higher strengths and lower ductilities. Volume change accompanying the austenite-martensite transformation can lead to high residual stresses and substantial distortion, along with a risk of part cracking, due to differential cooling in parts with large changes in cross section. Hence, hardened parts are usually tempered to relieve the stresses and to stabilize the part dimensions.

Structure-change processes in nonferrous (i.e., aluminum) alloys are widely used in aerospace construction and are finding increased use in the automotive industry to reduce vehicle weight. These materials depend on change in solubility of alloying elements with temperature. However, in the absence of allotropic transformation in the base material, changes in mechanical properties depend on solution treatment followed by precipitation aging. The final structure and properties in these dispersion-hardened materials depend on the times and temperatures used for the precipitation treatment. The upper temperature limit for the use of these alloys is determined by the propensity of the precipitates to coalesce and coarsen.[1]

For example, superalloys used to build the hot-section components of turbine engines rely on a structure comprising a nickel matrix with a fine dispersion of highly stable gamma prime precipitates (i.e., Ni_3Al) that possess a good lattice match with the matrix. Such a microstructure retains its strength even at relatively high temperatures, hence the name "superalloy."

Ceramic And Glassy Materials

Principles of structure change in ceramics are similar to those for metallic materials. However, the thermal treatment practice is handicapped by the low thermal diffusivity inherent to ceramics. Also, slow heating and cooling rates are used to minimize risk of cracking by thermal stresses. This problem is aggravated by the higher thermal treatment temperatures necessary for structure change in ceramics.

Structure change in nominally amorphous ceramic materials uses thermal and thermomechanical treatments comparable to those for metals and alloys (Weidmann et al., 1990). Glass-ceramic oven tops, for example, are mechanically processed and thermally treated to create a final microstructure with a very low thermal coefficient of expansion. Exceptional thermal shock resistance is obtained through control of microstructure.

Ceramics pose problems in structure change because of the directionality of their molecular bonding, high inherent hardness, slow achievement of

[1] Generally, the finer the precipitates, the stronger the material.

equilibration, limited number of slip systems with resulting very low ductility, and the presence of hard and soft glide planes. Despite these limitations, thermally treatable, tough ceramics such as partially stabilized zirconia have been developed and are finding increasing use as structural ceramics.

Polymers

Nominally amorphous polymeric materials are normally processed by melt-to-solid transformations. However, extraordinary strength gains can be obtained in some polymers (e.g., polyethylene) by controlled deformation in the processing of fibers. Precise strain, strain rates, and thermal treatments are necessary.

Structure-change processing to obtain high strengths in common polymers is not widely used. Injection-molded tubular polyethylene terephthalate preforms are stretched and blow molded when the material is elastomeric. Processing conditions are selected and used to prevent any structure change between injection molding and heating for blow molding. Process temperature and time are adjusted to suppress spherulite formation and to promote partial crystallization. Final strengths obtained in the part (e.g., plastic beverage containers) are comparable to those of aluminum alloys.

SURFACE TREATMENT

Many coating processes have been developed to deposit microthin films that allow close control of coating thickness and composition not possible with traditional surface treatment processes (e.g., surface hardening, electroplating, and plasma spraying). These processes also allow well-bonded thin films to be deposited at relatively low temperatures. Examples of these thin-film deposition technologies currently in commercial use include halide metallurgy (i.e., chemical vapor deposition [CVD] processes) and electrically assisted vacuum coating (i.e., physical vapor deposition [PVD] processes). In CVD processes, halide compounds such as $TiCl_4$ with hydrogen are used to deposit thin films on hot substrates. The coating temperature is typically above 750 °C. Process streams and operating conditions are chosen to obtain viable coating rates and to maximize deposition efficiency. Specially developed CVD phase diagrams and computation packages are used. Kinetic variables such as the total flow rate, coating system geometry, substrate chemistry, and surface finish play a role in determining the nature and quality of films deposited (Bhat, 1989). Cobalt and other metal-bonded carbide tool inserts are now routinely CVD-coated with compounds such as TiC, TiN, and $A1_20_3$, singly or in combination. High temperatures used in CVD make post-coat thermal treatments necessary. for steel tools and parts. Coating internal stresses and thermal stress-induced cracking of the deposited films are common. CVD for hard coating of steel products is therefore not common. Light alloy parts are *not* coated with CVD processes.

Since hard coating of ferrous components and most mechanical parts requires lower deposition temperatures, PVD processes are used. To date, a variety of film-deposition techniques have been developed to produce the needed coatings:

- activated reactive evaporation (Bunshah and Raghuram, 1972);
- ion plating;
- direct current, radio frequency and magnetron sputtering (Bunshah, 1982);
- hollow cathode discharge (Komiya and Tsuruika, 1976); and
- are coating (Ramalingam et al., 1987).

The structure, properties, and adhesion of the films deposited with PVD processes depend on coating-source characteristics, the substrate temperature, bias applied, and the ambient pressure (Thornton, 1974). By admitting reactive gases during film deposition, coatings of compounds are obtained. Control of compound stoichiometry requires coupling of the gas admission rate with the coating-flux generation rate.

All the thin-film deposition technologies mentioned above, as well as the more recently developed microwave-assisted plasma deposition processes, are in commercial use to support integrated circuit fabrication. In these applications, deposition occurs on very flat surfaces in relatively thin films (less than 1 millimeter in thickness).

LASER PROCESSING

Lasers can be used to alter the microstructure and properties of metals, polymers, ceramics, and glasses. Lasers can change the surface properties of finished parts without affecting the parts' inherent bulk properties. This capability can be used to clad material onto a worn surface, thereby greatly extending a part's useful life, or to repair high-value components without causing extraneous damage. Although lasers do not require any special processing environment, such as a vacuum, environmental control can be utilized when the material being processed requires it.

Laser heat treatment involves traversing the laser beam over a large surface area of a metal workpiece. Through rapid heating by the laser beam and subsequent quenching, the microstructure of a layer of material near the surface can be modified without affecting the bulk of the workpiece. Laser heat treatment of alloy steels can significantly increase their strength, toughness, sliding wear resistance, and abrasive wear resistance. The microstructure formed near the surface is essentially dislocated packets of martensite surrounded by retained austenitic films. Laser heat treatment can also be used to relieve residual stresses caused by mechanical processes through annealing. One example is selective stress relieving of glass components using a carbondioxide laser.

Laser heat treatment is currently limited to specialized operations, mainly due to its low processing speeds for continuous production. However, as the energy densities of new lasers increase, laser heat treatment may become economically viable for the large-scale continuous processing of metals, since much higher scan rates and beam velocities could be attained. Another development may be the use of an array of diode lasers as a direct heat source. This approach has a number of advantages. First, the diode array would allow area coverage of the workpiece, resulting in a uniform heat treatment. Second, the diode array is stationary, providing better reliability than a moving laser head. Finally, diode arrays can be placed next to both the top and bottom surfaces of the workpiece, allowing simultaneous heat treatment of both sides (Warner and Sheng, 1993).

Lasers can be used for surface modification processes (i.e., laser melting, cladding, alloying, and peening) in which the microstructure of a workpiece surface is modified through laser melting and rapid solidification of a thin layer of material (Ortiz et al., 1990). This melting and solidification is often accompanied by the introduction of powder elements or a predeposited layer of new material to combine with the base material. These processes are influenced by factors such as the laser power and power density, size and shape of the beam profile, scan velocity, and chemistry and metallurgy of the substrate.

Laser melting involves rapid heating and phase change of a small surface layer of a substrate through beam impingement and subsequent rapid quenching. To melt a material, a laser power density of 10^5-10^7 watts/cm^2 is usually required. The melting and solidification rates are so rapid that most elements go into solution with little opportunity to precipitate back to the grain boundaries. By controlling parameters (e.g., laser power, translation speed, peak power, pulse rate, etc.), the substrate melt depth can be controlled to range from a few micrometers to a millimeter.

Laser surface alloying is a process in which the surface of an alloy is melted to a desired depth using a continuous-wave or pulsed laser beam with the simultaneous addition of powdered alloying elements. The alloying element can be either preplaced or added as a powder stream during processing. The combination of convection and diffusion redistributes the alloying elements uniformly throughout the molten pool. Laser surface alloying can result in the synthesis of nonequilibrium metallic phases that could lead to a wide variety of microstructures, including extended solid solution and amorphous phases. Alloying depths can range from less than 1 micrometer to over 1 millimeter and be free of porosity or cracks. An advantage of laser surface alloying over conventional methods is the small heat-affected zone created, which allows the finished part to retain the bulk characteristics of the base material. The metallurgical bond also helps to provide a high degree of adhesion between the bulk material and the laser alloyed region.

Laser cladding is similar to laser surface alloying except that the powder constituents introduced into the melt pool are also melted by the laser beam. The main objective in laser cladding is to overlay a surface or substrate with another material that has a different chemistry by melting a thin interfacial layer to produce a metallurgical bond with minimum dilution of the clad layer. Typical laser power densities range from 10^5 to 10^6 watts/cm^2. The most significant advantages are production of novel alloys, minimized clad dilution, reduced alloy material loss, reduced machining, and reduced distortion. Due to the laser's rapid melting and quenching capabilities, fine microstructure, increased solid solubility of alloying elements, and nonequilibrium crystalline and amorphous phases are possible. Laser cladding is especially useful for creating wear-resistant surfaces when the component material is not conducive to transformation hardening due to the high process speeds and minimization of heat distortion. A potential problem with parts subjected to localized surface melting is that high residual tensile stresses are developed unless a phase change, with volume expansion, takes place.

Shot peening is a well established process that typically uses small particles to impart localized plastic deformation. Properly done, it results in a residual state of compressive stress at the surface. An innovative approach uses a pulsed laser beam to perform peening (Ortiz et al., 1990). The beam impinges on a layer applied to the substrate; normally a paint layer (with impingement occurring underneath a water film) or copper foil are used. The vaporization of the paint layer or foil creates a plasma plume. The expanding plume creates an intense pressure wave that is directed onto the surface; it results in a compressive stress region that extends approximately 0.5 mm in depth from the workpiece surface. This compares favorably with the compressive stress depths of 0.2-0.3 mm that are achievable through shot peening. However, with a Q-switched laser operating at pulse lengths of 10-30 nanoseconds and 0.1 joules/pulse, only 1 mm^2 of surface area can be treated per pulse. This translates into a relatively slow processing speed of 10 inches^2/min.

RESEARCH OPPORTUNITIES

Structure change in metallic alloys, ceramics, and polymers has a sound theoretical basis, and the structure-change processes in use are well established and understood. The ease with which structure change can be effected in metallic alloys has led to the widely used industrial practice of fabricating metallic parts in their soft condition, followed by structure-change processing either as a final or penultimate treatment to obtain the design properties. A major deficiency in structure-change processing for discrete parts is its frequent dependence on batch processing for thermal treatment, since undesirable storage queues are typically required. Two recent developments offer a means of overcoming this problem: solid-state, high-frequency power sources and continuous-mode, pulsed, and solid-state lasers. Both developments permit rapid, in-line structure-change processing, which eliminates the need for batch processing, and hence in-plant storage is minimizied.

Thermal Treatment

The technology base related to thermal treatment processes (e.g., annealing, normalizing, spherodizing, solution treatment, aging, hardening, tempering, homogenizing) applies to all types of materials. Some high-priority research needs are described below for the critical areas of microstructure control, product/process control, and process development.

Models applicable to all materials of interest are needed to simulate the evolution of a microstructure as a function of thermal history and process conditions (furnace and ambient) to predict final structure distributions and product properties. Extension of these simulation models into process control can be used for real-time process optimization. Specifically, the microstructure evolution models should be capable of incorporating:

- dissolution and precipitation processes;
- physics of structure change effects during quenching;
- models of kinetics of recovery, recrystallization, and grain growth; and
- models of microstructure change in metastable materials (such as rapidly solidified materials) during thermomechanical processing.

Rapid thermal treatments including induction, laser, or directed-beam heating are increasingly important in structure-change processing. Extension of microstructure response models to include these rapid thermal processes would enable identification of the process condition windows that are required to predict product properties and process economies.

Product quality of thermally treated parts is usually expressed in terms of mechanical properties (e.g., strength, hardness, toughness) and geometric tolerances. Since typical problems encountered during thermal processing are part distortion and cracking, a better understanding of thermal and mechanical mechanisms is required to allow prediction of conditions that cause shape change (distortion) and cracking during thermal processing.

Improved thermal treatment processes for structure change of metal alloys require robust sensors to monitor furnace atmosphere and conditions (temperature, partial pressures, flow patterns), as well as product state (i.e., microstructure), during processing. In-process measurement of quenchant characteristics is also needed. In-process measurements will assist quantifying process improvement, enable further process refinement, aid in planning preventive maintenance, and improve equipment utilization. Development of in-process sensors will also be useful to minimize the environmental impact of thermal treatment processes (e.g., decrease emissions) and to enhance process energy efficiency.

Structure-change processes for product property and quality enhancement require further development for ceramic materials and polymers. (Notable exceptions are the pyroceramic materials and polyethylen tenephthalate, which are well developed.) Improving structure-change processes for these materials will also require R&D in sensors and process characterization.

Surface Treatment

Although thin-film coating treatments are finding wide use in the tooling industry,[2] use of such surface treatments in the mechanical component industry is less common. Processes that deposit thin wear-resistant coatings could be extended to many mechanical component applications in which wear and durability are key concerns. Such technology applied to automotive applications, for example, could facilitate the increased use of nonferrous lightweight alloys (e.g., aluminum, magnesium, and titanium alloys) and thus indirectly lead to

[2] Use of thin films to improve the life of metalworking tools and injection molds is now becoming common. CVD and PVD processes are used to deposit extremely adherent single or multilayer films, usually less than 10 mm thick, to improve tooling performance.

substantial improvements in manufacturing efficiencies and fuel economy.[3] Mechanical applications require coating three-dimensional parts with complex materials possessing precise stoichiometry. Films deposited must also have exceptional film-to-substrate adhesion to withstand high contact stresses and severe localized power dissipation due to frictional contact.

Despite use of thin-film deposition technology to support the cutting tool industry, a science base to support the coating process needs of mechanical industry has not yet emerged. The following research is needed:

- *Process characterization*. High-priority issues include the determination of coating flux density, distribution of the flux emerging from the coating source, and mean energy of the flux, in order to assure reproducible stoichiometry in films, high-film deposition rates, microstructure control (i.e., control of grain size, morphology, texture, and orientation and control of film porosity), and coating uniformity. Understanding the film stress evolution and mechanism of good film-to-substrate adhesion is vital in order to take advantage of thin films to reduce surface distress, especially in nonferrous materials.
- *Coating flux generation*. While flux generation processes are well understood for thermal deposition and sputtering processes, basic processes involved in emerging coating processes (e.g., cathodic arc deposition and anodic arc-based processes) require further study.
- *Process modeling*. Understanding process characteristics and the mechanisms involved in the generation of coating flux will enable process models to simulate film deposition so that coating processes can be designed. Process development now depends on trial and error to identify acceptable processing conditions. Process modeling will allow control of nucleation and growth in films, especially as the models relate to structure development, film-to-substrate adhesion, and generation of film stresses.
- *Scale-up*. Laboratory-scale PVD processes are difficult to scale-up to production-level systems. This difficulty is partly due to the three-dimensional shape of mechanical products and the relatively large spatial volumes over which stable and metastable materials have to be synthesized homogeneously in order to coat large pans uniformly. Process scaling parameters must be identified and understood.
- *Sensors*. Concurrent synthesis and reliable deposition of high-performance materials require development of sensors to monitor changes in critical process variables. Sensors that only measure vacuum and flow-rate cannot

[3] Recent Department of Energy workshop recommendations support and emphasize this suggestion (Courtright, 1993).

provide an adequate basis to monitor synthesis of film materials and their deposition on substrates, so that well-bonded films with minimal film/substrate stresses are consistently produced.

- *General process understanding*. Studies are required for better understanding of processes for the deposition of ultra-high-hardness materials including diamond and cubic boron nitride, deposition of multilayer films such as microlaminates, deposition of synthetic microstructures (patterned, two-phase coatings), and the deposition of alloyed hard materials.

Laser Processing

The recommendations presented in Chapter 4 regarding the development of new types of lasers, modeling, sensors, and control apply also to the use of lasers for structure change. (At the present time, the use of lasers for surface treatment is a very small fraction of their use for cutting and welding. The reason lies in the ability of a laser to generate an extremely high energy density at its focal point that can readily be used to cut and weld thick plates. However, for surface treatment, the beam must be defocused to avoid vaporizing material. As a result, the laser loses some of its unique advantages.)

Progress in laser surface treatment must include the development of alloys optimized for laser treatment. (Many of the alloys used in laser treatment were originally developed for welding.) Material characterization and modeling will be required to fully understand the effect of extreme heating and cooling rates on the nonequilibrium microstructures that may result.

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6

Deformation Processes

Deformation processes transform solid materials from one shape into another. The initial shape is usually simple (e.g., a billet or sheet blank) and is plastically deformed between tools, or dies, to obtain the desired final geometry and tolerances with required properties (Altan, 1983). A sequence of such processes is generally used to form material progressively from a simple geometry into a complex shape, whereby the tools represent the desired geometry and impart compressive or tensile stresses to the deforming material through the tool-material interface, as illustrated in Figure 6-1 for the cases of extrusion and deep drawing. Deformation processes are frequently used in conjunction with other unit operations, such as casting, machining, grinding, and heat treating, to complete the transformation from raw material to finished and assembly-ready discrete parts. Deformation processes, along with machining, have been at the core of modem mass production, because they involve primarily metal flow and do not depend on long-term metallurgical rate processes.

CLASSIFICATION AND CHARACTERISTICS OF PROCESSES

Deformation processes can be conveniently classified into bulk-forming processes (e.g., rolling, extrusion, and forging) and sheet-forming processes (e.g., stretching, flanging, drawing, and contouring). In both cases, the surfaces of the deforming material and of the tools are usually in contact, and friction between them has a major influence. In bulk forming, the input material is in billet, rod, or slab form, and a considerable increase in the surface-to-volume ratio occurs in the formed part. In sheet forming, a sheet blank is plastically deformed into a complex three-dimensional configuration, usually without any significant change in sheet thickness and surface characteristics.

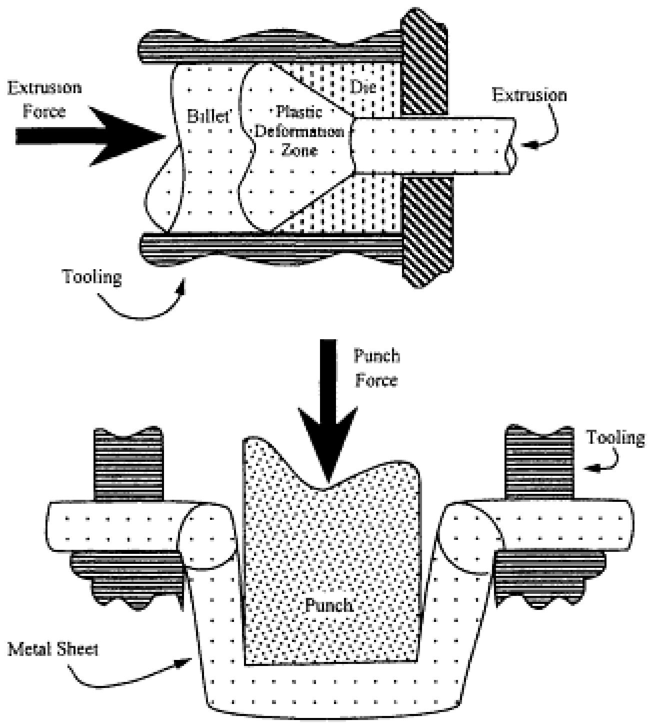

Figure 6-1 Basic components of process modeling.

Bulk-forming processes have the following characteristics:

- The workpiece undergoes large plastic deformation, resulting in an appreciable change in shape or cross section.
- The portion of the workpiece undergoing permanent plastic deformation is generally much larger than the portion undergoing elastic deformation. Therefore, elastic recovery or springback after deformation is negligible.

The characteristics of sheet-metal forming processes are as follows:

- The workpiece is a sheet or a part fabricated from a sheet.
- The deformation usually causes significant changes in shape but not in cross-section of the sheet.
- In some cases, the magnitudes of permanent plastic and recoverable elastic deformations are comparable; therefore, elastic recovery or springback may be significant.

Some processes can fall under both categories (e.g., sheet-metal and bulk-forming), depending on the configuration of the workpiece. For example, in reducing the thickness of a tube, if the starting workpiece is a thick-wall tube, the reduction (ironing) process would be classified as a bulk-forming process, whereas if the starting workpiece is a thin can, the ironing process could be considered to be a sheet-metal forming process.

In addition to shape change, forming processes also alter the metallurgical structure of the workpiece and may be used to enhance material properties. Such improvements may eliminate the need for heat treatment and provide property combinations that were previously unattainable. Formed parts may be produced to net, or near-net, dimensions and surface, reducing or eliminating the need for finishing steps and the material loss due to machining and trimming (Kudo, 1990). Deformation processes are less energy intensive than casting processes because they are carried out at lower temperatures, and the deformation energy required for shape change is much less than the thermal energy required to reach the molten state.

Deformation processes are especially attractive in cases where:

- the part geometry is of moderate complexity, and the production volumes are large, so that tooling costs per unit product can be kept low (e.g., automotive applications, such as those depicted in Figure 6-2); or
- the part properties and metallurgical integrity are extremely important (examples include load-carrying components used in aircraft, jet engines, and steam or gas turbine components that require very high in-service reliability).

Design of proper tooling is the key to successful deformation processes, but it requires extensive experience and know-how to reduce the expense and time involved, since process development is still heavily based on trial-and-error effort. Although this approach has been highly successful, future competitiveness requires complementary model-based methodologies for process design. There is great need for a predictive capability through which material and process control can be exercised to achieve desired product features economically and without defects.

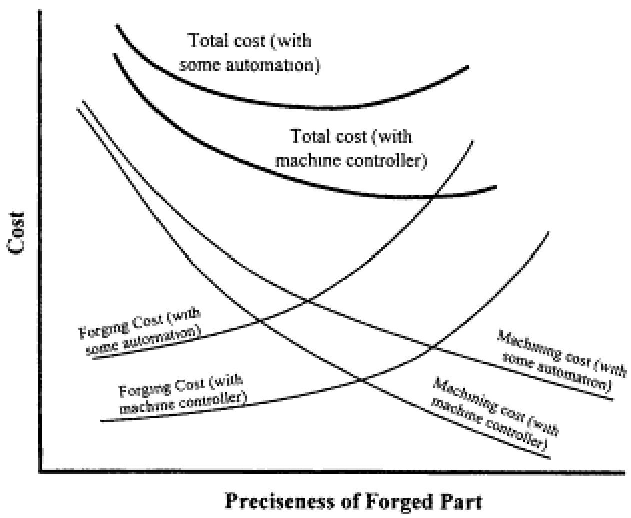

Figure 6-2 Minimum total manufacturing cost arising from a compromise between forming and finish machining costs (adapted from Kudo, 1990).

Toward this end, it is useful to consider generalizations about the physical phenomena that are common to all deformation processes: this forms the basis for a rational approach to understanding the characteristics of each process and to enhancing the art of metalforming. In Figure 6-1, incoming material is transformed into outgoing material by passing through a zone of plastic deformation.[1] During transformation through the plastic deformation zone, in addition to changes in shape and dimensions, metallurgical structure and surface are altered as well. Energy transfer occurs within the plastic deformation zones as heat and external forces are transferred to the workpiece material by forming equipment through the tooling and the interfaces between the tooling and workpiece.

[1] In forging, the entire workpiece may undergo plastic deformation nearly simultaneously.

SIGNIFICANT PROCESS VARIABLES

Shape, structure, and surface transformations occurring in the plastic deformation zone, for a given material, are controlled by the equipment, tooling, and interfaces. The metal flow, the friction at the tool-material interface, the heat generation and transfer during deformation, and the relationships between microstructure/properties and process conditions are difficult to analyze and predict. Therefore, complete knowledge of the complex interactions between the process parameters and the workpiece material form the basis of the predictive capability required for rational process design. This systems approach, as illustrated in Figure 6-1 and Table 6-1, allows the study of the input/output relationships and of the effects of process variables on product quality and process economics.

The key to successful metal deformation (i.e., to obtaining the desired shape and properties) is the understanding and control of metal flow. The direction of metal flow, the magnitude of deformation, and the temperatures involved greatly influence the properties of formed products. Metal flow determines both the mechanical properties related to local deformation and the formation of defects such as cracks or folds at or below the product surface. The local metal flow in turn is influenced by the process variables, as summarized in Table 6-1.

Discrete parts often undergo several sequential forming operations (e.g., preforming) to transform the initial simple geometry into a complex one, without causing material failure or degrading material properties (Sevenler et al, 1990). A typical sequence is shown in Figure 6-3. Consequently, one of the most significant steps for future enhancement of deformation processes is the capability to predict the optimal forming sequences. For a given operation (e.g., preforming or finish forming), such design essentially consists of three steps:

1. predicting metal flow by establishing the kinematic relationships (e.g., shape, velocities, strain rates, and strains) between the deformed and undeformed part;
2. establishing the limits of formability or producibility within which the part can be formed without surface or internal failures; and
3. selecting equipment and tooling designs based on the prediction of the forces and stresses necessary to execute the forming operation.

Incoming Material—Billet Or Sheet Blank

Material properties under processing conditions (i.e., flow stress of the deforming material under various temperature, strain, and strain-rate conditions) must be known in order to analyze, simulate, and optimize a deformation process. The flow properties of the incoming material are determined by its chemical composition and previous thermal and mechanical treatment history. Accurate determination of these data allows reliable estimation of tool stresses and equipment loading, as well as prediction of metal flow and elimination of forming defects.

