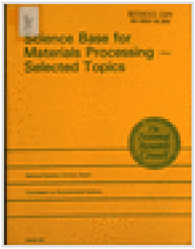

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The report presents the highlights of a workshop on four selected topics, namely, high-speed metal removal, metal deformation processing, advanced composites, and high-modulus polymers. The objectives of the workshop were to identify areas of materials processing that could benefit from an improved science base, to define scientific information to be obtained for each process to achieve technological and economic improvements, and to explore institutional problems that must be overcome to achieve greater academic participation in processing science and more effective industry-university interaction.

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SCIENCE BASE FOR MATERIALS PROCESSING-- SELECTED TOPICS

Report of the

Committee on Science Base for Materials Processing

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

Publication NMAB-355
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1979

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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 competences and with regard to 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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PREFACE

Concern that advances in materials processing were being impeded by an inadequate foundation in science led the Department of Defense (DoD), under the stimulus of the Air Force, to request that the National Materials Advisory Board (NMAB) organize a committee for the purpose of convening a workshop to examine the matter. This workshop, Science Base for Materials Processing, was held September 27 and 28, 1978, at the Battelle Columbus Laboratories, Columbus, Ohio.

The objective of the workshop was to assemble knowledgeable people from industry, universities, and government to:

- identify areas of materials processing where an improved science base* could be expected to have a major beneficial impact on processing technology or processing economics;
- define the scientific information that must be obtained for each process to achieve the anticipated technological and economic improvements; and
- explore the institutional problems that must be overcome to achieve greater academic participation in processing science and to develop long-lasting procedures for effective industry-university interaction.

At the suggestion of the Department of Defense, the workshop was limited to four topics, namely, high-speed metal removal, metal deformation processing, advanced composites, and high-modulus polymers. The selection in no way implied lack of interest in other material processing topics, such as powder metallurgy, hot isostatic pressing, explosive forming, or, for that matter, in other materials, such as ceramics and glasses. It was hoped that, by limiting the areas for consideration, it would be possible for the workshop to be small enough to allow good interaction and to achieve a more specific, in-depth coverage of each of the four selected topics.

* The term science base is used here to mean systematic inquiry with a foundation in scientific principles as opposed to the empirical, trial-and-error methods that have dominated materials processing in the past.

The workshop format consisted of a plenary session with three keynote talks, followed by separate meetings of four separate panels charged with investigating the four selected topics. At each of the four panel meetings, the status, problems, and prospects in the respective areas were discussed by a group of experts, who included personnel from industry, academia, government, and not-for-profit institutions.

This report presents the highlights of the workshop: an introduction, a summary, the three keynote lectures, and the reports of the four panels. Since the issues concerning institutional barriers and industry-university cooperation to some extent apply to all four areas, the discussion of these issues has been included in a separate chapter following the four panel reports. Appendix I is a copy of the workshop announcement; Appendix II, a list of participants; Appendix III, working group reports on metal deformation processing.

The principal authors of the various sections of the report are identified in the body of the report. Special mention should be made of Dr. George E. Dieter, Jr., who chaired the Workshop Subcommittee; Dr. Thor L. Smith, who chaired the Report Subcommittee; and Dr. Harold Gegel, whose incisive analysis and far-reaching vision provided stimulus and focus for the committee and the workshop.

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INTRODUCTION

Harold L. Gegel

Reducing the impact of inflation and coping with ever-changing international supply and demand situations have become top-priority problems throughout the Department of Defense (DoD) and U.S. industry.

A whole set of problems--energy, raw materials shortages, global inflation, etc.--has been emerging. These problems threaten our economic system and reduce our national defense dollar. Specific objectives relating to these problems have been developed within DoD. They include reduction of acquisition costs and lowering the life-cycle costs, and, at the same time, increasing reliability and durability of the products in the DoD inventory. These objectives are being stressed on current and future military systems, which will continue to demand more attention as desired performance increases.

Production and manufacturing functions may offer the best chances for meeting these objectives. A new concept of productivity must be developed that will offset cost growth of defense systems in order that we can effect an acceptable compromise between performance capabilities and quantities of systems. This requires that the United States invest in research and development (R&D) for improvements in productivity and advances in technology for the future as well as for solving today's near-term problems. DoD-related industries are suffering from reduced production efficiency caused by fewer orders, lagging production schedules, and increases in inflation so that costs exceed original estimates. The cost tradeoffs that relate to the acquisition costs of each part of a defense system are of growing significance.

U.S. industry is now in the same economic box as DoD. Innovations must be sought that are functionally broadening and reduce the cost of the manufactured product. General concepts are available for developing a functionally broadening approach to design and manufacturing; however, these methodologies have not received the formal recognition that they should have. Certainly, they have not been practiced as a systematic, scientific technology. Computer-Aided Design and Manufacturing (CAD/CAM), for example, falls into this category. Its potential advantages are only now being appreciated, because the optimal practice and application are more readily acceptable when increasing problems of cost growth exist. New textbooks and monographs to teach the concepts of advanced manufacturing technology must be written for universities and for the continuing education of engineers and managers, and they should be made available at affordable prices.

There is no single area of manufacturing and education that will by itself significantly change the cost growth of new technology. Changes must occur in management, in systems design, in manufacturing methods, and in engineering and management education if we are to systematically alter the cost growth rate in our current economic environment.

Recent analyses of the science base for materials processing have shown that there are major gaps when it is evaluated from the viewpoint of definable needs. This gap is due in part to the tenuous rapport between universities and industries and to institutional barriers that exist in many American universities. Some of these barriers arise in part from the way support for interdisciplinary R&D is viewed by such government agencies as the National Science Foundation (NSF) and by peer groups that evaluate the interdisciplinary proposals. Thus, there is a need for increased governmental support of R&D and for improved relations between industry, universities, and government to ensure that it will be effective.

A number of barriers exist that prevent the implementation of a national program to achieve improvements in productivity, and there are serious deficiencies in government-industry relations. The deficiencies concern identifying national materials goals and priorities; determining the types of materials and processes R&D programs needed to sustain a healthy economy; and creating an atmosphere conducive to the effective transfer of materials technology between government and industry.

The key to the success of R&D aimed at improvements in productivity and advances in technology is the careful definition of goals plus strong industry-university participation, and the presence of at least one strong leader--a person who is capable of serving as the interdisciplinary bridge between research and development in a vertical sense. Such leadership may be difficult to find in universities because of their institutional barriers, and even when it exists in industry it may not be available to direct these interdisciplinary efforts.

The purpose of this workshop was to identify the gaps in the science base; to establish the criticality of need, breadth of application, and cost benefit; and, whenever possible, to identify specific impact areas and possible payoffs. The background for the workshop was set by three keynote speakers, covering the status of processing research in the United States and Europe, institutional barriers to interdisciplinary R&D, and an example of a basic research program in processing that typifies interdisciplinary R&D. The need for cooperative R&D efforts between academia, industry, and government was presented. It was clearly recognized that, although the workshop focused on increasing the flexibility of manufacturing at the process level, this is not the only place where improvements in productivity can be made. However, it was recognized that transforming processing from an experience-based technology to a knowledge-based technology can achieve great cost benefits, can conserve energy and materials, and can have economic impact on a large sector of the U.S. industrial base. It follows too that the strength of our national defense is no stronger than the perceived strength of our industrial base.

Investment in this type of R&D by both industry and government can enhance the long-term economic growth of the United States, which is now lagging, and it will be an effective inhibitor of the growth of acquisition and maintenance costs of American manufactured products. Fundamentally, we are dealing with the problems of scrap minimization and product durability. Scrap saved in manufacturing can be equated with energy conserved, and durability can be equated with defect avoidance and with property/microstructure control. Each of these benefits and possibly more can be achieved by raising manufacturing at the process level to a new paradigm of capability.

SUMMARY

Francis L. VerSnyder
and
Serge Gratch

General Conclusions

All four panels concluded that significant advances could be achieved in the processing of most materials by more thoroughly extending and applying the science base. Large potential payoffs were identified in terms of increased productivity, reduced costs, improved properties, better shape and dimensional control, etc., both for military and civilian applications.

Some examples of applications with major potential payoffs are:

- the development of components with multiple properties and microstructure within the same part, as illustrated by the dual microstructure (with accompanying dual property) compressor disc described in a subsequent section;
- the potentially dramatic increase in productivity and reduction in manufacturing costs that could result from high-speed machining (specific examples are given in the section on High-Speed Metal Removal);
- the significant increase in productivity, reduction in cost, and improvement in physical properties that has been demonstrated to be possible with high-pressure metal forming;
- improved materials and processes for the fabrication of advanced composites that may reduce costs and at the same time improve properties of these promising lightweight materials; and
- in the very long range, the development of practical high-modulus, high-strength, and high-softening-point polymers in shapes and for applications much broader than the currently available high-modulus aramid fibers.

Although progress is being made in these and many other materials processing areas, it was the consensus of workshop participants that progress could be greatly accelerated by more extensive use of science to complement the empiricism currently used for process development. It was the general consensus that the main barriers to more extensive utilization of science in this connection include the low regard in which processing research is held in academic circles, the lack of communication between practitioners of materials processing and researchers, and the inadequate funding available for scientific research in this area. The workshop participants recommended that means be found to strengthen the science base in many specific areas, as discussed later in this report. The consensus was that the first step to achieve this goal is to find means for drastically increasing available funding. As long as the additional funds are channeled wisely, it was generally thought that the increase in funding would of itself greatly increase the respectability of research on materials processing and at the same time would provide the incentives for greater industry-university interaction. Specific observations, conclusions, and recommendations of the individual panels are summarized below.

High-Speed Metal Removal

The problems associated with the ultimate commercial implementation of high-speed machining are complex and demand an interdisciplinary management and applications approach. The four highest priorities for research are: extension of the data base on aluminum, steel, and titanium to higher speed; cutting mechanisms and related phenomena; modeling tool degradation and failure mechanisms, lubrication, and real-time sensing techniques; and improved machine-tool systems.

The panel evaluated the scientific base for high-speed metal removal (machining and grinding), outlined the additional scientific base required to implement on a cost-effective basis high-speed metal removal, and reached the following conclusions and recommendations.

1. High-speed machining in the range of 5,000-15,000 sfm (surface feet per minute) on aluminum alloys has been demonstrated successfully in production environments. However, inconsistencies in the preliminary data due to variations in tool geometry and other factors indicate that further studies are warranted. Specifically, work on aluminum alloys should be extended to a cutting speed of 30,000 sfm to verify anticipated favorable trends with respect to metal removal efficiency, tool forces, tool life, and workpiece quality. Throughout this endeavor, emphasis should be placed on establishing if such trends are associated with a change in chip segmentation mechanism occuring above a critical cutting velocity. Additional studies on titanium, nickel, and ferrous alloys also are required to

determine whether similar beneficial effects exist for these materials as well.

2. With the exception of tool wear, conventional metal removal processes are comparatively well understood. Above 5000 sfm, however, little is known about chip segmentation, tool wear, and other parameters that play major roles in controlling process economics. In order to achieve substantial increases in productivity, the influence of these factors on metal removal efficiency must be sufficiently well understood and modeled so that systematic approaches can be applied effectively in a production environment. Future investigations of cutting mechanisms and related phenomena should, at the very least, address workpiece deformation and fracture behavior, chip segmentation, tool wear, interface reactions, and temperature, resonance, and shock wave propagation effects.

3. Knowledge of tool wear and tribology is limited to conventional metal removal rates. These aspects of the cutting process will most likely impose major barriers to the commercial implementation of high-speed machining technology. Definition and modeling of tool degradation and failure mechanisms as functions of tool geometry, thermal history, and tool and workpiece materials properties, and the chemistry and lubrication characteristics of cutting fluids are required. In addition, on-line, real-time sensing techniques for monitoring tool forces and cutter wear must be developed to avoid damage to tools and parts.

4. Preliminary design concepts for high-speed machining centers now exist. However, funding to examine alternate system and subsystem approaches is needed to ensure the timely and successful implementation of the process technology generated from research and development efforts. High-speed machining programs will require new spindle systems, control networks, coolant and lubrication systems, high-speed tool changers, and automatic parts and materials handling equipment.

5. The problems associated with the ultimate commercial implementation of high-speed machining are complex and interactive, and they span a wide range of technical fields. In all probability, an interdisciplinary systems approach to technology management and application will be required to achieve specific research and development objectives. Needed scientific disciplines include metallurgy and materials science, theoretical and

applied mechanics, physics, machine design, control theory, computer programming, and others.

6. High-speed machining research and development and process implementation goals can be achieved through a cooperative effort involving industry, university, and government participation. Furthermore, sufficient long-term funding should be allocated to the overall program to ensure completion of individual tasks and to maintain a high level of interest and activity by supportive organizations. How such an effort may be stimulated and funded is not entirely clear at present and is in need of further study. However, several suggestions emanating from panel discussion included establishing national high-speed machining centers to conduct basic experimental studies and an industry-university metal removal advisory board to assist in the planning, guidance, and implementation of such work. The construction and operation of such a facility would be derived from governmental and industrial funding in which the latter could be written off by participating companies in the form of tax credits. University participation might possibly be encouraged by governmental support of graduate students pursuing careers in the area of high-speed machining, and assurance that individual professors receive publication privileges and recognition (i.e., advancement toward tenure) by their respective universities for directing such studies.

Metal Deformation Processing

This panel identified the processes that would most benefit from an improved science base and specified the scientific areas needed for advances in deformation processing. Since metal deformation processing involves a multitude of physical phenomena in a complex interaction between the workpiece material and processing hardware, it was useful to divide the topic into functional areas of mathematical modeling, material behavior, and tribology.

Fundamental to many aspects of the subject matter considered in this, as well as most of the areas covered in the workshops, were the basic science areas of surfaces, interfaces, and wear. In most processing technologies, critical problems involve surface phenomena of some sort. Wear (abrasive and adhesive) was found to be an important mechanism by which useful objects are shaped or formed and also ultimately lose their usefulness. In recent years, a new era has been born for the surface scientist, due largely to advances in instrumentation. Fundamental studies using these new techniques applied to processing problems should be exploited to add to the science base for materials processing.

The section on metal deformation processing illustrates the limitations of current approaches in the cases of several common processes such as forging, controlled rolling, sheet metal forming, and high pressure forming. The requirements for improvements in the science base were identified for these and other processes. Highest priority was given to deformation modeling techniques, development of constitutive equations, and mathematical and physical modeling of interface friction.

Advanced Composites

Compared with metals processing, processing of advanced composite materials is in its infancy and therefore, as could be expected, a large number of problem areas and programs to solve them were identified by the working group. The four highest priority categories of science programs to be addressed are raw material variability at the start of the processing cycle; scatter of physical property data needed for modeling processes; relationships between microstrucure, processing, and properties; and modeling and control of fiber dispersion and orientation in molding.

The panel evaluated the scientific basis for processing advanced composites with polymeric matrices. The panel discussed the basic science that underlies these processes in an attempt to pinpoint those areas where increased knowledge will have the greatest influence in improving the properties, decreasing the costs by confronting the factors that increase costs, and improving the reproducibility of composite structures and the reliability of systems.

In the development of composite hardware, the designer is concerned not only with raw material forms and the distribution and orientation of the reinforcing fibers in the polymeric matrices, but also with the complex interaction between materials selection, design configuration development, analysis, manufacturing technologies, joining methods, nondestructive evaluation, etc. Areas of investigation recommended by the panel cover a number of these important considerations. Specifically, problems and recommended science base programs or research needs were prepared by the panel in each of the following areas:

- Raw material variability at start of processing cycle
- Scatter of physical property data needed for modeling processes
- Relationships between microstructure, processing, and properties
- Modeling and control of fiber dispersion and orientation in molding

- Material forms required for high-speed processes
- Rapid curing techniques (thermosets)
- Rapid curing and fabrication techniques related to thermoplastics
- Automated fabrication of thermosetting resin composites
- Automated fabrication of thermoplastic resin composites
- Thick laminate processing
- On-line process control methodology
- Process-flaws-failure interaction
- Fiber degradation
- Tooling for composites
- Bagging for tool closure
- Joining of composites
- Machining of composites.

High-Modulus Polymers

The key objective is to establish a sound science base for the development of nonreinforced high-modulus polymers that might find applications in much the same areas where fiber-reinforced materials are now used. The two recommendations given highest priority were that additional strong support be given for basic research on the solidification of anisotropic fluid systems and for developing the processing science to produce items other than fiber, such as membranes, foams, and sealants.

The panel agreed that a fundamental understanding of the following six items would provide the necessary science base:

- the structure of the state of anisotropic fluid systems, whether this anisotropy arises from the inherent properties of the molecule, from the imposed flow, or by other means;
- the rheology of the anisotropic fluid systems state, and the effect of type and rate of deformation upon the molecular order;
- the solidification of anisotropic fluid in both the dynamic and quiescent states;
- the chemical, physical, and microstructural changes that occur during post-solidification processing, e.g., heat treatment and drawing;
- the microstructure of the product, the processing condition that influences it, the means of measuring it, and its relation to molecular and physical properties; and
- the molecular and supermolecular design required for optimizing processing and ultimate properties.

Implementation

Throughout the workshop sessions as well as the subsequent committee meeting, the urgent need of an action plan was acutely recognized. As can be seen from the detailed panel reports, the needs are clear and have been known for some time; similarly, the panel's recommendations are not new. The key issue is, What can be done differently so that these needs of vital national concern will be met without further delay?

It was generally agreed that the key to the solution is a substantial increase in funding. This funding should be well publicized and should be given enough emphasis in the budgets of the appropriate federal agencies to ensure reasonable permanence. One cannot expect leading faculty to enter the field of material processing if there is no assurance that funding will continue to be available for a number of years. Plans should be made so that recipients of grants or contracts can count on continued support for many years.

Better coordination should be developed between the numerous agencies -- NSF, DoD, DoE, DoT, etc. -- that have a natural interest and would benefit from increased research and development in material processing and related areas. The long-range needs probably should be addressed by a national study of material processing and manufacturing in the context of the national productivity problem. But action should start <u>now</u>, without waiting for further study. The workshop has pointed out the importance of this undertaking and its urgent need; furthermore, it has identified certain specific projects that would be of great, immediate benefit. Joint university-industry research and development in these areas should be funded by the affected federal agencies without further delay.

The workshop concluded that the next most important requirement, after funding, is the development of an effective mechanism for coupling the universities with the industrial activities. The obstacles to the development of effective cooperation are discussed in greater detail in one of the keynote talks, and the conclusions reached by the workshop are summarized in the last chapter of this report. The broad area is important enough to deserve the attention of a national study, which would examine both the potential incentives, such as tax credits and federal funding, desirable to achieve effective industry-university interaction, and the current disincentives, such as certain provisions of the antitrust laws. However, some constructive action must be taken without delay, without waiting for such a study. Even though the workshop recognized the difficulty of the task and was aware that past efforts in this country have not been fully effective in a completely self-sustaining mode, nevertheless the consensus was that the need is too pressing to wait until further studies identify the optimal coupling mechanism.

Certain promising approaches are now being implemented in other research areas, and similar arrangements should be exploited in the area of materials processing. A suggested approach is discussed in the final chapter of this report, on industry-university interaction. This and other promising approaches should be implemented as soon as possible.

The body of the report recommends priorities of different projects within each of the four areas covered in the workshop. No priority is given among the four areas. This is deliberate: even though some areas (e.g., high-speed machining) have the potential of much quicker payoff than others (e.g., high-modulus polymers), it would be a mistake to concentrate on one rather than the other. In all cases, it may be expected that a long time will elapse between the establishment of the science base and its exploitation in commercial processes. Adequate effort must be provided now for the longer-range applications in order to avoid the past deficiencies that force most of the current processes to be based on empirical development.

STATUS OF PROCESSING SCIENCE RESEARCH IN THE UNITED STATES AND EUROPE

Harris Burte

Air Force Materials Laboratory
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Processing Science

A convenient way to define and illustrate processing science in the broader context of materials science could start with the conceptual framework suggested by Buessem[1] to describe ceramic science which can be modified and used for any area of materials science and technology.[2] [3] Its application to titanium welding is illustrated in Table 1. The engineering art of welding normally attempts to correlate preparation or processing conditions (including composition of input materials), with commonly measured properties. Processing conditions are modified until desired or satisfactory properties are attained. The first step in converting this art to a science involves inserting knowledge of the materials structure between processing conditions and properties. Physical metallurgy, polymer physics, etc. are, of course, the areas of materials science concerned with elucidating relationships between structure and property. Next, the definition of what properties to measure for the purpose of initial engineering design or to predict performance during actual service should be based on more than long experience or intuition. The expanding development and use of the science of fracture mechanics is a good example of such activity. Finally, given knowledge of which structures can yield properties appropriate for the intended uses, the goal of processing is to synthesize this structure. (The term synthesis, although more familiar to the chemist dealing with polymeric materials than to the metallurgist or ceramist, is quite appropriate for all materials.) Processing research is, in part, concerned with how to do this and can thus be differentiated from the other areas of materials science which involve relationships between structure and properties, or properties and use.

In a more general sense the goals of processing are:

- to achieve the desired geometry (size, shape, and tolerance) of a part or component with adequate defect control;
- to develop a controlled microstructure to yield the desired properties and in-service performance; and

Table 1. The science of welding titanium (illustrative rather than all-inclusive)

Processing (synthesis) ↔	Structure ↔	Properties ↔	Use
Gas tungsten arc welding (GTAW)	Inclusion type and morphology	Yield strength	Wing box
Plasma arc welding (PAW)		Bend radius	Spars, ribs
Electron beam welding (EBW)	Amount of beta phase	Hardness	Landing gear
Pulsed current	Alpha platelet size	Ultimate strength	Turbine discs
Preheat	Grain size		Tubing
Post heat	Dislocation content	Fracture toughness	Heat exchangers
Joint preparation	Interstitial segregation		
Arc gas	Pore size and distribution	Corrosion resistance	Engine frames
Travel speed	Residual stress level	Lap shear strength	
Heat input	Composition variations		
Filler composition			
Degree of constraint			

- to optimize economic aspects of production.

The term microstructure as used here includes the chemistry of the material that makes up the component. It differs from structure as used previously in that defects or discrete flaws are not considered part of the microstructure. Since microstructure can refer to any dimensional level, from atomic involving distances of angstroms to macroscopic structures visible to the unaided eye -- whatever influences the properties of concern to the intended use -- the boundary between it and defects can become quite hazy and is subject to the customs or taste of the author. Nevertheless, differentiating defects from microstructure is widespread. It has some utility and will be continued in this paper, while recognizing that a given structural feature in a given part might often be described from either point of view.

Many engineers still think of processing primarily in terms of the first goal given above. Obtaining desired microstructures and properties is considered to be the function of subsequent and unrelated heat treatment. Increasingly, however, as materials are developed and used whose properties are a function of their entire processing history, it is necessary to consider the first and second goals <u>together</u> to attempt a total synthesis of a component. The process must attempt to control and perhaps effect trade-offs or compromises between microstructures (often at different dimensional levels), absence of defects, and geometry, while also finding the economic optimum demanded by the third goal. Processing science attempts to provide the knowledge that will encourage concurrent attainment of these goals. For instance, in metalworking operations such as extrusion, forging, or rolling, it is fundamental to determine what conditions the forming process demands of the workpiece material, and how the workpiece material responds to those demands.

How can workability limits for a given material and process sequence be predicted so that the desired geometry can be obtained without gross defects such as the central burst shown in Figure 1? How can the environment of, and changes occurring to each differential volume element of the material, as partially illustrated in Figure 2, be tracked throughout the entire process to permit predicting and/or controlling the microstructure of the final product? Answering these questions can involve either theoretical analysis or empirical correlation, or most effective, a combination of these.

To many, the term processing science connotes a theoretical model that permits the prediction and description, for example, of the flow fields that occur during extrusion as a function of material properties, initial and final geometry, die design, temperature, rate of extrusion, lubrication, etc. For most industrial processes such theoretical mathematical descriptions can become extremely complex, and closed-form solutions are not

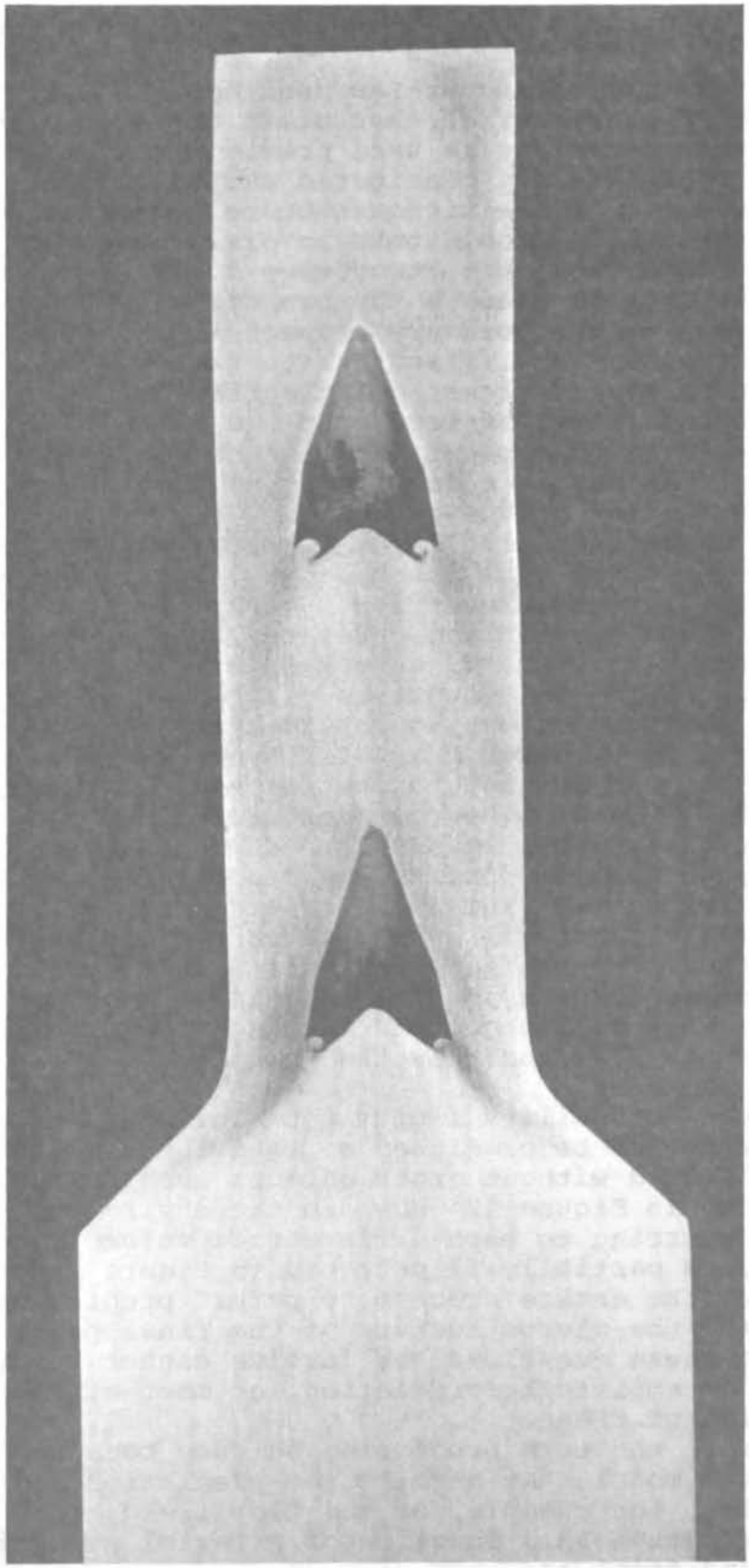
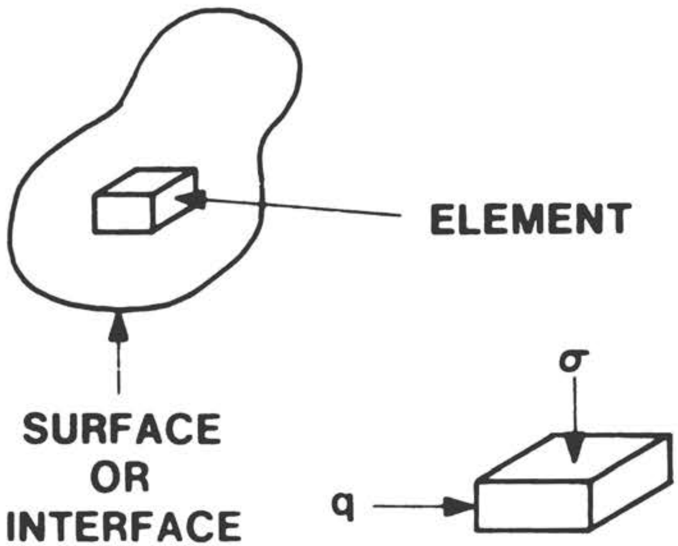


Figure 1. Illustration of central burst fracture during extrusion

BULK MATERIAL



MINIMUM ENVELOPE:

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DEFORMATION

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- MORPHOLOGY/ MICROSTRUCTURE
- MOLECULAR STRUCTURE

Figure 2. Material Focus in Processing[4]

attainable. The challenge is to develop usable and adequate approximation solutions, and in this modern era of "computational plenty" it has become increasingly feasible to develop process models suitable for use on relatively inexpensive computers. The utility of empirical correlations should not, however, be overlooked. For example, the effective analytical treatment of the chemical engineering unit operations (processes) of heat or mass transfer to or from turbulent flowing fluids depends upon empirical correlations between dimensionless groups of variables rather than a theoretical analysis proceeding from first principles. Again, the evolution of computational plenty provides powerful new tools (such as adaptive learning networks) for finding significant, meaningful correlations within tremendous masses of data. The possibility of useful combinations of theoretical and empirical approaches has great promise. (For example, approximate theoretical solutions applicable in limited process regimes can be used for initial training of adaptive learning networks, which can then, by operating on empirical data, develop more widely applicable correlations. Of course, even a qualitative theoretical analysis, will help ensure that no significant parameters are left unmeasured and thus untreated in attempts to find empirical correlations. Theoretically derived relationships between key parameters may also provide confidence for extrapolation from the limits of an empirical data base.) The potential for rapid and significant advances in the ability to quantitatively model many processing operations is one of the trends that suggests that increased attention to a science base for materials processing is warranted at this time.

It should not be inferred from the above discussion that the field is restricted to known processes. Processing science also includes activity that yields innovative new processes; new ways, for example to synthesize desired or unexpected microstructures, or to reduce cost. (The initial laboratory-scale explorations of novel processes such as directional solidification, hot isothermal pressing, or superplastic forming are metallurgical examples that should be included in this view of processing science.) The search for new ways to make things has been institutionalized in chemistry; organic synthesis is an example of a recognized subdiscipline. (The development of methods for stereospecific polymerization is a breakthrough of the recent past.) Similar levels of organized activity do not exist for metals or ceramics.*

*The synthesis and processing of electronic materials for solid state devices warrants separate treatment which will not be attempted here.

Nevertheless, an increasing number of novel and intriguing approaches to synthesis and processing seems to be emerging. Some were clearly stimulated by need, e.g., by the very large savings possible if the cost of manufacturing high-performance components, such as those used in jet engines, could be reduced. Some may have been stimulated by expansion of knowledge of the relationships between structure and properties, which has been characteristic of most of the rapid growth of materials science in the past two decades. If there is a hint that certain microstructures may lead to unusual, interesting, or useful properties, creative individuals will search for ways to synthesize them. In many cases, however, the new processes came first, yielding previously unknown or unstudied microstructures (stimulating fruitful structure-property research as well as potentially useful new materials or manufacturing approaches). How to generate searches for innovative new processes might well be a subject for the workshop. Perhaps a better understanding of existing processs would provide a useful stimulus.

Goals for Processing Research

In this workshop, emphasis will be on the processes, as outlined in Figure 3, i.e., the steps from bulk materials to products. Research into these is important (Figure 4) because it yields new materials, increases productivity, contributes to reliability, and permits rapid response to market demands.

New Materials A major contributor to the development of new materials has been the fact that new processes often lead to novel or unexpected microstructures with interesting and sometimes useful properties. The use of directional solidification to provide improved turbine blades or vanes through elongated grains running the length of the part or, potentially, growing single-crystal blades or developing eutetic composite microstructures are current examples. The enthusiasm generated by such innovative possibilities quickly leads from the laboratory to attempts to produce and to put them to use -- but this is often done empirically. At best there is some qualitative understanding of the phenomena involved and the interaction of different parameters, there is rarely a quantitative understanding or a model that can be used for quantitative procedures. As a result, it is often very difficult to control uniformity or prevent defects from occurring as the processes are scaled up. The use of chemical vapor deposition to produce coatings or free-standing parts has led to several examples where transition from a small scale in the laboratory to larger, more complex parts in production did not go smoothly and even led to abandoning the projects. The lack of a science base and the consequent need to proceed in an almost completely empirical manner proved too big a task for the

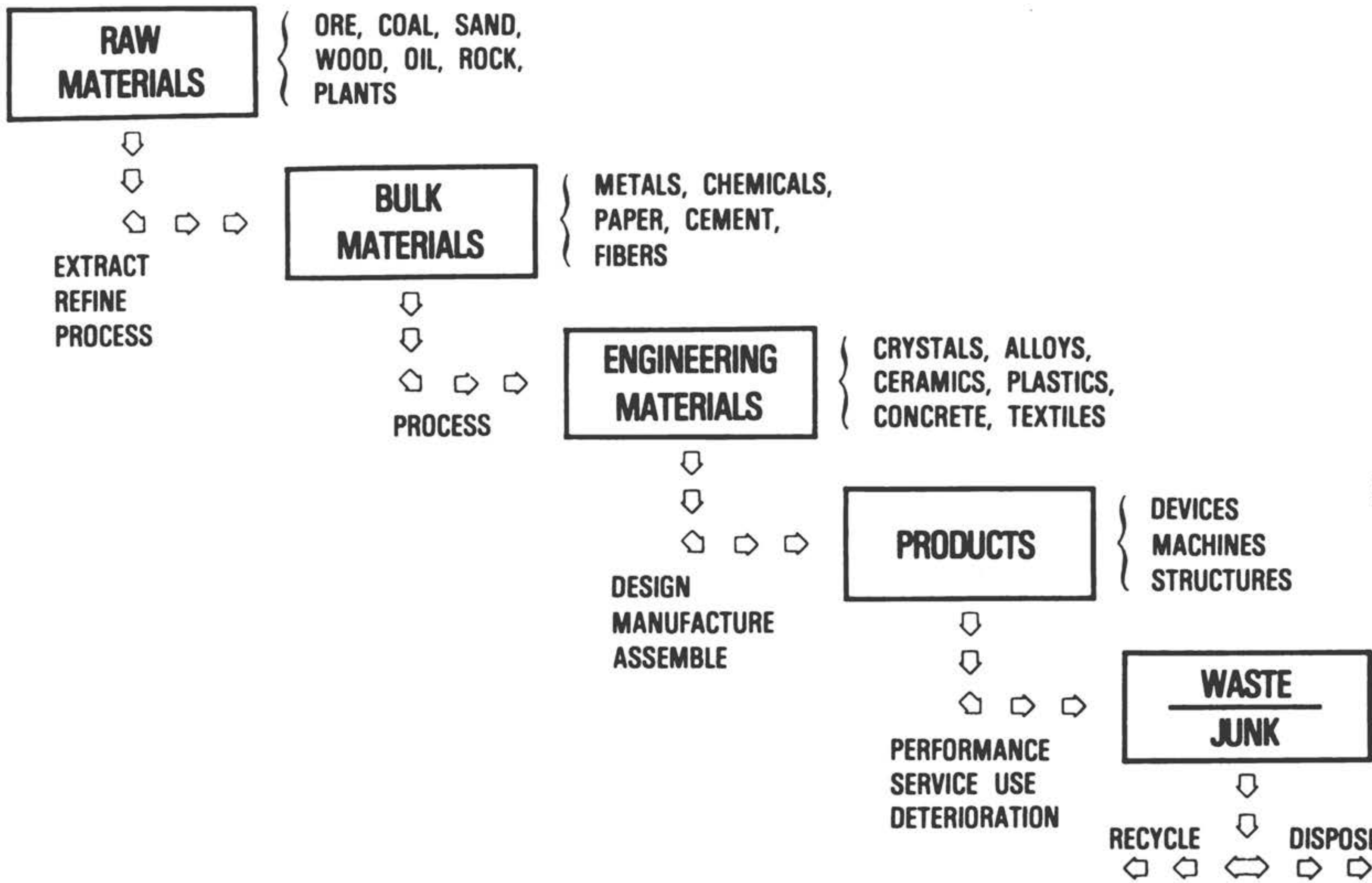


Figure 3. Materials and processing sequence

WHY PROCESSING RESEARCH?

NEW MATERIALS

- NOVEL PROCESSING APPROACHES OFTEN YIELD NEW MATERIALS OR MICROSTRUCTURAL POSSIBILITIES

- CONTROL UNIFORMITY AND PREVENT DEFECTS DURING SCALE UP
- REALIZATION OF FULL POTENTIAL OF INNOVATIVE NEW PROCESSES

WHY PROCESSING RESEARCH?

PRODUCTIVITY

- NOVEL PROCESSES MAY SIGNIFICANTLY REDUCE COSTS
- FLEXIBLE PROCESSES COMPATIBLE WITH 'COMPUTATIONAL PLENTY'

- NEW PROCESS ACCEPTIBILITY
  - REDUCE RESOURCES REQUIRED FOR SCALE UP AND/OR DEBUGGING
  - REDUCE TECHNOLOGICAL UNCERTAINTY INHIBITING LARGE CAPITAL INVESTMENT
- MODELS FOR COMPUTER AIDED MANUFACTURING (AND CAD/CAM OPTIMIZATION)

WHY PROCESSING RESEARCH?

RELIABILITY

- UNIFORMITY, REPRODUCIBILITY, ABSENCE OF DEFECTS
  - HIGH PERFORMANCE MATERIALS USED NEAR THEIR LIMITS AND WHERE CONSEQUENCES OF FAILURE CAN BE CATASTROPHIC
  - INCREASING IMPACT OF PRODUCT LIABILITY CONCERNS IN 'NORMAL' CONSUMER PRODUCTS
- CONTROLLED GRADIENTS ('ONE HORSE SHAY' COMPONENTS)

WHY PROCESSING RESEARCH?

RESPONSE

- REDUCE TIME, COST AND UNCERTAINTY OF NEW PROCESS SCALE UP AND/OR APPLICATION TO A SPECIFIC TIME ORIENTED MARKET
- RAPID RESPONSE TO MARKET CHANGES
- RAPID PRODUCT CUSTOMIZATION

Figure 4. Reasons for processing research

resources available. The development of rapidly solidified powders presents a new challenge where lack of a science base for further processing might hinder realization of their full potential. There is the intriguing possibility of preparing powders with novel, often metastable, microstructures which might be retained during further processing into parts, or used as the precursors to totally new microstructures in the final product. An empirical approach to finding the optimal processing conditions to yield the desired geometry and absence of flaws at the lowest possible cost will involve exploring a matrix of $\underline{N}$ possibilities. The cost of this may be significant, but to also explore a variety of new microstructures that will be controlled or influenced by the flow and temperature, etc. of different consolidation and/or subsequent processing steps can easily generate a matrix of $\underline{N}^a$ (a>1) possibilities. The cost of a purely empirical approach can now become so prohibitive as to retard development of the technology. An improved ability to model the processes involved (even approximately) should provide some guidelines to at least reduce the magnitude of the empirical task and help ensure that the best possibilities are evaluated.

Productivity Emergent, sometimes novel processes often lead to significantly lower cost methods. Concurrent superplastic forming and diffusion bonding of titanium is a current example that allows not only cost reduction, but the practical fabrication of more structurally efficient configurations in components. Processing science is concerned with the "discovery" of such processes and the knowledge that permits their rapid, effective application. (See the panel on high-speed metal removal.) It appears that some interesting phenomena may occur when aluminum is machined at very high speeds. Although there is debate not only about the existence or explanation of the phenomena or whether they would have practical significance for aluminum even if they are real, there is widespread interest in their potential for reducing the cost of machining titanium, stainless steels, or superalloys. However, a direct, empirical exploration of their existence or potential for metals difficult to machine would require constructing extremely expensive equipment. Will anyone make such a high-risk capital investment? Unfortunately, the current science base permits very little undersanding of what is observed with aluminum or extrapolation from aluminum to other metals to help reduce the risk of such a decision.

Even in familiar existing processes, rational analysis and modeling can be quite fruitful. Whenever large capital investments are at stake in modifying or replacing existing processes, there is bound to be irrational conservatism. Asking meaningful questions about what we are doing and why, and what would really be the effects of proposed changes, and the ability to use a science base to add credibility to the answers can help provide the necessary confidence.

Another active field for increasing productivity involves the application of computers to everything that happens in a factory. Clearly the use of computers for process control requires models of the processes, and an improved science base can help develop these. However, there are additional possibilities since integrated computer-aided manufacturng (ICAM) may have its greatest impact in reducing the cost of overhead or secondary functions such as inventory control or purchasing or process routing, thus offering the possibility of very flexible overall manufacturing systems. This presents a challenge to develop processes that will be compatible with such a system. Instead of one machine restricted to one process and a narrow range of products, there will be increased need for flexible machines that can quickly be adapted to a variety of situations. There must be many ways in which an approved use of science can help reach this goal.

<u>Reliability</u> Increasingly, in many aspects of the technology that underlies modern society, materials are being used closer to their limits; the consequences of failure can be catastrophic. A jumbo jet, an energy-generating or conversion plant, or an implant for prosthetic use in the human body are some familiar examples. Even in low-performance technology -- in more common consumer products -- demands for reliability have been rapidly growing in response to new laws, regulations, and court decisions involving product liability. The role of reproducible, uniform, defect-free materials is obvious, and will undoubtedly impose requirements for improved processes to yield them. An improved science base should provide a significant contribution toward process control.