Table 6-1 Significant Variables in a Deformation Process

Starting Material	**Tooling**
Flow stress (constitutive equation)	Geometry
Workability (forming limit curves)	Surface conditions/coatings
	Material/heat
Surface condition	treatment/hardness
Thermal/physical properties	Temperature
Initial conditions	
Microstructure evolution	
	Conditions at Tool/
Product/Final Material	**Material Interface**
Geometry	Lubricant
Dimensional accuracy/tolerances	Heat transfer
Surface finish	
Microstructure and properties	
	Process Equipment
Deformation Zone	Speed/production rate
Deformation mechanics	Force/energy capabilities
Kinematics	Rigidity and accuracy
Stress state	
Temperature	**Resources and Environment**
	Available manpower
	Air, noise, and waste water
	pollution
	Plant and production
	facilities and control

Another material parameter requiring improved understanding is the influence of geometric characteristics of incoming material (i.e., tolerances, quality of sheared edge, and surface finish) on the subsequent forming operations.[2]

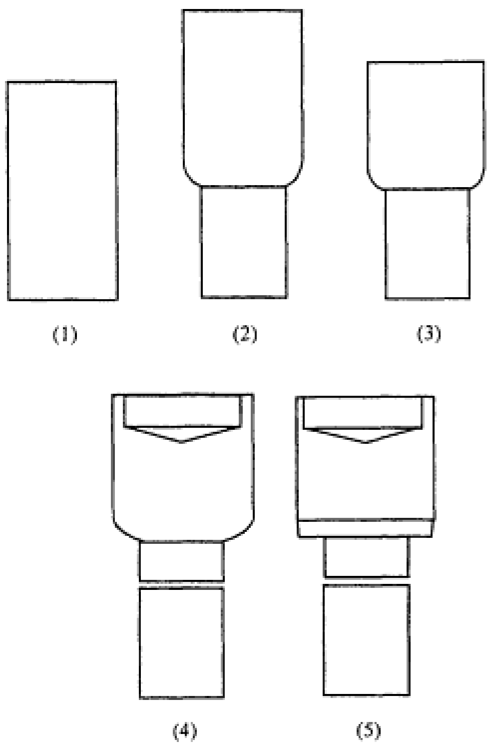

Figure 6-3 An example forming sequence retrieved from the Forming Sequence Database. (The exact dimensions of the part are in the database.) (adapted from Sevenler et al., 1990). (1) is cut off; (2) is forward extrude; (3) is upset; (4) is backward extrude; and (5) is upset.

Information essential for the prediction of microstructure evolution during deformation processing using process modeling must be developed and made

[2] Development and application of material preparation processes, typically mass-change processes, are improving dimensional control of incoming materials.

available to process-design practitioners in industry, research laboratories, and educational institutions.

Product

The two main characteristics of a deformed product are its geometry (e.g., dimensions, tolerances, and surface finish) and its mechanical properties. As in all manufactured products, the design of the deformed part—that is, the consideration of ease by deformation processing during the design stage—determines the magnitude of the effort necessary for process and tool development (Altan and Miller, 1990). For example, geometric features that satisfy various functional requirements such as stiffness and strength could be evaluated regarding their formability. This information would greatly reduce the effort necessary for tool and process design. To date, research efforts have had limited success in developing knowledge-based systems to aid in part designs and process sequence selection for improved formability.

Current major trends in manufacturing products by deformation processing include:

- deformation-formed parts with complex geometries, such as gears with formed teeth, trunnions, and universal joint components (Pale et al., 1992), that are replacing parts produced by other processes, such as casting and machining, due to their lower cost (e.g., see the cost trade-off in Figure 6-4 for a precision gear);
- better surface finish, tolerances, and elastic springback control, which allow elimination of finish machining and grinding operations; and
- microstructure and properties optimized to reduce the need for heat treatment or use of high alloyed materials.

Deformation Zone And Mechanics

The understanding and prediction of process kinematics (velocities, strain, strain-rate), stresses, and temperatures of a deformation process are essential in estimating process conditions (tool stresses and deformation forces), understanding defect formation, and predicting the microstructure and properties of formed parts. This capability would allow the process conditions and tooling design to be optimized to obtain high-quality products with a minimum amount of trial and error during process development.

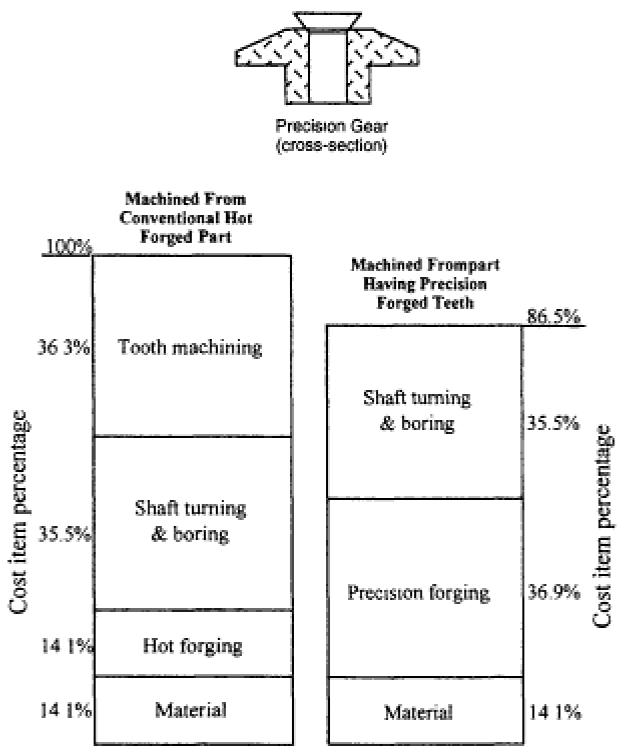

Figure 6-4 An example of manufacturing cost reduction by combining net-shape forming and partial machining for a precision gear.

Advances in the development and use of finite-element methods to solve nonlinear plastic deformation problems have led to practical solutions for two-dimensional deformation processes (Kobayashi et al., 1989). Work is now being done to extend process models that are based on finite-element methods to estimate parameters such as elastic defection of tooling, tool life, distortion of the formed part, and microstructure and properties of formed parts and to predict the occurrence of workpiece defects (Knoerr et al., 1992). Further progress in the use of finite-element methods in three-dimensional deformation has been slow due to difficulties in three-dimensional mesh generation, automatic remeshing, formulation of efficient solution algorithms, and effective visualization or post processing of results.

Tooling

Design and manufacture of tooling are essential factors determining the performance of deformation processes. The key to successful deformation processing is tool design, which has been, to a very large extent, experience based. Innovative multi-action tool designs are being developed for near-net shaping of increasingly complex parts, such as gears and universal joint components. These tooling approaches can be extended. Many companies already are using computer-aided engineering and computer-aided manufacturing to design and fabricate process tooling (Tang et al., 1988).

Advanced heat treatment and coating techniques can extend tool life. Studies are being conducted to measure and predict lubricant behavior and heat transfer at the tool-material interface in support of lubricant coatings development based on an understanding of mechanisms of erosive tool wear. This is an extremely important area, since tool life directly influences the economics of deformation processes.

Conditions At Tool-Material Interface

The quantitative knowledge of friction and heat transfer at the tool-material interface is essential for adequate design of the process. New and environmentally benign lubrication systems are being developed to establish a reproducible process that provides parts with high quality and excellent surface finish. For instance, in hot forging the quality of lubrication and the oxidation of the billet surface greatly influence the thermal conditions at the tool surface and determine tool life and process economics.

Equipment

The productivity, reliability, and cost of equipment used for deformation processes are extremely important factors, since they determine the economics and practical application of a given process. In both sheet and bulk forming, the stroking rate of the forming machine tools are being continuously increased. Thus the machine dynamics and machine stiffness are of increasing concern. As in other unit processes, the use of sensors for process monitoring and control is essential and continues to increase.

Sensors can also be used to continuously monitor the condition of the tooling. Such systems can not only improve part quality but enable higher production rates from expensive deformation process equipment by greatly reducing unscheduled break-downs.

Safety And Environmental Factors

Safety is the paramount concern in deformation processes where machine speeds and forces are relatively high. Other concerns include the environmental effects of lubricants, cooling and heating fluids, scrap material, and noise. In developing a new unit process, it is necessary to minimize or eliminate adverse environmental effects caused by the process.

RESEARCH OPPORTUNITIES

Considering the systems view of deformation, as shown in Table 6-1, the opportunities in deformation processing may be reviewed in terms of process or system components. Improvements in process design capability can be divided into two general areas:

1. enhanced numerical methods for accurate representation of material and friction behavior, including microstructure and defect evolution; and
2. expanded capability to measure material behavior, friction, and part quality.

Listed below are research opportunities to advance the state of the art in deformation unit processes.

- Research efforts are needed to generate, evaluate, and systematically store flow stress and formability data for both sheet and billet materials under actual processing conditions (i.e., high temperature, strain, and strain-rate regimes).
- The relationships between process variables and obtainable microstructure and properties, after deformation and heat treatment, must be developed for many new materials.
- Design for producibility requires further research. Research is needed to develop expert systems to assist part designers in the design of components to be produced by forming, particularly in manufacturing complex-shaped parts.
- Prediction of microstructure and property evolution, as well as surface and internal damage caused by processing, is required for advanced process modeling.

- The effect of lubricants and coolants on thermal conditions at the tool-material interface is a significant research topic. The result will be extended tool life through improved heat treatments of the tools and the incorporation of new coatings.
- Further development of suitable sensor systems that can maximize machine utilization rates and reliability through real-time condition monitoring of machine performance is required, so that the resulting information can be used to schedule preventive maintenance.
- Research is needed to establish tooling design guidelines for reducing tool stresses, improving lubricant distribution, and influencing metal flow in dies. Work is needed to link the tool stresses, calculated by using finite-element programs, to tool fracture and fatigue criteria that are obtained experimentally for various tool materials and configurations.
- Better understanding of the effects of coatings and surface treatments on heat transfer and interface conditions is needed to improve the selection of existing coatings and guide the development of new coatings.
- Research should be extended in innovative and practical design of multi-action tooling and machines for forming parts with complex shapes and tight tolerances. Key research areas include increasing dynamic stiffness to improve tolerances; on-line monitoring of machine and tooling performance to avoid unscheduled down time; and techniques and methods for on-line monitoring of part quality, particularly for high-rate forming systems.
- R&D efforts must be conducted with multidisciplinary research groups so that theoretical and experimental developments concurrently benefit each other and thus lead to a high degree of realism and confidence in the process models. Collaborative mechanisms for the development and widespread dissemination of the data and methodologies may be required, particularly for small manufacturers who typically do not have in-house groups of multidisciplinary researchers.
- Implicit in these needs is the requirement for training and education at a much higher level than is currently available in the majority of companies using deformation processing in manufacturing.

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7

Consolidation Processes

Consolidation processes consist of the assembly of smaller objects into a single product in order to achieve a desired geometry, structure, or property. These processes rely on the application of mechanical, chemical, or thermal energy to effect consolidation and achieve bonding between objects. Interaction between the material and the energy that produces the consolidation is a key feature of the process. This interaction can be either beneficial or detrimental to the final product. In some cases, the consolidation energy enhances the structure or properties of the material and is an integral part of the process. For example, in the forging of powder preforms, the mechanical energy not only consolidates the powder but also imparts macroscopic geometry to the part while improving the microstructure of the material. In other cases, the energy used to effect consolidation is detrimental to the structure or properties of the product. For example, in fusion welding, the heat of melting achieves bonding between the objects but also can create an undesired microstructure in the heat-affected zone of the joint, causing distortion and detrimental residual stresses.

Consolidation processes are employed throughout the manufacturing sequence, from the initial production of the raw material to modification of the final assembly. One group of consolidation processes involves the production of parts from particulate or powders of metals, ceramics, or composite mixtures. These consolidated products are typically semifinished and require final thermal or machining processes. In some material systems, consolidation of powders produces feedstock billets for extensive processing into continuous mill products of bar, rod, wire, plate, or sheet. Other consolidation processes produce composites, with either polymer, graphite, metal, or ceramic matrices. Welding and joining processes, a unique group of consolidation processes, are used to combine subcomponents, often of dissimilar materials, into permanent assemblies. The performance of the final component is often governed by the quality of the joining process. This chapter presents an overview of the research needs and opportunities in powder processing, consolidation of polymeric composites, and welding/joining unit processes.

POWDER PROCESSING

Among the various manufacturing technologies, powder processing is the most diverse because of its ability to economically fabricate high-quality, complex components to close tolerances from almost all materials. Powder processing starts with particles having specific attributes of size, shape, packing, and composition and converts them into a strong, precise, high-performance component. Key process steps include the shaping or compaction of the particles and thermal bonding of the particles using sintering. The two steps can be combined into a single operation, as in vacuum hot pressing, or more typically, performed in sequence. In production, these processes effectively use automated operations with relatively low energy consumption, high material utilization, and low capital costs. Further, the process sequence is inherently flexible, since it can be applied to a wide range of materials (German, 1994; Jenkins and Wood, 1991; Klar, 1983, 1984; Lenel, 1980).

Powder processing uses a different approach than traditional component fabrication. Not only are the chemistry, heat treatment, and microstructure variable, but the distribution of phases and microconstituents, including porosity and reinforcing phases, is controllable.

Powder is a finely divided solid—typically smaller than one millimeter in size—of a controlled composition and can be combined with other materials, such as polymers, to ease forming or create composites. An important characteristic of powder is its high surface area to volume ratio, which leads to behavior that lies between that of a solid and that of a fluid. Powders will flow under gravity to fill containers or die cavities, so in this sense they behave like liquids. They are compressible like a gas, but the compression of a powder is essentially irreversible, like the plastic deformation of a solid.

Powder processing is widely used and growing. Powder-based components are often selected for their low costs, but there are recognized advantages in improved quality, homogeneity, and performance properties. A few examples illustrate the established diversity of products: lamp filaments, dental restorations, oil-less bearings, spark plugs, aircraft brakes, connecting rods, timing gears, lightweight armor, electrical contacts, nuclear fuel elements, orthopedic implants, business machine parts, high-temperature filters, sporting equipment, horseshoes, and jet-engine disks.

The specialization of R&D in the powder processing field is a reflection of the manufacturing segmentation by production schemes and materials. For example, a typical research concentration might be on metallic powders or ionic materials. Furthermore, the fabrication approach tends to further subdivide the industry, based on specific production routes. Because of this segmentation, the powder processing industry largely performs application-specific research with most of the fundamental process improvements coming from suppliers. Much of the powder processing industry does not have a strong research history and often lags in technological applications. Fundamental research is performed at universities, with some recent, successful industry-university partnerships in atomization, spray forming, powder injection molding, and advanced ceramics. The transfer of this technology to industry has been effective through industrial hiring of the university graduates.

The important technology areas in powder processing are based on key aspects of the fabrication sequence: development of powder alloys, production of powders, compaction, sintering, densification, process control. A necessary focus for U.S. research is on emerging powder-processing technologies to sustain industrial growth. Current opportunities for such growth include magnetic materials (especially the high-performance, rapidly solidified iron-neodymium-boron magnets), microelectronic components (such as tungsten-copper parts formed through powder injection molding), functionally gradient composites (for example, metal-ceramic acoustical energy absorbers), electromagnetic materials, and ultra-small biomechanical components.

Advanced Powder Alloys

The iron-neodymium-boron alloy system offers exceptional hard magnetic properties. Since this system exhibits segregation in casting, powder-based techniques using rapid solidification are the mainstay fabrication approaches. Research directed at moving these materials into widespread production is needed, especially in the context of a high-productivity route such as injection molding. This development would benefit several other high-performance powder products, including alloys and composites based on tungsten, beryllium, magnesium, and aluminum. Several ceramic powders, namely nitrides, carbides, and borides are also viable candidates for this process.

The number of materials being successfully processed by powder injection molding techniques continues to increase. The current list includes most common engineering materials. The future promises to add several composite materials, including tungsten-copper, molybdenum-copper, silicon carbide-aluminum, and aluminum nitride-aluminum for applications in microelectronics. Although considerable research activity is occurring in the area of composites, more attention is needed to establish a balance between cost, microstructure, properties, and performance. Powder processing techniques play a critical role in the fabrication of new metal-matrix composites; however, ceramic-matrix composites appear to offer major property benefits. Functionally gradient materials are another area needing more research. One emerging application is in the area of acoustic materials, where elastic modulus and density can be tailored to give passive sound attenuation. Such materials are useful in forming lightweight soundproofing.

Powder Production

The advent of total quality programs in the powder processing industry has resulted in considerable evidence that subtle variations in the powder production process reflect changes in powder characteristics. This realization suggests the importance of producing uniform powders characterized by high purity and compositional homogeneity. This requires in situ diagnosis of product quality during powder production. Further, there is increased need for smaller powders for applications such as injection molding and microelectronics. As powders become smaller, handling problems increase, often leading to contaminated powder and high scrap generation. Thus, research on powder production must be closely coupled with studies on properties, processing, and handling concerns.

Plasma processing, reactive synthesis, mechanical alloying, chemical precipitation, and gas atomization techniques are being applied to the generation of novel powders, especially fine powders produced from reactive or refractory materials. The use of plasma techniques for the generation of uniform micrometer-sized powders is an exciting development. Mechanical alloying is recognized for its key role in the fabrication of dispersion-strengthened alloys and amorphous alloys. Powders fabricated using atomization techniques include most of the high-performance alloys (e.g., superalloys and titanium alloys). Chemical precipitation techniques have demonstrated unique abilities to form small, uniform powders, but much effort is needed to scale-up these approaches to viable production quantities. Near-term research efforts need to focus on production of large quantities of small powders to identify potential scale-up difficulties.

Considerable recent research attention has been directed to the generation of coated powders. Coatings are formed by electrolysis, chemical vapor, physical vapor, fluid bed, spouted bed, and mechanical deposition techniques. This technology represents engineering at the individual particle level, forming coated particulates. These coated powders create opportunities at the microlevel to engineer improved processing and homogeneity. These efforts should to be focused on establishing processing benefits using fine powders. Research is needed to determine the conditions for minimizing segregation of constituents during handling and compaction.

Shaping

Die compaction is currently the mainstay of powder shaping. Equipment that integrates the latest sensors, control logic, and defect detection schemes, together with artificial intelligence for process monitoring and control, can substantially advance these processes. Also, tool design and press operation in die compaction can be improved by applying process simulation and modeling. With progressive improvements coupled to developing powders for uniform die filling and compaction, die pressing can be applied to larger and more-complex components.

The field of powder injection molding has attracted considerable manufacturing attention. While the technical concepts are in hand, the technology for automating and producing large quantities of inexpensive parts is immature. A standardized process is required to establish a protocol for improved quality. Research aimed at the implementation of in situ sensors, vision systems, and defect detection schemes is necessary before widespread adoption will be practical. Further links are needed between the molding operation and rational process specification in terms of the powders, binders, and tooling for successful molding.

Computer simulation software exists to optimize several aspects of plastic injection molding. Similar research can be conducted for powder injection molding, taking into account the differing rheology, thermal conductivity, momentum, and density.

Considerable research is needed to develop processing technologies to fabricate larger components, with greater shape complexity and closer precision. The fabrication of high-performance materials, such as titanium and silicon nitride, by powder injection molding is widely discussed, but improved processing control to move them into commercial reality is lacking. Thus, several aspects of this exciting manufacturing technology must be addressed by future research, as the technology promises enormous potential benefits.

Sintering

A major effort is needed to integrate the fundamental knowledge of sintering into production practice. As an example, considerable progress has been made in modeling fundamental mass transport events during sintering. However, this information has not been linked to prediction of performance attributes, so it is largely ignored by the industrial community. Consistent with the trend toward improved performance, there is continued interest in better sintering practices, especially those using liquid phases. The widespread use of liquid-phase sintering reflects the benefits of faster atomic transport. Further, rate-controlled sintering is a concept wherein the cycle time remains short while the time-temperature program is varied to suit the microstructure or other product goals.

As new sensors and control and analysis techniques become available, there is an urgent need to apply these to sintering. Effective application will require assessment and integration of in situ inspection and processing into the furnaces to move into a true real-time controlled mode of operation. Additionally, much effort is needed to upgrade the models of sintering, such as the need to consider the furnace as a dynamic thermal processing system. These developments will allow the production of sintered products of high dimensional uniformity and specific final attributes.

Densification

Most products formed by powder processing suffer property decrements in the finished component from residual porosity. The exceptions are distended materials for energy absorption and filters in which the void spaces provide the desired property. Several post-sintering densification steps can be applied to remove pores, and there are batch processes in which shaping and sintering are performed simultaneously. Examples include spray forming, semisolid forging, powder forging, hot forming using pseudo-isostatic conditions, gas forging, and hot isostatic compaction. Most of these processes are expensive and poorly utilized by industry. In each case, there are prospective components for application, but the application development is guided by trial and error and needs to be better supported by contemporary process understanding. Fundamental research is needed to bring together a unified view of densification that includes consideration of stress state, strain rate, powder characteristics, temperature, and time to allow rational analysis of complex geometries.

Instrumentation And Control

The powder processing industries require research to develop, integrate, and adapt modem tools to improve production processes. The application of microcomputers is progressing as the requirements for consistent products become widespread. Further, there is increased use of computational techniques in support of die compaction, hot isostatic compaction, injection molding, and sintering. There is a need for research on advanced instrumentation and control of production equipment, including compaction presses, sintering furnaces, and injection molding machines. In the latter example, die-cavity instrumentation can be used to make instantaneous machine corrections to ensure uniform quality compacts.

Although the concepts are known, the types of sensors and signals and their interpretation and utilization need thorough research. The coupling of such instruments to expert systems eventually will allow intelligent processing of materials. Efforts are in progress to implement such a system for control of powder atomization using in situ particle size analysis and of hot isostatic compaction using in situ density measurements. These concepts need to be extended to shaping and sintering. For example, vision systems need to be developed for both die compaction presses and powder injection molding machines. Such systems would allow automated inspection of the tooling after each cycle to identify damage from an improperly ejected compact and excessive tooling wear. Another potential advance is in diagnostic thermal imaging of high-temperature processes (e.g., sintering, atomization, and plasma spraying), which would allow real-time analysis and process control.

POLYMERIC COMPOSITES

A composite material consists of two or more discrete materials whose combination results in enhanced properties. In its simplest form, it consists of a reinforcement phase, usually of high modulus and strength, surrounded by a matrix phase. The properties of the reinforcement, its arrangement and volume fraction, define the mechanical properties of a composite material. The matrix performs the important functions of acting as a stress transfer medium for the fibers.

Continuous fiber-reinforced materials offer the highest specific strengths and moduli among engineering materials.[1] A carbon fiber-epoxy structural part, for

[1] In this section, only aligned continuous fiber composites will be considered, since these are the materials with the highest properties of interest. Short fiber composites, such as injection-molded glass or carbon fiber-reinforced polymers, will not be considered here, since the manufacturing processes for such materials are mature and are direct extensions of processes used in the plastics industry. Metal-matrix composites are addressed in Chapter 4, "Phase-Change Processes."

example, has only about 20 percent of the weight of a steel structure of equal stiffness. In addition, the weight savings obtained by substituting composite materials in one component often results in the achievement of additional weight savings in other components of the system, due to lowered inertia, increased fundamental structural frequencies, and other factors. Composites also have the advantage of good corrosion resistance and the potential for integration of component piece parts, such as molded-in rib stiffeners, without the need for subsequent assembly operations and fasteners, which are often required for metallic structures.

Consolidation in composites can be considered to occur at two levels: the fibers are infiltrated with the matrix to form a lamina or ply, and the individual laminae are consolidated together to form the final structure. In the prepreg process, these two levels are distinctly separated, since the fiber/matrix consolidation process forms the prepreg, which is then laid-up to form the laminate or final component (NRC, in press). In other processes, such as resin transfer molding (RTM), fiber/matrix infiltration and the consolidation of the final part are done in a single stage. Single-stage consolidation processes are attractive, because they eliminate the additional cost associated with prepreg production; however, two-stage consolidation processes have major advantages that often outweigh the benefits of single-stage consolidation. These include flexibility in part geometry, high fiber content, excellent fiber wet-out, and better control of fiber volume fraction distribution. Because of these advantages, prepreg processing is firmly entrenched in high-value products, such as aerospace applications, in spite of its high cost.

The high fiber volume fractions (50-75 percent) in aligned continuous-fiber composites require the matrix material to have low viscosity to allow infiltration into fiber-to-fiber spacings that are a small fraction of the fiber diameter. Alternatively, high pressures can be used with high-viscosity matrices for successful infiltration. The latter approach is used in polymer processing of filled thermoplastics; however, this approach is only possible for short-fiber composites. In continuous-fiber polymer composites in which fiber integrity and orientation must be maintained, the approach is to use low-viscosity resins such as epoxies or polyesters, which are cross-linked once infiltration is completed. In prepreg manufacture, the matrix is partially crosslinked after infiltration. Consolidation of prepreg plies in the final component is done during the curing process.

The prepreg process has the advantage of being able to accommodate a wide variety of part geometries and fiber orientations with tight resin-content control. However, the high cost of composites structures manufactured using prepreg processes is due in part to the high cost of prepreg production, handling, cutting, and manual assembly of the final composite part.

In resin transfer molding, catalyzed resin is injected into a closed mold that contains the dry fiber reinforcement (preform). After the mold is filled (i.e., after fully infiltrating the fibers), curing of the resin results in completion of the consolidation process. In structural reaction injection molding (S-RIM), reacting resin streams are mixed and injected under pressure into a closed mold containing the fiber preform. S-RIM processes are relatively rapid (cycle times of 1-10 minutes), while cycle times for resin transfer molding range from 10 to 100 minutes. The resin transfer molding process can accommodate a higher fiber content than S-RIM with concomitant higher mechanical properties.

Pultrusion is a mature technology but is presently restricted to the use of polyester resins. Pultrusion has the advantage of being a continuous process; however, it has the disadvantage of having poor transverse strength (transverse to the pultrusion axis). This problem has been addressed through the incorporation of felts, mats, and woven fabrics that provide transverse reinforcement. However, there is still the problem of low delamination strength in the direction perpendicular to the section profile. The pultrusion of closed-hollow sections, such as square and round tubing, is still difficult and uncommon. Hollow cross-sections are difficult to grip and have high surface-friction forces in the die, which necessitate high pull loads that can cause fiber failure during the process. Braided over-wrapped plies have been introduced in pultrusion to provide off-axis reinforcement. However, the slow speed of the braiding process severely restricts this approach. Tape wrapping could provide the same benefit at much higher production rates.