A related possibility involves the use of improved process control to yield different microstructures in different regions of a single component. A dual property disk (described below) is a current example. Ideally, if all regions of a component have their own optimum microstructures, maximum performance and efficiency can be combined with maximum lifetime as in the famous one-horse shay where everything wears out at the same time. Here is an area where processing science can make meaningful input to the widespread call for more of a conservation ethic in our society.

<u>Response</u> As society becomes increasingly complex, effective competition requires short response times to very diverse markets. To the extent that an improved science base can reduce the time and cost of manufacturing new products or introducing new processes, it can be a significant aid. The work of Altan[5] has shown, for example, how analytical models based upon the existing science base can significantly reduce the time for design of extrusion or forging dies from that required by usual experience-based, empirical methods.

Health of the Materials Science Base in the United States

An analysis of the health of the materials science base in the United States from the viewpoint of the needs of the aerospace industry was undertaken at the Air Force Materials Laboratory by the author in 1976.* Among the stimuli for this was the recognition that as a result of obvious requirements to reduce cost and increase reliability, many sources of R&D support were providing large resources for relatively short range, put-it-into-use developments such as the expanding manufacturing technology programs in DoD. Concern for whether this was an inverted pyramid resting on an inadequate base of fundamental knowledge led to interest in the status of fundamental research activity in the United States, and the effectiveness with which its results were being transited to use.

It should be clearly understood that the case cited was an analysis from the viewpoint of need; it did not address that portion of the science base (usually referred to as truly basic) which is knowledge-driven and motivated by the extent of new understanding that can be obtained irrespective of the predictability of its utility. This portion of the science base should be judged on the quality of the investigators and research, not its relevance to definable need, and there is no implication herein that need-related work should be supported at the expense of such truly basic work. The most affluent society in history should support a significant truly-basic activity. It will enrich our culture and inevitably satisfy our need in innumerable ways. It is however, appropriate that some portion of fundamental research activity be motivated by perceived needs and the purpose of the analysis was to determine where there were major gaps in such need-related national activity.

The process used was to prepare two lists, one identifying long-range generic needs and concerns for aerospace materials technology, the other enumerating specific needs for fundamental knowledge in several broad areas or disciplines. The former was derived from planning studies and exisiting knowledge. The latter was generated during a budget allocation exercise conducted to define the laboratory program for a future fiscal year. For example, if proposed new development programs were rejected by the laboratory senior management because there was no adequate knowledge base to support the proposals even if the goals were desirable, a need for knowledge could be identified. Ongoing or successfully advocated new development or manufacturing technology programs were reviewed to identify instances where, it was judged, the availability of additional knowledge would increase the probability of success or make the results more generally applicable. Proposals directly from the working level to obtain more fundamental knowledge to point the way for future developments were obvious additions to the growing list of specific needs.

All the items so identified were sorted into a set of disciplines or multidisciplines. For each item the question was asked, "Is there a minimum level of activity consisting of two to five fundamental research groups (depending on the judged importance and difficulty of the item) doing productive work in the general topic of the item that might yield knowledge which could be incorporated into development programs or engineering use in 5-10 years." Note that this separated the item from the specific need for knowledge which generated the item. If there were not a minimum number of two to five such groups (each consisting of at least one active professor and several graduate students) the topic was identified as a gap and it was left on the lists. The lists thus generated were then iterated through more than 50 industrial and university groups throughout the country. The industry people were usually asked to focus on the areas where they could identify a need for new fundamental knowledge, i.e., what was left off the lists. The university people were usually asked to focus on the lists' assessment of whether minimum productive activity was under way in a specific topic. Both were asked to comment on long-range generic needs and concerns. Expectation that the early lists would generate controversy and additional input was confirmed. This input was incorporated into successive versions of the long-range needs, and lists of specific gaps.

As the rate of change slowed, tentative conclusions were drawn and also exposed to the iterative process, including now people who had been instrumental in earlier reviews of materials science and technology, such as the COSMAT study,[7] other government agencies, and selected gatherings of knowledgeable individuals such as the National Materials Advisory Board and representatives to the Federation of Materials Societies. Table 2 shows the major long-range generic needs and concerns at a late stage in the process, after which there was almost no disagreement with the statements shown. Note that the first two items on this list are technical needs, the last three are institutional concerns. Table 3 shows a partial list of the gaps in processing science at an early stage in the process. Some might disagree with the inclusion or absence of specific topics, or the way in which they were stated, but eventually in the iterative process there was little further change in the relative sizes of the lists of gaps under the nine disciplines or multidisciplines (see Table 4) eventually chosen as a "table of contents" of the materials science base.

Table 2. Long-range generic needs and concerns of aerospace materials technology

Few new systems will be introduced in the future, current systems must last longer
- high acquisition costs, maintenance costs
Air Force continues to require materials that are used near their limits where failure can be disastrous
Changing nature of industrial research shifts major burden for high risk, innovative research to federally funded programs
Industry/University interface is weak
Effectively coupled, multidisciplinary programs at universities are rare due to institutional barriers

Table 3. Processing science gaps

Analytical modeling of forging
Analytical modeling of sheet forming
Mechanisms of superplastic forming
Modeling of the curing process and mechanisms of microstructure development in structural resins and adhesives
Analytical modeling for directional solidification
Analytical modeling of hot pressing and hot isostatic pressing (HIP)
Solution and melt behavior of stiff chain, highly-interacting polymers
Mechanisms of microstructure development in oxidation resistant coatings
Constitutive equations and fracture mechanisms under hot working conditions
In situ measurement methods for use during processing

Table 4. Applicability to aerospace needs of the 1977 materials science base

INADEQUATE	MARGINAL	ADEQUATE
Processing science	Metallurgy	
	Ceramic science	
	Polymer science	
Surface physics and chemistry	Mechanics	Solid state physics
	Thermophysics and chemistry	
Nondestructive evaluation (NDE) science		

Note that processing science was an area of broad need where there were many significant gaps. (It should be reemphasized here that the purpose of the study was to identify areas of gross inadequacy. It does not imply that even more effort in solid state physics would be bad, rather it found that the potential of this discipline is well recognized and that there are very few topics in it where at least a minimum effort is lacking.) Although the analysis was initiated to evaluate the health of the materials science base from the viewpoint of the Air Force, in particular, and the aerospace industry, in general, it became apparent during some initial visits to materials producers and fabricators serving several sectors of the economy that the results might be similar for all sectors. The long-range needs and generic concerns shown in Table 2 are as applicable to the needs of new-energy generation or conversion technology, for example, as they are to aerospace. Therefore, during the latter iterations, individuals and companies representing many different potential uses of materials science and technology were included, in the conviction that the conclusions indicated in Table 4 need not be restricted to aerospace, and are generally applicable.

When in June 1978, these conclusions were tested against the general perceptions of several senior individuals government laboratories and ministries in West Germany and Great Britain who are involved with materials R&D, there was almost total agreement. In fact, Germany is deeply involved in increasing its activity in processing science, and in both Germany and Britain significant new initiatives in nondestructive evaluation (NDE) science are being pursued or considered. The only deviation was that the Germans did not have a strong impression that surface chemistry and physics (of concern in the United States because of its applicability to understanding complex degradation processes) was an area of significant inadequacy.

The recommendations that resulted from this analysis are:

- Increase activities in science and technology coupling.
- Undertake a major new initiative in processing science.
- Define and (courageously) pursue more good surface science, applicable to the messy problems of degradation and real interfaces.
- Stimulate broader participation in the new and growing areas of NDE science.

This workshop is itself an attempt to increase activities in science and technology coupling, and is designed to help clarify desirable new initiatives to undertake in processing science. Some of the new initiatives that the Air Force has already undertaken, after review of some comments about processing science frequently heard at universities, follow.

The Image of Processing Science

There seems to be little perception in American universities of the usefulness of the process modeling and quantitative understanding of processing science. Several individuals who were deeply involved in attempts to stimulate processing science about 10 years ago cited lack of interest in their work. Others perceive processing science to be a low prestige, even pedestrian area. It is not an established or recognized discipline, and at best it is a very complex area in which it is difficult to do good work. Therefore, young professors interested in tenure, are reluctant to stake their careers on the area. Finally, there is a widespread opinion that industrial support for processing research in universities has been and would be inhibited by proprietary secrets and the fear that adequate confidentiality cannot be maintained. Institutional barriers such as these, as well as the more general ones, (see Table 2) must be dealt with if processing science is to become "more healthy". (See the discussion of institutional barriers to industry-university interaction.)

Once again, the situation in the United States can be compared with recent observations in Western Europe. Germany and Sweden <u>do</u> have adequate size, well-equipped, university-related centers of excellence in metals processing research, development, and education (to the doctoral level) that are closely coupled to industry. There is optimism about the potential for processing research.

Effective, government supported (often with industry's support also) university-industry "coupled" research programs do exist in contrast to the failure of many U.S. efforts to generate such in the last 20 years. However, the "grass was not completely green" on the other side of the Atlantic. Many comments from industry, government, and university representatives about faults in the system were similar to those heard in the United States, e.g., "industry is concerned about exposure of proprietary interests" or "most university work is too fundamental to be of practical use."

The Current Situation

At the institutes visited in Germany and Sweden the bulk of the work, at present, seems to lean toward the applied. However, these institutions intend to devote an increasing fraction of their total effort to provide fundamental understanding and an ability to describe analytically the processes being investigated, and such thrusts do seem to be under way. It is not yet apparent how productive this work will be. Nowhere in European metal processing research were there major multidisciplinary fundamental efforts (like the goal of the current Air Force metal processing initiative described in the next paper) attempting to combine control of microstructure with control of geometry and defects -- although this was generally accepted as the eventual goal, and as mentioned above, there is optimism about the potential for processing research.

In the United States, as a result of the analysis of the materials science base just discussed, the Air Force has recently undertaken three major processing science initiatives. One is concerned with carbon-carbon composites, one with ordered polymers (the subject of one of the workshops to follow), and one with analytical process modeling of metal working described in the next paper). These are large programs, and resources were not adequate to pursue other obvious areas such as curing of thermosetting resins that are the matrices for modern advanced composites. However, considerable interest in providing the necessary support is developing at several facilities in addition to the Air Force. There are also signs of a shifting climate at several universities, indicating a greater interest in engineering sciences such as processing. The widespread and growing membership in the new American Society for Metals Process Modeling Activity is a further indication that the time may be ripe for a major expansion of effort in the science base for materials processing.

Processing Science in the Future

To effectively capitalize upon the increasing need for and interest in processing science will require three things beyond mere availability of money for support -- "windows," a sense of ownership, and leadership.

The term window has been used for several years by the Air Force in its materials technology reduction-to-practice programs. It is that part of the goal of a development or manufacturing technology program that can be expressed as a realistic potential application, or even a specific first generation use of the technology. Defining a credible window involves answering difficult and sometimes embarrassing questions such as: "Even if I successfully meet these technical goals, who will use my product and for what application? Does it offer sufficient potential beyond the existing state of the art to overcome inertia due to the normal reluctance to change, or the risk of eventual failure? How will it fare against competing developments?" A suitable window provides a baseline against which the new technology can be evaluated. The possibility of actual near-term production and use stimulates enthusiasm in both program participants and potential sources of support. The problem, of course, is to define a specific potential initial application that will provide these advantages, and also be sufficiently stimuating and generic that it can act as a vehicle for advancing the technology along a broad front toward potential uses well beyond the window selected.

An example of such a window is the fuselage structure for the Advanced Medium STOL Transport (AMST) being built and tested as part of the Air Force's Primary Adhesive Bonded Structures Technology (PABST) Advanced Development Program. The evolution of the phosphoric acid anodizing process for aluminum, about eight years ago, provided microstructures in the interphase layers beween aluminum alloys and epoxy adhesives that were much improved in their resistance to degradation by moisture. Furthermore, phosphoric acid anodizing seemed in the laboratory to be much less sensitive to the variations in process parameters that might be difficult to control during large-scale production. These, plus the realization that the previously uncontrollable variability in the service lifetimes of adhesive bonds for aluminum was primarily due to a small amount of anodized surface that was liable to hydrolytic attack, rather than variability in the properties of the adhesive, led to the postulate that adhesive bonding valuable enough to permit its use for primary structure in aircraft might at last be attainable. This might provide attractive performance and manufacturing cost advantages over the usual riveted and bolted structures, and since fastener holes are a major source of fatigue cracks, could also lead to significant maintenance cost savings. After considerable evaluation, a section of the AMST transport fuselage was suggested as the window. This prototype aircraft was already being designed and built using the latest state-of-the-art mechanical fastening methods so a baseline for manufacturing cost, structural weight for a given performance level, fatigue life, and costs of repair and maintenance would be available. It would enable advantages or disadvantages of adhesive bonding to be clearly defined and quantified. The structure was sufficiently advanced, diverse, and generic for the lessons learned and technology developed to be applicable to a wide variety of aircraft structures that might be built in the next two decades. Finally, the program timing was such that if the PABST program were successful, and a decision to produce the AMST made, adhesive bonding might be available as a credible alternative to mechanical fastening for actual production. The enthusiasm this generated was a significant factor in motivating the unusually close interdisciplinary cooperation between structural design, materials develoment, manufacturing, and quality control people that was necessary for optimum technological progress. It probably helped generate the large resources needed for such a program. As it turns out, the AMST was not put into production, but the new technology flowing from the PABST program, stimulated and guided by the availability of a well-defined window, is already finding broad use in many aerospace applications.

When applying this approach to focused fundamental research it is, of course, rarely possible to define specific windows for specific first-generation use. Not only does the time scale involved prohibit it, but as has often been said, if one can define the outcome of a fundamental research project, it may not be worth doing. As the research proceeds, the prediction of what is possible will change and the goal or window must be modified. However, it is possible to express goals in terms of potential windows. One can postulate the microstructures, properties, and geometries desired for a specific component and then ask who would use the lower cost process, or the improved performance component, etc., if it can be attained. This, of course, requires an intimate knowledge of the state of the science to predict what might be possible, and an alert awareness of how this can and does change with time. Such an evocative way of describing the potential for a particular area of research not only can help generate support, it can provide the enthusiasm to help overcome many of the institutional barriers to processing research. The goal provides a focus for interdisciplinary cooperation enabling people from different fields to find a common ground for communication. It also permits the development of "adequately elegant" theoretical models. The development of useful-approximation solutions usually requires a fairly specific goal since different approaches have different utility for different problems.

A sense of ownership speaks to the desirability for coupled programs, for the eventual users in industry to participate in planning and selection of the research as well as in doinq part of it. Finally, leadership will be necessary in universities to overcome institutional barriers; and in industry to ensure that valid problems are selected, to overcome unwarranted fear of losing a competitive position, and to overcome inertia. This leadership will have to be of both a horizontal (mechanics, metallurqy, etc.) and vertical (research to production) interdisciplinary nature.

Processinq research cannot be effectively pursued in isolation. It must be done with respect to real situations and real problems -- current or potential. Given credible qoals for fundamental research, and energetic interdisciplinary leadership, optimism that support will be found to generate an improved science base for materials processinq is warranted.

References

1. W. R. Buessem. Ceramic problems for the consideration of the solid state physicist. In Physics and Chemistry of Ceramics. C. Klengsberg, (Editor), Gordon and Breach, Science Publishers, New York, 1963, pp. 14-29.
2. G. M. Ault and H. M. Burte. Technical applications for oxide dispersion strengthened materials. In Oxide Dispersion Strengthening. Metallurgical Society Conferences Vol. 47. Gordon and Breach, Science Publishers, New York, 1966, pp. 47-50.
3. H.M. Burte. Some comments on the potential for and synthesis of components from rapidly solidified powders. In Rapid Solidification Processing, Principles and Technologies. R. Mehrabian et al. (Editors). Claitor's Publishing Division, Baton Rouge, 1978, pp. 393-396.
4. F. Kelley, Personal communication.
5. N. Akgerman, T. L. Subramanian, and T. Altan. Manufacturing Methods for Computerized Forging Process for High Strength Material. Air Force Report AFML TR 73-284, January 1974.
6. F. Kelley and H. Burte. Unpublished study (1976).
7. Committee on the Survey of Materials in Science and Engineering (COSMAT), "Materials and Man's Needs," National Academy of Science, Washington, D.C., 1974.

SCIENCE BASE PROGRAM TO DESIGN A DUAL MICROSTRUCURE AND DUAL PROPERTY COMPRESSOR DISK

Harold L. Gegel

Background -- The Need for Processing Science

The United States is experiencing an era of rising costs and there is growing concern about the likelihood of a slowdown in the long-term growth of the U.S. economy.[1-3] This trend is coupled with the danger that we are losing the industrial leadership which the United States has maintained for many years.

The rate and adequacy of the economy's growth depends on three factors: capital investment, improvements in productivity, and advances in technology.

While research and development expenditures as a percentage of gross national product (GNP) have steadily declined in the United States during the past decade, just the reverse has taken place in West Germany and Japan. Our declining leadership in technology lowers productivity, slows growth in employment, and spurs inflation. The United States, at the present time, has the highest percentage of obsolete production capacity among the industrial countries.[2]

Over the past 15 years, the productivity in manufacturing has been rising at an annual rate between 4 and 7 percent for most countries.[2] The United States and Japan are two notable exceptions to this trend. The average annual rise in productivity for the U.S. was 2.7 percent, while the average increase for Japan was over 9 percent. The data for 12 countries are shown in Table 1. The areas in U.S. industry in which productivity increases are particularly low are primary metals, fabricated metal products, and machinery. These areas of low productivity encompass the whole of materials processing.

A number of reasons have often been given by businessmen, economists, and public officials for our present economic situation. Government is urged to adopt investment incentives such as higher tax credits and more liberal capital recovery allowances.[3] Research dollars spent to satisfy the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administation (OSHA) are cited as significant factors in our declining economic growth. There is no doubt that these government-related factors do play an important role in creating incentives for R&D and capital expenditures; however, they should not be used as an excuse for not investing in R&D for productivity and in new technology. Industry's concern for near-term profits has also been a strong contributing factor to our lag in long-term economic growth.[1]

Table 1. Average annual rates of change, 12 countries, 1960-75 (percent)[2]

Country	Output per Hour	Output	Hours
United States	2.7	3.8	1.1
Canada	4.0	5.7	1.6
Japan	9.7	11.2	1.4
Belgium	7.0	6.1	-0.8
Denmark	7.2	5.7	-1.4
France	5.6	6.0	0.4
Germany	5.7	5.0	-0.7
Italy	6.2	6.4	0.2
Netherlands	7.1	5.8	-1.2
Sweden	6.6	5.2	-1.4
Switzerland	5.1	4.1	-0.9
United Kingdom	3.8	2.7	-1.1

Government regulations and industry's interest in near-term profits are not the only factors creating our country's lag in economic growth. University research, for example, has largely been compartmentalized, i.e., R&D that should have involved both materials behavior and mechanics is usually one or the other but not interdisciplinary. On the other hand, funding agencies have not supported work on these interdisciplinary problems, because their thinking too has been compartmentalized. Good interdisciplinary programs in processing R&D have been bypassed for too much materials or too much mechanics research. University professors have not had great incentive for working on industrial problems or for working in a consortium with industry and other research institutions.

A trend is now starting in industry to develop management incentives that would encourage investment for long-term economic growth.[3] Fifteen percent of the major industries in 1976 based their top executives' bonuses on long-term, performance-based plans.[4] More U.S. industries are recognizing the need to invest in the future, and the stage is being set for investment in R&D and capital expenditure that will increase productivity and create new technology.

The Air Force recognizes this need and is making a bold attempt to stimulate research in two areas of manufacturing: integrated computer-aided manufacturing, (ICAM) and research at the process level of manufacturing.

This paper deals with a processing science program that will demonstrate how computer simulation can be used to design a forging process for producing a dual microstructure compressor disk, providing the properties appropriate to the cold center and to the hot rim. The problem is approached as a system with inputs and outputs, and it recognizes the connections between the process level and the associated activities of an integrated factory.

Approach to Solving the Dual-Property Disk Problem

Scientific methodologies are being used to obtain realistic solutions for an important industrial deformation process, and, in order to define the problem precisely and to avoid a never-ending research project, all the necessary materials and process information that is required for simulating axisymmetric forging will be generated. The long-term goal is to produce a disk that has high tensile strength and low cycle fatigue properties in the bore region, and good creep and stress rupture properties in the rim.

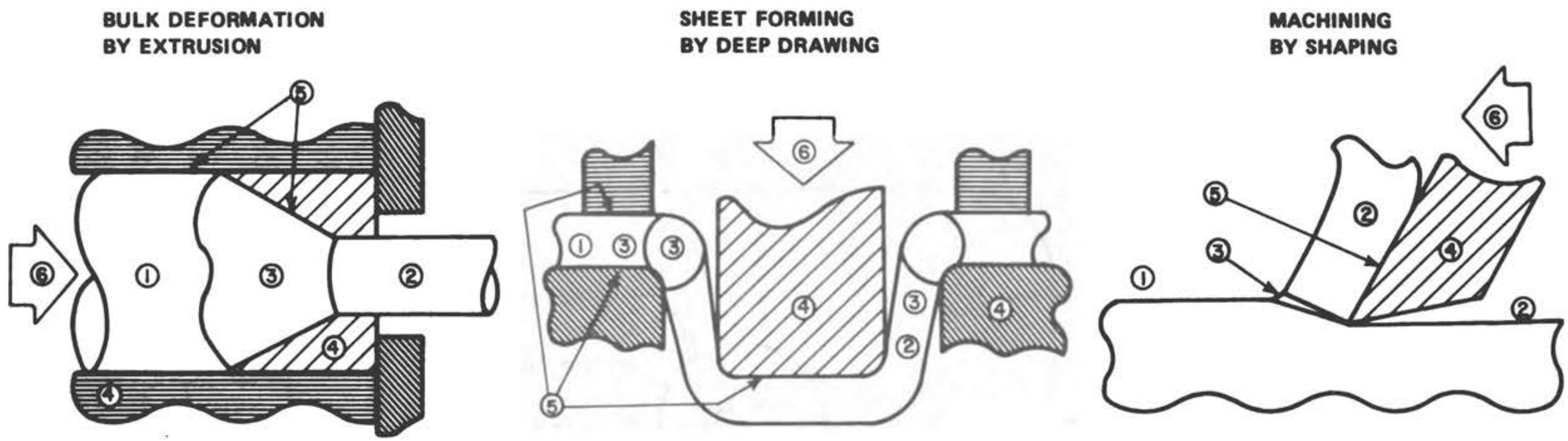
Success in solving this problem ultimately depends on how the processing system is defined and on the degree of abstraction that must be achieved in the simulation. Because the goal of this program is to control the microstructures in the design-critical regions of a monolithic disk, the degree of abstraction will be much higher than were the problem merely to predict forging loads. The basic ingredients in this problem are schematically described in Figure 1. The input to each of the processes shown is matter and energy, with the billet or workpiece, area 1, representing the matter. The output of each system is the product, scrap, and pollution, area 2. The remaining parts of the system are: area 3, the plastic deformation zone; area 4, the tooling; area 5, lubrication; and area 6, the equipment.

An imaginary boundary separates this system from the remainder of the universe, the manufacturing environment (see also Figure 2). The environment is assumed to be an ICAM system and its associated activities. The system being developed will provide an external link between the forge shop and the aerospace designer, and it will be the computer-aided design (CAD) part of an integrated (CAM) factory. This CAD tool will permit the designer to execute part geometry-materials-cost trade-off studies at the design stage of manufacturing. The CAD system when coordinated with an economic model for manufacturing will thus permit specialists to conduct process alternative studies and to generate an automatic process plan.

Much can be gained by considering each of the basic materials deformation processes and by recognizing their similarities. Problems that are basically similar in nature, such as vibratory behavior of either cutting or forming machines, can be advantageously solved using similar methods, aids, and equipment. Having obtained a basic understanding of the important process variables, the production specialist then can adjust the manufacturing process around the material behavior. Manufacturing becomes possible at much less effort than would be needed with the best organized but technically unsuited process. This situation often occurs when production is organized around an existing process. This CAD program is organized to be compatible with future flexible ICAM systems as well as to have potential near-term payoff.

Five important factors were considered when this particular problem was selected for study: the availability of structure property trends for titanium alloys; some knowledge of how to control microstructures; the existence of a mathematical solution; the usefulness of the process if successful; and the possibility for developing bridges between designers and production specialists.

It is extremely important to have some preliminary understanding of the structure-property trends of the alloy being considered, because these are the metallurgical features that must be synthesized in the finished product. Titanium is an anisotropic material, and final properties depend on the texture developed by the time-temperature-deformation path during processing. Two microstructures may look alike, but the differences in their mechanical properties, e.g., fracture toughness and low cycle fatigue



1 – ORIGINAL MATERIAL CONDITION
2 – FINAL MATERIAL CONDITION (INCLUDES MACHINING CHIP)
3 – PLASTIC DEFORMATION ZONE OR SHEAR ZONE
4 – TOOLING EFFECTS
5 – FRICTION EFFECTS
6 – EQUIPMENT CHARACTERISTICS

Figure 1. Basic components of process modeling

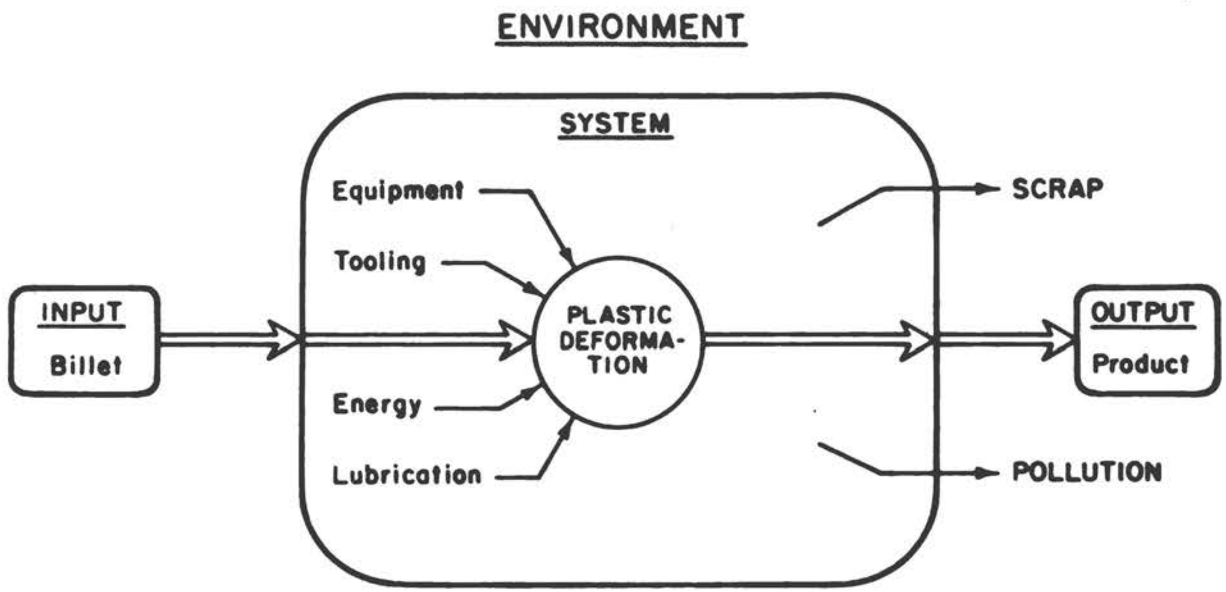


Figure 2. Deformation process as a system

strength, can be significant. Processing temperature determines the morphology of the phases in the product. For example, beta phase processing of titanium alloys always produces a Widmanstatten or transformed beta structure (see Figure 3). Processing in the alpha plus beta region of the phase diagram generally leads to a microstructure containing primary alpha plus transformed beta phase that is much less coarse than the transformed beta structure produced by cooling from the beta field (see Figure 4).

It was absolutely essential that an axisymmetric forging problem be selected for modeling since there are no known solutions for problems that are not nearly symmetrical and the axisymmetry permits the forging process to be treated as a two-dimensional plasticity problem. Workability can be treated as a two-dimensional problem and validated experimentally. As soon as the symmetrical problems can be handled mathematically--that usable constitutive equations, workability, and interface models can be developed--the really difficult three-dimensional modeling problems can be approached with confidence.

Solutions for symmetrical cases, can be especially useful because many manufacturing processes are axisymmetric, e.g., extrusion, gear, ring, and disc production processes. These processes are, commercially speaking, very important. The capability for manufacturing a dual property titanium alloy compressor disk is extremely important because all advances in jet engines depend on the development of compressor and turbine disks that can be spun without failure at higher speeds than the current state-of-the art product. It will have been demonstrated that a disk can be designed that has optimum properties, making it possible to use titanium in an application where it could not have been used before. Thus, forging can be viewed as a shape-making microstructure control process.

Finally, this particular problem was selected because it would involve the maximum number of people in the laboratory working in the areas of life prediction of compressor and turbine disks, microstructure and property relationships, and processing science. Thus, it will engender awareness of the importance of a systems approach to designing production processes.

Program Organization

The processing system was divided into five basic areas: metallurgy or material behavior, mechanics, interface effects, finished shape and microstructure, and the system.

The metallurgical area deals with material behavior under processing conditions and centers around strain hardening, recrystallization, phase transformations, and related subproblems of Ti-6242 alloy. The problems of inelastic constitutive equations and workability grow out of this area. The mechanics area treats the strain-time-

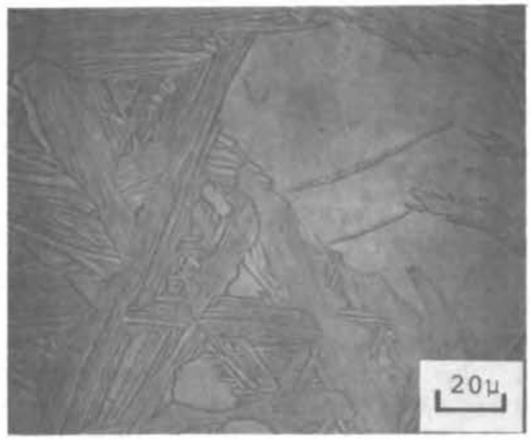


Figure 3. Widmanstatten or transformed beta Ti-6242 microstructure

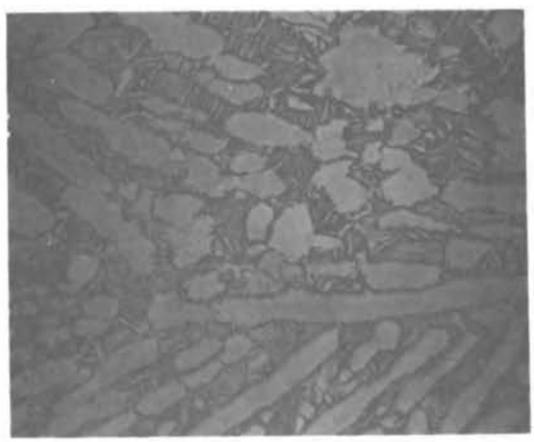


Figure 4. Primary alpha plus transformed beta Ti-6242 microstructure

temperature path through the deformation zone as it is influenced by boundary conditions of the tool and workpiece interface. The resulting processing path influences the final microstructure along with the metallurgical behavior area in terms of its recrystallization and workability characteristics. The interface phenomena play the role of boundary conditions in the process model. The interface between the tool and the surface of the workpiece provides the boundary conditions that influence metal flow, the interface shear strength, and heat transfer across the interface. The finished shape and microstructure area treats the stability of the microstructure produced by the complex interactions of the first three and the mechanical properties in the bore and rim regions, respectively. Microstructure in the broadest sense controls the mechanical properties in the finished part. The time-temperature-deformation path influences the subdivision of grains, the appearance of the various transformation products, mechanical banding, and texture. The events that occur along this path interact to produce the final mechanical properties in the finished shape. The system includes the primary deformation equipment, handling, and general process control.

Task I--Material Behavior Under Processing Conditions

The mathematical analysis of a deformation process is of little value unless it is based on the real behavior of materials, and the material behavior must be characterized and described in terms of the complex stress and strain states, temperature, and strain rate conditions found in the actual deformation process. The nature of Task I is depicted in Figure 5.

A constitutive equation will be developed for Ti-6242 for the strain rate range of 10^{-4}-10^{2} s^{-1} and for a temperature range that covers the normal forging temperatures for this alloy. It is recognized that the classical constitutive equations such as:

$$\sigma = K^{n} \quad \text{Parabolic Hardening Law} \qquad (1)$$

$$\frac{\sigma}{\sigma_{\omega}} = (1-u)e^{-\varepsilon/\varepsilon^{*}} \quad \text{Voce} \qquad (2)$$

may be unsatisfactory from the point of view that they describe only the time-independent properties of the material.

The analytical techniques required for the solution of the boundary value problems that will provide the rheological description of metal flow during forging will require more accurate constitutive relations than can be provided by equations (1) and (2).

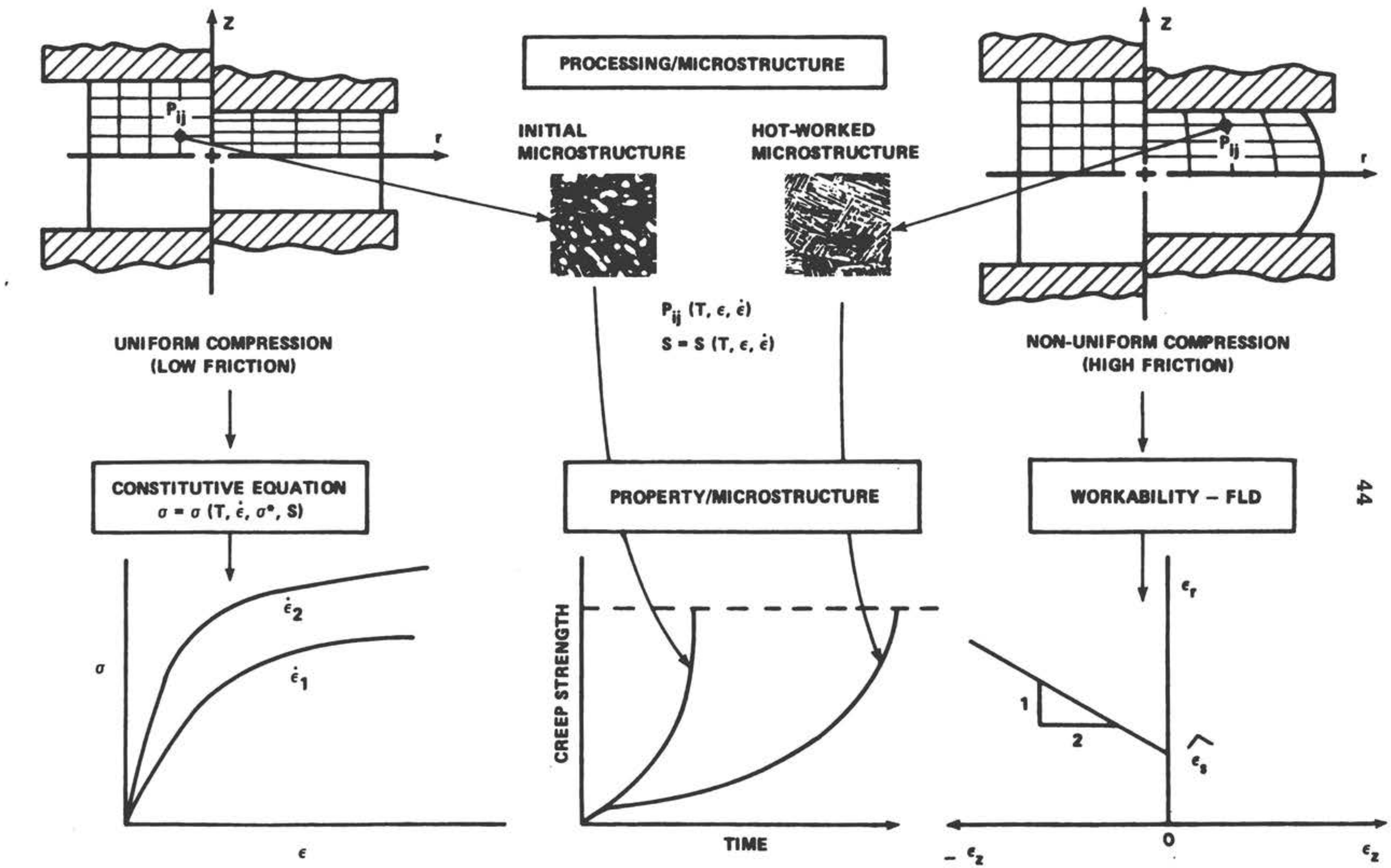


Figure 5. Material behavior modeling

Currently, the most reliable approach[5] to developing usable and accurate constitutive equations is based on a model-inspired phenomenology developed by Hart.[6] Ti-6242 will be forged at temperatures that exceed 0.2 Tm, where Tm is the absolute melting temperature of titanium, so an accurate constitutive equation for this alloy will probable have to be based on a physical and mechanistic foundation.

Deformation will also be occurring under multiaxial stresses. The concepts developed for rate-independent plasticity must be carried over to rate-dependent deformation. The relationships that have been developed to describe uniaxial behavior must also hold true for multiaxial conditions in terms similar to those employed for theories of incremental plasticity where the general isotropic relationship between the deviatoric stress tensor, σ_{ij}, and the strain rate tensor, $\dot{\epsilon}_{ij}$, can be prescribed by:

$$\dot{\epsilon}_{ij} = (\dot{\epsilon}/\sigma)\sigma_{ij} \tag{3}$$

where σ and ϵ are the tensor invariants given by:

$$\sigma = \sqrt{\sigma_{ij}\ \sigma_{ij}}$$

and

$$\dot{\epsilon} = \sqrt{\dot{\epsilon}_{ij}\ \dot{\epsilon}_{ij}}$$

$$d\epsilon = \dot{\epsilon}dt$$

All the equations developed for uniaxial conditions can be envisioned as equations relating the stress, strain rate, and strain increment invariants. Titanium alloys have special considerations due to crystallographic anisotropy that must be taken into account.

It is not clear whether the behavior observed to be so regular for relatively simple systems will be so for multiphase Ti-6242. This must be experimentally determined, as must a description of strain hardening and strain rate sensitivity under practical processing conditions.

Axisymmetric forging behavior of Ti-6242 should correlate with the mechanical properties derived by Camplastometer compression testing in the strain rate range of 10^{-3}-10^{2} s^{-1} and with the flow behavior during processing. A model[7] is available to calculate the local conditions of temperature T, strain ϵ, and strain rate $\dot{\epsilon}$. Metallurgical analysis of the microstructure along with analysis of the local conditions will provide information useful for constructing a processing-microstructure map and for developing a concept of ductility as it is influenced by strain hardening rate, strain rate sensitivity, and phase transformations that occur during processing. Quantitative information about the microstructural changes that occur for Ti-6242 both during and after hot working will provide the basis for predicting the influence of processing variables on the mechnical properties of the finished product. The literature, however, is lacking in regard to the dynamic recovery behavior of multiphase materials during high temperature deformation at large strains, and the non-equilibrium conditions that govern their behavior during processing. This information must be obtained for Ti-6242.

Ductile fracture is an important limiting factor in the forging of complex shapes to final dimensions. The dominant fracture mechanism that governs the amount of strain the material can provide is controlled by the complex stress state and the temperature and strain rate conditions found in the actual deformation process. Here we are dealing with fracture processes that occur by the initiation, growth, and coalescence of cracks and cavities within the material. Fracture maps will provide a useful tool for defining the temperature T and strain rate ϵ domains where fracture or defect generation can be avoided.

Bulk deformation processes have different forming limit criteria, and the simple tests used to characterize metals will be of little value to bulk deformation processes. The axisymmetry of the process will permit workability to be investigated as a two-dimensional problem and to represent it as a two-dimensional forming limit diagram (FLD). Kuhn[8] has developed an experimental FLD for the axisymmetric case. The similarity between this representation and the FLD for sheet metal is very striking. An attempt will be made to express workability in a form that is appropriate for problem solving. The FLD in combination with the process model will provide a technique for refined solution of workability as it relates to product reliability and durability.