Current research in composites processing has followed three basic avenues:

1. *Prepreg processing*. Improving production rates by automating prepreg handling and ply placement techniques has been investigated with mixed success. Part of the problem is the long cure times required for prepreg resin systems. In addition, handling thin tacky sheets is a difficult task to automate. Much work has been devoted to tape laying machines, cutting plies to shape, and layup geometries. The results have been useful in identifying the limits of prepreg layup processes; however, the basic drawbacks of prepregs—long cure times, low-temperature storage, and secondary waste generation—have not been adequately addressed. The lack of success in prepreg automation is illustrated by the fact that the largest user of carbon fiber prepregs, the sporting goods industry, has largely concentrated its production in countries where labor can be obtained at a low cost, since almost entirely manual processes are used.
2. *Process control in resin transfer molding and S-RIM*. Current R&D efforts are devoted to improving process control through the incorporation of sensors and microprocessor control of injection rates, temperature, pressure, and time. The aim is to automate these processes further. In addition, several efforts

are under way to automate the manufacture of preform and reinforcement mats. While resin transfer molding can produce parts with high fiber volume-fraction, the cycle times are long; efforts to speed cycle time and develop models for improving mold and gate design, as well as process design, are necessary in order to increase the production rate of this promising process.

3. *Composite sheet forming*. Several research programs have been conducted on the mechanics and modeling of composite sheet forming. Production rates are still low, and there are difficulties inherent in forming sheets in which compressive strain fields, which cause fiber microbuckling, are unacceptable, because the strength of the part is severely compromised. In addition, this process, unlike resin transfer molding, requires high pressures, which call for expensive tooling. Low-cost tooling concepts for this process need to be developed to bring unit cost down, especially for the low production volumes inherent in many composite products.

WELDING AND JOINING PROCESSES

Evolution of welding and joining technologies can be traced by process, materials, or application. Historically, these processes have developed empirically and have been rapidly applied to technological problems, driven by the tremendous commercial benefits derived from improvements in joining processes in manufacturing. For example, lasers were used within less than five years of their discovery as a source of controlled energy delivery for repair welding of vacuum tubes.

Today, virtually any new source of heat energy is immediately evaluated as a candidate joining technology. In most cases, the emerging technology has preceded a fundamental understanding of the process. The need for welding and joining is ubiquitous, as most manufactured products rely on welding or joining in some form. Indeed, only monolithic parts can be made without joining. Unfortunately, joining methods are generally imperfect, either in properties or in affordability, and there is a constant search for improved processes. In addition, welding and joining progress has become a prerequisite for applications in advanced materials. The ultimate quality and reliability of manufactured products is often determined by the quality of the joints (Eagar, 1990; David and Vitek, 1993).

The perfect joint is one that is indistinguishable from the material surrounding it. Some processes, such as diffusion bonding, come very close to this ideal; however, such processes seem to be either cost-intensive or restricted to a narrow group of materials. Experience indicates that there is no universal joining process that will perform adequately on all materials in all geometries.

As a result, an engineer must be able to select wisely the best process for a particular material in a given application.

Given the great economic and technical importance of welding and joining to any manufactured product, one might ask why a fundamental science has not developed around this field. There are several answers to this question. First, welding and joining are not scientific or engineering disciplines but are processes. As with any process, scientific principles from many different disciplines are involved (e.g., physics, chemistry, mechanics, electronics, and materials). In this sense, there is a science base for welding and joining already in existence, and it is up to the engineer to gather the available information and to apply it judiciously to the problems of welding and joining.

Second, welding and joining are material- and application-driven technologies. The revolution that has occurred in materials science and engineering over the past two decades has not been matched by improvements in joining science and technology. It is becoming increasingly apparent that the usefulness of many new materials is limited by the ability to manufacture products made from these materials in an economic, reliable, and rapid manner. As designs utilizing new materials require higher performance standards, the number of acceptable joining technologies becomes more restricted. In contrast, as the functionality of materials becomes more specific, the number of joints and the number of dissimilar material combinations increases. The result is a manufactured product with increased cost and decreased reliability.

Welds are often the weakest part of the structure and are generally located at highly stressed locations. In addition, joining often comes near the end of the manufacturing process, when the cost of scrap is high. This is particularly, critical because designers are specifying an increasing diversity of materials in their products, which increases the number of joints. As the materials become more specialized, they are used closer to their performance limits, and, hence, greater requirements are placed on the joints. The result is an increased number of joint failures in spite of improving joining technologies and quality control processes.

A number of new materials and processes are emerging, though what can be considered "emerging" depends on the industry as well as the type of material being considered. A novel material for one industry may be a traditional material in another industry; therefore, the challenges facing use of an emerging material are specific to an industry. Since few, if any, novel materials will be used in a monolithic form, they must be integrated into the structure or product using joining technology. Unfortunately, joining technologies do not exist for many of these new materials. On the other hand, industry has a significant need for joining traditional materials more economically, at high productivity and with high quality. This may or may not require new joining processes, but it certainly will require new resources. In summary, new joining technologies are needed to provide both effective, reliable processes for joining novel materials and improved or novel processes for joining traditional materials.

Although there are many nontraditional processes that offer significant advantages in specialized applications, many of the traditional welding processes have unique advantages, which will continue to make them the processes of choice in a number of applications. For example, in the fabrication of heavy structures, arc welding will continue to dominate due to the flexibility and economy of this process. Resistance spot welding will continue to be used in the automotive industry, because it is relatively inexpensive compared with more expensive and complex laser and electron beam processes (see Figure 7-1). Nonetheless, these newer processes will continue to grow in importance and need to be studied in increasing detail.

With regard to novel materials, productivity is not the major challenge in joining such materials. Rather, the question is whether some of these materials can be joined at any cost. As materials designers use more-complex structures, which are tailored to specific applications, the use of the material is pushed to its limits of performance. This creates severe problems for the performance and integrity of the welded joint. Whereas design engineers traditionally designed with available materials, they now design materials for specific applications. As an example, consider the production of aircraft structures. Fifty years ago, designers selected from available materials such as wood, canvas, and aluminum. Today, design engineers dream of a hypersonic passenger airplane (known as the Orient Express), which must endure surface temperatures of 1500 °C, in addition to being lightweight, high strength, and resistant to hydrogen degradation.

These materials—advanced intermetallics and composites—must be developed to meet the design rather than the design being tailored to the properties of available materials. Unfortunately, joinability is rarely factored into the design of these new materials, creating great difficulties when an attempt is made to utilize the materials in a real structure. The cost of many new materials is so high and their properties are so specialized that they will only be used where they are essential. As a result, products will contain more joints, and a greater fraction of these will be between dissimilar materials. This will only compound problems of quality and reliability in the final product.

The common design rule of eliminating all possible joints is being violated at an increasing rate. Due to a desire to use the minimum amount of costly, high-function materials, joints are being placed in more aggressive environments. The properties of joints are being pushed to the limit. One challenge for joining engineers is failure at the joints. It is no longer possible to select the joint configuration or joining process as an afterthought of the design. Joining technology must become an integral part of the product design.

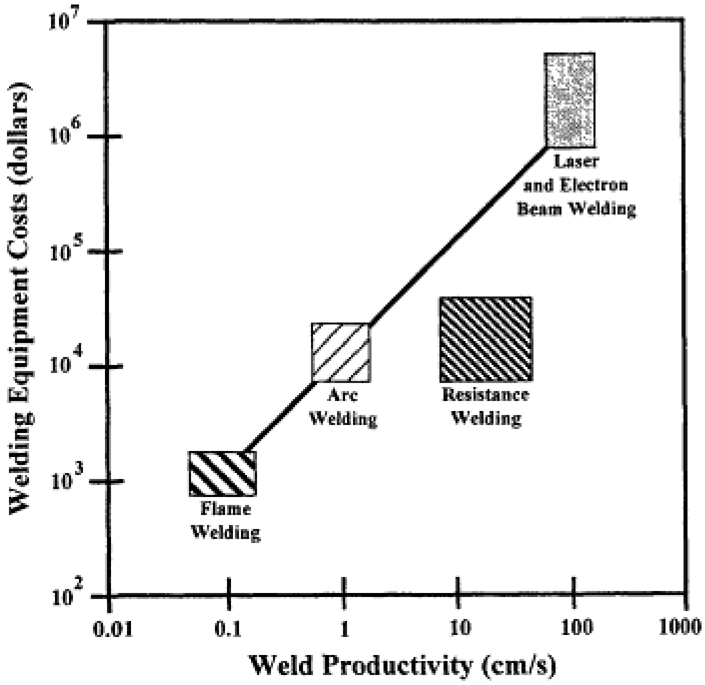

Figure 7-1 Production costs for commercial welding processes (adapted from Eagar, 1990).

Thus, some of the challenges in joining emerging materials include faster new product development cycles; fabrication of smaller components, especially in the electronics industry; and more dissimilar material combinations. The development of new materials should include parallel development of the necessary manufacturing processes, such as joining, as a critical priority, especially considering the specialty applications with small numbers of parts. Otherwise commercial use of these materials will be severely retarded. With regard to traditional materials whose properties and joining methods are well known, incremental improvements will continue to be made in the quality and economy of the product.

RESEARCH OPPORTUNITIES

Powder Processing

- There is a clear need for production technologies geared to homogeneous, clean, reproducible, small powders, typically from the higher-performance materials. Future applications and processing developments are largely contingent on the availability of these powders.
- Research on scale-up of production processes for small, high-quality powders at low cost is an urgent need. There is considerable potential for improved powder products that are based on developing coating techniques for forming composite particles. Such research must focus on producing uniform, homogeneous materials in large quantities.
- Consolidation technology upgrades depend on improved modeling and analysis capabilities, coupled with implementation of a new production control logic.
- Shaping technologies have similar needs for uniformity, dimensional control, and productivity. Die compaction is the dominant shaping technology and needs research support to better design and control the shaping operation. This research should include attention to more-intelligent presses and better tooling design strategies.
- Powder injection molding has enormous potential. Research is needed on sensors and analysis techniques to isolate defect sources and institute defect detection schemes within the molding operation. Interactions between the powders, binders, molding process, and component geometry must be better understood, and this knowledge must be incorporated in control system software.
- For sintering there is a need to link the atomistic scale understanding to the macroscopic level in terms of furnace instrumentation, control, and optimization. Intelligent processing schemes are needed to examine the atmosphere, component size and shape, thermal goals, and furnace conditions to ensure proper sintering.
- Research on densification is needed to allow rational process analysis. A generic analysis framework that includes a materials stress state, strain rate, powder characteristics, and temperature during sintering should be developed.

Consolidation Of Polymeric Composites

- Thermosetting prepreg materials with more-robust shelf lives and the ability to be stored at room temperature are needed. Also, improved thermoplastic prepreg materials are needed that address the materials' high cost, relatively high processing temperatures, and lower resistance to solvents.
- Innovative equipment designs are needed that allow for the flexible introduction of hybrid construction (i.e., multiple families of fiber types) and woven reinforcement configurations. Such equipment can fully utilize the unique properties of prepreg materials.
- Optimization of fiber coatings to provide good adhesion to the resin and ease of composite processing is required. Good wetting fiber preforms may go a great way in extending the process limits and increasing processing speeds, particularly in resin transfer molding. For example, it is well known that sizing (coating) applied to glass fibers greatly improves the fibers coupling to an epoxy matrix.
- Developments in automated layup and vacuum bagging that enable these processes to be accomplished without the need for secondary materials (e.g., vacuum bags, bleeder, and sealant) are important research needs. Such developments will overcome environmental concerns due to the amount of waste attributed to the secondary materials inherent in present prepreg production methods.
- Equipment technology borrowed from the textile and paper industries may prove useful in its application to prepreg processing in which nontacky prepregs are used.
- The integration of sensors and heating elements in an intelligent mold is needed for production of high-quality composite structures containing variable thickness features and hybrid materials.
- Models for RTM and S-RIM are needed that adequately address the reaction kinetics and the time- and temperature-dependent dynamics of reactive fluid flow during processing. Further, sensors and real-time control schemes must incorporated in present equipment to improve quality control, surface finish, and the production of hybrid composites.
- Low-viscosity resin systems are needed for RTM and S-RIM processes to provide sufficient rigidity to the part, so that it can be ejected from the mold in a short time and subsequently post-cured to reduce in-mold cycle times.
- The construction of accurate fiber preforms is essential to the production of high-quality pans by resin transfer modeling or S-RIM techniques. Innovative equipment design is needed for automated handling of dry fiber and creating preforms with the required local fiber orientations and fiber distribution densities. The application of textile technology, including stitching, braiding, and

weaving, should be further studied in the context of handling high modulus fiber preforms.

- The delamination strength of pultruded products must be improved if this process is to gain wide use. Investigation of bulked rovings and scrim fabrics are potentially useful research directions.
- Innovative approaches to reduce pull forces, improve surface finish, and incorporate higher-temperature resin systems are crucial for the development of pultrusion to make closed hollow sections.
- Reinforced polymer composites have poor surface finish due to high fiber volume fraction and resin shrinkage during cure. Research is needed on improving surface finish through the use of in-mold coatings or, in the case of pultrusion, through co-extrusion of an unreinforced polymer.

Welding And Joining Processes

- Joining of novel metals, composites, and ceramics will require validation of existing processes, as well as invention of new technologies. Characterization of the properties and performance of the joints are required before designers will have the confidence to specify use of these materials in new products.
- Innovative processes that have great potential for achieving superior joints in advanced materials include high-energy density processes (e.g., laser and electron beam), solid-state joining processes (e.g., diffusion bonding and friction welding), and advanced arc processes that provide independent control of base-plate heating and filler material melting rate.
- Lower-cost, more-reliable sensor technologies are required for the automation of joining processes that could lead to significant enhancements in productivity. The challenge is particularly great to develop sensors for fusion welding, where the high temperatures and large thermal gradients make process measurement extremely difficult.
- Research is needed to develop approaches to eliminate or control the residual stresses and distortion that result from localized heating and nonuniform cooling of many joining processes, so that parts can be manufactured with precision.
- The greatest limitation to improving the quality and reliability of joints is improved understanding of the process physics; therefore, this should be a high priority for future R&D.
- More-powerful simulation models are needed, and they should be verified by thoughtful experimentation.

- Most welding processes are extremely complex from the viewpoint of conventional control theory. The process physics must be understood, and control algorithms developed that can handle the nonlinear behavior of welding systems.

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8

Integrated Processes

Integrated processes are those that combine more than one specific unit process into a single piece of equipment or into a group of work stations that are operated under unified control (NRC, 1992). Within the context of the unit process families defined in Chapter 2, integrated processes can combine multiple processes that fall within the same family, such as different material removal processes, or they can combine processes that are in different unit process families, such as a mass-change process and a structure-change process.

A number of factors are accelerating the push toward integrated unit processing. These include the need for reduced equipment and process cost, shorter processing times, reduced inspection time, and reduced handling (NRC, 1992). On the other hand, by their very nature, integrated systems require a higher level of synthesis than does a single unit process, such as for in situ process control. Therefore, development of integrated processes will generally be more complex than that of individual unit processes, but it could provide simplified, lower-cost manufacturing.

Microelectronics fabrication of integrated circuits employs beam-processing "cluster tools" to perform multiple process steps. The initial tools were multichamber etch or deposition systems. The experience of the microelectronics industry is that the development of integrated processing tools has been constrained by many factors, including high development cost, limited range of process expertise at a typical equipment vendor, unknown market requirements, and lack of industry-wide equipment interface standards.[1]

[1] The Modular Equipment Standards Committee of Semiconductor Equipment and Materials International was formed to develop standards for mechanical, utility, software, and control interfaces for future integrated processing systems. These standards will enable circuit manufacturers to choose

Processes based on directed-energy beams lend themselves to integrated processing. The characteristics that favor their use in integrated processing systems include short interaction times with the part due to high, directed-energy densities; a beam that does not require contact with the part; and operational flexibility in the processing environment. Atomic and molecular material beam technologies of interest include physical vapor deposition (direct evaporation processes, direct reactive evaporation processes, direct sputtering, reactive sputtering, ion beam sputtering) molecular-beam epitaxy, chemical vapor deposition, microwave plasmas, ion beams, and directed-energy beams (electron, laser, x-ray, and microwave).

Laser beams in particular offer new opportunities for integrated processing. The advantages of lasers include (1) decreasing cost while durability improves some ability to tune the wavelength of a laser so as to maximize the absorption of the energy by the material processing that can be conducted in a variety of atmospheres and (2) processing that can be automated.

The amount of energy deposited in a region in an interval of time determines the temperature change and the effect on materials. Thus there are three characteristics of lasers that are very important for applications in an integrated processing system: the spatial and temporal energy intensity distributions and the wavelength. The distribution of intensity in space and time determines the degree of localization of the effect. The spatial distribution of intensity depends on the mode of the laser—it can be highly localized or spread-out (i.e. defocused). The temporal distribution can be a continuous wave or pulsed; a variety of wave shapes and duty cycles are possible.

Laser-beam technologies have already found many applications in the traditional manufacturing environment, as is discussed in Chapters 3 (machining and cutting), 5 (heat treating and surface modification), and 7 (welding). As mentioned in Chapter 3, an emerging area of development exploits the flexible nature of laser machine tools; a laser beam can perform a variety of processes on many classes of engineering materials by changing process parameters (e.g., beam diameter, scanning velocity, beam focus, assist gas, etc.) instead of changing machine tools. This is an example of an integrated process.

There are several reported examples of integrated processing systems in use. Many employ directed-energy beams, such as lasers. Several examples are discussed below, and a vision of what could be possible in the future is presented.

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the component systems necessary for their fabrication processes and have assurance that the systems can be integrated into a working whole (Dorsch, 1991).

A fully integrated laser processing system has been developed to manufacture precision gears (Storma and Chaplin, 1987). As indicated in Table 8-1, the operation is simpler than the standard approach, which requires multiple steps accomplished by many different processes; the integrated process is also reportedly less expensive.

It is interesting to note the similarity of steps involved in gear making to those involved in integrated-circuit fabrication. In gear making, the use of masks and copper plating corresponds to the use of masks and photoreist in integrated-circuit chip making. The purpose in both cases is to produce localized property changes on the surface. In gear making, the aim is to locally change the surface hardness, thereby increasing the resistance of the gear to fatigue and wear failure. In integrated-circuit chip making, the goal is to produce a localized change in electrical properties.

Table 8-1 Comparison of Processes to Produce Precision Gears

CONVENTIONAL PROCESS	INTEGRATED PROCESS
— A low-carbon steel preform is initially rough machined into a gear blank. — The blank is then annealed to remove residual stresses. — The gear teeth are machined by milling, hobbing, or broaching. — The gear is carburized to increase its hardness, strength, wear resistance, and fatigue resistance in the contact areas. — Prior to carburizing, the gear is copper plated in those areas in which the increased carbon content is not wanted. — After the carburization, the gear must be reheated and then slow quenched in oil in order to develop a fully hardened case layer at the surface. — Finally, the gear is ground to its finished shape	— The gear blank is made from a high-grade carbon steel, avoiding the need for carburization to achieve required strength and wear resistance. — A laser beam is used to harden the gear at a station in a flexible machining system that is used for shaping the gear.

Laser-beam processing can be used to change various structure-sensitive properties, such as corrosion resistance. Laser surface alloying combines laser irradiation with surface alloying and provides a way to produce a broad range of surface compositions and microstructures. For example, a relatively inexpensive mild carbon steel could be processed to have the corrosion resistance of a much higher priced stainless steel by effectively forming a thin surface layer of stainless steel. Alloying material can be either predeposited on the surface in a separate step prior to laser treatment or co-deposited by injection into the melt at the time of laser treatment. The advantage of using direct powder injection is that it eliminates the electroplating step. A high-powered laser melts the injected powder and the surface layer in the relatively wide beam-spot area. A uniform level of laser alloying 1 mm deep has been reported using this technique (Riabkina-Fishman and Zahavi, 1990).

Further development of beam technologies may lead to the development of innovative approaches. For instance, a very flexible integrated manufacturing system could use gases at the beginning of the process to produce the starting materials. The gases could react either directly at the surface to produce a deposit, or within the vapor phase to produce nanophase particles that are then deposited on the surface. The deposition would be carried out selectively to produce a three-dimensional structural part in accordance with the design resident in a computer database. It could be possible to rapidly produce both parts made from homogeneous and composite materials that have unique and desirable properties. An integral part of the process would be noncontacting measurement and nondestructive evaluation sensors.

Not all integrated processes employ beam technologies. For example, powder processing (see Chapter 7) starts with metal, ceramic, or polymer particles that have specific attributes of size, shape, packing, and composition and converts them into a strong, precise, high-performance shape. Key process steps include the shaping or compaction of the particles and thermal bonding of the particles using sintering. These two steps can be integrated into a single operation, as in vacuum hot pressing.

A cost-effective integrated process has been demonstrated to produce dispersion-strengthened copper alloys (Lee et al., 1992). It can be applied to a wide variety of dispersion-strengthened alloys and metal-matrix composites. The process involves two or more crucibles of molten metal of desired composition. These liquids are then injected into a mixing chamber such that the jets impinge on one another, causing localized turbulent flow and mixing at a very fine microlevel. Macrolevel mixing (i.e., avoiding compositional inhomogeneity) occurs as a result of the bulk swirling motion of the fluids in the mixing chamber. The reinforcement phases are generated within the mixing chamber by an exothermic chemical reaction between selected chemical elements. The liquid mixture then directly enters a mold, which can be designed to provide a near-net shape requiring little final finishing. In theory, a large number of phase-change unit processes are available, such as ingot casting, die casting, and centrifugal casting. The size and distribution of these particles can be tailored, along with the microstructure of the matrix material, by adjusting process parameters. For example, copper with 50 nm TiB_2 particles has been produced. The selection of the casting process would depend on the material system and the desired microstructure (Lee et al., 1992). This integrated process is representative of combining several unit processes such that a final component can effectively be produced in a single step that starts with the introduction of basic materials.

RESEARCH OPPORTUNITIES

There are promising opportunities to develop integrated processes that transcend the capabilities of an individual unit process. The results can lead to significant processing breakthroughs for low-cost, high-quality production.

- *Integrated tools for solid modeling, expert system design assistants, and process development*. The goal is to make a complex part right the first time, or with one iteration, using one or more unit processes that are themselves integrated so that outside intervention is not required. This would result in dramatic time savings for the design and manufacturing processes, and would represent realization of concurrent engineering. The various elements of such a system exist, but with the exception of some high-volume electronic components (e.g., integrated circuits) additional research is needed to provide a fully integrated design-manufacturing capability.
- *Architecture and analysis of integrated processes*. Significant problems of information flow, process step development throughput, cost, and real-time control must be overcome before significant use of integrated processing can occur. Extensive development programs could accelerate progress in this vital area. Efforts directed at incorporating multiple operations within a single piece of equipment, as well as at integrating multiple pieces of equipment, are required.
- *Development of standards for process integration*. Standards must be developed that address mechanical, utility, software, and control interfaces between unit processes that are candidates for integration (similar to the effort currently underway by the Modular Equipment Standards Committee of Semiconductor Equipment and Materials International). These standards will allow process designers the option to select the combinations of unit processes for easy integration.

- *Control architectures*. Other future directions for research include the development of new or improved lasers and control systems that provide a high degree of dimensional accuracy and production tolerance.

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PART III: UNIT MANUFACTURING PROCESS ENABLING TECHNOLOGIES

INTRODUCTION

The committee examined the many research opportunities that were identified within each family of unit processes in Part II to determine which were the most important to the advancement of unit process technology. The Unit Manufacturing Process Research Committee concluded that the efficacy of a new unit process, or process improvement, could only be assessed in the context of a specific application, although criteria could be developed to identify promising research opportunities. This led the committee to synthesize the various research opportunities identified for each family of unit processes. The common ones, known as enabling technologies, were those that underpin and enable a wide variety of unit processes, and thus their advancement would benefit multiple unit processes. As a result of the committee's analysis, these six technologies were found to be critically important:

- material behavior;
- simulation and modeling;
- sensors;
- process control;
- process precision and metrology; and
- equipment design.

Each of these technologies is discussed in a separate chapter that summarizes the current general research status and recommends research opportunities that would be key elements in securing the long-term competitiveness of U.S. manufacturing. Research in these enabling technologies must be connected to the basic physics of processes, and the results verified through experiments on specific unit processes.

Chapter 9 deals with the first enabling technology, the characterization of material behavior. This technology involves understanding the relevant material properties and microstructure that exist at the start of a unit process and how they change in response to the processing. The evolution of microstructure, conditions under which fracture occurs, and an understanding of the role of interface conditions such as friction are among the elements that must be understood. A major issue is the enormous variety of materials that need to be studied, as well as the large number of parameters required to specify the behavior of each material.

Chapter 10 provides an overview of simulation and modeling technology. Simulation and modeling can oftentimes eliminate time-consuming and expensive trial-and-error process development and lead to rapid development of processes for new materials and new products. Impressive progress has been made in recent years in the numerical representation and solution of modeling process behavior. Improved understanding of material behavior is a prerequisite to more-precise numerical simulation of processes.

The next two enabling technologies, sensors and process control, are closely interwoven. Chapter 11 considers sensor technologies that play a critical role in the establishment of advanced process control architectures and the production of quality products. There are a wide range of sensor application needs to control the operation of unit processes monitor and diagnose equipment condition and to inspect and measure the product. Unit processes of the future are expected to be heavily dependent on advances in sensor technology.

Chapter 12 covers process control. The incorporation of improved computer software and hardware can make unit processes more flexible and adaptable while maintaining optimum operation of the process equipment. In the past, the predominant control methodology was the "black box" approach, which employed a simple invariant description of the unit process. Improved control algorithms, controller hardware, and sensors offer significant opportunities to advance process control.