An analytical approach is being pursued along with the empirical FLD to increase the design capability for the system that will evolve. The basic incredients for the development of an analytical curve are constitutive equations, yield function, failure criterion, and plasticity laws. By selecting an appropriate failure criterion, for example, the processing specialists will be able to control the manufacturing objective more closely. If, for example, the fracture toughness were the most important property that had to be imparted by the process to the part, the designer would probably use a maximum strain criterion to prevent void formation growth and coalescence in a multiphase alloy. An example of an analytical forming limit curve (FLC) for 2024-O sheet metal for the case of localized necking is presented in Figure 6. The analytical FLC's will have strain rate effects built into the analysis; because strain rate can have a large effect on the amount of strain achievable, particularly at the plane strain axis. The flexibility of the FLC concept can also be increased by incorporating the effects of curved and reversing strain paths. The FLC for bulk deformation as developed by Kuhn differs from the typical FLD for sheet metal forming. The slope of the curve, for example, appears to be a universal

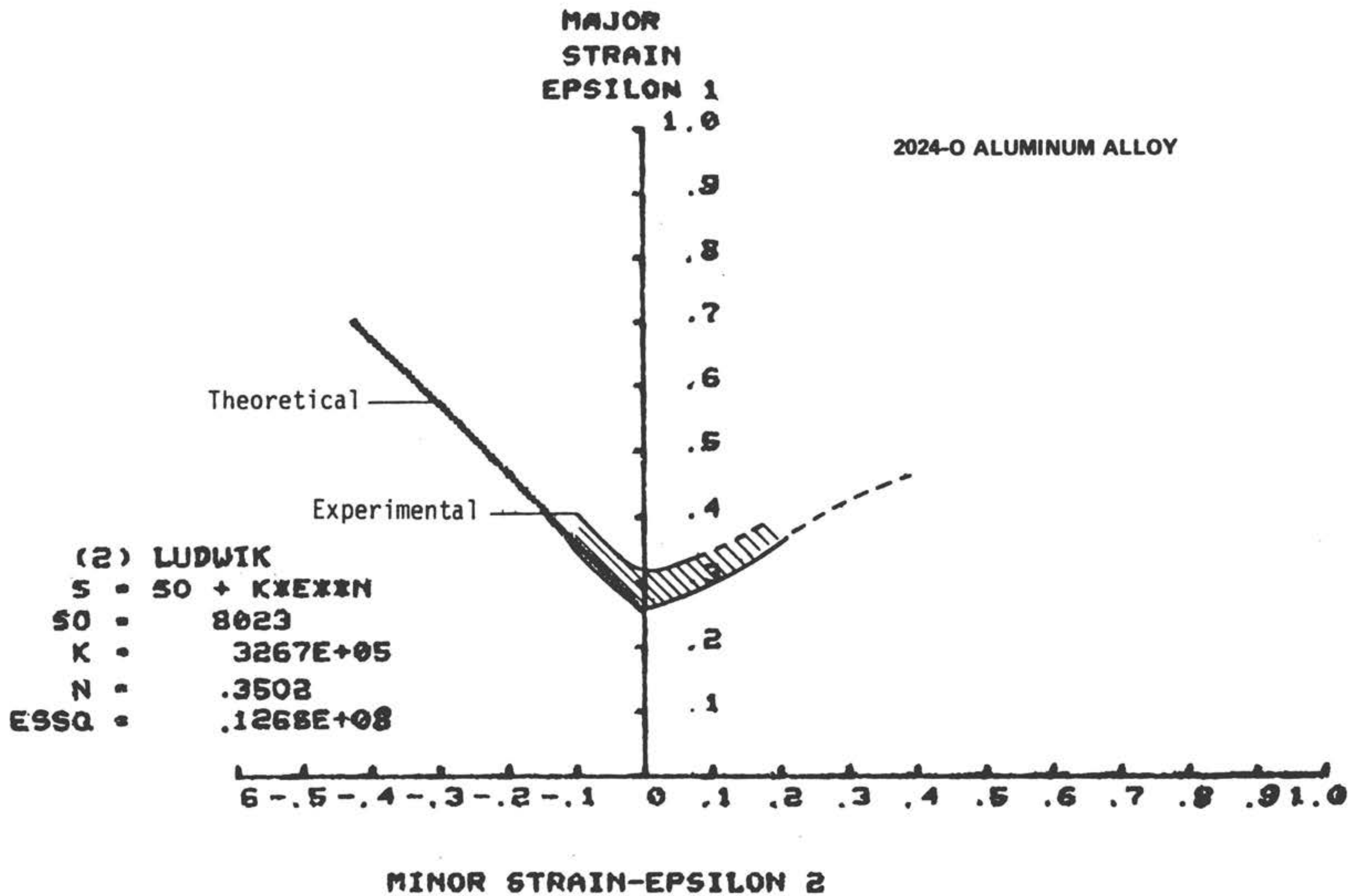


Figure 6. Comparison of theoretical forming limit curve with experimental curve

constant of -1/2 for all material except brass. The intercept $\hat{\epsilon}_s$ is the plane strain ductility of the particular material which is a dependent of the failure mechanism. Approximate values of $\hat{\epsilon}_s$ are given in Table 2. The implication of this formability data is that only $\hat{\epsilon}_s$ must be measured for Ti-6242 as a function of strain-strain rate-temperature paths that are of import to axisymmetric forging. It may not be possible to obtain a solution for all processing paths, but, as long as a sufficient number of solutions can be obtained for useful paths, the process designer can design the forging preform and dies, and select the lubricant, temperature, and process rate that will produce the desired results. The goal of this task is to develop a workability concept that combines forming limits of the material with strain analysis for the axisymmetric closed-die forging process.

Task II--Process Modelling for Disk Forging

The mathematical analysis for this forging process will provide the necessary information for proper design and control of the process. Therefore, the method of analysis must be capable of determining the effects of various parameters on metal flow characteristics. In addition, the computational efficiency, as well as solution accuracy, is an important consideration for the method to be useful in analyzing the process. The objective of this work is to develop an efficient analysis method that will take into account the dependence of material behavior on strain, strain rate, and temperature, while providing a solution to the problem of nonsteady-state heat transfer in a moving incompressible medium with heat sources. Because the overall goal of this program is to demonstrate the feasibility of producing a dual microstructure dual property disk, the process model will be designed to accept microstructure and workability information that is being simultaneously developed in Task I.

The approach to controlling microstructure, and, hence, properties must be sufficiently general to permit, for example, the microstructure to be controlled locally by changing the velocity field and by controlling the local strain and temperature conditions. The problem of preform and die design and lubrication will play a strong role in this situation. The possibility for having different friction conditions at critical locations in the die will have to be considered, so the process model will have to be developed keeping in mind its relationship to the interface model.

Table 2. Plane strain ductility for different alloys

Material	Temperature, °F	$\bar{\epsilon}_s$
303 stainless	300	0.18
1020 steel	300	0.32
1040 steel	300	0.28
1% C steel	300	0.39
1213 steel	300	0.25
Oxygen-free high conductivity Cu	300	0.55
201 AV, 601 AB	300	0.14
Al powder compacts		
90% density	700	0.28
4620 steel		
80% density	1800	0.14

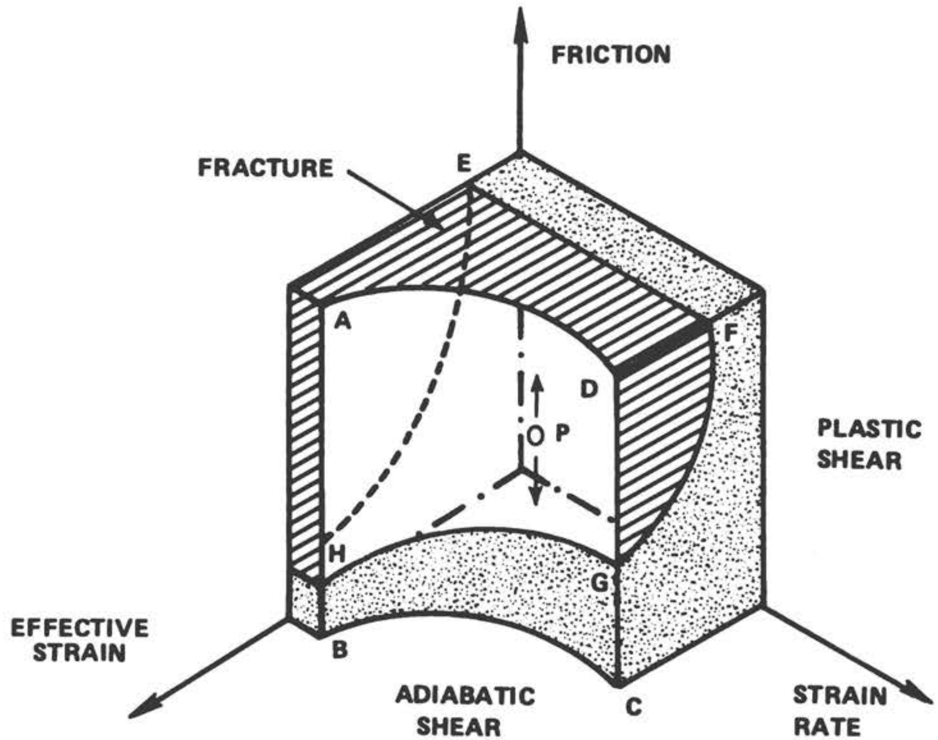
Task III--Interface Effects

The interface phenomena of friction, lubrication, and die wear are of controlling importance in forging, sheet metal forming, and machining processes. Interface phenomena deal with the effect of friction on forces, power requirements, strain and velocity distribution, and process limitations set by friction. Interface conditions, with respect to process modeling, can be thought of as playing the role of boundary conditions. The lubricant at the interface between tool and workpiece plays multifunctional roles. It can control heat transfer depending on its effective heat transfer coefficient, and it can change the friction conditions of the tool/workpiece interface. The lubricant must do both functions in addition to controlling the oxidation of the workpiece. The literature is lean in data that correlate compositional effects with processing behavior for the commercially available lubricants, and this lack of fundamental knowledge about lubrication mechanisms and lubrication systems presents a fundamental limitation to modeling metalworking processes.

The importance of friction in metalworking processes is shown schematically in Figure 7 by a form of deformation diagram originally developed by Ashby.[9] During deformation, the workpiece is deformed by the motion of a hard geometrically shaped tool. Generally speaking, in the analysis of this process it is assumed that the workpiece material shears plastically in some relatively well defined zone. This enables the concepts of mathematical plasticity to be applied. One of the more important variables in such analyses is the severity of the friction force between the material being deformed and the fact of the tool and die.

Plastic shearing is not the only possible mechanism that enables the workpiece to accommodate the movement of the tool. In addition to continuous shearing, some materials deform by adiabatic shearing or shear localization and by processes that involve fracture and the propagation of cracks. In metals, the initiation of such processes can lead to shear band formation and possible fracture (Figure 8) and the generation of internal fractures such as extrusion center bursts (Figure 9), or void formation around second phases or inclusions. It is known that some of these changes can be encouraged by metallurgical factors as well as preform and die design. Figure 10 shows a shear band defect caused by die chilling and the strong temperature dependence of titanium's flow stress. Shear band defects are a result of deformation on internal metal surfaces that are energetically more favorable than surface flow. Shear strain concentration defects are caused by embrittling factors such as high strain rates or low temperatures.

We can thus imagine three possible mechanisms operating to accommodate the motion of the tooling: plastic shearing, fracture, and adiabatic shearing. Each of these limiting mechanisms can be described by a constitutive equation.



ABCD – ONSET OF CONDITIONS FOR ADIABATIC SHEAR

EFGH – BOUNDARY BETWEEN PLASTIC SHEARING AND FRACTURE

Figure 7. Friction effects typical for forging with free surfaces

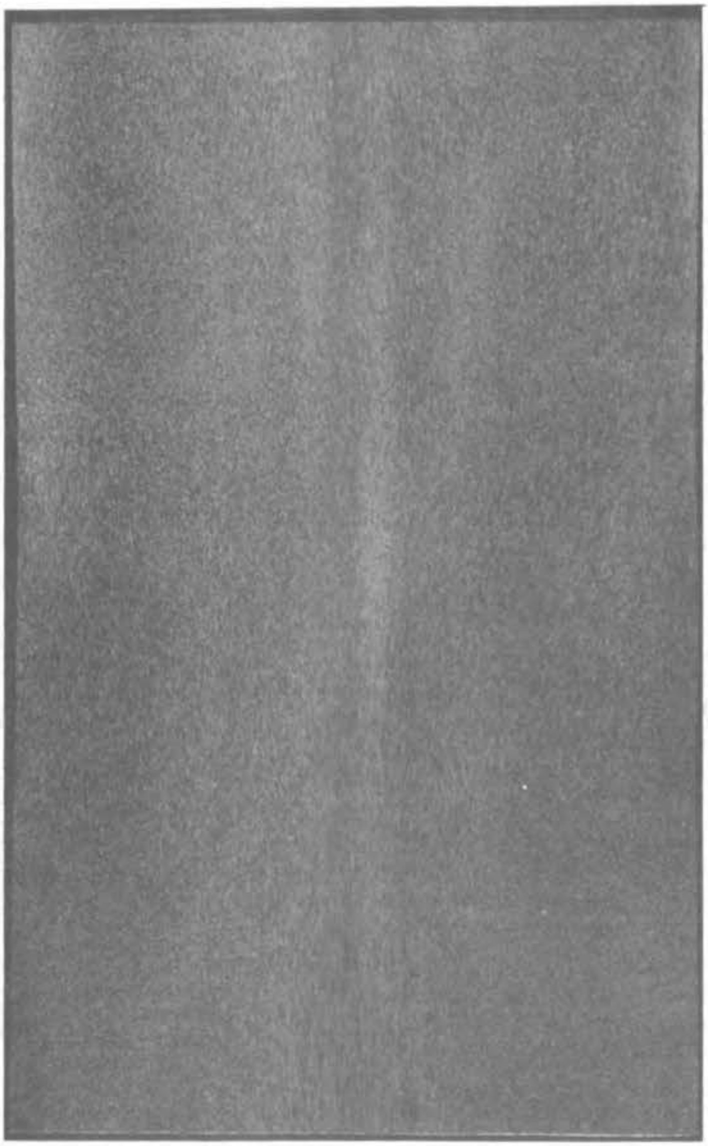


Figure 8. Diffuse shear band in 7075 aluminum alloy forging

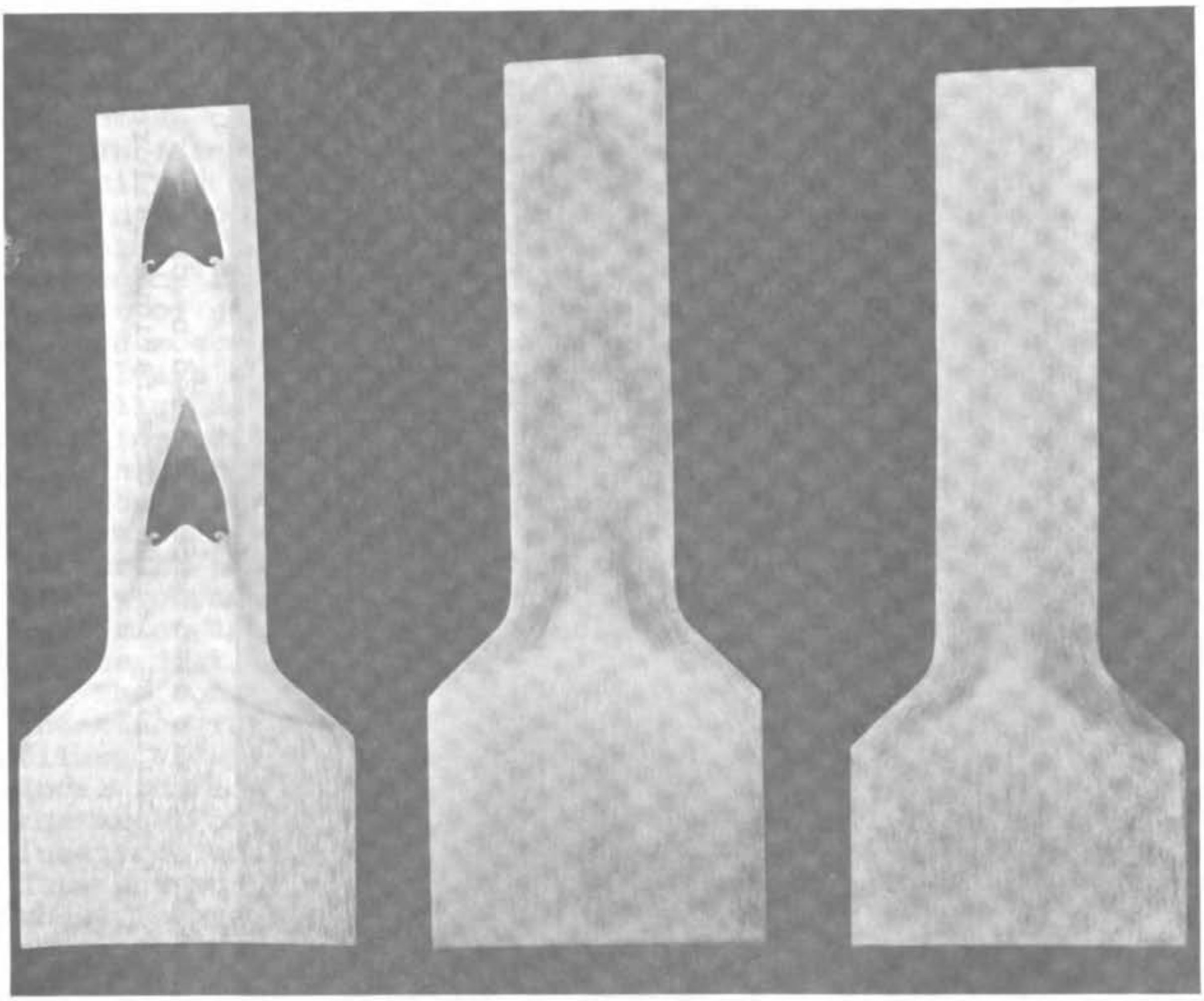


Figure 9. Shear band defect leading to an extrusion center burst

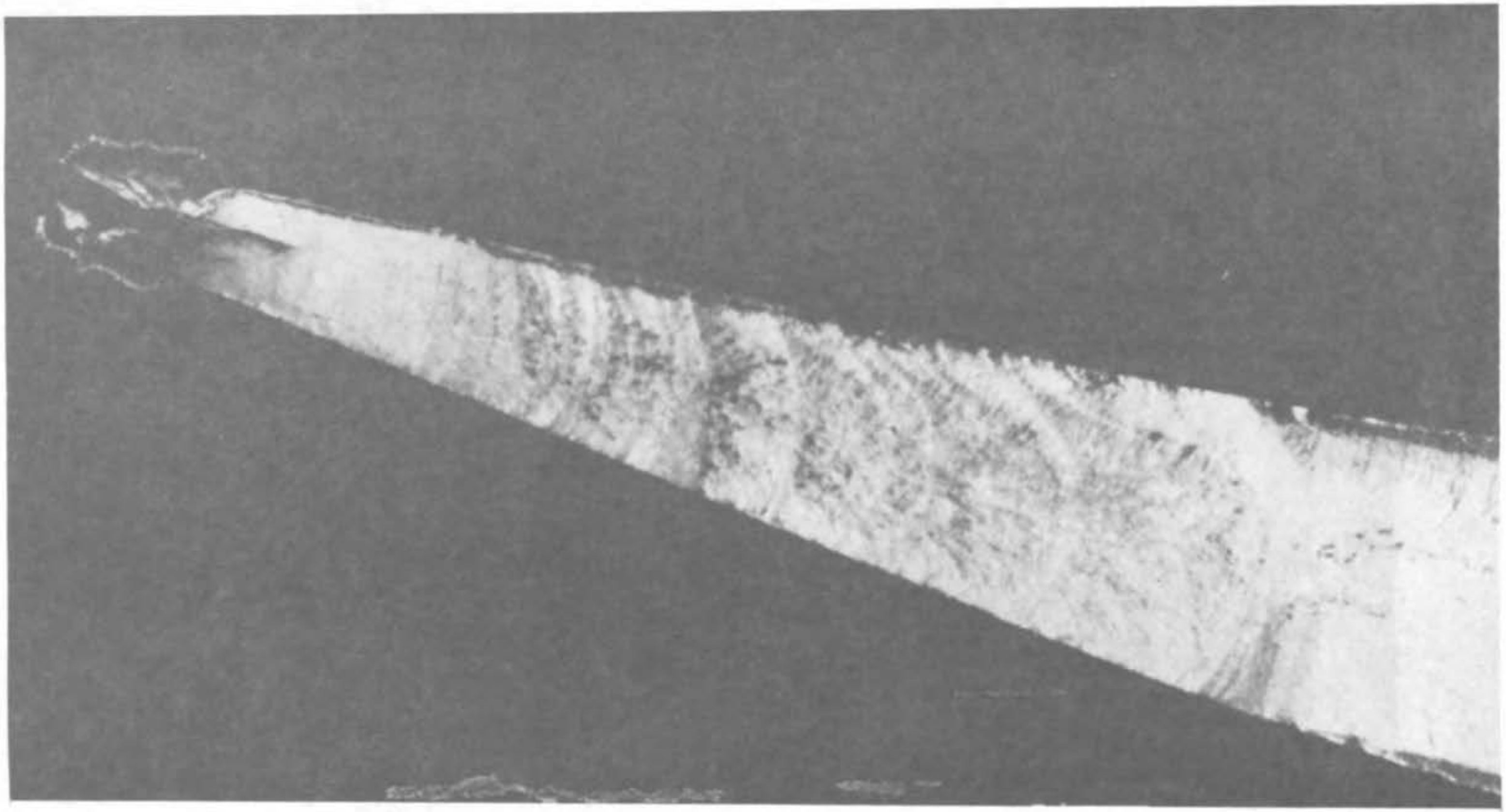


Figure 10. Shear band defect caused by die chilling leading to a fatigue failure

The surface ABCD shown in Figure 7 represents the onset of conditions for adiabatic shear, and surface EFGH represents the boundary between plastic shearing and deformation with fracture. Thus, if the experimental point falls in the volume contained between EFGH and ABCD, fracture processes will occur during deformation. The transition from plastic shear to deformation with fracture can be illustrated by considering the starting point P in the volume characterized by plastic shear. If the friction were to be increased in the direction of the arrow, then deformation with fracture would occur. Now the connection between the areas of material behavior and interface phenomena can readily be seen.

The diagram indicates that plastic shear flow is associated with very low friction levels, and, in most forming processes, low friction levels over the tooling and workpiece interface are desirable. Low friction levels tend to reduce forming loads, increase tool life, and reduce the number of sequences in forming a part, thereby favoring a more homogeneous deformation process. But low friction may not always be desirable; there are situations, depending on the alloy and deformation process, where moderate levels of friction can be effective in preventing defect generation.

In context with this particular problem, our goal is to develop an interface model for designing a lubrication system that will provide controlled friction levels in different parts of the tool and workpiece interface, since it may be an important factor in achieving the proper strain histories and temperature distributions in different parts of the disk cross-section.

The control of heat transfer across the lubricated interface requires an interface model that can treat thick films, and it should have the capability of predicting the local lubricant film thickness. The strong interaction of the areas process modeling and lubrication is obvious. The interface model will require surface velocity and pressure data and surface temperature information from the process model. Thus, it is apparent that none of the models can be developed without considering the required inputs and outputs of the other models. In summary, the objective of this task is to characterize the interface effects in axisymmetric compression of disk-type forgings. This will include the characterization of the effective heat-transfer coefficient and the friction conditions at the tool and workpiece interface.

Task IV--Integration of Material and Process Models

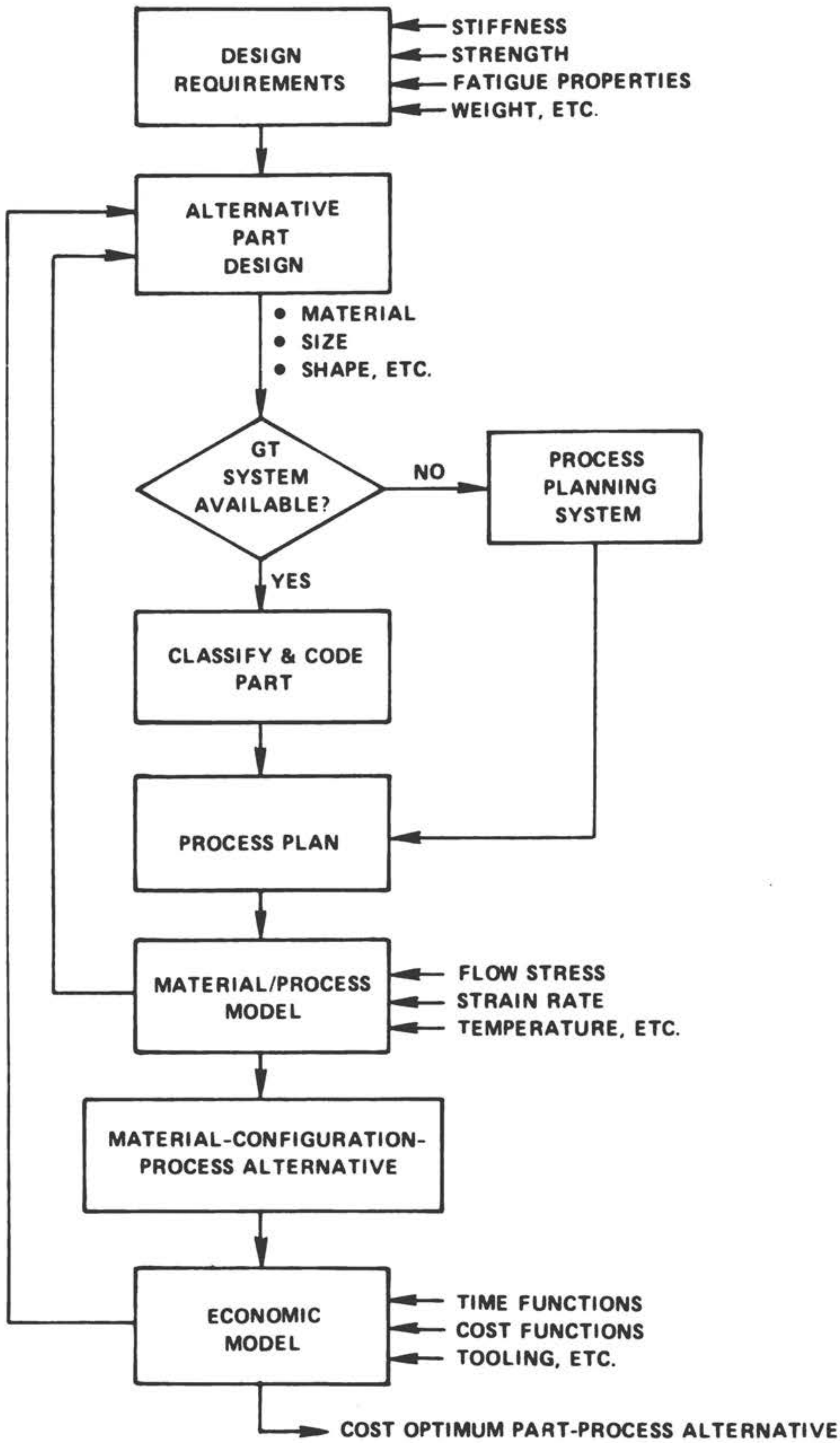
An interactive computer system will be developed that will integrate the material behavior models with the process model to investigate the interaction of the basic components of this processing system. The system will be used to design the forging preform and the dies; to calculate loads, temperature distributions, and metal flow patterns; and to predict microstructure. In addition, an economic model will be developed based on existing process plans in order to establish a figure of merit for the new CAD system.

The basic system structure is presented in Figure 11. The flow chart organization assumes that the designer has determined that titanium could be used for a new gas turbine engine provided the processing specialist can design a forging process that can not only produce the correct shape, but be capable of synthesizing the proper microstructure in the bore and rim regions, respectively. Thus, the system must incorporate and utilize all the information developed in Tasks I, II, and III. In addition, the process specialists must take into account the economic limitations of the various process alternatives, which necessitates incorporation of an economic model in the interactive system. The objective of this task is, therefore, to develop a detailed process plan for forging the dual property compressor disk and to produce a number of subscale disks according to this plan to demonstrate that the processes established in Tasks I, II, and III are adaptable to production conditions.

Information regarding the preform and the forging conditions, i.e., strain, strain rate, temperature, and initial microstructure, generated from research involved in Tasks I, II, and III will be applied to produce disk forgings. The geometry and dimensions of the subscale compressor disk forging are shown in Figure 12. The projected plan view area of the disk forging will be about 23.76 square inches, and the die set will have an impression volume of 12 cubic inches, web thickness ranging from 0.26-0.52 inches, and rib thickness of 0.35 inch. This part is very attractive for the present program because it represents a basic simple disk shape, and it also characterizes a typical compressor disk production part for advanced turbine engine components. The results from producing this part forging should serve validly to apply the processing model developed to produce the larger compressor forgings commercially used. Thus, the systems could have near-term payoff with long-term ICAM implications.

The long-term implications evolve around the possibility for automated process planning and for the development of flexible manufacturing systems that are capable of increasing the ratio of productivity to capital invested in manufacturing. The basic system structure shown in Figure 11 is somewhat advanced for this particular program. It has incorporated into it a hypothetical group technology system for coding or classifying rotating parts of the same generic family. This system would use data bases that are common to both the designer and the process specialist, making it possible for the designer working with the process specialist to select the material, the part configuration, and the process plan that is most cost effective and

Figure 11. Basic system structure



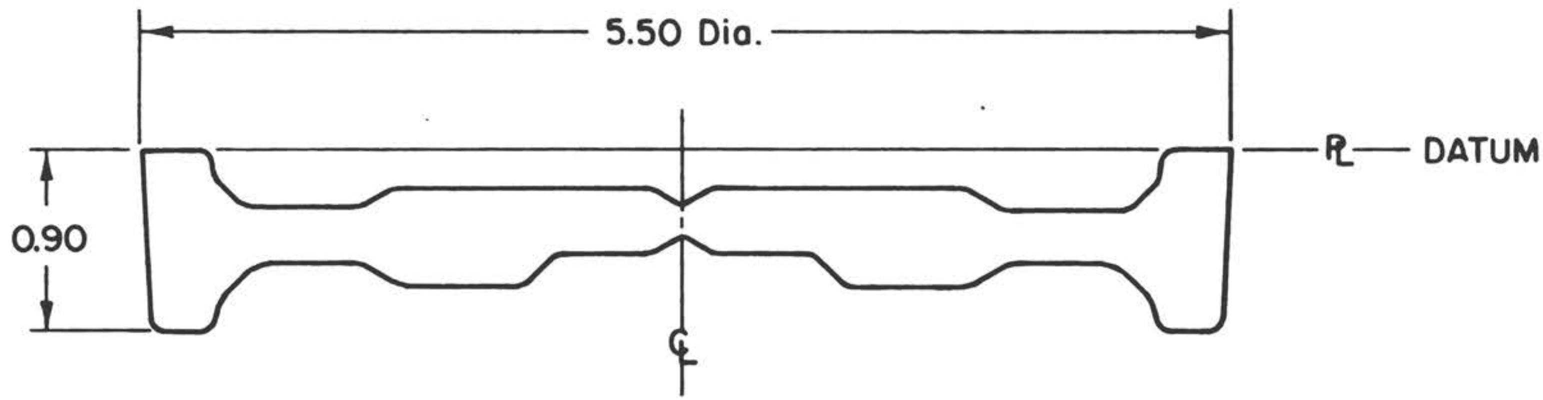


Figure 12. Subscale compressor disk forging

satisfies the design requirement. Having selected the processing sequence that satisfies the design requirements, automated process plans can be generated that represent the most cost-effective manufacturing plan.

Task V--Microstructure and Property Relationships in the Forged Disk

The forgings designed and produced under Task IV will be metallurgically investigated to determine whether the resulting microstructures and properties for the dual property disk correspond to the predictions. The web thickness of the disk will be controlled so that the web portion of the material may be used for fracture toughness, fatigue crack growth rate, and fatigue tests. The microstructures will be evaluated with respect to calibration studies conducted in Task I. Appropriately sectioned disks will be subjected to mechanical property tests--room temperature tensile, 950°F tensile, 1050°F tensile, 950°F - 35 ksi - 0.2% creep, 1050°F - 25 ksi - 0.2% creep, 1050°F - 50 ksi stress rupture, K_{IC}, post creep (950°F and 1050°F) tensile, and post da/dN (950°F and 1050°F) tensile. These mechanical properties of the forgings will be evaluated with respect to models developed under Task I.

Summary Remarks

This effort is a first-generation program aimed at producing an advanced process design system. But it deals only with one material and one process -- considerably more research must be done during the next 20 years to develop and implement such systems on a large scale. The objective is to demonstrate the feasibility of using analytical techniques for solving a nontrivial industrial problem, and, in addition, to underscore the various areas of materials technology and manufacturing that need the attention of competent university-industrial teams.

We are continuing to look to the future in attempting to identify research areas that will lead to the development and implementation of the computer-integrated factory. Some guidelines have been developed around the scenarios of components with optimum localized structures and properties, and fabrication processes for CAM-based factories of the future. One scenario represents an advanced process design system and the other represents an advanced flexible manufacturing system. Together, they represent a CAD/CAM system at the production level of manufacturing that interfaces with production coordination levels of an ICAM system (see Figures 13 and 14). A key issue here is that 20 years is not a long time frame. Some technology available today is being used by only a few companies, but in 10

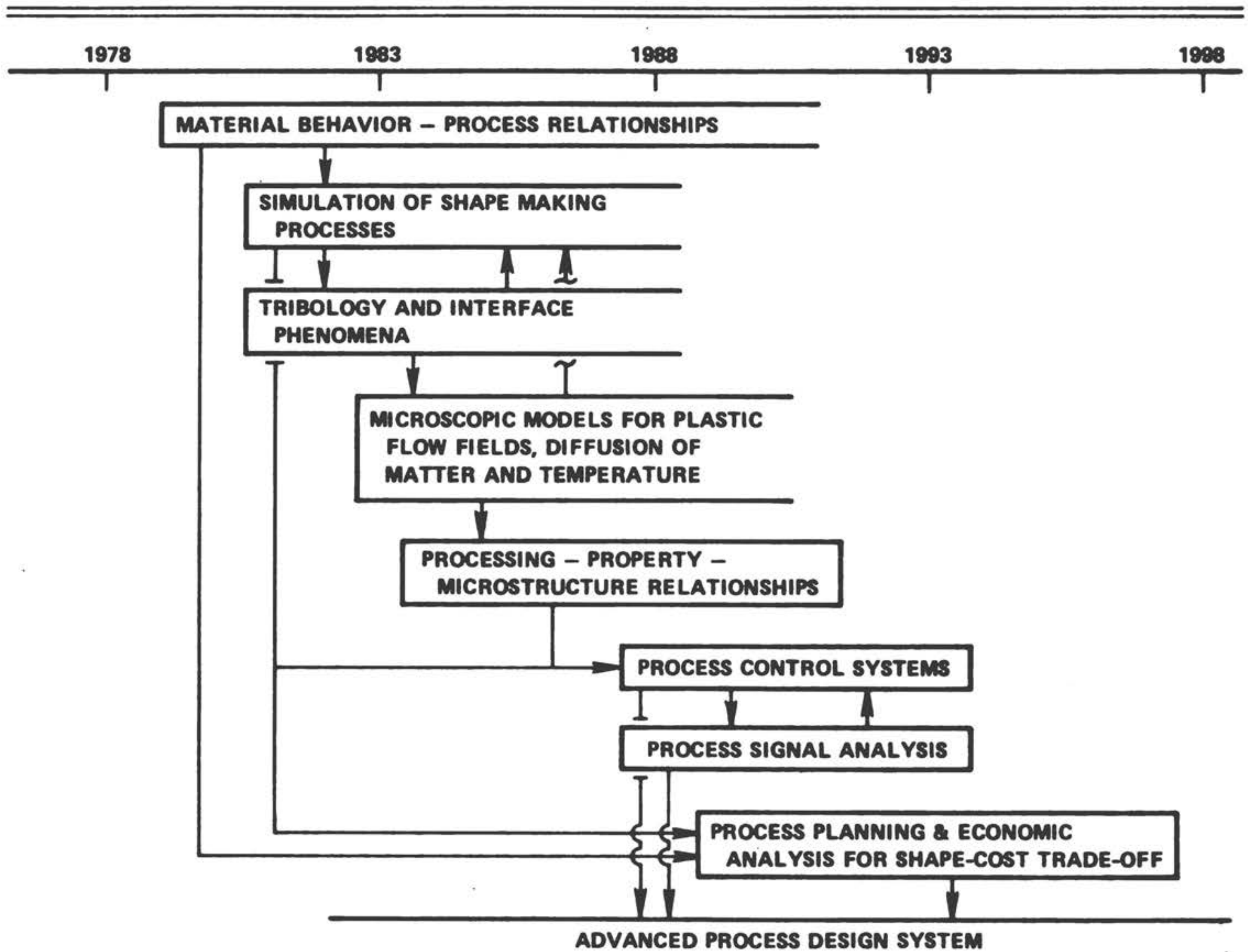


Figure 13. Components with optimum localized structures

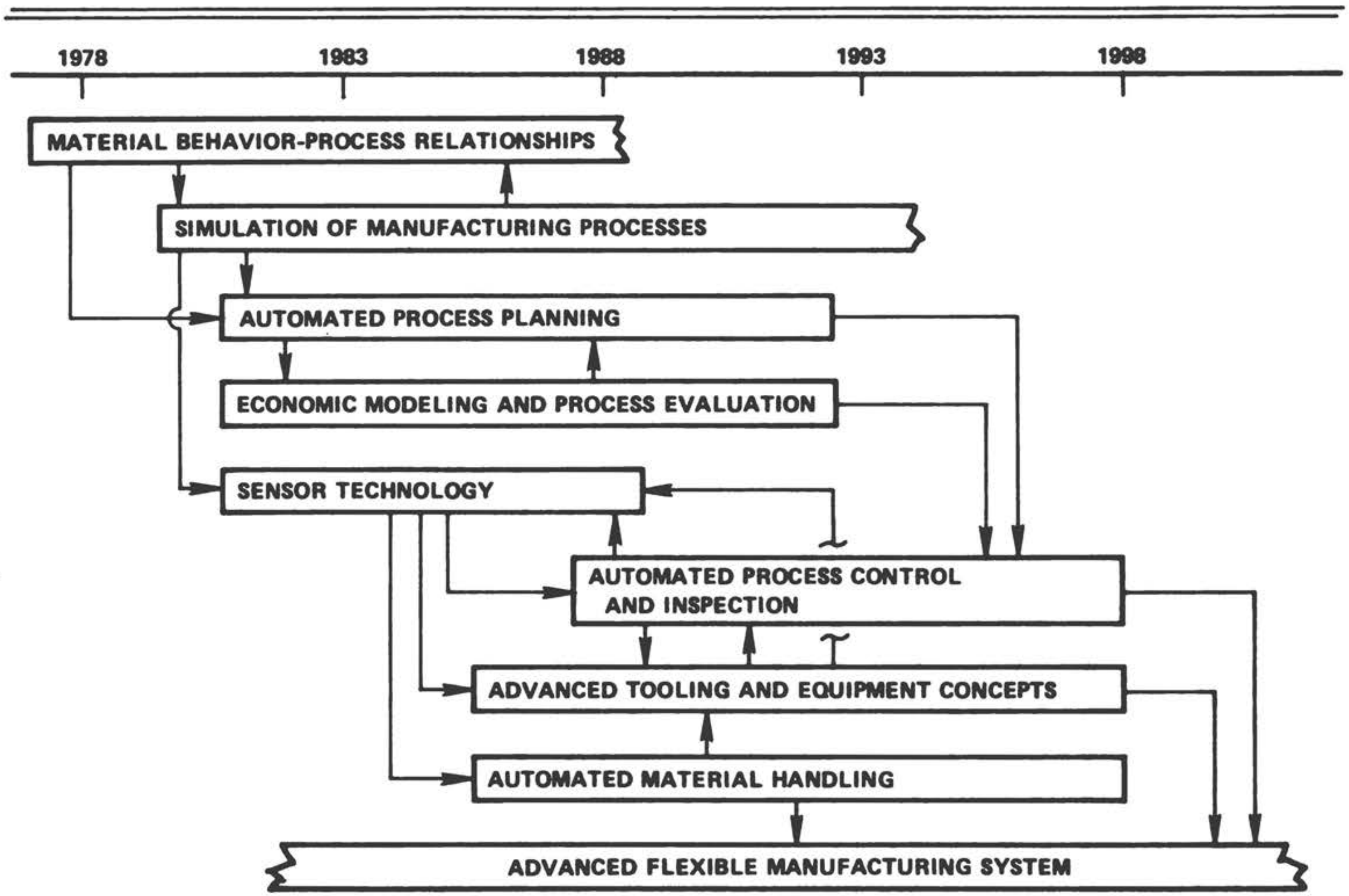


Figure 14. Fabrication processes for cam-based factories of the future

years, for example, other organizations will be implementing these systems for the first time. There is a large amount of basic and applied research that must be accomplished just to generate data bases that can be used by both designers and production specialists. Engineers with interdisciplinary backgrounds in materials technology, manufacturing system design and analysis technology, sensor technology, and business must be trained and diffused into industry and government. These same people must have time to rise to management positions where decisions are made to invest capital in productivity-enhanced, flexible manufacturing systems.

References

1. A. Rappaport. Executive incentives vs. corporate growth. Harvard Business Review, July-August 1978, 81.
2. Bulletin 1958, Comparative Growth in Manufacturing Productivity and Labor Costs in Selected Industrialized Countries, U.S. Dept. of Labor, Bureau of Labor Statistics, 1977.
3. Vanishing innovation. Business Week, July 3, 1978, 46.
4. 1977 Survey of Top Executive's Compensation, McKinsey and Company.
5. A. S. Argon. Physical Basis of Constitutive Equations for Inelastic Deformation. In: Constitutive Equations in Plasticity, ed. A. S. Argon, MIT Press, Cambridge, MA, 1975, p. 1.
6. E. W. Hart, C. Y. Li, H. Yamada, and G. L. Wire. Phenomenological Theory: A Guide to Constitutive Relations and Fundamental Deformation Properties. ibid., p. 149.
7. G. D. Lahoti and T. Altan. Prediction of Temperature Distributions in Axisymmetric Compression and Torsion. ASME Trans., April, 1975, p. 113.
8. H. A. Kuhn. Forming Limit Criteria-Bulk Deformation Processes. Advances in Deformation Processing, ed. J. J. Burke and V. Weiss, Plenum Press, New York, 1978, p. 159.
9. M. F. Ashby. Acta Met. 20:887, 1972.