The last two enabling technologies, process precision and metrology and equipment design, are closely linked to one another but also depend on the other four enabling technologies. Chapter 13 addresses the vitally important area of process precision and metrology. Effective product design and manufacturing hinge, in part, on matching process capabilities to part specifications and on applying measurement methods that support inspection and process control. As activity progresses from nominal design to final manufacture, the control of variability becomes the central issue.

Chapter 14 discusses process equipment design, which is the broadest and most critical of all the enabling technologies. This technology must be a critical focus of any unit process that will be commercialized. The equipment and associated tooling must be designed to fulfill a specific function in a production environment. Unit process equipment should be viewed as a platform for advanced sensors and control systems. Furthermore, practical considerations such as costs associated with the purchase, installation, and maintenance of the equipment must be competitive with those of alternative processing equipment. Despite their extreme importance, academic teaching and research in the area of processing equipment and machine tools are just about nonexistent in the United States. This area needs increased emphasis and support, not only in research but also in terms of establishing new faculty positions and new academic programs.

KEY RECOMMENDATIONS

Technologies that underpin and enable a wide variety of unit processes are critically important. Within this category, the following enabling technologies should receive the highest priority:

- *Improved and innovative advanced sensor technologies that could be used to enhance unit process control and increase productivity* . These sensors would be capable of real-time measurements of such quantities as geometric tolerances, material condition, and process conditions.
- *Improved unit process control resulting from extending advanced control theory and concepts, such as self-tuning controllers that employ expert systems and embedded process models*. These controllers would take full advantage of the real-time data provided by advanced sensors. Currently, advanced unit processes are not utilizing recent developments in control theory to the extent possible.
- *Materials behavior research aimed at providing information that can be used by process simulation models*. The vast amount of information already available needs to be collected, analyzed, and organized in a form usable by these models. The use of improved descriptions of material behavior in simulation should be validated with experimental data.
- *Models for characterizing the precision of unit processes in ways useful to both design engineers and process planners*. These models should provide for the organization and codification of disparate process precision and metrology information. They should support methods for assessment of scalability of precision levels and intrinsic precision.
- *Methodology and practice for process equipment (e.g., machine tools) and process modeling design*. The engineering design of process equipment should be developed into a special engineering practice with the necessary supporting analysis tools, since it requires the integration of many other supporting technologies.

9

Behavior Of Materials

OVERVIEW

Characterization of material behavior during its residence in a unit process allows for an accurate understanding of workpiece response to process conditions. For instance, the constitutive relationship describing material behavior is an essential starting point for simulation of a unit process (see Chapter 10). In many instances, the material behavior is nonlinear and dependent on its past history in the unit process. Therefore, each increment along the process route requires a more complex, complete solution of the governing equations. This chapter discusses material characterization for unit process simulation, focusing on the concept of microstructure evolution.

Microstructure evolution is an extremely important factor in unit manufacturing process science. Product properties and resulting performance are ultimately governed by microstructural features, which can be characterized by their respective composition, size, shape, and distribution.

In a processing system, which consists of several unit processes chained together, the evolution of microstructure is a serial, progressive phenomenon. The microstructure can be considered the "carrier" of the process history from one unit process to another. The final product properties, as determined by the final microstructure, are the integration of the incremental microstructure evolution of each unit process in the system. Knowledge of this material microstructure evolution sequence is essential to the understanding of the intermediate properties, as well as to the final resulting properties of the product.

The workpiece surface and interior microstructure comprise many components, each with its representative chemistry, size, shape, and distribution. The structures and their evolution may be viewed at several different levels of detail. The levels range from the macroscale down to the atomic scale or nanoscale. Each level has its characteristic microstructural features and quantitative descriptions. For example, shape changes resulting from a deformation process are readily understood on a continuum level, while the crystallographic texture of a highly mechanically worked product can be understood from quantitative information at the polycrystalline level.

Defects and damage are also very important microstructural features and are typically dependent on process conditions and history. Process maps that incorporate process criteria and a mapping of defects and damage in terms of process parameters are useful tools. These criteria can be combined with simulation output (i.e., distributions of material conditions of stress, strain, and temperature) to identify conditions corresponding to formation of defects or damage.

Microstructure changes caused by a unit process involve both the interior and the surface regions of the workpiece. The interior represents the bulk of the workpiece material and governs many of the properties and performance aspects of the product. The surface region is typically subjected to a wide variety of conditions imposed by workpiece interactions with tooling, molds, lubricants, heat sources, atmospheres, and other physical and chemical process agents. The effects of these agents influence the mechanisms of heat transfer and friction, as well as the chemical reaction products that are unique to the surface region of the workpiece. The resulting surface microstructure may differ from the interior microstructure, as would the performance of the surface material. Surface conditions also influence the energy flux from the unit process to the interior region and thus affect the microstructural evolution of the bulk material.

A description of the surface of a part involves three components: the topography or geometry, defined as surface finish plus waviness; the metallurgical state of the material; and the residual stresses produced by processing. For example, mass-change processes can alter all three factors by introducing concentrated, localized, high-energy gradients on the workpiece surface, which, in turn, create high surface temperatures with extended thermal gradients, plastic deformation accompanied by plastically deformed debris, and chemical reactions with subsequent diffusion into the workpiece surface.

The mathematical descriptions developed to model the material behavior of the workpiece in the unit process (i.e., the constitutive models) typically do not include the influence of microstructural evolution, although recent efforts have begun to consider the evolving microstructure of the workpiece. The next step would be to develop the understanding and mathematical description of the surface material behavior, including the chemical, tribological, and thermal transfer characteristics of the workpiece surface. Specific needs include the description of the "mushy" liquid-solid state that occurs during the casting process. Similar characterization of the visco-elastic flow of polymers is also required for injection molding.

RESEARCH OPPORTUNITIES

Based on the preceding discussion of research status and needs of unit process material behavior, the following areas emerge as strong candidates for future research emphasis.

- *Quantification of the material microstructure as it evolves*. An important research area is developing the capability to model a microstructure as it evolves during the course of a unit process. Ideally the entry microstructure and process parameters for a unit process would be specified; the model could then predict the resulting microstructure at any stage of the process.
- *Systematic representation of the relationship between the microstructural features developed during processing and the resulting constitutive behavior*. This representation would incorporate into the constitutive models the microstructural evolution of the workpiece. These tools would incorporate fracture mechanics concepts and damage mechanisms into their phenomenological models of damage initiation and growth.
- *Process maps that contain defect and damage criteria*. Processing maps are needed to identify processing windows (i.e., appropriate combinations of process parameters) to ensure defect-free (at the surface as well as the interior) products. These maps could be developed in part through the application of the microstructure evolution models and enhanced constitutive relationships discussed above.
- *Characterization of boundary conditions*. Understanding the mechanisms occurring at workpiece interfaces (e.g., heat transfer, friction, and chemical reaction products) is essential to a thorough understanding of a unit process, since these boundary conditions often determine the process limits.
- *Materials property databases*. Databases are required that contain the many physical properties of materials under a variety of conditions (e.g., temperature, strain rate, defect density) that are needed for process modeling and control. These databases should be readily accessible by researchers and design engineers.

10

Simulation And Modeling

OVERVIEW

Analytical simulation and modeling of unit manufacturing processes based on knowledge of the underlying process physics and validated by experimental results is becoming a powerful tool to advance the optimization of unit processes. In this context, simulation is defined as the "representation or model of the operation of a system on a digital computer" (NRC, 1988). The availability of high-powered engineering workstations allows simulation of many complex unit processes that often require three-dimensional solutions. Examples cited in Part II range from polymer injection molding to high-temperature forging of jet-engine components.

In many process development and design situations, simulations are beginning to replace full-scale process trials, reducing development time and cost compared with those of the normal iterative methods. Tooling and dies and material specifications can also be optimized based on the results developed from the preliminary design and geometric modeling stages (NRC, in press). The most important task is selecting the optimum processing conditions, which will ensure that the required mechanical and physical characteristics of the product design can be produced at a high-quality level.

The mathematical underpinnings of unit process simulations typically involve the solution of the classical laws of conservation of mass, momentum, and energy, coupled with constitutive formulations of the material behavior during its residency in the unit process. The solution procedure is governed by initial and boundary conditions that represent the process conditions of the situation being modeled. The complexity of the simulation model may be simplified with first-order assumptions that provide solutions with reasonable accuracy and converge to the correct solution.

Simulations of unit processes are largely based on the computer-aided approaches that include three important activities: modeling, visualization, and design. Simulation output consists of information on the processed component characteristics of geometry, surface, and microstructure, including defects. The finite-element method is widely used for modeling unit processes. Presently available software for computation includes a variety of three-dimensional elements and offers a coupled thermomechanical and fluid-flow analysis capability. A wide variety of analysis options, material models, and interface elements are supported. Three of the desirable analysis options include Lagrangian or Eulerian formulation; implicit/explicit solution algorithms; and automatic, time-step control. In addition, the analysis packages have robust nonlinear solution algorithms that guarantee convergence and are able to take into account complex displacement, velocity, stress, and thermal boundary conditions.

With the present requirement of representing a variety of physical phenomena that occur during unit processes, the constitutive modeling capabilities of the analysis packages have become extremely important. For example, as discussed in Chapter 9, analytical packages used in deformation process simulations should provide both elastic-viscoplastic and elastic-plastic material models, so that rate-dependent and rate-independent phenomena can be modeled. In addition, models should be capable of using constitutive equations that can evolve specific metallurgical features during the simulation.

The suitability of a finite-element package to model the interface phenomena of a unit process is critical, because only accurate representation of the interface situation (e.g., friction, heat transfer, etc.) can provide an accurate set of boundary conditions for the modeling of the bulk workpiece behavior. For example, the robustness of deformation process models is influenced by contact modeling capabilities. Current generalized three-dimensional contact algorithms include general three-dimensional sliding capability, automatic detection of element contact and release, contact between deformable bodies, and single surface contact capability for modeling the formation of defects such as lap formation. A future enhancement of contact algorithms would be the representation of interface phenomena such as friction and heat transfer. In addition, this deformation process representation should include detailed interface models that are functions of various process parameters. A particular need for analysis of unit processes with large strain deformations is adaptive finite element meshing, which rezones the mesh as needed (i.e., automatically redefines the finite element grid) and continues the analysis with little or no user interaction.

Most of the previously discussed modeling requirements are currently addressed at a two-dimensional level by available finite-element method computer codes. These programs are usually general purpose packages capable of handling the nonlinear partial differential equations typical of unit process models, as well as the traditional linear partial differential equation required to solve thermal and mechanical problems. The constitutive descriptions of material behavior are limited in most of these packages; however, some user-defined formulations can be inserted into the more advanced programs. The versatility of these packages is traded off against the efficiency of the problem solution, particularly in the three-dimensional versions of the codes. The programs are available on most workstations; mainframes; super computers; and, more recently, on reduced instruction set computing processor workstations and parallel processor machines.

As in any computation, the use of physical insight to eliminate less important variables can simplify a solution with little loss of accuracy. In addition, consideration of revised variables that incorporate coupled or related variable groups ("super variables") may also simplify the partial differential equations and their solution. Simplified equations can result in faster computation times with a minimal loss in simulation accuracy. Further increases in simulation performance may be attainable with the development of specialized processors that are tailored for the numerical solution of process simulations. These processors trade program versatility for enhanced precision, speed, and accuracy of their solutions.

The use of knowledge-based engineering systems in unit process simulation relies on past experience to estimate the behavior of the process. For example, this approach has been used for tooling and die design and input stock geometry estimation for two-dimensional simulation of forming processes (Tang and Oh, 1988). This technique, however, has had limited success, because it has not yet addressed three-dimensional problems and does not include consideration of the workpiece material behavior. Application of knowledge-based engineering systems to the prediction of defects and microstructure has been reported for forming processes (Demeri, 1989). Future simulation tools should incorporate both knowledge-based engineering systems and analytical techniques.

Validation of simulation results with data obtained from critical experiments is necessary to establish confidence in the predictive capabilities of simulations. This is a critical, and continuing, activity. The range of the validation (i.e., process conditions) should be based on the robustness of the assumptions in the simulation to identify the limits of process conditions for future application of the simulation.

Application of simulation tools to the design of unit processes (e.g., tooling configuration, input material characteristics, and process parameter operational scheme) is an increasingly important element in successful product manufacture. In general, unit process design evolves as experiences are gained from product to product. Limited confidence is normally assigned to design situations outside of the region of past experiences. The design procedure draws upon different types and levels of knowledge at different stages of the design sequence and relies heavily on the creativity and intuition of the user (Richmond, 1986).

Hence, from a user's perspective, the modeling system should be user-friendly and should provide a user interface that enhances productivity. In addition, it should contain features that ease a user's task burden during iterative process design. The modeling system should assist the user differently at different stages of the design process, since the needs vary.

In a concurrent engineering environment, the modeling system should provide a framework to establish, in the early stages of product development, the technical feasibility of manufacturing the product. The processes can be optimized once the final design is completed. Incorporation of such an iterative capability allows the system to be a true design tool rather than a verification tool (Richmond, 1986).

Unit process design can be viewed as comprising three distinct stages: preliminary design, geometric modeling, and process modeling. Typical activities that occur during each of the stages include part design for assembly, preliminary part design for processing and producibility (or net shape manufacturing), preliminary die/mold design (if process uses dies or molds as in forging, stamping, die casting, or injection molding), and process simulation to verify die/mold as well as product and process design. Figure 10-1 is an example of the design steps that occur for discrete part manufacture (Altan and Oh, 1987).

Each design stage uses particular tools and information about the product under design, as well as information about past product development. An integrated unit process modeling system would seamlessly transfer information and data among the three stages, so that the effect on the other two stages of decisions made during preliminary design could be visualized.

Preliminary design is heavily influenced by the geometry of the product's components. Limited consideration is given at this stage to how selected material properties will be affected during processing or how difficult a material will be to process. Preliminary design typically draws extensively on previous design experience. If a knowledge-based engineering system were available, the following important areas could be addressed interactively during preliminary design:

- selection of suitable unit processes;
- optimum sequencing of the unit processes;
- preliminary estimation of the unit process operational parameters; and
- preliminary tooling design for each unit process.

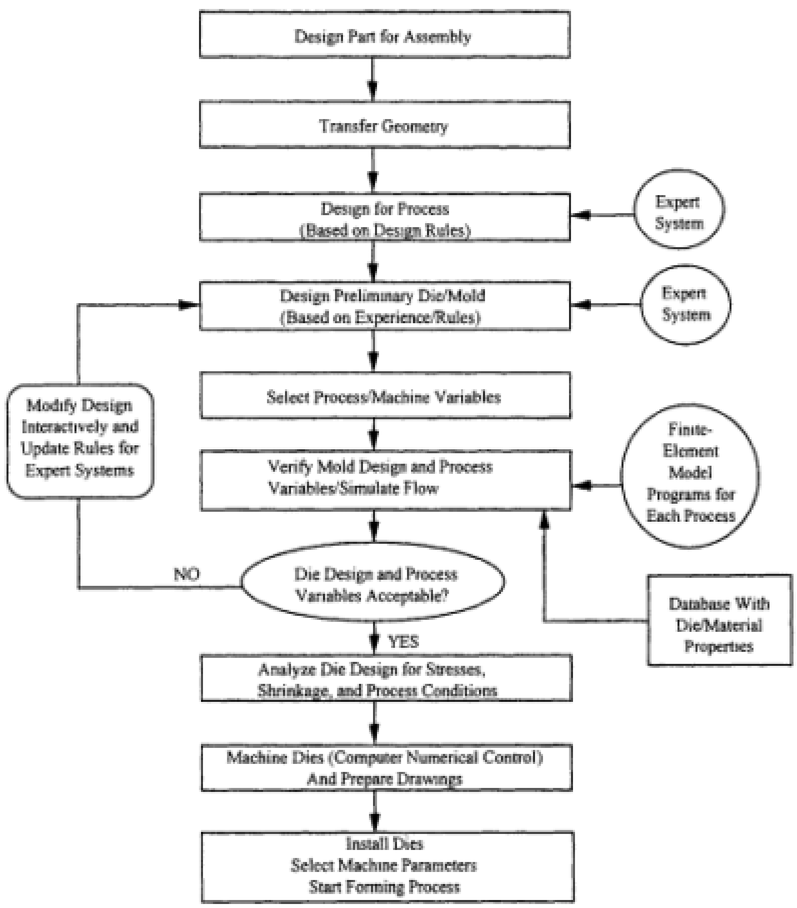

Figure 10-1 Schematic illustration of steps involved in manufacturing discrete parts via a unit manufacturing process (adapted from Altan and Oh, 1987).

The importance of a robust geometric modeler and reliable transfer of three-dimensional geometry as a part of the integrated modeling system cannot be overemphasized in light of some of the difficulties in three-dimensional modeling mentioned earlier. The geometric modeler should also allow the creation of process geometry specific to a particular unit process to aid the design engineer in visualizing the process. The geometric modeler should also provide accurate information concerning assembly details, such as interference between different parts and tools. Current geometric modeling tools utilize advanced solid modeling techniques for creation of part and tool geometries and include automatic mesh generation. The modelers also include several geometric manipulation functions for process geometry visualization.

Automatic mesh generation assumes a special importance in process simulations that have severe material distortions because of the problems with remeshing that were discussed in Chapter 9. Hence, a three-dimensional remeshing utility for arbitrarily shaped geometries is needed, especially for complex components.

Important elements of a geometric modeler include the following.

- *Feature definition*. Features provide the mechanical detail to the geometry of the part and the process. Through features, the geometric model is supplemented with a variety of essential nongeometric data (e.g., surface-finish information, material type, heat treatment requirements, etc.) that result in a complete product model. An ideal geometric modeler would support these three basic modes of inputing feature information: design by features, automatic recognition of features, and interactive identification of features.
- *User specification of product and process attributes at the solid model level*. This information should be transferred to the downstream applications, such as finite-element mesh generation and process modeling. The attributes of interest include material properties and boundary conditions (e.g., mechanical loading and heat transfer across an interface).
- *Three-dimensional contact information*. The information required for finite-element methods analysis should be generated at this stage from the solid model after classifying the geometry into different features, namely workpiece and tooling. Once the workpiece and the tools are identified, intersections can be calculated and appropriate contact information generated. This contact information can be supplied to each node after the finite-element methods mesh is generated.
- *Electronic data transfer*. The data should be transferred according to standard procedures, such as those based on the Initial Graphic Exchange Standard or the newly emerging Product Data Exchange Standard/Standard Exchange Protocol standards.

RESEARCH OPPORTUNITIES

The preceding discussion of research status and needs of unit process simulation and modeling has identified certain issues that should be addressed by future research.

- *Development of comprehensive, fully interactive geometry modelers* . Geometric modelers are needed that can bridge the capabilities of computer-aided design and analysis. Such model should provide less-detailed models with clearly defined topological characteristics and be capable of easily linking to finite element models.
- *Engineering design tools*. Advanced design tools are required that employ knowledge-based engineering systems and analytical techniques to aid in selecting and developing the specification for unit processes.
- *Low-cost, dynamic, three-dimensional, finite-element meshing techniques* . Simulations of processes exhibiting large strain deformations often result in very distorted finite elements. A remeshing capability that requires little or no user interaction is needed to provide for computational efficiency with no compromise to accuracy.
- *Representation of dynamic interface phenomena*. Contact algorithms must be improved to include interface phenomena, such as friction and heat transfer.
- *Improved computational performance*. Research is needed to accelerate the run-time performance of the computer models with no loss of fidelity to the real world. Promising directions include streamlining of the partial differential equations and the use of revised variables that incorporate physically coupled behavior.
- *Specialized computer processors*. There is a demand for computer processors that are specialized for handling process simulations.

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11

Sensor Technology

OVERVIEW

Achieving optimum performance of unit processes and complex manufacturing systems is only possible if accurate and timely information is available concerning the unit process, particularly with respect to the five process components—equipment, tooling, interface, workzone, and workpiece material. Three strategies (not mutually exclusive) can be envisioned for ensuring that this information is available: data bases and knowledge bases that capture empirical data and heuristic rules; models of the process and its components, from which performance can be predicted; and direct measurements from sensors for process monitoring and feedback to controllers. All focus areas are subject to monitoring needs, often with competing requirements for time response or location of sensors. Sensors play a critical role in the development and implementation of advanced and new unit processes. Today many sensors are selected for use in unit processes on the basis of their reliability and low cost, not because they measure parameters that are fundamental to the material being processed. As the processes that make up the manufacturing systems become more complex, the challenge and the benefits of developing new, enhanced, and reliable sensing systems has increased (NRC, in press). Sensors and sensor systems that are inexpensive, robust in the processing environment, and easy to use are required.

The chapters in Part II of this report identified a large number of unit processes, and components within those processes, in which sensors are required to advance the technology or enable the existing technology to perform to its limits. Sensor-based inspection and quality-control technologies are widely recognized as crucial for major advancements in manufacturing capability and productivity. Thus, sensors are key elements in the other enabling technologies of process control (Chapter 12) and in process precision and metrology (Chapter 13).

There are a wide range of applications for sensors within the domain of unit processes. Some examples, in roughly the order of increasing sensor-system sophistication, are

- interfaces or nodes within the system to pass information (e.g., tolerances, orientation, material characteristics, sequence, etc.; Ayres, 1988);
- quality-control schemes involving only pre- and post-process inspection; that is, finding the defect before the part enters the unit process (when nothing is happening) or after it exits the process;
- in-process inspection, in which deviations can be detected in real-time and perhaps corrected before additional processing occurs; and
- self-directed processing, in which the control settings are determined by the response of the material, as measured by sensors, to the processing conditions, as opposed to following a pre-established schedule of process parameters.

Sensors are vital for intelligent processing. The requirement for improved sensor systems for process monitoring and control will become increasingly important as more-complex processes are developed for small-quantity production of precise and expensive components made of advanced materials. Because research on process modeling and material characterization cannot remove all uncertainty in the manufacturability of advanced work pieces, sensors will always be necessary for successful production. Part II contains examples of unit processes that would be extremely difficult to control without in-process feedback or of which it would be difficult to accurately predict the outcome in advance due to a number of material, tooling, and environmental variables, such as tool-workpiece interface conditions that govern the rate of energy transfer from the equipment and tooling into the workzone. For example, precision machining requires adaptive control based on sensor readings.

The committee envisions manufacturing systems that are so finely controlled that they achieve very stringent requirements of new materials, processing techniques, tolerances or shapes, production speeds, and yields that would be extremely difficult to achieve without the real-time aid of computers in which process models are embedded and to which an array of sensors constantly communicate the process state and provide system diagnostics of potential problem areas. The speed of response and level of attention required for these new unit processes exceed the capabilities of the most adept machine operator.

The adoption of sensor technology can make viable those unit processes that are inherently so complex or unstable that they demand continuous monitoring and control to ensure acceptable yields. All unit processes for advanced materials with intricate near-net shapes, high-quality surface treatment, and compositions controlled exactly to precise specifications share these characteristics of complexity and potential instability as they are pushed to their full potential. Research on sensors should address the challenges posed by these applications.

Some of the best information regarding performance of sensor systems in industry comes from the automotive manufacturer Mercedes-Benz (1990). A survey was conducted of approximately 120 sensor systems applied to drilling (35 percent), multiple spindle drilling (7 percent), turning (57 percent), and milling (1 percent). The results are summarized in Table 11-1. The benefits derived from the successful applications far outweighed the costs of the failures. For example, Mercedes-Benz reports significant realized savings for the machining of a transmission shaft using a sensor-based process monitoring system (Mercedes-Benz, 1990).

Machining of advanced materials such as ceramics provides another example of the need for sensing as part of the process. For the most part, ceramic materials are not intrinsically expensive. The principal production costs are in the shaping of the ceramic part, including initial shaping (such as injection, casting, or pressing), green and white machining, and the finish machining after sintering (König and Wagerman, 1993). Up to 90 percent of the cost can be attributed to the final finish machining of the sintered parts by grinding; lapping; or other less conventional techniques, such as electrical discharge or laser-assisted machining.

The machining process itself may induce surface defects in the component, which severely limit its usefulness. Because it is not possible to predict the circumstances under which these defects occur (due to machine performance, tool performance, and process variability, sensors must be utilized in-process or post process (König and Wagerman, 1993). Sensor-based monitoring could address

Table 11-1 Results of Mercedes-Benz Manufacturing Sensor Implementation

Sensor Implementation Result	Percent
Fully functional (performed as expected)	46
Conditionally functional (had one or more deficiencies)	16
Technical failures (poor resolution, false alarms, etc.)	25
Replaced by alternative systems	13

the machine (e.g., diagnostics and performance monitoring); the tools or tooling (e.g., state of wear, lubrication, and alignment); the workpiece (e.g., geometry and dimensions, surface features and roughness, tolerances, and material damage); or the process itself, including the interface between the tooling and the workpiece (e.g., chip formation, temperatures, and energy consumption).

The objectives of machine condition monitoring also include safety, prevention of damage to the machine, prevention of rejected workpieces, prevention of idle time on the machine, and optimal use of resources (Tonshoff et al., 1988). Tonshoff et al. point out the importance of the sensor as part of a system that includes signal conditioning, models relating measured values to monitoring and control variables based on fundamental process physics, and strategies for information utilization. This technology is often referred to as an "intelligent sensor" and implies much more capability than just the transducer and preamplifier might in a simple monitoring setup. Many of these intelligent sensor systems employ multiple sensors for process monitoring. A variety of sensors are used to provide a range of coverage of process characteristics with the goal of ensuring higher reliability. This multisensor approach requires more attention to real-time feature extraction, information integration, and decision making to be effective.

The increasing demands of sensor systems have encouraged the development of systems using a variety of sensors. This is especially true for monitoring processes that are categorized as precision manufacturing, that is, for which the tolerances on form, dimension, or surface features are very stringent. In the case of machining, these processes are characterized by very small material removal rates, very low process power consumption (often in the presence of high tare power consumption), and the requirement that the sensor not intrude in the process or require substantial physical modification to the machine. These requirements tend to reduce the effectiveness of, or eliminate consideration of, a large number of traditional sensing methodologies—for example, in the case of tool condition sensing in machining, force, torque, and motor current or power measurement.