INSTITUTIONAL BARRIERS TO INDUSTRY-UNIVERSITY INTERACTION IN MATERIALS PROCESSING

George E. Dieter

Based on the 1978 Metallurgy/Materials Education Yearbook, published by the American Society of Metals, and counting only departments that grant doctorates, it is estimated that the principal research interests of academia are distributed mostly in physical metallurgy or materials science (Table 1). It is noteworthy that the distribution for Canadian metallurgy faculties is less heavily weighted in that direction (Table 2). A marked lack of interest and/or expertise in manufacturing is apparent. (Note that mechanical and industrial engineers tend to speak about manufacturing while metallurgists and materials engineers talk about materials processing.) There are probably no more than five or six mechanical or industrial engineering departments with three or more faculty members specializing in manufacturing and there are only two programs accredited in manufacturing engineering by the Engineering Council for Professional Development. To make matters worse, it is likely that over half of the mechanical engineers in this country graduate without taking a single elementary course in manufacturing methods. Such a course is not required in the accreditation guidelines for undergraduate mechanical engineering departments given by the American Society of Mechanical Engineers.

The reasons for this state of affairs are related to the general patterns of growth and development of engineering education and research since World War II. As a result of scientific developments, many catalyzed by the War--radar, jet propulsion, atomic energy, television, computers--and our fascination with the powers of science, practically all industrial corporations started or expanded their research laboratories. Federal funding for scientific research in the universities was formally established, first with the Office of Naval Research (ONR) in 1948 and then with the National Science Foundation (NSF) in 1950. By the late 1950s, when the National Aeronautics and Space Administration (NASA) was established, the universities were almost completely dependent on the federal government for funding, and therefore oriented toward the government relative to acceptable problem areas, values, and rewards. Even today, long after federal research support leveled out, of the $500 million spent by engineering colleges for research in 1977, 73 percent came from federal sources and only 8 percent from industry.

Clearly the federal resources available to the universities for basic research were a strong stimulus in shaping academic development in the postwar years.

Table 1. Research interest of U.S. metallurgy and materials faculty

Physical Metallurgy or Materials Science		656	84%
Extractive or Chemical Metallurgy		39	5%
Mineral Processing		17	2%
Materials Processing		68	9%
Deformation Processing	15		
Casting	22		
Powder Processing	13		
Welding	14		
Design	4		

Table 2. Research interest of Canadian metallurgy and materials faculty

Physical Metallurgy of Materials Science	55	57%
Extractive or Chemical Metallurgy	22	23%
Mineral Processing	7	9%
Materials Processing	12	13%

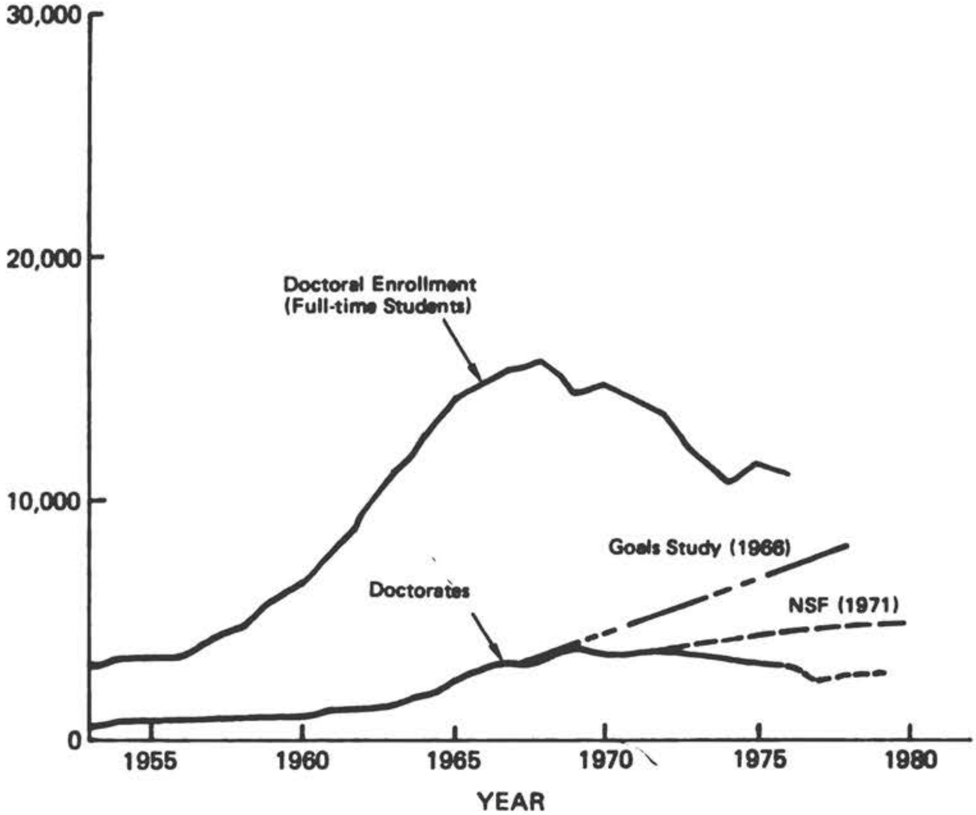
Experience with engineers in World War II showed a need for major curriculum revisions -- greater facility in mathematics, more analysis in engineering courses, and more time devoted to humanities and social science. Practice- and skills-oriented courses, and especially manufacturing-oriented courses, were abandoned to accommodate the curriculum revisions. These courses deserved to be replaced at the time because of their weak problem-solving content; but once gone from the curriculum it has been difficult to reinstate their modern replacements.

The strong trend toward more analysis (engineering science) and greater involvement in research has had major impact on the nature of engineering faculties. Prior to World War II only a small number of engineering faculty had doctorates, and most had significant industrial experience. (There were less than 50 engineering colleges granting doctorates.) Today there are nearly 150 doctorate-granting engineering colleges and nearly all faculty have doctorates. There are 773 doctorate-granting engineering departments. Figure 1 shows the increase in the number of doctorates in engineering. While this faculty is better able to teach advanced-level material and to introduce more analysis into the curriculum, it is weaker in industrial experience and broad engineering perspective than the faculty of 30 years ago.

A strong influence on campus has been the prestige and freedom for undirected basic research of NSF grants. The strong ethic in the engineering schools for research -- practically identical with that in physics and chemistry -- places greater emphasis on publication in refereed journals and forces the young professor to become a highly specialized expert in a well-defined discipline. Those areas that tend to be interdisciplinary -- such as materials processing -- suffer from this well-established research ethic.

If the field further requires strong industry interaction, e.g., for problem definition and experimental facilities, as does materials processing, there is a further difficulty for the academic researcher. Industrial interaction does not currently rank high in the academic value system. Industry has the reputation of being hard to deal with and not worth the bother if you can get nice clean, no-strings-attached NSF or ONR money. There is no well-established tradition for industry-university-government interaction in this country as there is in Germany and Japan. Some people have traced a correlation between the ascendancy of U.S. science and the decline in our relative economic position in the world, and the widening gulf between the universities and industry.

Finally, there is a question about what constitutes proper research by an engineering professor. One academic research administrator has said that no young professors could expect to obtain tenure for research on the mechanics of grinding. No investigation was made of the quality of



SOURCE: Engineering Manpower Commission

Figure 1. Engineering doctoral enrollment and degrees U.S. totals, all schools

the work, just that the subject area did not appear academically suitable. The subject area was too applied to be considered an acceptable academic research area. There is no question that there are "safe areas" for a young researcher to work in -- areas where funding is relatively good and peer acceptance is high. For most of the 1960s and 1970s these have been subjects related to materials science, where one could use an elegant thermodynamic analysis or produce eyeboggling photographs of dislocation behavior in thin films. Materials processing was just too macro and messy. The three characteristics that make materials processing a particularly difficult field of science for the universities to address are that it is interdisciplinary, it is applied, and it requires interaction with industry.

Also, there is no question that funding for academic science is determined by peer acceptance. As a field shows scientific promise more people enter with more proposals and papers, and a "community" begins to develop. Through a variety of media (advisory committees, seminars, proposals, conferences) they begin to convince the federal research administrators that the field is growing in importance and hence needs more funding. More support brings more people into the area, and thus it grows.

While there are many indications that the situation is changing slowly, it must also be realized that currently we have a period of frozen resources and status quo for the universities. Pure science and "big science" are fighting hard to retain their share of the resources. That they are succeeding can be judged by the plight of the Research Applied to National Needs (RANN) Program in NSF.

It would seem that the key to changing the academic role in materials processing is industrial interaction which will provide the relevance, the stimulus, and the help to achieve meaningful progress. But, to achieve this will require considerable accommodation by both parties.

Table 3 lists possible modes of industry-university interaction. Generally, the fiscal involvement flows in the same order, from top to botton. Of this long list, the only meaningful mode of interaction that can have a substantial impact on academic science for materials processing is sponsored research. Faculty are rated on their research activity. Their careers are built on it, and their salaries depend on it. Thus, it is an area in which one can get their attention.

What are the barriers to achieving this industry-university interaction, which we all agree is missing and is needed for a healthier, more viable research climate?

Within industry there is some doubt concerning university interest in and commitment to collaboration with industry because of the universities' history of changing attitudes and rebuffs. Another factor is that industrial support for R&D has barely kept up with inflation, and it is therefore difficult to find funding for universities; especially since industry has an unrealistic appreciation of

Table 3. Modes of industry-university interaction

Part-Time Graduate Programs
Instructional TV
External MS Program
Mid-Career Education

Short Courses	One to Two Weeks
Major Courses	Four to Eight Weeks
Year Program	

Seminar Speakers
Plant Visits
Student Projects

Coop Programs
Practice School
Summer Jobs for Students

Consulting
Resident Professor in Industry
Visiting Industrial Professor

Visiting Committee
Associates Program

Fellowships or Unrestricted Grants
Sponsored Research

the cost of academic research and the needs for sustained funding, and does not understand that most university research efforts are driven by availability of funding.

The issue of patents and proprietary rights often is raised as an impediment to industry-university interaction, but it seems apparent that this is an excuse to avoid confronting the real issues.

As for the universities, initially the desired technical expertise may not be found among existing faculty. We have seen how few faculty members are oriented toward materials processing; unless there is the promise of a long-term funding commitment, many may not want to move into a new field, and one that does not offer the valued specialization.

A key element in industry-university interaction is producing a research program that provides a good educational experience for the student and is possible within the constraints of time, resources, etc. For basic processing science the time frame should coincide fairly well with the usual doctoral time frame. However, whenever a university deals with industry, more responsiveness to deadlines and schedules is required than is usual in the university atmosphere. Though blame usually is attributed to the graduate students, it may be that the faculty do not place high enough value on reporting to the sponsor and delivering results on schedule. Published papers are held in high regard since they enable the authors to attain promotion, peer recognition, and prestige. Interaction with industry may restrict publication, and therefore it must substitute something in its place -- a real sense of accomplishment or a special excitement in being a part of a highly successful project. In fact, industry must be more concerned with peer recognition for its own engineers, as well.

The only significant barrier to industry-university interaction on basic processing science is the availability of a reliable source of funding. If NSF, The Department of Defense (DoD), or the Department of Commerce would announce a $20 million per year program for processing science there would be no dearth of competent engineering faculty who would establish long-term ties with industry. Perhaps the number of good investigators and worthwhile ideas would be inadequate at the beginning, but within a few years, a program with high standards and long-term funding, would attract them and their students as it did when the Advanced Research Projects Agency (ARPA) Labs were established. Existing doctoral programs could easily accommodate interaction with industry <u>at the basic science level</u> -- if the money were there.

In my opinion support for basic processing science is clearly a function for government -- not industry. However, industry could and should do a better job of articulating the need for a massive effort to upgrade the science base of processing and manufacturing, and informing government.

Industry should have a major input in formulating problem areas and participating in the research where they have special facilities or expertise.

There is another important area for industry-university interaction -- advanced engineering research. This research is not so basic that it leads to a doctoral thesis, but it is essential to developing a technology and maintaining technological preeminence. Most good industrial labs spent much of their time in this type of research before they were forced by government regulations and competitive pressures to emphasize shorter-range or more proprietary research.

It appears that universities are the place to do this type of research because:

- Advanced engineering, more than basic research, requires industry interaction, so the problems of interaction must be solved in order to do the research.
- Universities' ability to do this research will resolve the credibility problem.
- This type of research is very appropriate for a solid master's degree, and it is at this level that most of our graduates need to be educated -- not at the doctoral level. We produce large numbers of doctorates chiefly because the basic research-oriented funding mechanism requires that we have doctoral students.
- An ongoing program that deals with some of industry's problems provides relevance and renewal for the longer-range basic research program.

The Processing Research Institute (PRI) at Carnegie-Mellon University (CMU) was such a program, offering a two-year professionally oriented Master of Engineering degree. Students worked on industry-sponsored projects half-time, and attended classes half-time. In the five years of its existence (it was closed in 1977), PRI involved about 25 faculty members and 45 students in 66 projects with an aggregate dollar value of $2.1 million. The program addressed all the barriers to industry-university interaction.

The credibility of university commitment was indicated by the existence of a special program of this type. The PRI program was started with a $2 million grant from NSF's RANN program; that is real commitment.

Because it had substantial funds, PRI was enabled to draw attention inside CMU, move slowly to choose the best projects, and help industry over the credibility gap by offering to share project expenses on a 50/50 basis.

It was able to address the proprietary problem by dealing at the master's and not the doctoral level. Doctoral theses are sacrosanct, and are available to all comers on the shelves of the university library, whereas master's theses are a dying breed. The PRI program did not require a thesis, but instead, a detailed comprehensive report to the sponsoring company. These reports were more closely held inside the University and not sent outside without the permission of the sponsoring company. This is not to say that proprietary issues were not a problem. The negotiation for practically every project was at one time or another held up by the sponsor's legal office, but there was no instance where a project did not go through because of proprietary concerns.

CMU was fortunate in having strong faculty expertise. There was a nearly one-to-one correlation with the level of faculty experience and expertise and the success of the project.

Because it was a two-year master's program, students had at least a half-time commitment to the project. PRI tried to create the attitude that the project was more important than the classroom studies. Graduate student performance overall was outstanding (they were a self-selected group) and the problems that did exist can be attributed more to poor faculty supervision than to the students themselves.

The two-year Master of Engineering degree program was created specifically to lower the barriers to industry-university interaction.

It was the last barrier, publishability of results, that proved the hardest to overcome. Faculty who participated in the PRI to a high degree had a low academic publication record -- and this led in some instances to difficulties with tenure and promotion. This is not an easy problem to solve -- but it would be ameliorated if there were more money for basic processing research so faculty could engage in a full spectrum of materials processing research.

The basic reason for closing PRI was funding. The processing area simply did not appear to be a good place to make a major investment. NSF money had run out and there was no ongoing NSF program that could be tapped. The Commerce Department and National Productivity Commission funding never materialized. Industry support for individual projects was available, but not nearly as easy to obtain as federal research support. As a simple business decision, it was not a good economic risk to continue this activity compared with other processing alternatives, say in the energy area.

What can be learned from this situation?

- It is possible to develop formats of graduate education that can interface with industry.
- Some form of long-term support, whether provided by federal or state government, is needed.
- The level of sympathy for and understanding of industry and its problems is low on most campuses. The best short-term solution to this is money.

METAL REMOVAL

Raymond W. Fenn, Jr. (Panel Chairman)

Introduction and Scope

It is well recognized that machining constitutes a major cost in manufacturing. Current estimates indicate that machining costs in the United States are now approximately $60 billion annually.[1] These costs are related directly to part design, physical characteristics of the workpiece, and the efficiency of the metal-cutting process involved. Cost reductions in the former two areas have been achieved mainly by minimizing the complexity and number of machining operations on a given part and by modifications in alloy composition and microstructure. Both approaches have proved to be highly beneficial. Significant cost savings also have been realized by improving the efficiencies of the processes themselves. Most notable in this respect has been the decreased labor costs brought about by the development and application of automated and numerically controlled machining equipment. While these installations have proved to be of great value, machining efficiencies have remained well below theoretical maxima. Furthermore, current inflation in material, capital equipment, and replacement costs coupled with increased labor rates have promoted a steady decline in the economic advantages of these facilities. If such trends are to be reversed, significant advances in metal removal technology leading to increased productivity must be made.

Automated machining involves a number of operating cycles that have a direct influence on process efficiency. A critical problem in attempting to improve machine performance is the identification of those processing steps whose modification would have the greatest impact on productivity. Through a rate analysis of all normal machine operating sequences, Schmidt and Boam[2] demonstrated that a reduction in chip-to-chip machining time (i.e., increased cutting speed) would provide the greatest immediate opportunity for reducing metal removal costs. Subsequent studies by King[3,4] using aluminum as a model material, verified this premise and demonstrated that a 50 percent reduction in contour milling costs was feasible at cutting rates up to 12,000 sfm (surface feet per minute). His results also showed that with increasing speed, cutting forces and tool wear decreased permitting thinner sections with straighter, deeper, closer tolerances to be milled than were heretofore thought practical. Because of the exploratory nature of these studies, little or no attention was given to chip segmentation mechanisms, tool-workpiece interface reactions, cutting tool wear behavior, and lubrication effects. Such information is now urgently needed for a wide variety of metallic materials including aluminum, titanium, and ferrous alloys to provide a definitive assessment of process capabilities in the high-speed metal removal regime ranging from 5,000-30,000 sfm and to establish a sound science base for commercial implementation of the technology.

Conclusions and Recommendations

Based on consideration of all inputs from participants attending the National Materials Advisory Board (NMAB) panel meeting on High-Speed Metal Removal, the following conclusions and recommendations were resolved by a consensus of panel members as being relevant to science base status and needs:

1. High-speed machining in the range from 5,000-15,000 sfm on aluminum alloys has been demonstrated successfully in production environments. However, inconsistencies in the preliminary data due to tool geometry variations and other factors indicate that further studies are warranted. Specifically, work on aluminum alloys should be extended to a cutting speed of 30,000 sfm to verify anticipated favorable trends with respect to metal removal efficiency, tool forces, tool life, and workpiece quality. Throughout this endeavor, emphasis should be placed on estabishing whether such trends are associated with a change in chip segmentation mechanism which occurs above some critical cutting velocity. Additional studies on titanium, nickel, and ferrous alloys also are required to determine whether similar beneficial effects exist for these materials as well.

2. With the exception of tool wear, conventional metal removal processes are comparatively well understood. Above 5,000 sfm, however, little is known about chip segmentation, tool wear, and other parameters that play major roles in controlling process economics. In order to achieve substantial increases in productivity, the influence of these factors on metal removal efficiency must be sufficiently understood and modeled so that systematic approaches can be applied effectively in a production environment. Future investigations of cutting mechanisms and related phenomena should at the very least address the following: workpiece deformation and fracture behavior, chip segmentation, tool wear, interface reactions, and temperature, resonance, and shock wave propagation effects.

3. Contemporary knowledge of tool wear and tribology is limited to conventional metal removal rates. These aspects of the cutting process most likely will impose major barriers to the commercial implementation of high-speed machining technology. Definition and modeling of tool degradation and failure mechanisms as functions of tool geometry, thermal history, and tool and workpiece material properties, and the chemistry and lubrication characteristics of cutting fluids are required. In addition, on-line, real-time sensing techniques for monitoring tool forces and cutter wear must be developed to avoid potential damage to machine tools and parts.

4. Preliminary design concepts for high-speed machining centers now exist. However, funding to examine alternate system and subsystem approaches is needed to ensure the timely and successful implementation of the process technology generated from research and development efforts. High-speed machining programs will require new spindle systems, control networks, coolant and lubrication systems, high-speed tool changers, and automatic parts and materials handling equipment.

5. The problems associated with the ultimate commercial implementation of high-speed machining are complex and interactive, and they span a wide range of technical fields. In all probability, an interdisciplinary systems approach to technology management and application will be required to achieve specific research and development objectives. Needed scientific disciplines include metallurgy and materials science, theoretical and applied mechanics, physics, machine design, control theory, computer programming, and others.

6. High-speed machining research and development and process implementation goals can be achieved through a cooperative effort involving industry, university, and government participation. Furthermore, sufficient long-term funding should be dedicated to the overall program to insure completion of individual tasks and to maintain a high level of interest and activity by supportive organizations. How such an effort may be stimulated and funded is not entirely clear at the present time and is in need of further study. However, several suggestions emanating from panel discussion included establishing a national high-speed machining center(s) for conducting basic experimental studies and an industry/university metal removal advisory board to assist in the

planning, guidance, and implementation of such work. The construction and operation of such a facility would be derived from government and industrial funding in which the latter could be written off by participating companies as tax credits. University participation might be encouraged by government support of graduate students pursuing careers in the area of high-speed machining and assuring that indivdual professors receive publication privileges and recognition (e.g., advancement toward tenure) by their respective universities for directing such studies.

Technical Background

The feasibility of machining metallic materials at high speeds (i.e., >5,000 sfm) has been demonstrated successfully in several comprehensive studies on iron-, nickel-, titanium-, and aluminum-base alloys. In 1958, Vaughn[5] explored the effect of cutting speeds ranging up to 240,000 sfm on the machining characteristics of 4340 and AM 350 steel, Inconel X, Ti-6Al-4V, and 7075-T6 aluminum. The tests, which simulated a planing operation, were performed by propelling alloy workpieces (projectiles) across a single-point cutting tool positioned in a gun barrel extension, using 20 mm cartridges to provide the driving force. His data showed that surface finish improved and tool forces, temperature, and wear behavior essentially remained unchanged with increasing cutting speed. Moreover, most of the heat generated during deformation was found to be retained by the chips, suggesting that the segmentation process involved adiabatic shear.