Unit process equipment can be viewed as platforms for advanced sensors and controls. High-speed machining is an excellent example of the need to integrate the development of machines, controllers, and sensors and the tooling to advance the process technology. This type of integrated development is more likely than not to be essential for all advanced unit processes. Sensor development has been most advanced recently for sensing methodologies that can take advantage of the microlevel silicon machines and devices now available. For example, researchers have developed and fabricated miniature vibration sensors and accelerometers that, if appropriately applied to a machine structure (like the resin concrete materials now in use as machine tool structures), could provide in situ sensing capability for control of machine stability and deflection.

Sensing techniques exist that, individually, are not sufficiently reliable for process monitoring over the normal range of process operation. However, if several different sensors are used, each of which is effective over a particular portion of the operating range, effective real-time process monitoring can be realized over the entire operating range.

There is a tremendous need to incorporate sensors in existing unit processes. For many applications, the research for relating sensor output to process characteristics has been completed but not yet exploited in a real production environment. For example, solid-state sensors are commonly used to ensure consistency for many chemical processes. These same sensors have the potential to monitor and report on interface variations due to lubricant contamination or loss in a variety of unit processes for which the interface is a key to product acceptability.

A persistent barrier in applying sensor technology has been matching application needs to sensor capabilities. A recent National Research Council study suggests a methodology that employs a set of descriptors that could be used to match needs with capabilities and thus provide a rational basis for evaluating candidate sensor technologies (NRC, in press). There are many advanced sensor technologies available which range from optical, infrared techniques to high-frequency ultrasonic and acoustic emission technologies (Shiraishi, 1989; NRC, in press). The motivation to increase the use of sensors is high. For example, estimates of the impact of sensing systems on process performance of existing systems indicate that a sixfold increase in effective operation time is possible (Eversheim et al., 1984). If sensors also enable increased product yields due to prevention of defects, the total benefit will be even greater.

RESEARCH OPPORTUNITIES

Key aspects of sensor technology to be emphasized for R&D include:

- sensor systems with digital architectures readily integratable with machine controllers;
- intelligent sensor systems that employ advanced sensor fusion and feature extraction techniques for reliable process-state determination and diagnostic decision making;
- process-specific sensor developments that address the need to monitor aspects of all five process components;

- new sensor materials and techniques capable of monitoring nontraditional processes and the processing of nontraditional materials;
- exploitation of sensor technology that was developed for applications other than unit manufacturing processes;
- digital signal processing techniques that can accommodate uncertainty in sensor-produced data;
- methodologies for readily assessing the economic viability of applying sensor systems in unit processes; and
- vehicles for speeding industrial evaluation and commercialization of new sensing technologies.

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12

Process Control

Process control can be viewed as the executive portion of a unit process. It provides the means to direct a process so that it produces the desired results. It is complementary to the role played by the process equipment itself (discussed in Chapter 14), which furnishes the physical means to accomplish the process. The trend for process controllers is to incorporate a greater degree of "intelligence" and to be integrated into a plant-wide information network that automates many management tasks, such as detailed scheduling (Considine, 1993). This chapter addresses issues and opportunities for the individual process controllers.

The traditional approach to process control involves an initial calibration of the equipment, monitoring of primary process parameters, and results in a final accept/reject inspection of the resulting product. This approach does not recognize the interdependence of process parameters and does not allow adjustment of the process to optimize yield. However it can be a realistic control strategy for relatively simple processes. A more sophisticated control strategy is known as feedforward control. It can compensate for dynamic delay in the feedback loop by anticipating the control settings using a process model. Such a control system has been commercialized in modem machine tool controllers that can provide an order of magnitude improvement in machining accuracy (Tomizuka, 1989).

Advanced control methodologies (such as adaptive control and intelligent control), as well as improvements in computer and information technologies (such as digital signal processors, workstations, and real-time operating systems), can be used to make manufacturing processes more flexible and adaptive, while maintaining optimum process performance (Wright and Bourne, 1988).

ARCHITECTURES FOR A SELF-SUSTAINING WORK ENVIRONMENT

Control system architectures that feature a closed feedback loop involving the process, sensors, controller, and actuators are a step beyond the traditional approach. Control algorithms, such as the PID (proportional, integral, derivative) algorithm, reside in the controller, which is a special type of digital computer. The challenge is to control what is basically a dynamic analog process (e.g., machining) with discrete digital logic. The control architecture must be designed to ensure that the process can always operate optimally under the presence of various uncertainties. Thus there may be multiple layers of feedback control loops (e.g., servo-control loops around the machinery itself, control loops around the tool and the workpiece for fine adjustment of operating condition, etc.).

The design of feedback control algorithms is affected by a number of factors. The key issue arises from the dynamics involved in the process. The controlled variable does not respond instantaneously to the controlling input, which results in a characteristic response curve with dynamic delay. Process models implemented in the controller must manage the dynamics properly. A fixed-parameter controller has difficulty in keeping up with the nonlinear, time-varying behavior of a process. Good control performance at one operating condition can give way to poor performance at another operating condition. These models may be further constrained by the amount of bandwidth for the feedback loop (i.e., the closed-loop response speed) and the product specifications, such as error tolerance.

Control algorithms currently used in manufacturing are commonly simple PID control algorithms that use a low-order transfer function model. This technology is adequate for traditional machining operations in which the machining speed is low. Also, the performance limitation of these PID controllers provides for only a low level of closed-loop performance in unit manufacturing processes, which is reflected in the final product quality level.

Sophisticated control architectures are required for modem unit processes that inherently possess time-varying, nonlinear process dynamics and are high performance in terms of speed and control accuracy (e.g., high-speed machining). For instance, a manufacturing manager recently observed that "a high-speed spindle is worthless unless the machine can feed fast enough to exploit it and the cnc [computer numerical control] is fast enough to keep everything under control" (Coleman, 1992). Advances in control theory, as well as those in microprocessor and digital signal processing technology achieved over the last several decades, can be and should be utilized aggressively to face these new challenges in modern manufacturing.

There are several advanced control methodologies applicable to manufacturing process control. One type of controller adjusts set points as a result of data received from sensor arrays (Hardt, 1993; Ulsoy and Koren, 1993). For example, a model-based adaptive controller[1] could employ an algorithm to compensate for dimensional errors induced by thermal distortion of workpieces.

Adaptive and robust control theory has been an active research topic for the past two decades. The research addresses the problem of how to attain optimum system performance when a process model is not known precisely in advance, the operating conditions are variable, the process parameters vary nonlinearly during operation, etc. The philosophy behind adaptive control theory is that the controller must adapt its control gains so that the overall system remains at or near the optimal condition in spite of varying process dynamics. Adaptive control is a key element to provide flexibility to unit manufacturing processes, which must be responsive to rapidly changing needs of products. On the other hand, the philosophy behind robust control theory is that a fixed-gain controller should be selected, so that the performance of the overall system remains acceptable under variations of process dynamics.

There is significant potential benefit to applying adaptive and robust process controllers. Disturbance observer theory, a robust control methodology, has been shown to be ideally combined with feed-forward control algorithms to provide high accuracy performance for servo-systems, which are essential in high-speed machining. Successful experimental results have been reported for adaptive force control in machining and adaptive weld-pool control in welding.

Important forms of adaptive control are the self-tuning controllers that were developed to overcome the limitations of fixed-point controllers in responding to time-varying process dynamics, variable operating conditions, nonlinear process dynamics, and lack of operator expertise during control-loop commissioning. Self-tuning controllers use process identification algorithms to estimate or track the time variation of key process parameters in real time. Based on these results, control parameters are computed in real time to ensure optimal system performance.

Two entirely different types of self-tuning controllers have been developed —expert systems and process models. An expert system consists of a set of rules that are derived from the knowledge of experienced process engineers and operators. A fuzzy logic controller is a viable candidate to translate human

[1] The word "adaptive" is used here to emphasize the use of temperature sensor information that goes beyond normal PID controls for servo-loops. However, it should be noted that, in the control community, adaptive control includes more than sensor and model-based feedback control.

knowledge to control strategies and algorithms suitable for computer implementation. Advantages of the expert system approach are that it is robust and thus additional rules can be readily added and that a process model is not required. But there are some disadvantages. The expert system usually is developed using a particular controller structure and thus cannot be readily ported to another type of controller. Also, the rule base itself can not be readily analyzed.

The model-based controller uses rigorously defined performance criteria, and hence mathematical analysis of these criteria is possible. It can be adapted for implementation in different controller structures, and it may be used for process diagnostics, such as to locate a failed sensor or actuator. The disadvantages include the chance that the model structure may not match the physical process; for example, an actuator dead zone or backlash could cause underestimation of process gain. Also, rapidly occurring process changes can cause problems if the model execution time is too slow.

The controller of the future will most likely incorporate both the expert system and the model-based technologies. A critical issue is the customization of these modem control algorithms to specific manufacturing applications such that stable performance results.

"Internal state" has been a key concept in modem control, and control theory has been advanced together with estimation theory. Estimation theory provides methodologies to estimate "state," which may not be directly measured. The estimated state can be utilized for state feedback control as well as for monitoring and failure detection.

Learning control can be used to learn the optimum control input through repeated trials (Dagli, 1994). When unit processes repeat the same task, this control methodology fine tunes the controller's performance. For example, in injection molding, the piston speed must be controlled so that the flow of molten plastic reaches all parts of the mold and no voids are created. Learning-control algorithms can be combined with simulation models and operational data to evaluate the performance of each trial injection. The time profile of the piston speed is adjusted after every trial until a quality product is produced. The number of trials required depends on the complexity of the process. This type of scheme also has been tested in machining to compensate for low-velocity friction forces. It has been demonstrated that a dozen or so trials are sufficient to construct a compensation signal to remove undesirable glitches, which are visible in the part geometry as irregularities in machining that are caused mainly by static friction.

Intelligent control has received increasing attention over the past few years. Intelligent control systems have the ability, to varying degrees, to find strategies autonomously in an uncertain environment. Intelligent controllers rely on a knowledge base, which may contain experts' knowledge about operations of unit processes. The knowledge base may come from process study and modeling and may be updated by a learning mechanism during operation. Intelligent controllers may provide a signal to switch operational modes for a process responding to sensor outputs. The development of strategies for intelligent controllers includes expert systems.

Introduction of a new controller usually requires some modification to other machine functions. For example, in some cases the controlling input (i.e., manipulated variable) for adaptive force control in machining is the tool feedrate. The adjustment of feedrate requires coordination of the machine tool's servo-controllers as well as its computer numerical control functions. Traditional computer numerical controls generate reference signals for servo-loops after linear and circular interpolation in accordance with the tool feedrate supplied by part programmers. However, this approach will not be feasible if the feedrate is varied in real time.

CONTROLLERS

To implement advanced control algorithms, modem technology in computer workstations, real-time operating systems,[2] and bus structures should be utilized. Today's computer numerical controls are very limited in terms of programming flexibility and communications with external computers and devices. Standard configurations cannot accommodate nonmachining devices such as work-holding accessories, force sensors, vision sensors, and other subsidiary devices. Although they use advanced electronics, computer numerical controls design concepts are conservative, especially in terms of hardware and user interfaces. Computer devices and architectures such as magnetic disk storage and data busses have only recently appeared—usually as proprietary products—and the application of computer innovations such as the latest microprocessors are always late.

Advancements in software engineering, such as object-oriented programming, should be exploited to allow rapid development of the computer programs that implement the advanced control algorithms.

Current computer numerical control communications are principally through slow serial lines, such as RS-232, which cannot support real-time control. Advanced communication networks (e.g., the Manufacturing Automation Protocol), introduced in 1989, provide for real-time control, but the effectiveness

[2] "Real-time" here means that the time constant for the measurement and analysis is commensurate with the time scale of the process itself.

depends on adherence to standard protocols that allow easy integration accommodation of computer programs and peripheral hardware.

Although full-scale integration of all the possible hardware peripherals has not been implemented, many of the individual technologies and components of unattended machine tools already exist as experimental devices or as commercial products.

For example, a self-sustaining machine, for any kind of processing operation, would be serviced by a dexterous manipulator or other automatic loading device, dedicated to the continuous needs of the process, such as supplying material and unloading finished parts. A variety of on-machine sensors would provide vision, touch, force, and temperature senses in order to recognize unexpected events, perform in-cycle inspection, and optimize the production parameters. Access to a rich supporting design environment would also be essential, including computer-aided design and computer-aided manufacturing for part and tool design, expert systems, and libraries of technical information for an optimal and efficient design. The following is a cursory list of available devices and products that can satisfy many of the needs of the above example:

- a dextrous manipulator (Greenfeld et al., 1988);
- sensors for machining (Tlusty and Andrews, 1983);
- an automated fixturing system (Hazen and Wright, 1988);
- in-cycle gauging (Valysis Corp., 1988);
- adaptive control;
- advanced computer-aided design and computer-aided manufacturing applications (Beeby and Collier, 1986);
- machinist expert system for setup planning (Hayes and Wright, 1986);
- tools and fixtures (CarrLane Manufacturing Co., 1988);
- manufacturing languages (Nackman et al., 1986 and Bourne, 1986);
- general purpose computer technology;
- communication protocol (World Federation of MAP Users Group, 1987); and
- communications networks for manufacturing (Hughes and Dytewski, 1987).

The greatest challenge in controller design is to select the appropriate computer environment for the integration and implementation of a complex machine tool environment that applies these individual technologies. This challenge cannot be met with current off-the-shelf controller technology.

OPEN SYSTEMS FOR CONTROL AND COMMUNICATION

An open architecture for the controller, which is based on mainstream, well-established computer technology such as the workstation, is highly desirable (Proctor and Michaloski, 1993). Such an architecture avoids the difficulties of using proprietary technology and offers an efficient environment for operation and programming, offers ease of integrating various system configurations and computer products, and provides the ability to communicate more effectively with computer-aided design, computer-aided manufacturing systems and factory-wide information management systems. It would also be cost-effective given the current price-performance trends in the general purpose computer industry. The controller may be based on a high-end personal computer or workstation, with additional control processors on a shared bus; it would be using a real-time operating system. An open architecture allows for universal and modular installation, since all the components share the same high-level operating system and programming environment, communication facilities, and other computer resources. An open system would, by definition, accommodate the installation of new devices and sensors as required for a machine-specific configuration.

There is a need for a real-time operating system that provides the response time and features essential for maintaining the speed, accuracy, and safety features for controlling advanced process equipment. This operating system should interface to industry standard operating systems such as Unix or OS/2 and provide high-level management, file system operations, communications, and a good programming environment.

To be part of a broad, intelligent environment, the machinery must make use of communications and networks that are universally accepted in the computer culture. Standard protocols, such as the Manufacturing Automation Protocol, must be supported easily. The machine should be adaptable to the changing environment and tasks and thus be modular in terms of its controller's computer configuration and its mechanical construction.

RESEARCH OPPORTUNITIES

- Advanced control architectures, such as adaptive and robust control, should be extended for application to unit processes that have time-varying dynamics and a high level of uncertainty regarding control inputs. This research would include analysis and simulation, as well as demonstration through critical experiments.
- Process-level analyses are necessary to understand the influence that the introduction of a new control algorithm will have on the overall operation of

a unit process. For example, a process-level study of advanced control algorithms for machine tool controllers is strongly encouraged in order to examine the issues related to the servo level, force control level, control for tool deflection, and computer numerical control algorithm and for the integration of all these technologies.

- Learning control can be applied to unit processes that involve the repetition of the same task or cyclical operations. Research issues include appropriate models for the design of learning-control algorithms and analytical and experimental investigation concerning the convergence characteristics of learning-control algorithms.
- The potential of extending the capability of equipment by smart control algorithms provides a research challenge. For example, researchers have shown that standard machining lathes can manufacture workpieces with noncircular cross-sections (e.g., an oval-shaped piston cylinder) by adding a servo axis in the direction normal to the workpiece surface.
- Incorporation of expert knowledge in an intelligent control system is a high priority. Fuzzy logic, neural networks, expert systems, and genetic algorithms are promising tools to capture and organize such information.
- Control needs of future unit processing machinery can be grouped into two central themes: a self-sustaining work environment and an open system for control and communication. The following are specific examples for R&D that will provide key elements for implementation of new control algorithms.

— the development of a real-time operating system suitable for the very high-speed control required for unit processing operations;

— the development of advanced manufacturing languages; while existing languages (such as APT and Compac for machining) will be supported, a more flexible language is needed; it should include provisions not only for real-time control but also for the operation of accessory devices in conjunction with the machining process, a more direct connection to computer-aided design and manufacturing systems, and a flexible interface for user applications; and

— experience with the integration of the Open System Machinery Controller, using an open-architecture operating system, based on readily available, well-established computer technology, such as the workstation.

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13

Process Precision And Metrology

The ability to produce quality products hinges on four key competencies: modeling of process form and precision levels, design tolerancing of parts and products, selecting production processes that match part specifications, and applying quantitative measurement methods for inspection and process control. The first two—process modeling and design tolerancing—are of primary importance and drive the second two; however, both are surprisingly ill-understood in a scientific sense. Mathematical models for predicting process precision, and quantitative precision and inspection data for actual processes, are scarce and often proprietary. Tolerancing today is based on informal definitions and on tolerance-assignment and inspection procedures of limited generality and validity. As a result, tolerancing; process selection and control; and, to some extent, metrology and nondestructive evaluation still rely largely on tradition.

Process modeling is discussed in Chapter 10. This chapter deals with process precision, a crucial but often overlooked component of quality technology.[1] Spatial precision (i.e., issues of form and fit) is particularly important, since it pervades almost all discrete goods production. This chapter reviews the current research status and needs of process precision and metrology. It concludes with recommended research opportunities.

[1] Quality technology encompasses all those technologies necessary to assure that a product can be/is produced to meet the design specification. It can be divided into two areas: (1) precision and metrology and (2) nondestructive evaluation.

RESEARCH STATUS AND NEEDS

The emphasis thus far in this report has been on processes and on the knowledge and technologies needed to implement them. An alternative approach is to shift the focus to parts and products and view unit manufacturing processes merely as the means to make quality parts and products. This approach exposes new issues that strongly influence the usefulness of unit processes and an overall ability to make quality goods. These issues arise, because manufacturing and assembly processes produce parts and products that vary. Variations in part geometry, as graphically illustrated in Figure 13-1, could result from inherently imprecise processes, or from variations in process control. Control variations could be due to a lack of knowledge concerning the process variables, inadequate means of process control, indifference to process control, etc. Distinguishing between the imprecise execution of a process and the execution of an imprecise process is at the heart of precision engineering. Most processes underlying

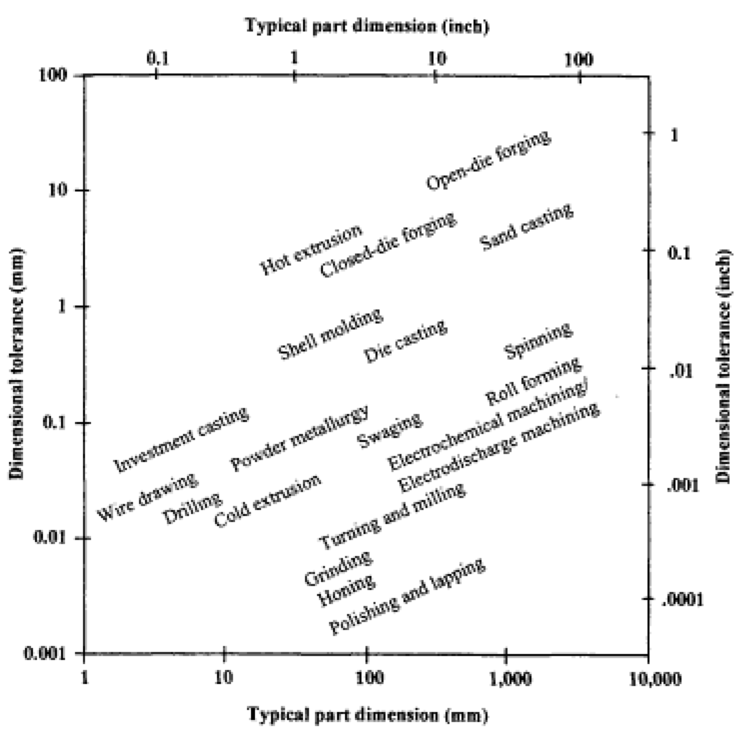

Figure 13-1 Tolerance as a function of components metalworking processes (adapted from Kalpakjian, 1992).

manufacturing and assembly are quite precise. Consequently, mechanisms that accommodate and control variability are woven throughout the entire manufacturing system.

When parts and products are designed, dimensional tolerances are assigned to specify allowable variations. Parts are then manufactured and products assembled by selecting processes that are repeatable and precise enough to meet the specified tolerances. Thus three key producibility themes emerge: design to accommodate variability arising from the control process design, design to ensure that the realized process variations do not exceed the design tolerance, and design to minimize the dispersion of variations within the allowed ranges of variability through careful control of manufacturing and assembly processes.

The nominal design of products, subassemblies, and parts is driven mainly by functionalism—that is, by what the items must *do*. The main tools are parametric modeling (e.g., dimensioned drawings, computer-aided design models) and analytical procedures (e.g., finite-element analysis). The next stage of design, detailed design, supplies the details that were ignored in nominal design and accommodates manufacturing and assembly variability by specifying allowable variations in spatial forms and relations. Interchangeable assembly usually becomes the dominant constraint. The main working tool is tolerancing (i.e., a set of standardized practices for determining and specifying variations). Current tolerancing standards prohibit specification by process and by reference to other artifacts. As a result, parts must be specified as free-standing geometric entities, rather than by procedures for making them or by requirements that they mate with other parts. (These restrictions were motivated by procurement problems; they have the intent of preserving full manufacturing freedom and facilitating competitive "out-sourcing.")

Manufacturing and assembly planning can be simplistically viewed as a mix-and-match exercise in which processes of adequate precision are selected to produce the various features of a part or to mate parts in assembly and then are sequenced to meet process, functional, and cost constraints. In physical manufacturing, parts are made using unit processes. The processes must be controlled passively or actively for predictable results, and every form of control uses some form of process model.

Physical assembly is analogous to physical manufacturing in that unit assembly processes (e.g., align, insert, screw, cement, etc.) are used to produce subassemblies and, finally, complete products. Assembly processes must be controlled passively or actively for predictable results, and every form of control uses some form of assembly process model.

The conformance testing (i.e., inspection) phase determines whether parts meet their specifications. The main techniques are conventional parametric measurements and binary (i.e., accept or reject) inspection using special gages.

Testing strategies vary from 100 percent inspection of all toleranced features of all parts through statistical sampling of small lots of parts to no inspection at all (when the manufacturing processes are very tightly controlled). Statistical design of experiments during the process development phase could guide the establishment of a statistical process control system that will lead to the minimum inspection program required to assure high quality (Taguchi et al., 1989). Performance testing of the final product is the analog to part conformance testing.[2]

Thus, as one moves downstream from nominal design, the control of variability becomes the major production concern. Variability arises from the physical processes used to make and assemble parts. Four central factors are involved:

1. tolerancing: the means used to specify allowable variations in parts and products;
2. metrology: the means used to determine whether artifacts meet their design specifications;
3. process form and precision modeling: the means used to specify, for a particular process, the expected accuracy based on knowledge of the sources of imprecision; and
4. process planning: the means used to select and sequence processes to make or assemble parts.

Tolerancing and process modeling dominate, because they influence, or provide critical data to, the other two factors. Some of the current topics in process precision and metrology are discussed below. They include issues in dimensional scale and precision in manufacturing, dimensional tolerances and metrology, process planning, and process modeling.

DIMENSIONAL SCALE AND PRECISION IN MANUFACTURING

Table 13-1 indicates that typical manufactured products vary greatly in scale and in their requirements for precision. In the table, dimension, D, is a normal size parameter and tolerance, T, is a typical limit on the allowable variation in D. The T/D precision ratio (i.e., fractional linear variability) is one measure of

[2] The tools and methods used for performance testing are highly dependent on the nature of the product.

precision. The scale of the items, as well as their T/D precision ratios, spans a range of 10^6. However, most components of conventional products (e.g., motor vehicles, aircraft, appliances, and machinery of many kinds) vary in scale by a factor of about 10^2 within a larger absolute range extending from about 1 mm to 10 m and have precision ratios in the range 10^{-3} to 10^{-5} (again, a factor of 10^2). Conventional parts and products are a main focus, since they constitute well over half of all discrete goods by dollar value and contribute close to 10 percent of the gross national product, and they are produced using the unit processes discussed earlier. Unit processes for the most part have been designed to operate in the scale and precision ranges spanned by these products.

Figure 13-2 distinguishes "precision" and "ultraprecision" machining from "normal" machining in terms of dimensional scale and tolerance. Precise and ultraprecise manufacturing and measurement processes are quite specialized and limited in applicability, but the volume, value, and technical importance of the products requiring processing in these regimes are growing. Obviously, this requires improvements in existing processes, either by implementing the practices of the next higher quality level or by improving the existing process. In either case, a cultural change is often necessary to institutionalize the higher quality level. A similar plot can be made for other unit processes, such as those listed in Table 13-1; the trends for those unit processes are directly analogous to the case of machining.

DIMENSIONAL TOLERANCES AND METROLOGY

Parts are specified in terms of their nominal (ideal) shapes and nominal material properties, with allowable variations on both. Assemblies are specified in terms of part associations and performance specifications, again with allowable variations on both.

The trend toward tighter tolerances is being motivated by a desire for longer life, faster but quieter operation, greater efficiency, and simplified assembly operations. For example, sorting piston pins for proper match into the piston was once a common practice. It is now considered obsolete, because accurate machining is currently inexpensive enough to enable all parts to match. By contrast, the fit required for diesel fuel injector plungers is so critical that current technology does not allow for economical manufacture of parts for universal assembly.

Table 13-1 Dimensional Scale and Precision for a Range of Manufactured Items (Swyt, 1992)

Part or Subassembly	Geometric Attribute	Process	Dimension D	Tolerance T	Ratio T/D
Auto door assembly	Panel size/ position	Die stamping	1 m	1 mm	10^{-3}
Auto engine piston	Diameter/ cylindricity	Machining	100 mm	7-8 mm	10^{-4}
Magnetic read/write heads	Cut-face position	Diamond slicing	125 mm	2.5 mm	2×10^{-5}
Wafer micropattern	Pattern position	Lithography	250 mm	0.2 μm	10^{-6}
Optical Fibers	Fiber diameter	Die drawing	125 μm	0.2 mm	10^{-3}
Integrated circuit	Line width	Lithography	0.5 μm	50 nm	10^{-1}

The conformance of parts and assemblies to geometrical specifications is assessed by physical measurements. The term "dimensional metrology" covers the various instruments and techniques used for making such measurements. There are three main classes of instruments and techniques in use today, all of which require physical contact with the specimen:[3]

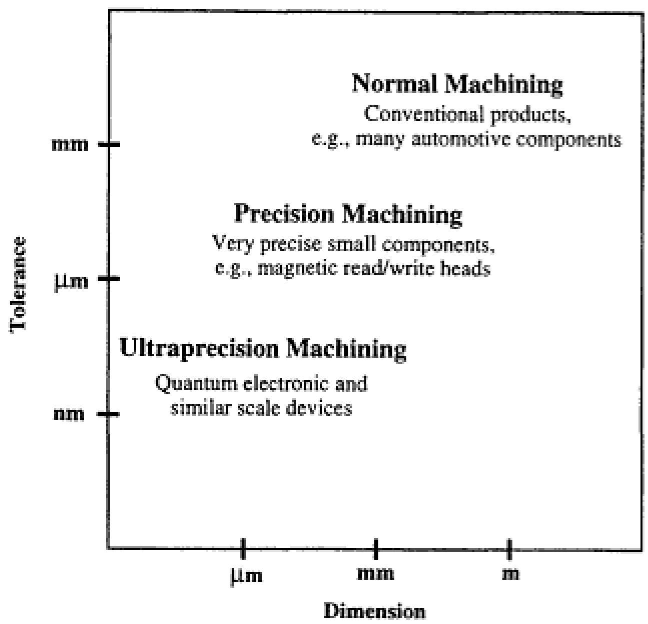

Figure 13-2 Three relatively distinct manufacturing regimes (adapted from Wirtz, 1991).

- *Manual instruments and so-called open setup, or manual, methods* . These include rules, calipers, micrometers, dial indicators, and surface plates. These are the classic measurement instruments used in manufacturing. They are low cost and widely available. However, their use is time consuming and subject to human error.
- *Functional (hard) gages*. These range from simple plug gages to custom fixtures designed to simulate features of mating parts. They effectively pick up maximum or minimum features with assurance and are made either fully mechanical (i.e., go/no-go) or with an analog transducer (i.e., dial indicator) that provides readout of deviations. Custom fixtures are expensive and difficult or

[3] Contact technologies are relatively precise and robust, but they are inherently slow and therefore expensive. They are likely to be replaced gradually with faster noncontacting technologies based on wave phenomena.

impossible to modify and hence are justified only for critical or large-volume production.

- *Coordinate measuring machines (CMMs*). These are very precise devices that measure the positions of points on the surface of a part by probing ("touching"), usually under computer control. CMMs resemble machine tools but are more precise and are often temperature-compensated. The digital data collected by a CMM must be processed by algorithms to assess whether the part conforms to its tolerance specifications, and this raises issues that cut to the core of tolerancing and metrology. There is growing interest in simulating hard gages with properly programmed CMMs for low-volume production.

The current American tolerancing standard, ANSI Y14.5M-1982 (referred to in this report as "Y14.5" for brevity), evolved from shop and drafting-room practice; its roots lie in gaging technology, although it is not a gaging standard (ANSI, 1982). The standard is best viewed as a collection of sensible principles, defined mainly through examples cast in prose and graphics. There is no companion standard to specify how pans are to be measured to assess conformance to the definitions in Y14.5.

The informal definitions of Y145.5, and the absence of a measurement standard, caused few problems in the pre-CMM era, when inspection was done manually or with automatic gages. When CMMs arrived, however, inspectors found that CMM results did not always agree with traditional inspection results. This is called "methods divergence," and its recognition triggered increasingly strident warnings in the 1980s about a "metrology crisis." A second problem, "specification ambiguity," was exposed when CMM and computer-aided design programmers found that some of the prose and graphic definitions in Y14.5 are ambiguous.

The American Society of Mechanical Engineers and the National Science Foundation convened a workshop in 1988 to discuss these matters. The major recommendations are as follows (Tipnis, 1989).

1. The Y14.5 standard should be mathematized and generalized, so that provably correct measurement procedures can be designed to assess conformance.
2. Education and research in tolerancing and metrology should be expanded markedly.

The standards community responded vigorously to the 1988 recommendations by establishing new committees in 1989 to mathematize Y14.5 and to address measurement methods. A new standard, "Y14.5.1: Mathematical Definition of Dimensioning and Tolerancing Principles," will be issued in late 1994 to accompany a new edition of Y14.5, and a second new standard, "B89.3.2: Dimensional Measurement Methods," is expected to be issued in 1996 (Srinivasan and Voelcker, 1993).

The advent of these new standards, in which mathematics is the defining medium, probably marks the end of the 200-year era in which tolerancing and metrology evolved as industrial practices without strong theoretical underpinnings. It is important to note that while a new era with a precise language (mathematics) for defining tolerances has begun, there is no proper mathematical theory to govern the use and interaction of tolerances. A theory can be expected, however, because research in tolerancing and metrology is growing (Menon and Voelcker, 1993; Menon and Robinson, 1993). Unfortunately there has been little progress in introducing these topics into engineering curricula.

It is worth noting that there is a movement in Europe advocating the adoption of vectorial tolerancing as a replacement for, or at least a co-equal alternative to, the International Standards Organization brand of geometric tolerancing. Vectorial tolerancing was formulated by Adolph Wirtz of Switzerland (Wirtz, 1991); Figure 13-3 conveys some of its essential elements. The basic concept is to cast tolerances in terms of parameters that are important in manufacturing and inspection, with the current formulation oriented toward machine tools and CMMs. This has the advantage of removing the language mismatch noted later in this chapter, but it does so only for one or two families of processes. It is a retrograde step in the sense that it re-establishes the coupling between design specifications and manufacturing methods that was deemed harmful in the early days of geometric tolerancing.

PROCESS PLANNING

Process planning directly links manufacturing to design. Process planning can be described using the simple example of machining the bracket described in Figure 13-4. Observe that the plan shown as output in Figure 13-5 is influenced strongly by the hole tolerances. Specifically, the central hole D should be generated first, because it serves as a position datum for the four-hole pattern.[4] Further, at least two processes—drilling, followed by boring—are required to meet the position and perpendicularity tolerances on D, and a final light reaming might be needed to meet the cylindricity tolerance.[5] The four holes

[4] This will not matter on numerically controlled machines if D is spot-drilled.

[5] Drilling is an imprecise hole-making process. Boring and reaming are hole-finishing operations that have different form and positional accuracies.

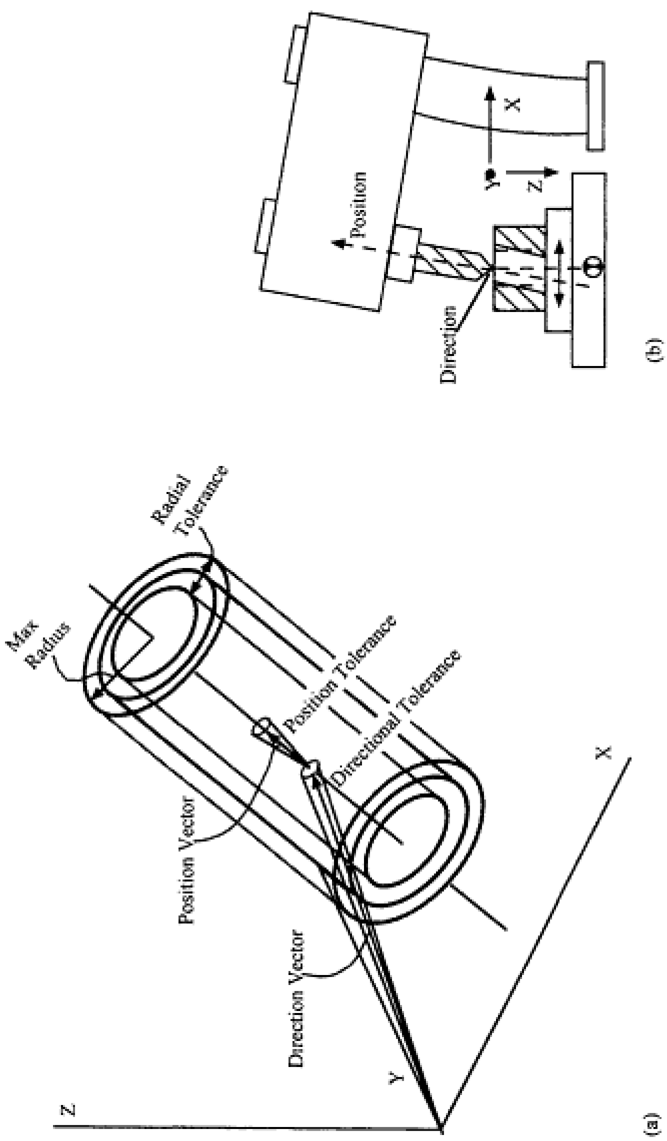

Figure 13-3 An illustration of (a) vectoring tolerancing and (b) its potential convenience (adapted from Wirtz, 1991).

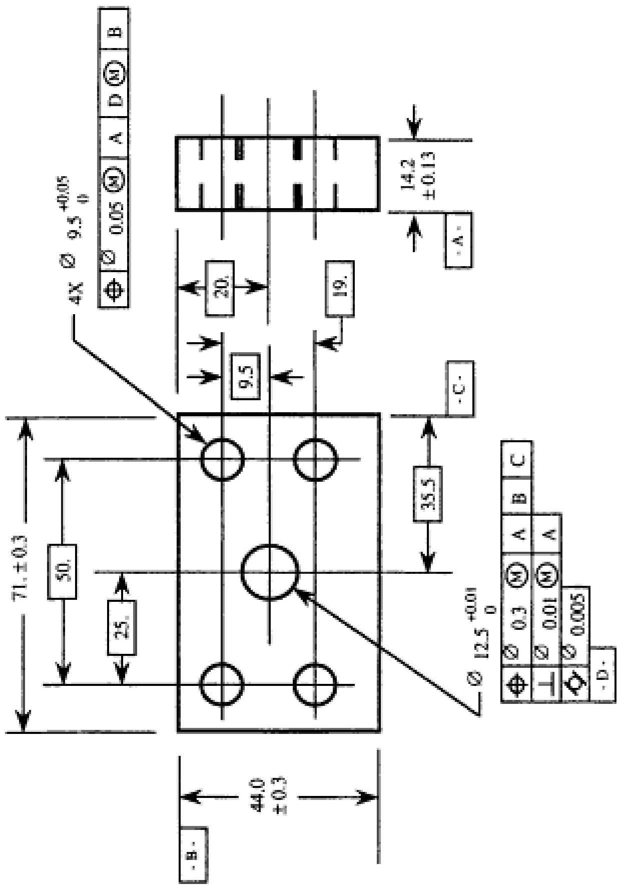

Figure 13-4 Example bracket.

in the pattern do not require special finishing, because their size tolerances are loose, but they do require spot-drilling for positional accuracy. Finally, note that the plan shown in the figure does not require special tooling. However, if a different process family had been used—molding, for example—then tooling (e.g., mold-system) design would have been a major activity.

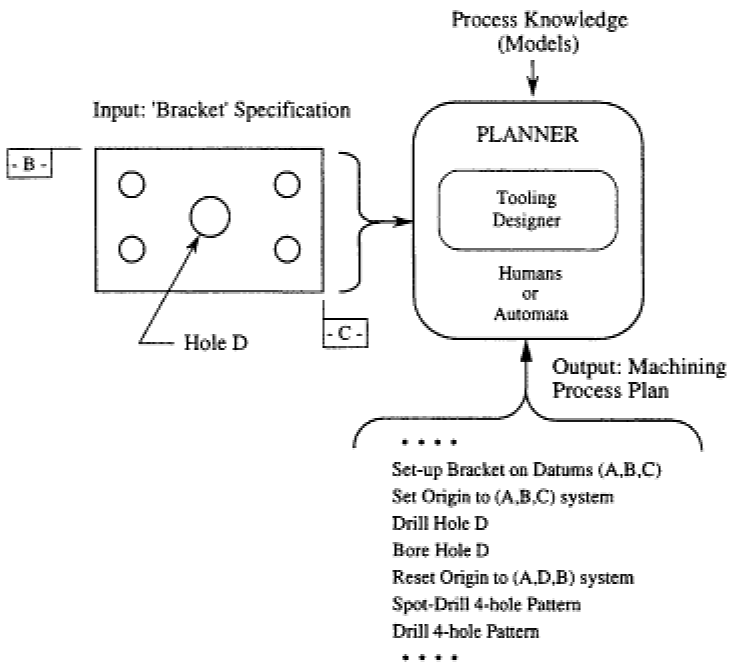

Figure 13-5 Planning the machining of the holes of the bracket in Figure 13-4.

Experienced machinists can easily construct plans such as that shown in Figure 13-5, because they possess a wealth of experiential data and subtle reasoning powers. To date, researchers have tried to codify, or to replace, this data and logic with automated process planning systems with little success.[6] Twenty years of research have failed to produce automatic machining planners

[6] An experienced machinist knows semiquantitatively, for example, that boring is positionally and orientationally more accurate then reaming but less accurate in terms of cylindrical form.

that have a reasonable degree of generality. To understand why, observe that the study of process planning raises two basic issues: what knowledge (e.g., models and data) is needed to do planning, and how is that knowledge used to produce plans? The first issue will receive focus here, because it is the *sine qua non* for understanding and automating planning (and deficiencies in this area almost surely are responsible for the lack of progress just noted). Readers interested in the second issue, planning logic, are referred to the research literature cited in *Manufacturing Intelligence* (Wright and Bourne, 1988) and *Computer-Aided Manufacturing* (Chang et al., 1991).

The main elements of process planning are selecting particular processes and operating parameters that can produce the specified part, either as a whole (e.g., by molding or casting) or as a collection of distinct features (e.g., machined features, forged features), and sequencing the selected processes appropriately. The first step requires that part geometry, both ideal form and allowable variations, be matched with *process capabilities*. Thus the central knowledge needed for process planning is a set of *process models* that prescribe for each process the nominal forms it can produce and the variability associated with each form.

PROCESS MODELING

A complete process model covers more than form and form precision; it also deals with the bulk and surface properties of the processed material, with the energy needed to apply the process, with the scaling laws of the process, and so forth. This section, however, focuses on form and fit and does not discuss material-property and kinetic modeling. The entire area of process-induced form modeling requires a significant increase in research, because there are few process models that provide explicit representations of the forms that can be produced, and even fewer that provide the precision data useful for manufacturing planning and tooling design.

Machining has been studied longer (for more than 100 years) and more intensively than other processes and therefore is a logical first place to look for form models. The obvious first sources, engineering texts on machining, yield little. However, machining handbooks and broad-scale manufacturing-process tests (Kalpakjian, 1992) have tabulations of form capabilities (such as Table 13-2) and linear precision graphs (Figure 13-6 has conservative tolerances; some applications demand much greater precision). Note that bounding-surface equations can be associated easily with most of the forms in Table 13-2.

The data summarized in Table 13-2 and Figure 13-6 illustrate the level of well-known current machining form and precision models.[7] The process models cannot cope effectively with 3-, 4-, and 5-axis machining, and they are virtually useless for selecting processes to meet given geometric tolerances. Recent and current research, however, are now providing models that, while still experimental, are more powerful and promising.

For example, mathematical and computational tools offered by solid modeling enable the nominal form-modifying effects of numerical control machining to be modeled mathematically and simulated computationally with increasing fidelity (Menon and Robinson, 1993; Menon and Voelcker, 1993).

Research on improved precision models for machining is more scattered, but several references provide useful introductory discussions and references (See Chang et al., 1991; Wood, 1993, for a different approach based on fractal theory). Much of this work is based on a three-step paradigm: (1) postulate a generic relation between form error and parameters of the process, (2) construct a phenomenological model for a particular class of errors to particularize the generic relation, and (3) use the result to guide the collection of experimental data to create a specific model.

Thus far the discussion of process modeling has focused on machining. Nominal-form and form-precision modeling seem to change character when bulk dynamic processes are addressed. Consider nominal form. In machining, form-feature process models (see Table 13-2) are needed for localized matching with part features. In casting and molding, nominal forms for entire parts are defined by molds, and a major component of process planning is designing mold-filling systems that will yield good parts (i.e., no voids or internal chill fronts, low residual stress, etc.). Elaborate computer programs to do the requisite hydrodynamical and thermodynamical analyses are under continuous development to aid such work. In deformation processes such as forging, nominal forms are defined by (final) dies, and the design of progressive die sets and preforms are major activities in process planning. Again, elaborate computer programs to analyze highly nonlinear plastic deformation phenomena are under continuous development to support such work.

[7] More-extensive precision data are often available within companies for processes important to each company, but such information is usually proprietary.

Table 13-2 Forms Produced by Selected Classical Unit Machining Processes

Process	Form
Drilling	Straight cylindrical hole
Boring	Straight cylindrical hole
Reaming	Straight cylindrical hole
Face milling	Plane surface
Profile milling	Ruled surface normal to a plane
End milling	The above plus approximations to general curved surfaces
Shaping, planing	Plane surface
Turning	Surface rotationally symmetric about an axis

The development of process-precision models for bulk dynamical processes involves such factors as shrinkage, creep, and residual stress prediction. Much of this work is in its infancy.

Research in process modeling is diffuse, because it is distributed over the many families (and associated communities of researchers) discussed in Chapter 11. With the exception of machining, there does not appear to be much work aimed at generating the types of process-precision models needed for process planning, although some of the sensitivity analyses done for some processes may be convertible into precision models.

The situation in machining is different. A group devoted to precision has a long history in the annals of machining and has paced the improvements summarized in Figures 13-2 and 13-7. Precision engineering is nearing recognition as a distinct subdiscipline within mechanical engineering and applied physics, and its new domestic professional society, the American Society for Precision Engineering, is growing and has a well-regarded journal, *Precision Engineering*, and strong ties to sister societies in other nations. The historical focus of precision engineers has been the construction of ultraprecise (for the era) artifacts and of the machinery to produce such artifacts. To pursue this work, precision engineers have had to probe deeply into the sources of process and machine variability, and thus process engineers should participate, or even take the lead, in building process-precision models (Slocum, 1992).

Process planning, as a distinct activity and as an area for formal study, has a much shorter history. Most of its research roots lie in computer science and artificial intelligence. These fields have a large literature centered on automatic planning, but little of it is devoted specifically to planning for manufacturing. It is probably safe to predict that automatic process planning for manufacturing will not progress very far until better process and process-precision models are available.

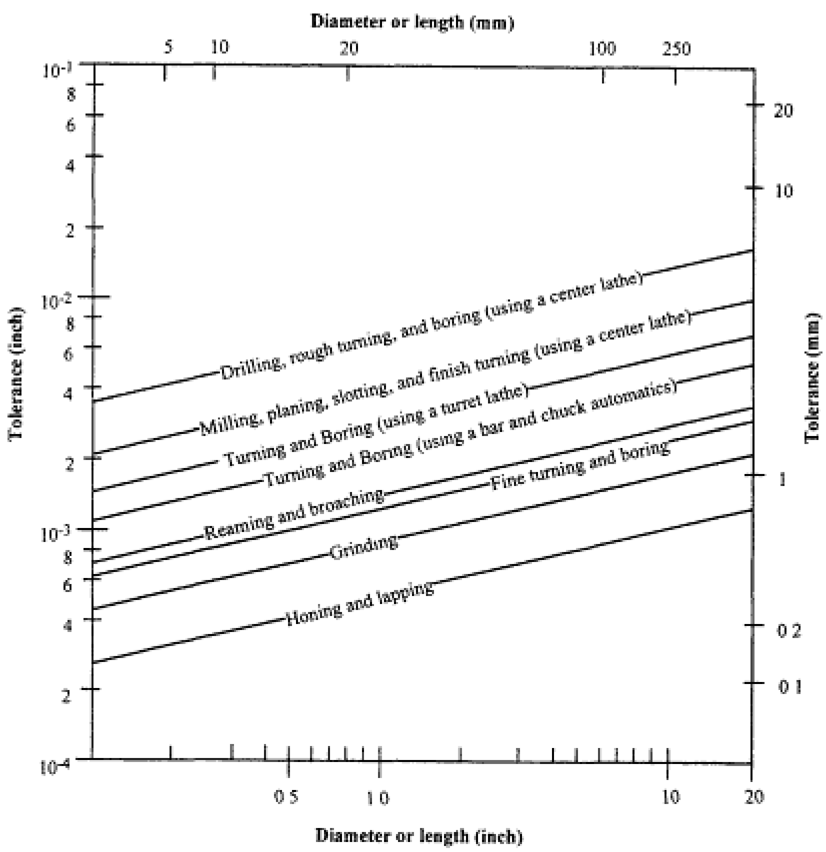

Figure 13-6 Tolerance versus dimension data for various machining processes (adapted from Kalpakjian, 1992).

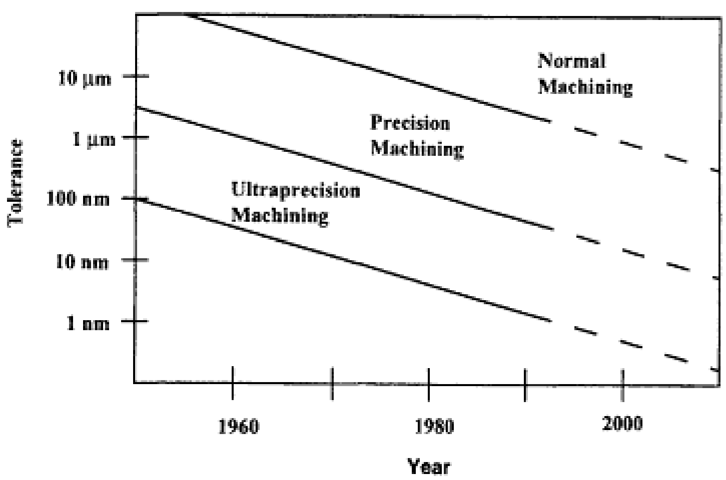

Figure 13-7 Precision machining domains (adapted from Taniguchi, 1983).

RESEARCH OPPORTUNITIES

Manufacturing and assembly processes are inherently imprecise, and mechanisms to accommodate and control variability are woven through the entire manufacturing system. In design, the primary mechanisms are dimensional, and surface tolerances assigned to ensure interchangeable assembly while preserving function. Dimensional tolerances are governed by national and international standards and are required to be manufacturing-process independent. In manufacturing, process variability is kept within acceptable bounds by process control. Models for characterizing process variability (or process precision) are not standardized, are not well developed for many important processes, and usually are cast in terms of parameters natural to the process rather than for consistency with part tolerances. Thus there is a pervasive language mismatch between the mechanisms used to limit variability in design (i.e., tolerances) and the mechanisms used to describe the variability of processes (i.e., process precision models). This mismatch complicates process planning considerably and is a major inhibitor of further manufacturing automation.

Based on the preceding discussion, the following areas emerge as strong candidates for future research emphasis.

- A major effort is needed to devise models and metrics for characterizing the precision of unit manufacturing processes in ways useful to process planners and designers. A two-pronged effort is likely to be needed, in which models and metrics are first sought in the natural parameters of each process, and then means are sought to translate or interpret these parameters in terms of design tolerances.

- The models and metrics developed above should be concurrently applied to unit processes of interest, particularly regarding their scalability; their intrinsic or ultimate precision, as set by the underlying physics or chemistry of the process; and the precision currently available in typical industrial implementations.
- The efforts now under way to mathematize and generalize Y14.5, the American national tolerancing standard, and to define systematic measurement procedures based on a rigorous tolerance standard, should be encouraged. The harmonization of the American National Standards Institute and the International Standards Organization standards should also be encouraged.
- University researchers should be encouraged to participate in all of this work, including that of the standards committees, and to take the lead for some of it. One of the most important contributions these researchers can make is the systematic codifying of the scattered knowledge in these important fields.
- Academia should be encouraged to teach the essential principles of tolerancing, metrology, and process modeling in engineering design and manufacturing courses. At present, only process modeling receives more than cursory attention.

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14

Process Equipment Design

Manufacturing equipment is the platform for the operation of unit processes. Properly designed equipment is essential for the production of high-quality, cost-effective products. Equipment design is necessarily the broadest category of the six enabling technologies, since it ultimately serves as the vehicle to implement all of the other enabling technologies. As pointed out in the introduction to this report (Chapter 1), the United States must be able to manufacture products of superior quality at competitive prices in order to maintain its standard of living and its standing in the world economy. The introduction also emphasized that competitiveness depends on new and improved processes and less on product technologies. Thus, *the design of the equipment used in manufacturing processes assumes a dominant role in industrial competitiveness*. This point was recently underscored by Eagar and Fine (1992):

> The processing equipment industries play a unique role in an economy. They provide the tools for all the other manufacturing sectors in the economy. Even though education of the workforce, improved operations management, faster transportation, and communication have each increased productivity, in the long run, the influence of improved processing equipment almost certainly provides a multiplier which exceeds all of these other factors combined.

The importance of equipment design is clear to the technical community. Many recent articles have discussed topics such as robust design, design optimization, design for manufacturing, and doctoral programs in design. A recent text that presents a valuable discussion of the many factors involved in equipment design is Slocum's *Precision Machine Design* (Slocum, 1992). A case can be made for the importance to domestic manufacturers of high-quality, locally produced processing equipment rather than reliance on foreign suppliers.

There are many research needs for innovations in equipment design, since this area is necessarily broader than the other enabling technologies. Rapid speed of operation, high accuracy of positioning, high structural rigidity, flexibility of operation, user friendliness, and safety are highlighted below, because experience has indicated that improvements in these areas are highly desired and thus most likely to be incorporated if they are shown to be cost-effective (costs associated with the purchase, installation, and maintenance of new equipment must be competitive with existing alternatives). Specific details would depend, of course, on the specific unit process under consideration. The end result would be world-class unit process equipment available at a competitive sales price with low lifecycle costs.

However, the committee suggests that the *greatest research need* in the area of *equipment design* is the *interaction of process equipment manufacturers with one another and with university research, national laboratories, and other government agencies* to identify needs that are broader and more long-range than those the committee has identified for the other five enabling technologies or in this section on equipment design.

Two strategies have been employed to develop advanced unit process equipment—incremental and breakthrough. The incremental approach involves a systematic series of improvements to the equipment that address specific needs. It is a relatively low-risk approach, usually involving a multidisciplinary team of researchers. Over a period of time, significant advancements to existing unit process equipment can result.

Innovative, breakthrough design concepts, on the other hand, have the potential for dramatic improvements in unit process equipment. This a high-risk, high-payoff approach that rarely results from a systematic approach to equipment design. It is a contentious issue, but the committee's opinion is that the creative, innovative, or inventive aspect of design apparently does not lend itself to a rigorous description or systematic instruction. This strategy involves exposing a talented, creative individual to the problems and providing a stimulating environment in which ideas can flourish without a great number of constraints. These innovative ideas can then be further refined and developed with a systematic approach.

RESEARCH OPPORTUNITIES

Efforts are needed to improve speed of operation. This topic includes fast movement of the equipment components during the unit process sequences with minimal dwell times during the unit process cycle. Examples of rapid operation speed in the machine tool area are the ultrahigh spindle speeds in milling and turning centers. Additionally, providing minimal warm-up time from process start-up to operational steady state are critical to attaining rapid speed of operation and achieving consistency of part characteristics, such as dimensional control.

Efforts to provide highly reproducible, accurate positioning of production equipment component motions are needed to support the precision levels discussed in Chapter 13. Positional errors in processes lead to variations in product tolerances and quality. Errors in equipment motion locations, either on an absolute (based on one reference point) or incremental (based on sequential locations) base, often are additive in nature, with errors that are introduced early in the process sequence influencing positioning problems later in the unit process sequence (Tomizuka, 1989). The areas requiring emphasis are unit processes with multiple action sequences that possess several reference points that could be used for positioning.

Very rigid, stiff structural elements of unit process equipment are required, since these are primary factors determining positional accuracy and the level of precision inherent to the process.[1] Required are innovative equipment designs that dampen vibrations (so that they are not transmitted to the tooling and workpiece), which originate from the process or external sources. For example, taking heavy machining cuts with nonideal coolant application and poor cutting tool conditions can result in self-induced "chatter" in the tooling and workpiece, often resulting in poor surface quality condition and dimensional variations in the machined part. Also, equipment designs that minimize thermal distortion due to nonuniform temperature variation that is caused by internal and external heat sources are needed so that the equipment can maintain positional accuracy during all phases of equipment operation.

Developing unit process equipment that can readily and rapidly change the operation format and tooling for a variety of parts is critical to the competitiveness of a unit process. Achieving short job-to-job setup times; flexible, versatile tooling and fixtures; and multiple process capability is important. Current trends in small-lot-size manufacturing place even greater emphasis on these aspects of equipment design.

The development and maintenance of the skill base needed to operate unit process equipment efficiently is a constant challenge in manufacturing. Equipment design should lend itself to efficient training of both operators and maintenance personnel. There are opportunities to improve the unit process

[1] Rigidity defines the elastic deflections that are experienced by the equipment components and the workpiece from the working loads induced during the unit process operation.

equipment design so that it is user friendly for the operation and maintenance aspects of the process. For example, designs that are compatible with control features, requiring minimal intervention during operation, are needed. Considerations that override all others are to develop equipment that is safe to operate and imposes no harmful effect on the workers or environment.

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PART IV: POLICY DIMENSIONS

INTRODUCTION

The preceeding parts of this report have described what unit processes are, discussed their importance to the national economy, explained their critical research needs, and suggested opportunities for further R&D. This final section discusses the contexts in which unit process R&D is conducted and the results implemented by industry.

Chapter 15, "Technical and Economic Contexts," provides background information regarding the importance of process technology in enhancing the global competitiveness of the United States. The chapter summarizes the rationale of why future technology-driven competitiveness may depend more on new process technologies and less on new product technologies. In line with this shifting of priorities, the work force supporting manufacturing endeavors will have to be educated and trained in manufacturing technologies to allow industry to gain maximum advantage from the advanced process technologies described in parts II and III of this report.

Chapter 16, "Resources in Unit Process Research and Education," examines key issues associated with the availability of resources within industry and the federal government to fund the many opportunities for unit process R&D. It also discusses the different roles for universities in unit process research, trends in education, and mechanisms for industry-university interaction.

Chapter 17, "International Experience," examines key elements of manufacturing-related research, implementation mechanisms, and unit process focus for several highly industrialized countries and regions: Germany, Japan, and Europe (excluding Germany). It summarizes the key elements of the strategies employed by those countries.

KEY CONCLUSIONS

- Several high-level measures indicate that the United States is underfunding both unit process R&D and education and training of the workforce. Particular care must be taken to direct available funding at the most promising opportunities and most pressing educational needs.
- Even though this report primarily addresses the development of unit process technologies, the committee does not believe that process technologies alone will contribute to overall improvements in manufacturing competitiveness. The nation must possess an educated, motivated workforce and industries committed to making appropriate investments in manufacturing facilities and equipment. Therefore, a national emphasis on manufacturing must address at least three factors: unit process technologies, workforce education, and implementation.

KEY RECOMMENDATIONS

- Government agencies involved in sponsoring R&D in manufacturing processes (e.g., National Science Foundation, Department of Defense, Department of Energy, and National Institute for Standards and Technology) together should carefully evaluate the kinds of manufacturing R&D being supported and the relative funding levels for defense and nondefense R&D. This evaluation could also examine the extent to which other leading industrial countries, notably Germany and Japan, have been effective in commercializing unit process technology, given their investment in research that is related to manufacturing which is considerably higher (as a proportion of their gross domestic product) than that of the United States.
- The committee recommends that incentives be found and implemented to increase the number of students majoring in manufacturing-related technology at universities, so that sufficient trained personnel are available to exploit research opportunities in unit processes and to guide their industrial implementation. For example, the National Science Foundation could convene a study group to determine the appropriate educational incentives in the context of expected technical opportunities, industry needs, and employment opportunities. One incentive that would quickly attract high caliber students would be an increase in the number of fellowships available to those specializing in manufacturing.

15

Technical And Economic Contexts

Unit manufacturing processes are the building blocks of a nation's manufacturing capability. They are the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product. The effectiveness and efficiency of unit processes are, therefore, key determinants of total production costs. Given their importance, to what degree should public and private funds be invested to conduct R&D to improve unit processes? This question can be examined from at least two perspectives: technical and economic.

Manufacturing has long been recognized as crucial to the economic health of a nation (Compton, 1988). The U.S. manufacturing sector contributes approximately one-fifth of the gross domestic product, directly employs a work force of over 19 million in 360,000 companies, and supports an additional 25 million workers in related industries (Manufacturing Subcouncil, 1993).

It has been forecasted that future economic success will be primarily driven by effective use of technology and the skill base of the work force (Thurow, 1992). Historical patterns of economic development (e.g., abundance of natural resources, established sources of capital, etc.) may not then be the future dominant drivers of competitive advantage. As evidence of these trends, global sourcing of raw materials is becoming commonplace, and capital markets are financing industrial development throughout the world.

Four studies published within the last several years have discussed the critical importance of technology to the economic future and security of the nation and the requirements for their timely research, development, and implementation. Each study was based on a different perspective:

- the Department of Defense looked at future weapon system superiority (DoD, 1990);

- the Department of Commerce looked at emerging technologies that are expected to have major economic importance by the year 2000 (DoC, 1990);
- the Office of Science and Technology Policy looked at technologies critical to national economic prosperity and national security (National Critical Technologies Panel, 1991); and
- the Council on Competitiveness looked at technologies critical for U.S. industrial productivity and economic growth (Council on Competitiveness, 1991).

The technology areas of advanced materials and manufacturing were identified as critical technologies in each of these reports. "Advanced materials" includes a diverse group of materials, such as structural ceramics and composites, biomaterials, and superconductors. Process capabilities to cost-effectively produce the properties needed for specific applications are key technologies required for commercialization of these materials. Such capabilities depend on a thorough understanding of the fundamentals of the unit processes. Thus near-net shaping, ultraclean processing, and artificially structured materials are essential for future competitiveness.

The areas of manufacturing designated as critical include flexible computer-integrated manufacturing, manufacturing systems management, and intelligent processing equipment, as well as microfabrication and nanofabrication. In order for these critical technologies to be fully developed and exploited in the marketplace, substantial process knowledge will be required. Other critical technologies, such as sensors, advanced computation, and materials, are also important to the development of manufacturing technologies. In addition, advanced simulation and modeling technology is crucial to improved process understanding. Applying these technologies in the manufacturing environment is essential to securing the long-term competitiveness of U.S. manufacturing.

Many of the other critical technologies in the above referenced reports are related to manufacturing, either as areas of application of manufacturing technology or as technologies that support or enable future development of manufacturing. For example, advanced materials, biotechnology, transportation, information, and communications all rely on manufacturing technologies for production of their respective materials and equipment. On the other hand, many of these technology groups are the keys to advanced manufacturing (e.g., computer-integrated manufacturing requires information and communications). Thus, advanced manufacturing technologies are interwoven with the critical technologies.

The current status and projected future trends of the critical technologies, relative to those of Japan and Europe, are discussed in the Department of Commerce report (DoC, 1990). For each technology, the report assessed whether its status and its projected trend in the United States were ahead, even, or behind the status and trend of competitors. A similar comparison was made by the Council on Competitiveness (1991), which judged the present position of several material processing technologies, production systems, and process equipment categories. While these assessments were done at a high level and may be overly simplistic, taken as a whole they raised concern about the condition of manufacturing technologies in the United States.

Several generalizations emerge from reviewing the characteristics of the technologies in each grouping. Those technologies for which the United States was judged as being globally competitive (i.e., ahead of the rest of the world) typically fit one or more of the following descriptions:

- The transition from research to commercialization was relatively short, without lengthy intermediate development stages. (An example is the development of catalytic materials.)
- Capital investment needs were not substantial for initial implementations. (Examples are sensor technologies.)
- Individual innovation was a key factor in their beginnings. (An example is artificial intelligence.)
- The R&D funding of these technologies was sponsored by government or encouraged by government policies such as environmental regulations. (Examples are emissions controls.)
- Private sector funding was used to leverage government funding at critical junctures during the development stage. (Examples are magnetic materials.)

Those technologies for which the United States was judged not to be globally competitive can be typified by the opposite characteristics. These technologies generally had one or more of the following conditions:

- They did not enjoy robust R&D support (either private or public).
- They had high capital requirements.
- They required lengthy, extensive development for their applications to become commercially available.

According to the data in Table 15-1, many of these weak technologies are related to the manufacturing sector. Industrial manufacturing-related R&D, and its transition to production, depends on engineers and shop personnel who are well trained in the science and engineering of unit processes. An educated, skilled work force can be the dominant competitive advantage for companies and nations. However, the typical engineering student in the United States does not

TABLE 15-1 Engineering and Production Technologies

TECHNOLOGY	**U.S. POSITION**				
	Strong	**Competitive**	**Weak**	**Losing Badly**	**Lost**
Design and Engineering Tools					
Computer-Aided Engineering	•				
Human Factors Engineering		•			
Leading-Edge Scientific Instruments				•	
Measurement Techniques		•			
Structural Dynamics		•			
Systems Engineering	•				
Commercialization and Production System					
Computer-Integrated Manufacturing		•			
Design for Manufacturing			•		
Design of Manufacturing Processes			•		
Flexible Manufacturing			•		
Integration of Research, Design, and Manufacturing			•		
Total Quality Management			•		
Process Equipment					
Advanced Welding		•			
High-Speed Machining				•	
Integrated Circuit Fabrication and Test Equipment					•
Joining and Fastening Technologies		•			
Precision Bearings				•	
Precision Machining and Forming				•	
Robotics and Automated Equipment					•

SOURCE: Council on Competitiveness, 1991.

sufficiently study the close synergistic relationship between design and manufacturing (NRC, 1993).

As a result of these trends, the committee determined that there are at least three key factors contributing to manufacturing competitiveness and productivity. Lack of attention to any of these factors will be detrimental to competitiveness. They are

- development of process technologies (the subject of this report);
- investment in manufacturing facilities; and
- education and training of the work force.

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16

Resources In Unit Process Research And Education

A large number of research needs have been identified for the unit process families discussed in Part II and the enabling technologies discussed in Part III. This chapter first examines issues related to the availability and application of resources to fund the many opportunities for unit process R&D. It then discusses the evolving role of universities in unit process research.

RESOURCES FOR RESEARCH

Research in unit manufacturing processes is conducted by a wide range of private corporations, federal agencies, and universities. Several years ago, federal funding supported a little over 25 percent of industrial R&D spending in the general area of manufacturing.[1] For universities, federal funding supplies the majority of the support for manufacturing process research with a significantly smaller contribution coming from industry. The majority of the federal funding for university research is supplied by the National Science Foundation.

[1] The percentage of federal funding in industrial R&D varies greatly by industry. Almost 80 percent of R&D in aerospace was provided by the federal government in 1988. The federal government supported 40 percent in communications technology but less than 5 percent in scientific instruments (NSF, 1991).

INDUSTRIAL RESEARCH

Specific information on how much industrial R&D spending is allocated to manufacturing processes is difficult to directly determine and must be inferred from other data. In 1989, industrial R&D spending on manufacturing in general is estimated to have been $80 billion (Eagar, 1989). Because many studies have noted that two-thirds of U.S. R&D investments is spent on product R&D and only one-third is spent on process R&D, a rough estimate of total U.S. spending on manufacturing process R&D would be $25 billion in 1989. The committee estimates that the majority of process R&D expenditure is for process development, with a much smaller fraction allocated to basic research.

While the variety of technologies and applications involved in industrial research programs is impressive, two major areas for improvement are evident: improved sharing of technologies within an industry group and migrating basic knowledge from universities to industry. Of these two suggestions, the sharing of technology between companies is probably the more controversial and raises fears of antitrust violations. However, Japanese companies have clearly demonstrated that cooperation in research does not translate into lack of competition in the marketplace (Eagar, 1989). As a consequence, new research results from throughout the world are rapidly disseminated within Japan. Although the United States has the beginnings of industry-wide research cooperations in organizations such as the Electric Power Research Institute, the National Center for Manufacturing Science, and Sematech, it appears that industrial research funds could be spent more efficiently through wider involvement in collaborative research.

Federal Research Programs

Although a few state governments fund applied research in manufacturing, for instance, Industrial Technology Institute in Michigan, most government spending on manufacturing process research occurs in federal agencies. The old Federal Coordinating Council for Science, Engineering, and Technology had proposed an initiative in advanced manufacturing technology for fiscal year 1994. The initiative represented a total funding level of roughly $1.4 billion from eight different federal agencies. Most of these resources were not additional funds but a compilation of agency programs within standard categories. The agencies with the largest fiscal year 1994 budgets in advanced manufacturing technology were the Department of Defense ($596 million); the Department of Energy ($367 million), the Department of Commerce ($141 million), and the National Science Foundation ($118 million). In addition, the Department of Interior, the

Department of Agriculture, the Environmental Protection Agency, and the National Aeronautics and Space Administration contributed a combined $151 million.

The National Science and Technology Council has replaced the Federal Coordinating Council for Science, Engineering, and Technology. Since NSTC is presently chaired by President Clinton, it will provide more visibility to science and technology. NSTC intends to focus the programs toward specific national goals. Under NSTC, the Advanced Manufacturing Technology Program has incorporated the Advanced Materials and Processing Program, which had identified approximately $2 billion in agency funding (OSTP, 1993; NSF, 1993).

The major federal programs in manufacturing R&D are managed by a handful of agencies:

- Within the Department of Defense, various programs fund manufacturing research by contractors, such as the Manufacturing Technology Program and the independent R&D programs in the services, as well as various programs in the Advanced Research Projects Agency; in addition, relevant research is conducted by defense laboratories such as the Air Force Materials Laboratory, as well as by the Office of Naval Research and the Army Research Office.
- Within the Department of Energy, the national laboratories have allocated large sums for process research.
- Within the Department of Commerce, the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology conducts research on a broad range of specific manufacturing processes, as well as on manufacturing systems integration.
- The National Science Foundation supports academic research in manufacturing processes and related technologies through the engineering research centers and the Strategic Manufacturing Initiative and through programs in the Division of Design, Manufacture and Industrial Innovation; the Division of Civil and Mechanical Structures; the Division of Materials Research; and others.

Rather than attempting to present a comprehensive description of these activities, it may be more useful to describe briefly a few of the most important programs, although these could very well change as the NSTC becomes more involved in priority setting.

Department Of Defense

The Department of Defense has defined "technology for affordability" as one of the seven major thrusts in its Science and Technology Strategy (DDR&E, 1992). This thrust includes a plan to integrate the department's manufacturing technology program and its science and technology program, creating a new manufacturing science and technology program. Technology for affordability includes four basic areas: process technology, concurrent engineering, factory floor systems, and manufacturing functions above the factory floor. The following unit process R&D areas are being emphasized:

- manufacturing systems;
- composites fabrication and processing;
- precision machining and forming; and
- electronics manufacturing.

Each of the military services and the Defense Logistics Agency has a manufacturing technology program. The Navy's is illustrative. The objective of the program is to improve the productivity and responsiveness of defense contractors while reducing the cost of weapon systems. In addition to the individual projects performed by contractors and in Navy laboratories, depots, and shipyards, the Navy also funds four centers of excellence in manufacturing R&D:

- The National Center for Excellence in Metalworking Technology serves as a national resource for the development and dissemination of advanced metalworking technologies and processes.
- The Electronics Manufacturing Productivity Facility helps the electronics industry improve manufacturing processes, process controls, and materials.
- The Center for Excellence for Composites Manufacturing Technology provides a national resource for the development and dissemination of composites manufacturing technology, including detecting and repairing damage in composite structures.
- The Automated Manufacturing Research Facility, cosponsored by and currently implemented at National Institute of Standards and Technology, is a research test bed that supports development of industry standards for automated manufacturing, particularly for the integration of new process and control technologies into practical manufacturing systems.

National Institute Of Standards And Technology

The National Institute of Standards and Technology conducts basic and applied research in the physical sciences and engineering and does generic and precompetitive work on new and advanced technologies. Considerable R&D in many aspects of manufacturing processes, metrology, automation, and information systems is performed within the Materials Science and Engineering Laboratory and the Manufacturing Engineering Laboratory of the institute.

The Materials Science and Engineering Laboratory includes programs in intelligent processing of materials, machining of ceramics, and metallurgy. The Intelligent Processing of Materials program, for example, integrates in-process material property sensors with process models to establish real-time control of material evolution during processing. Currently, the processes of metal powder atomization and steel alloy processing are being investigated; in the future, injection molding of polymers and processing of ceramics will be investigated.

The Manufacturing Engineering Laboratory has programs in precision engineering, automated manufacturing, robotics, manufacturing data interface standards, and manufacturing technology transfer. These activities relate both to manufacturing systems and to unit process technologies. For instance, the Factory Automation Systems Division provides leadership in the development of standards and technology relating to information systems for manufacturing, especially manufacturing interface standards and product data exchange standards. The Precision Engineering Division's efforts are aimed at metrology and understanding the inherent limitations in process precision.

Department Of Energy

The Department of Energy national laboratories contain significant resources and activities for R&D in advanced manufacturing technologies. Currently, there are intensive efforts by Department of Energy laboratories to interact with industry at a variety of levels. One mechanism is Cooperative Research and Development Agreements, which involve contracts between private companies or consortia of companies and laboratories to develop and transfer specific technologies. Relevant technologies include manufacturing processes, such as materials processing, near-net shape processing of ceramics, advanced welding and joining techniques, diamond coating, and new investment casting processes, as well as materials such as structural polymers, polymeric and organic superconductors, structural ceramic-matrix composites, transportation materials, and ceramics.

Without question there is a remarkable collection of talent and facilities in the national laboratories. With the rapid reduction in nuclear weapons programs in recent years, there are two obvious alternatives for redirecting these resources. One is massive downsizing of some laboratories. The other is redirection of research to national needs, which would include manufacturing processes. The Cooperative Research and Development Agreement process is intended to direct the laboratories to projects important to industry. Other innovative approaches are needed to enable major sections of national laboratories to contribute to improving unit manufacturing processes.

National Science Foundation

The National Science Foundation currently has three principal programs under which research in unit processes is sponsored. First, engineering research centers are university-based, multidisciplinary centers designed to strengthen the linkages between engineering education and research in academia and the skill and technology needs of industry. Funding for the centers comes from a combination of National Science Foundation, industry, and state and local funds. Over 400 companies participate in the engineering research centers providing between 9 and 61 percent of total funding at individual engineering research centers. Since the program's inception in 1984, twenty-four centers have been started, three of which have been phased out. Of the twenty-one remaining centers, nine focus on manufacturing processes:

- Carnegie-Mellon University (engineering design);
- Georgia Institute of Technology (low-cost electronic packaging);
- Massachusetts Institute of Technology (biotechnology process engineering);
- North Carolina State University (advanced electronic materials processing);
- Ohio State University (net shape manufacturing);
- Purdue University (intelligent manufacturing systems);
- University of Florida, Gainesville (particle science and technology);
- University of Minnesota (interfacial engineering); and
- University of Wisconsin-Madison (plasma-aided manufacturing).

Second, the Division of Design, Manufacture, and Industrial Innovation of the Engineering Directorate supports academic research in the areas of manufacturing processes and equipment, design and integration engineering, and operations research and production systems. The emphasis is on research employing a blend of experimental, analytical, and computational efforts directed toward developing economically competitive technologies. Examples include methodologies for concurrent design and production of products with engineered microstructures and properties, innovative fabrication and assembly techniques, and integrated production systems. Research leading to the development of manufacturing machines, sensors and control technologies for computer control of manufacturing process, and operations research and systems methodologies is encouraged. Funding mechanisms include grants for single principal investigators and small groups of investigators with complementary skills. Collaboration with industry and national laboratories is also invited. To encourage appropriate teaming, the division conducts several special initiatives, an example of which is the Strategic Manufacturing Initiative.

The Strategic Manufacturing Initiative supports generic research that assists the U.S. manufacturing community in developing innovative and cost-effective manufacturing technology. The initiative focuses on systems and process issues in mechanical processing of materials and is limited to discrete parts manufacturing; specific areas of interest are precision machining and forming, composites manufacturing, and electronics packaging. The initiative supports research activities at an intermediate level, between the individual investigator and the engineering research center. Grants enable teams of three or more investigators to perform focused research in specific technology areas. Active participation of industry is a requirement of the initiative. Two rounds of awards from the Strategic Manufacturing Initiative have been made, in 1990-1991 and 1992-1993. Examples of initiative projects in unit process research include:

- solid, freeform fabrication of ceramics;
- research in ultraprecision machining;
- computer-integrated analysis of deformation processing;
- three-dimensional printing;
- microconstructive manufacturing;
- science base for drills and the drill grinding process;
- net shape manufacturing by plasma technology; and
- the role of grinding protocol in cam service life.

The final National Science Foundation program is the mechanics and materials program, which is supported by the Division of Mechanics and Structural Systems. This program is concerned with the modeling and simulation of thermomechanical aspects of materials processing.

National Center For Manufacturing Sciences

The National Center for Manufacturing Sciences is a nonprofit manufacturing research consortium of approximately 180 small, medium, and large manufacturing companies. The center has an annual budget of approximately $200 million and is financed by manufacturers, the federal government, and philanthropists. It conducts a broad range of production research and technology transfer activities in support of industry. The center focuses on the overlapping R&D concerns of its members and on matching complementary abilities of member firms to achieve workable new technology applications. The use of ductile iron as a substitute for structural steel in nonmoving parts of machine tools is an example of some of the center's work.

ROLE OF HIGHER EDUCATION IN UNIT MANUFACTURING PROCESSES

Overview

From the brief review of federal programs, it is clear that they support activities that range from establishing a basic understanding of material synthesis and processing, as is typical of the National Science Foundation, to developing processes required in specific focused programs, as in Department of Defense or Department of Energy weapons systems. Except for the National Science Foundation, the university involvement in other federal programs is limited but growing. As discussed in connection with industrial research, the coordination of federal research programs, other than the National Science Foundation, with industry and universities does not appear to be as well developed as in major competitor nations, Japan and Germany (see Chapter 17).

Of all the federal agencies, the National Science Foundation, through its prestige and funding, plays a dominant role in influencing research directions in manufacturing at the nation's universities. The agency currently spends about 12 to 15 percent of its budget in engineering and about 4 percent in manufacturing (this percentage has been constant since 1990). Since the fraction of the National Science Foundation's budget devoted to manufacturing is small, an increase in funding for manufacturing should be considered after taking into account the impact on the agency's overall budget. In any event, university research in manufacturing must be relevant to industrial needs and able to be implemented by industry.

The existing education programs related to unit process R&D may be found in mechanical, industrial, and materials (metallurgical) engineering departments. In some universities, a formal manufacturing department exists, however, in most cases manufacturing engineering is offered as an option in a broader department, for example in mechanical or industrial engineering, or as an interdisciplinary program. Compilations of the number of institutions with a manufacturing program may present a misleading picture of the academic effort in this area. For example, the *Directory of Manufacturing Education*, compiled by the Society of Manufacturing Engineers, lists 220 colleges and universities with undergraduate programs in manufacturing engineering or manufacturing engineering options (SME, 1992). At the graduate level, 108 institutions were identified. However, in 1992 only twenty undergraduate programs in manufacturing engineering and three masters programs had received accreditation.

The lack of accredited degree programs in manufacturing engineering may not be as serious a problem as the numbers might indicate. Many educators and prospective employers believe that an undergraduate degree in one of the mainstream engineering areas, such as electrical or mechanical engineering, followed by more-specialized graduate study is the most effective preparation for later work in manufacturing. For this reason, this committee places little emphasis on the number of degree programs with or without accreditation. More important issues in the committee's opinion are the need to support and train more engineers in manufacturing and the recruitment and support of faculty members with industrial experience.

Manufacturing has only become an acceptable topic for research and education at the nation's leading research universities within the past decade. In recent years, universities have begun to accept part of the responsibility for a decline in national competitiveness in manufacturing. This is illustrated by comments made in a recent article by the president of the Massachusetts Institute of Technology.

> Take, for example, the decline in the United States' ability to compete in the world marketplace for many manufactured goods. The reasons for this are complex, but a major issue has certainly been the attitude of industry and of engineering schools toward the design and manufacture of consumer products. If we are to compete in the international marketplace, we need to place a new emphasis on basic engineering for design and production. We must, of course, do so armed with the tools that engineering science has provided for analysis and simulation, but we must instill a respect for, and indeed a passion for, effective, efficient, and socially responsive design and production.

> In the process, we must recognize, teach, and participate in the development of the new techniques of lean production, total quality management, and continuous quality improvement. Beyond these buzzwords lies a core of important new concepts. We must expose our students to these concepts and to more teamwork, as well as educate them in the basic and applied sciences. We must prepare engineers who have the self-discipline, analytical skills, and problem-solving abilities, but who also are prepared to work and lead in the manufacturing sector. We need to educate students who combine the attention to precision, design and manufacturing that is often associated with German or Japanese engineers with the innovative and analytical skills that characterize American engineers. Vest, 1993

The committee supports this viewpoint and hopes it will be appreciated by the faculty committees who make appointment and promotion recommendations at U.S. universities. The perceived need for a greater involvement of academicians with industry is not new. In 1835, Andrew Ure wrote:

> The university man, preoccupied with theoretical formulae, of little practical bearing, is too apt to undervalue the science of the factory, though, with candor and patience, he would find it replete with useful application of the most beautiful dynamic and statistical problems. In physics, too, he would there see many theorems bearing golden fruit, which had been long barren in college ground. Ure, 1881

The committee strongly encourages closer university-industry cooperation. Several universities are actively pursuing such programs (Altan, 1993).

KEY RECOMMENDATIONS

- Government agencies involved in sponsoring R&D in manufacturing processes (e.g., National Science Foundation, Department of Defense, Department of Energy, and National Institute of Standards and Technology) together should carefully evaluate the kinds of manufacturing R&D being supported and the relative funding levels for defense and nondefense R&D. This evaluation could also examine the extent to which other leading industrial countries, notably Germany and Japan, have been effective in commercializing unit process technology, given their investment in research that is related to manufacturing, which is considerably higher (as a proportion of their gross domestic product) than that of the United States.

- The committee recommends that incentives be found and implemented to increase the number of students majoring in manufacturing-related technology at universities, so that sufficient trained personnel are available to exploit research opportunities in unit processes and to guide their industrial implementation. For example, the National Science Foundation could convene a study group to determine the appropriate educational incentives, in the context of expected technical opportunities, industry needs, and employment opportunities. One incentive that would quickly attract high caliber students would be an increase in the number of fellowships available to those specializing in manufacturing.

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17

International Experience

Unit processes are an important element in the R&D strategy of most of the nations who compete with the United States in manufacturing. For example, Japanese manufacturers devote about two-thirds of their R&D funding to process technologies, while United States manufacturers use one-third of their R&D funds for manufacturing process improvement (Hudson Institute, 1992). This chapter will discuss the R&D strategies of major competitor nations, the mechanism used to implement those strategies, and the corresponding influences on the status of unit process understanding.

The R&D strategies employed by major competitor nations are very different from those of the United States (Nelson, 1993). Japan and Germany,[1] in particular, foster industrial global competitiveness in their domestic industries with direct involvement of the government in the R&D process. This approach creates partnerships between government and industry, often coupled with a university relationship, that lead to the development of systematic product and process advancements and improved industrial competitiveness. In contrast, United States policy has been to fund generic, precompetitive R&D or program-specific R&D, as in a Department of Defense weapon system or a National Aeronautics and Space Administration program.

The problem has been compounded by a decline in R&D funding in recent years and a lack of culture that encourages university-industry cooperation. Most Japanese engineering faculty, like their American counterparts, do not have extensive industry experience. However, Japanese faculty participate in the activities of industry-sponsored meetings of professional societies, where engineers from industry and universities have a forum for communication and exchange of views. In Germany, nearly all engineering professors have ten to

[1] Germany is treated separately from the other European Community nations because of its large amount of unit process research.

fifteen years of industrial experience, a fact that greatly facilitates industry university communication and cooperation.

The Council on Competitiveness (1991) has noted that the 1989 expenditures for R&D of Japan, Germany, and the United States are comparable —3.0, 2.9, and 2.7 percent of gross domestic product, respectively; however, the nondefense portion of these expenditures is very different. Japanese R&D spending remains at 3.0 percent of gross domestic product, German R&D funding is reduced to 2.8 percent of gross domestic product, and U.S. expenditure drops to 1.9 percent of gross domestic product. These measures of nondefense R&D better reflect the amount of R&D investment with the greatest potential to impact commercial markets and suggest that both the Japanese and German programs are more likely to improve their commercial competitiveness than the U.S. R&D program. These data on total and nondefense R&D since 1970 are depicted in Figure 17-1.

The government-funded portion of each country's R&D budget varies from a low of 20 percent for Japan to 35 percent for Germany and nearly 50 percent for the United States. The portion of the R&D program funded by the government reflects the direction of technology policy of that government. Examination of the R&D agendas for the United States, Japan, and Germany reveals different priorities for each country. Figure 17-2 illustrates the distribution of government funding in several major application areas: defense, civil space, advancement of research (basic research); health; industrial

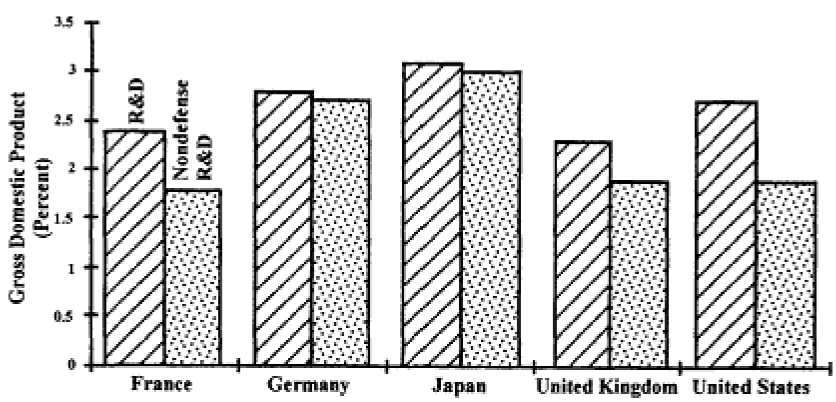

Figure 17-1 International comparison of percentage of gross domestic product.

development; energy; the combined group of agriculture, forestry, and fishing; and other.[2] Following the dominant defense-related R&D category, the U.S. agenda emphasizes the health area. Japan focuses on energy and advancement of research (nondirected fundamental R&D), while Germany has an equal emphasis on defense, advancement of research, and industrial development technologies.

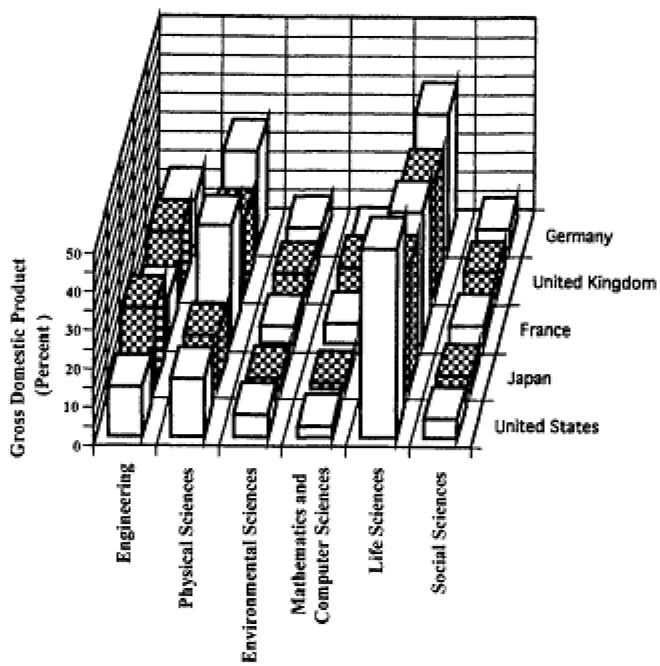

Figure 17-2 International comparison of governmental R&D budget priorities. Source: Manufacturing Subcouncil, 1993.

The emphasis of the general university funding for the United States, Japan, and Germany is shown in Figure 17-3. All of the countries emphasize the life sciences in general university funding. The Japanese also have strong support in engineering R&D, while Germany supports academic R&D in the physical sciences.

[2] General university funding by the individual governments is excluded from these data and will be discussed later.

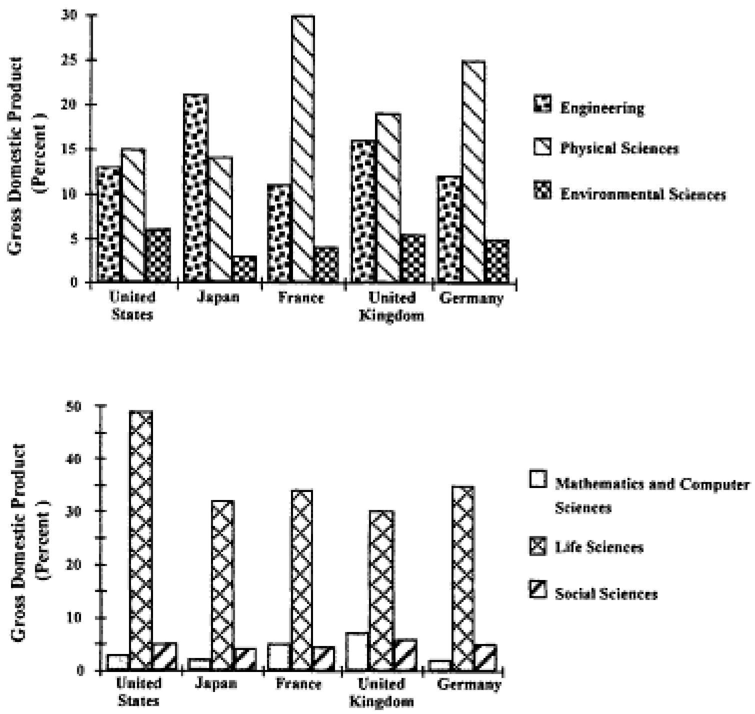

Figure 17-3 International comparison of university R&D priorities.

R&D IN GERMAN MANUFACTURING

Industrial success is a specific goal of German R&D policy. Industrial R&D is conducted through a network of R&D institutions and industry-based organizations that is designed to ensure the relevance of the results and rapid dissemination to industrial users. The system is structured to accommodate changes in industry needs, while providing in-depth technology for near-term solutions. The system of innovation focuses on incremental improvements to existing manufacturing processes of existing established markets such that products of higher quality result along with improved efficiency in the processes. The target markets and processes are usually related to traditional German industries and produce a short-term return on investment in the R&D project. Input from industry on technological needs defines the direction of the innovation system and the individual projects.

German engineering faculty is selected from industry. German engineering education emphasizes conducting individual projects prior to completing the Diplomingenieur degree (which corresponds to the Master of Science degree) and the associated Diplom project. In addition, every German engineering student must complete a six-month internship in industry. These traditions contribute to German universities' interest in conducting industrially relevant production engineering research.

The German technical innovation system is aided by a network of cooperative research groups who conduct projects and diffuse the research results. This network is especially important to small and medium-sized businesses, which benefit from the efficiency of the combined resources of the cooperative groups. These industry groups and trade associations directly influence the R&D agenda of the German government. This interaction is a specific requirement of the German technological policy and ensures that the R&D program addresses commercially relevant projects that will bolster German industrial competitiveness.

The key element of the German manufacturing R&D network is the Fraünhofer Society, a network of applied research institutes located throughout Germany. As a rule, a Fraünhofer institute is established near a major *technical university*. The institute's director is a professor who holds a chair at the university on the same topic as the institute, thereby avoiding major managerial problems and potential competition between the Fraünhofer institute and the university. The institutes conduct applied industrial contract research with facilities and personnel of the technical universities. The university locations stimulate interaction between industry and universities while introducing the industrial technological agenda to the students. The research is required to be industrially relevant, and there must be stated interest by industry groups. Research projects are performed under contract to industry, with the government providing some percentage of matching funds; additional funding is provided by local governments for institute infrastructure and long-term projects. The Fraünhofer institutes have full-time employees and also employ students half-time to work on industrial contract R&D. This scheme allows engineering students to work on industrially significant problems while they are still in college. It also allows German students, who do not have to pay any tuition and fees, to earn additional money toward their living expenses.

The Fraünhofer Society currently has more than 50 institutes throughout unified Germany that address the following manufacturing technologies:

- applied materials research (Bremen);
- automation and robotics (Stuttgart);
- computer integrated manufacturing (Stuttgart);

- computer simulation and graphics (Darmstadt);
- information technology (Karlsruhe);
- laser technology (Aachen);
- material handling (Dortmund);
- measurement and sensor technology (Freiburg);
- production equipment and design technology (Berlin);
- production technology (Aachen); and
- production technology transfer (Stuttgart).

It was of interest to the committee that these institutes address all of the enabling technology requirements of unit processes. This comprehensive group offers research results that can provide continuous incremental improvements to manufacturing processes.

R&D IN JAPANESE MANUFACTURING

As with the R&D strategy of Germany, the Japanese R&D strategy involves government funding leveraged with industrial resources to improve commercial manufacturing technologies. Industry is a key contributor in the development of government policies and programs and ensures that the programs are designed to benefit practical commercial applications. Several mechanisms are used to promote newly developed technology into the private sector, including R&D at the national research institutes, cooperative research projects, and economic incentives.

Japanese policy is predicated on the fact that technology development will be conducted by the private sector and that the government role will be to facilitate and support the industrial R&D agenda. Some government funding is used for long-range precompetitive R&D, as in the Exploratory Research for Advanced Technology program.

The national research institutes typically conduct programs funded by both the private sector and government, with the prime goals of transferring R&D results to industry and promoting economic competitiveness. The programs often include several institutes, consortia, and corporations, with open communication of the research findings.

These cooperative research programs involve approximately one-third of corporate R&D programs. While the government agencies do not directly participate or provide funding, they do serve as facilitators and help develop consensus within industry groups and consortia. This involvement helps focus the industrial R&D agenda on critical technology areas.

The technical rationale for these R&D programs consists of incremental problem solving that leads to product and process development gains for the targeted technology area. Since these targets are tied to specific commercial applications, the incremental benefits can be realized in short order, leading to continuous improvements in process and product. For example, in the development of advanced materials (e.g., high-performance ceramics and composites), integrated teams of material suppliers, fabricators, and users investigate innovative processes (e.g., combustion synthesis, gas pressure combustion sintering) and consider the development of advanced manufacturing equipment needed to produce these high-performance materials (Rogers, 1991). Most of the process development in Japan is empirical, with limited use of process modeling. Additional process-related areas in the Japanese R&D agenda include metallic and inorganic process technologies, design and simulation technologies, photoreactive process technology, and processing technologies for extreme environments (Dertosis, 1988; Council on Competitiveness, 1991).

R&D IN EUROPEAN MANUFACTURING

Since 1984 the evolution of the European Community has included several R&D programs known as "frameworks." The most recent framework is scheduled for the 1990-1994 period and consists of several major programs that address manufacturing technologies. The Basic Research in Industrial Technology for Europe (BRITE) efforts and their supporting European Research on Advanced Materials (EURAM) have the objective to make European manufacturing industries more competitive in world markets. This BRITE/EURAM program promotes collaboration between industrial firms, universities, and other research centers. Small and medium-sized enterprises are prime participants in the program. The technical objectives of the program are to improve both manufactured products and manufacturing processes and transfer the resulting technology to the European industrial base. The specific technical areas of the BRITE/EURAM program are

- development of advanced materials and the processes for commercial production;
- creation of design methodology and assurance procedures for products and processes;
- identification and improvement of the technology needs of the manufacturing industry; and
- development and application of advanced technologies and processes for manufacturing.

The program teams consist of industrial, university, and research institute partners. The industry is expected to have a related manufacturing need and means to apply and demonstrate the R&D results. Full funding is provided for the university and institute partners, and the European Community provides 50 percent of the funds of the industrial partners. Each project is funded at a minimum effort of 10 person-years for a period of two to four years. The current program contains efforts that address emerging materials and the process for their production; a wide variety of unique unit processes, including modeling and simulation; and methodology and instrumentation for process and product quality. All of the enabling technologies described in Part III are being developed in the BRITE/EURAM program.

A second program, European Advanced Technology Programme (EUREKA), also is intended to strengthen the European competitive position by developing products and processes with near-term commercial value. The program involves partners from both industry and the R&D community (i.e., universities and institutes) and includes financial commitments from team members. Several manufacturing technology areas are covered: laser processing, new materials, robotics, and production automation.

CONCLUSIONS

Several observations relevant to manufacturing R&D and unit process R&D are gathered from the preceding overview of international R&D trends:

- The U.S. nondefense R&D funding is a lower fraction of gross domestic product than that of Japan or Germany;
- The U.S. government portion of this funding provides little support to manufacturing R&D, while the Japanese R&D plan stresses engineering and the German R&D strategy targets industrial development projects, both addressing the technologies of manufacturing. For example, in the past the National Science Foundation has spent approximately 12 to 15 percent of its budget on engineering and approximately 4 percent on manufacturing or production research. The corresponding numbers in Germany, for example, were estimated to be 30 percent for engineering and 15 percent for production engineering.[3]

[3] The estimates are from a private communication with Professor Hans Toenshoff, in 1992, when he was the assistant director of Germany's DFG-Duetsche Forschungsgemeinschaft, which is equivalent to our National Science Foundation.

The committee concludes the following from the review of the R&D agenda of the major industrial competitors to the United States:

- Industry and industry groups are very involved in establishing the R&D agenda and providing technical direction for respective federal agencies.
- R&D projects are conducted by teams consisting of industry, universities, independent R&D institutes, and government laboratories.
- R&D projects are established with clear application to commercial products.
- Long-term, precompetitive R&D projects are conducted by government research facilities to benefit the industrial base. In addition, a portion of the R&D projects are devoted to incremental improvements for near-term implementations.
- Industrial funding is leveraged with federal funding.

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BIOGRAPHICAL INFORMATION

UNIT MANUFACTURING PROCESS RESEARCH COMMITTEE

IAIN FINNIE received his B.Sc. from the University of Glasgow in 1949 and a D.Sc. in 1974. He also received his doctorate in mechanical engineering in 1953 from the Massachusetts Institute of Technology. His research interests are in mechanical behavior of engineering materials, especially creep; wear; and fracture, design, and failure analyses. He is a member of the National Academy of Engineering and an Honorary Member of the American Society of Mechanical Engineers. He serves as professor emeritus of Mechanical Engineering, University of California, Berkeley.

TAYLAN ALTAN received a diploma in engineering from Tech. University, Hannover, Federal Republic of Germany in 1962; an M.S. in mechanical engineering from the University of California, Berkeley, in 1964; and a Ph.D. in mechanical engineering in 1966 from the University of California, Berkeley. His research interests include metal forming, die/mold manufacturing process, and modeling. He has co-authored three books and contributed over 200 articles to professional journals. He is a fellow of ASM International, American Society of Mechanical Engineers, and the Society of Manufacturing Engineers. He is also one of the United States active members of CIRP (Institution for Production Engineering Research). He presently is professor and director, Engineering Research Center for Net Shape Manufacturing, The Ohio State University.

DAVID A. DORNFELD received his B.S., M.S., and Ph.D. in mechanical engineering from the University of Wisconsin-Madison. His background includes teaching at University of Wisconsin-Milwaukee in the systems-design department, and Directer de Recherche Associe, Ecole Nationale Superieure des Mines de Paris. His research interests are in sensors and precision manufacturing. He is presently professor of manufacturing engineering and director, Engineering Systems Research Center at the University of California, Berkeley, where he has been since 1983.

THOMAS W. EAGAR received his S.B., and his Sc.D. in Metallurgy from the Massachusetts Institute of Technology. His interests are in materials processing and manufacturing with special interests in welding and joining of metals, ceramics and electronic materials, deformation processing, alternate manufacturing processes, selection of materials, and failure analysis. His has worked with the Homer Research Laboratories of Bethlehem Steel Corporation, and is now POSCO Professor of Materials Engineering and co-director of the Leaders for Manufacturing Program at Massachusetts Institute of Technology.

RANDALL M. GERMAN received his B.S. in materials science and engineering from San Jose State University in 1968; M.S. in metallurgy engineering from The Ohio State University in 1971; and Ph.D. in materials science from the University of California, Davis 1975. His research and teaching focus is on particulate materials processing. The research applications include high-temperature composites, tungsten heavy alloys, intermetallic compounds, ferrous structural components, electronic ceramics, and cemented carbides. He currently is the Brush Chair Professor in Materials with the Engineering Science and Mechanics Department, Pennsylvania State University, University Park, Pennsylvania.

MARSHALL G. JONES received an A.A.S. in mechanical engineering technology from Mohawk Valley Community College in 1961, B.S. from the University of Michigan in 1965, and M.S. and Ph.D. in mechanical engineering from the University of Massachusetts in 1972 and 1974. His interests are in mechanics of laser and material processing of material removal, welding, and heat treating, and in heat transfer as related to laser bean-material interaction. His current research focus is in laser fiber-optic integration for factory automation and processing for electronic packaging. He is presently senior research engineer and project leader, Research and Development Center, General Electric.

RICHARD L. KEGG received his B.S., M.S., and Ph.D. in mechanical engineering from the University of Cincinnati. His research interests are in machine tools, plastics machinery, grinding wheels, cutting tools, and manufacturing processes. He is presently director of technology and manufacturing development, Cincinnati Milacron, Inc.

HOWARD A. KUHN is Vice President and Chief Technical Officer at Concurrent Technologies Corporation. He received his B.S. in 1962 and Ph.D. in 1966 from Carnegie-Mellon University in mechanical engineering. Dr Kuhn previously was professor of Materials Science and Engineering and professor of Mechanical Engineering at Drexel University and at the University of Pittsburgh, conducting research, teaching and consulting in metalworking processes, powder metallurgy and failure of materials.

RICHARD P. LINDSAY received his B.S. from Northeastern University, M.S. from the Massachusetts Institute of Technology, and Ph.D. from Worcester Polytechnic Institute in mechanical engineering. His research interests are in metal and ceramic grinding. He is a consultant for Contemporary Technologies, having retired from Norton Company in August 1994.

CAROLYN W. MEYERS received her B.S in 1968 from Howard University in mechanical engineering. She received her M.S. in 1979 and her Ph.D. in materials in 1984 from the Georgia Institute of Technology. Her interests are in structure-property relationships of materials, microstructural characterization, solution heat treatment kinetics, and micromechanisms of wear. She has had numerous awards and honors: in 1986 she was awarded the Ralph A. Teetor Educational Award from the Society of Automotive Engineers; in 1988 she was presented the Presidential Young Investigator Award from the National Sciences Foundation (first black woman to receive this award); in 1990 she was named Black Engineer of the Year, Promotion of Higher Education Council of Engineering Deans of Historically Black Colleges and Universities and U.S. Black Engineer Magazine. She is presently associate professor, The George W. Woodruff Scholl of Mechanical Engineering and associate dean for research and interdisciplinary programs for the College of Engineering, Georgia Institute of Technology.

ROBERT D. PEHLKE received his B.S. in engineering from the University of Michigan (1955), S.M. (1958), and Sc.D. (1960) from the Massachusetts Institute of Technology. He also performed postgraduate work at the institute. He was a researcher at the Technical Institute, Aachen, Germany, from 1956 to 1957. His interests are in broad range of metallurgical and materials topics, with an emphasis on high-temperature physical chemistry of materials systems, iron and steelmaking, metal casting, and materials process modeling. He has authored, co-authored, or edited 11 books and has contributed over 260 publications to technical and professional journals. He is presently professor, materials science and engineering, College of Engineering, The University of Michigan, Ann Arbor.

S. RAMALINGAM received his B.T. from Indiana Institute of Technology, Kharagpur, India (1952-1956), M.S. in 1961, and his Ph.D. in 1967 in mechanical engineering from the University of Illinois, Urbana. His research interests focus on sensor and sensor systems for manufacturing automation and real-time process control; machining theory, plasticity and modeling materials processing; computer-aided manufacture; friction and wear modeling; coatings for friction and wear control; physical vapor deposition random and steered arc technology; surface modification for improved tribological performance; wear and erosion modeling; technology and industrial policy; and power electronics applications for advanced manufacturing systems. He is presently professor, Department of Mechanical Engineering, University of Minnesota and director, The Productivity Center, University of Minnesota.

OWEN RICHMOND received his B.S. in general engineering in 1949 from Bradley University, Peoria; M.S. degree in structural engineering from the University of Illinois, Urbana in 1950; and a Ph.D. in engineering mechanics in 1959 from Pennsylvania State University, University Park. His research interests are metallurgy, elasticity, and plasticity; theory and basic testing of mechanical behavior of metals and polymers; application of theory of plasticity and viscoplasticity to metal casting and forming processes and to materials analysis and design; and the theory of flow and failure of granular and porous materials including applications to bulk materials handling and mining. He is presently corporate fellow, ALCOA Technical Center.

KUO K. WANG received his B.S. in 1947 from National Central University, Nanking, China, in engineering, his M.S. in 1962, and his Ph.D. in 1968 from the University of Wisconsin-Madison. His research interests include materials processing, numerical control, computer-aided manufacturing systems, and engineering. He is presently a Sibley College Professor of Mechanical Engineering, Sibley School of Mechanical & Aerospace Engineering, Cornell University.