Although the implications of Vaughn's work with respect to increased productivity were recognized, the necessary machine tools for pursuing the method on a commercial basis were not available. Milling studies at speeds up to 12,000 sfm, however, subsequently were conducted on titanium alloys by Colwell and Quackenbush[6] in 1962 and aluminum alloys by King[3,4] in 1976, using conventional machines with modified spindle systems. Their results concerning workpiece perfection, tool performance, and thermal effects, particularly with regard to the adiabatic nature of the chip formation process, were in agreement with those of Vaughn.

In recent years, advances in spindle design, drive mechanisms, and computer control systems has stimulated some degree of commercial implementation of high-speed machining technology. The Lockheed Missiles and Space Company recently installed a high-speed milling center which is now routinely cutting a complex-shaped aluminum alloy missile component at 5,000 sfm on a production basis. Manufacturing costs for this part have been shown to drop sharply as a direct result of the concomitant reduction in machining time. Major operating difficulties of the center primarily are associated with downtime promoted by spindle and table drive mechanism malfunctions. A list of organizations presently engaged in high-speed machining production and development work and a description of the operation(s) being performed has been assembled by Kahles, et al.[7] Portions of these data which involve utilization of cutting speeds above about 5,000 sfm are reproduced in Table 1.

Panel Discussion

During panel discussion, it was revealed that at least two U.S. companies had machined titanium-base materials and low-carbon steels successfully above 15,000 sfm in a laboratory environment. Although details of the operations were not advanced, it was indicated that results paralleled those of King[3,4] and showed that once a critical cutting speed was exceeded (viz. approximately 15,000 sfm), tool forces and wear decreased. Previous experimental findings at conventional metal removal rates, even with aluminum alloys, do not reflect these beneficial effects and are in direct conflict with the high-speed machining data. At conventional cutting speeds approaching 5,000 sfm, the apparent lack of agreement appears to be associated with tool geometry variations and other ill-defined factors such as lubrication and resonance effects, machine rigidity, etc. It was concluded by a consensus of panel members that as a first priority in establishing process feasibility, systematic machining studies should be performed on aluminum alloys at speeds of 5,000-30,000 sfm to resolve existing inconsistencies between conventional and high-speed machining data. Specific attention should be given to defining the effect of cutting speed on metal removal efficiency, tool forces and wear behavior, and workpiece quality. The work subsequently should be extended to include similar evaluations on selected titanium, nickel, and ferrous alloys to determine whether these materials exhibit cutting and tool wear performance trends similar to aluminum alloys. Ultimately, the economic advantage of high-speed machining should be critically assessed.

At its present stage of development, high-speed machining has evolved on an empirical basis essentially without any fundamental scientific knowledge of the chip segmentation and tool wear mechanisms involved. Both mechanisms are difficult to interpret because of the large strains and high strain rates encountered during processing coupled with the fact that plastic deformation is unconstrained. Because of their important influence on process economics, these mechanisms must be modeled for various workpiece and tool material combinations operating at cutting speeds above 5,000 sfm in terms of constitutive equations that interrelate the effects of critical process variables. At the very least, such investigations should include both single and polycrystal workpiece materials and

Table 1. Current high-speed machining production and development work (from Metcut Research Associates, Cincinnati, Ohio)

Investigator	Operation	Work Material	Tool Material	Speed ft./min. (m/min.)	Feed in(m) per rev or per tooth	Depth of Cut in (mm)	Cut Fluid	Tool Life min.	Machine Tool Features	Remarks
Lockheed MSC United States	Milling	Aluminum 7075	2-flute, solid carbide mills (1¼" rough; ¾" finish	Up to 18,000 rpm	Up to 180 ipm				XLO-208 CNC with liquid cooled Bryant spindle	
	Milling	Aluminum 7050 and 7075	Carbide end mill, 2-flute, ¼" to 1" dia. & 8" dia.	1000-12,000 (305-3670)	70-250 ipm 70-250 ipm	.0625-.250 (1.6-6.1)			Sundstrand OM-3 mill, 20 HP, 30,000 rpm & 3 HP, 100,000 rpm spindles; Bullard VTL, 20 HP, 6000 rpm milling spindle: XLO-208, 25 HP, 18,000 rpm spindle	
General Motors Co. United States	Turning and milling	Aluminum	C-2 carbide or diamond	2000-5000 (610-1524)				10,000-60,000 in^2	Transfer and high volume lathes	In production and development
	Turning and milling	Aluminum	C-2 carbide or diamond	2500-5000 (610-1524)				10,000-60,000 in^2	Transfer and high volume lathes	
Ford Motor Co. United States	Face milling	Aluminum 380 diecast housing cryst. diamond tips	14" dia. 12-tooth cutters with poly-cryst. diamond tips	12,645 (3855)		.065-.015 (1.65-.38)			LaSalle 14-station pallet type transfer machine	
	Boring	Aluminum 38- diecast housing	Polycrystalline diamond	4967 (1514)		.080-.015 (.2-.38)				Boring and chamfering are done with diamond inserts set in the face mill cutter
	Chamfering	Aluminum 380 diecast housing	Polycrystalline diamond	4967 (1514)		.080-.015 (.2-.38)				
Pneumo Precision, Inc. United States	Turning	Aluminum extruded	Single crystal	2400 rpm	9.6 ipm	.001 (.025)	Mist		Pneumo MSC-305 lathe, 2 HP spindle, 4500 rpm	2.0 microinch finish
	Single-point milling	Aluminum 6061, 4" dia. flat mirror	Single crystal diamond	12,000 (5658)			Mist		Pneumo MSC-500 fly-cutting machine 1.5 HP spindle, 12,000 rpm	10 microinch finish vacuum chuck
Mercury Machine Div. Brunswick Corp. United States	Face milling	Aluminum 380 diecast outboard engine blocks	Polycrystalline diamond	10,000 (3050)			Dry	18,000 castings		
Centre Technique des Industries Métcaniques	Turning	1018 ann; 4110 Q&T, 301 SS	Ceramic	1610-11,810 (500-3600)	.004-.008 (.1-.2)	.008(.2)	Dry	15 at 1000 m/min	Special lathe, 20 KW 12,000 rpm	
Kyoto Univ. Japan	Turning	Medium carbon steel S45C billets, 274 HB	Carbide, ceramic and cermet	492-9840 (150-3000)	.0004-.004 (.012-.1)	.004-.035	Dry	500-.02	VDP lathe, 15 KW, 5600 rpm 520 mu	Wet and dry cuts compared; force & surface finish data; 4 mm flank wear TL criterion
Osaka Univ. Japan	Orthogonal Cutting Oblique Cutting	Mild steel, 145 HV Aluminum, 28 HB Mild steel, 143 HV Aluminum, 28 HB	Carbide and ceramic Carbide and ceramic	3280-22,960 (1000-7000) 3280-26,240 (1000-8000)		.004(.1) .006(.15)			Ultra-high speed lathe 1300-7000 rpm Grinder spindle, 4800 rpm	Measured forces, wear, surface roughness Forces measured
General Electric Co. United States	Turning	1045 steel, 150 HB	Carbide and ceramic	500-18,000 (152-5488)	.010(.25)	.100(2.51)	Dry	120-6	160 HP lathe, 2500 to 5000 rpm	Measured forces and wear
University Ljubljana Yugoslavia	Turning	Aluminum alloy D50 (free cutting)	P20 carbide	330-13,120 (100-4000)	.002-.009 (.044-.222)	.020-.080 (0.5-2)	Dry		Experimental lathe, 8500 rpm	Investigated forces and surface quality
Valeron Corp. (reporter) United States	Milling	Aluminum ingots	Carbide inserts (16) mounted on 6 ft. dia. cutter	12,000 (3658)	100 ipm	0.125 (3.18)			Retrofitted planer mill	
Vought Corp. United States	Milling	Aluminum 7075-7651 6061-7651	2-flute brazed carbide (1½" dia.)	7,900 (2,408)	0.005 ipt	0.250 (6.350)	Dry	>372	Sundstrand OM-3 mill, 20 HP, 20,000 rpm spindle	Measured forces, wear, and deflection

should address the following phenomena: workpiece deformation and fracture behavior, chip segmentation, tool wear, interface reactions, temperature, resonance, and shock wave propagation effects. The mathematical formulations so developed must be evaluated in a production environment and preferably be adaptable to CAD/CAM utilization.

Many models have been proposed to account for the gradual loss in cutting response of a tool material during conventional machining operations.[8-13] For the most part, tool performance is interpreted in terms of flank and crater wear rates that are dependent on a host of machining and cutting tool variables. When the workpiece has a relatively high melting point, wear mechanisms, which strongly depend on the tool-workpiece interface temperature, severely restrict the rate of metal removal. These include a shearing away of tool surface layers, plastic deformation of the tool, and interdiffusion reactions between tool and workpiece. With increasing cutting speed, interface temperatures rise, and the rates of crater and flank wear increase rapidly. The tool material, tool geometry, and the characteristics of the workpiece play dominant roles with respect to which wear mechanism will predominate.

Tool wear and tribology effects undoubtedly will impose major barriers to the commercial implementation of high-speed machining technology. To date, no data have been published on tool wear behavior for cutting materials other than aluminum alloys at speeds exceeding 5,000 sfm. As a consequence, a severe gap exists in the technology, which has caused many panel members to question the potential breadth of application of high-speed machining. In the opinion of the panel, definition and modeling of tool degradation and failure mechanisms as affected by tool geometry, tool and workpiece material properties, and the chemistry and lubrication characteristics of cutting fluids are of utmost importance. Moreover, on-line, real-time sensing methods for monitoring cutter forces and wear must be developed for industrial machining centers which can be utilized effectively as a means for avoiding damage to machine tools and parts.

A number of design concepts presently exist for high-speed machining centers. The limitation in cutting speed when machining aluminum is determined by the machine tool, tool changing mechanism, and work handling system rather than by the cutting process itself.[7] Several panel members, however, expressed the belief that other materials such as titanium, steel, and cast iron will require further development of machine and cutting tools and subsystems including control networks, coolant and lubrication mechanisms, tool changers, spindles, and automatic parts handling equipment. Such studies, however, should be reserved pending the outcome of economic analyses.

Potential Benefits

The successful commercial implementation of high-speed machining promises dramatic increases in productivity and significant concomitant reductions in manufacturing costs. One of the more profitable types of operations is where the parts being machined require the removal of large quantities of material. Figure 1, for example, demonstrates the improvement in metal removal efficiency obtained with increasing cutting speed during the milling of aluminum alloy blocks to various depths.[3] The results demonstrate that cutting speed increases of 500-percent yield a reproducible 300-percent increase in metal removal efficiency regardless of the depth of cut. Machines performing a complex contouring sequence may not reflect all of these savings; however, as cutting speeds increase, production costs decrease. An excellent case in point is illustrated in Figure 2 which compares actual conventional and computer-simulated high-speed machining costs for manufacturing an L-1011, wide-bodied jet aircraft, aluminum alloy rib hinge. Based on a production run of 100 parts, a cutting speed of 5,000 sfm, and assuming the same set-up time for both operations, the high-speed machining method was projected to result in a 63-percent cost saving. A similar economic study on a steel automotive reverse transmission gear has indicated that equally impressive manufacturing cost reductions can be effected by high-speed machining in a large-volume production environment. The data in Figure 3 illustrate the marked improvements in productivity which can be attained as functions of cutting speed and feed per tooth.

When compared with casting and forging, additional benefits can be gained from high-speed machining production techniques. Several months often are required to generate sufficient numbers of cast and forged parts to support production requirements. As a consequence, such parts frequently become the pacing items when new products are introduced. High-speed machining, when economically justified, can significantly reduce the time span between engineering design and production thus bypassing the need for castings and forgings. Moreover, the need for costly elaborate holding fixtures for machining the latter configurations, would be eliminated.

While the major economic advantage of high-speed machining lies in the reduction of required cutting time, other elements of production also are beneficially affected. Large inventories of different tool materials, for example, can be replaced, with stocks of low-cost, throw-away carbide or ceramic inserts of required geometries. The fact that most of the heat generated during high-speed machining is retained by the chips also suggests that parts with thin walls and extremely close tolerances could be produced on a routine basis. Inspection costs, therefore, should be reduced substantially. In addition, the comparatively low

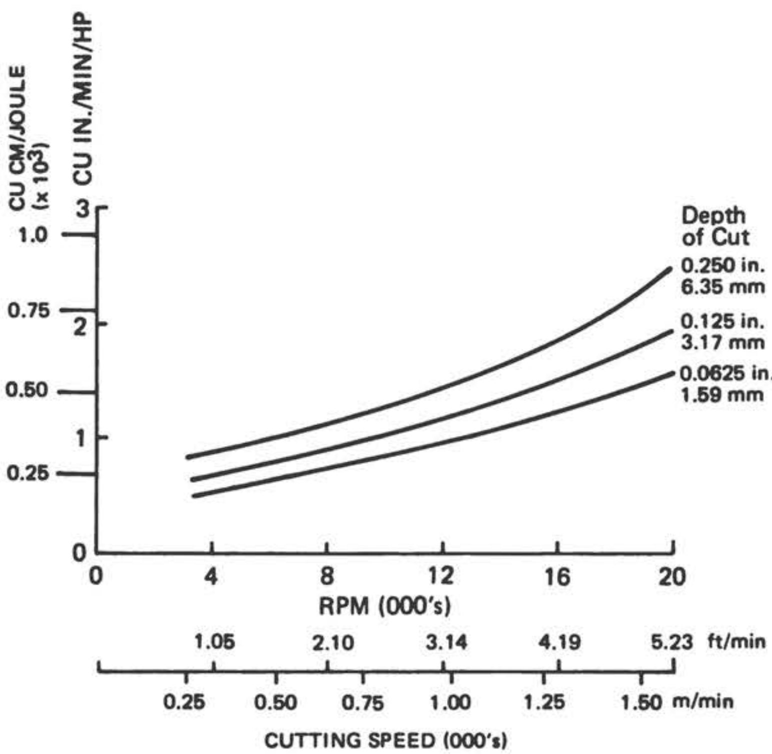
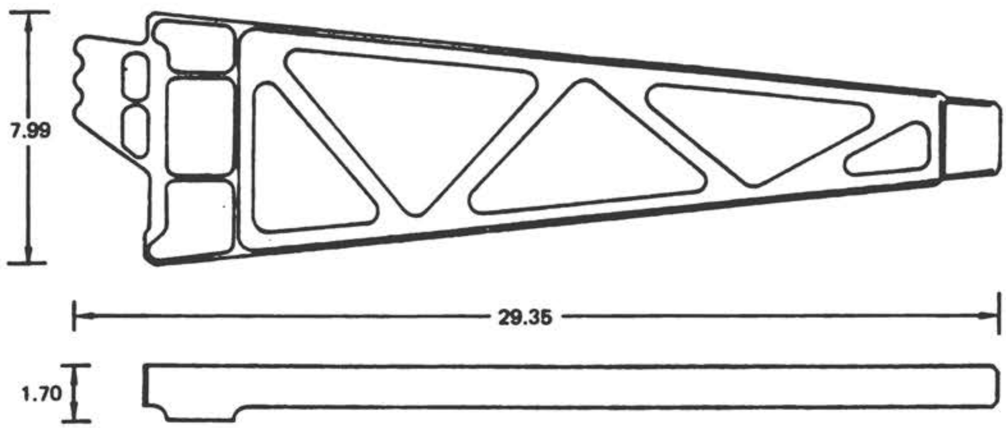


Figure 1. Effect of cutting speed on metal removal efficiency for aluminum alloy blocks milled to various depths with two-flute, 0.5 in. diameter carbide cutters[3].



Operation	Conventional (Hours)		High-Speed (Hours)		Savings
	Set-up	Run/100	Set-Up	Run/100	
Profile Near	6.96	159.43	6.96	58.60	100.83 Hr
and Far Side	Cost	$3,188.60	Cost	$1,172.00	$2,016.60

MACHINING RATE INCREASE 272%

Figure 2. Comparative conventional and high-speed machining manufacturing costs for producing L-1011, wide-bodied jet aluminum alloy rib hinge

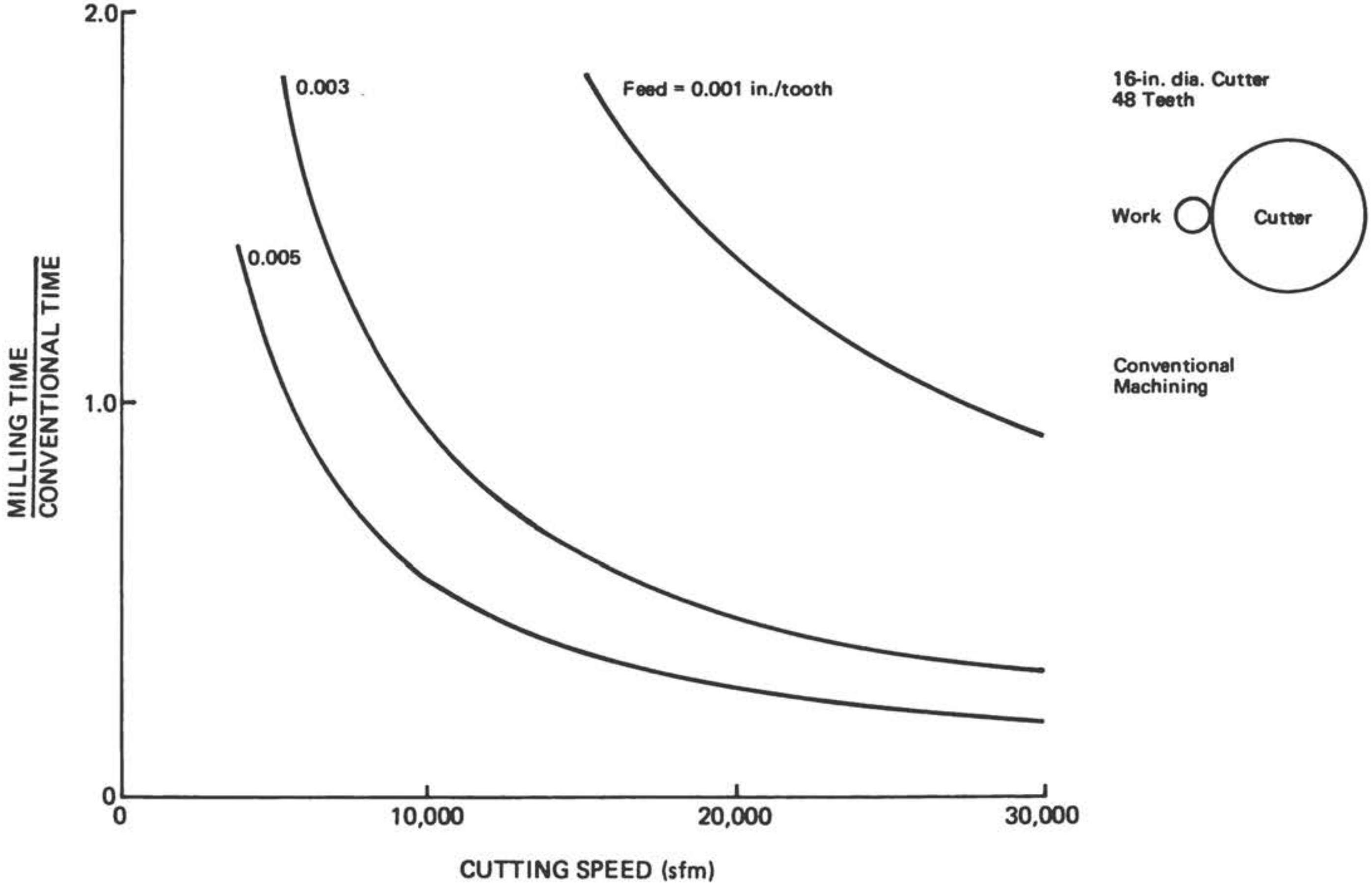


Figure 3. Effect of cutting speed on the ratio of milling time to conventional time as a function of feed/tooth for machining a steel automotive reverse sun transmission gear

tool forces encountered would be anticipated to decrease the level of induced residual stress and eliminate the need for post-machining stress relief heat treatments.

As high-speed machining is implemented, overhead as well as operating costs will be reduced significantly. Fewer machines will be required to produce the same number of parts with the result that needed machine tool inventories, floor space, and peripheral equipment such as monitoring and control devices and computer subsystems also can be reduced.

References

1. "Manual for Panel Chairmen and Working Groups." Department of Defense/Industry Metal Chip Removal Conference, p. 16, 8-10 Feb. 1977, Daytona Beach, Fla.
2. R. R. Schmidt and W. N. Boam. Minicomputer monitoring of numerically controlled machine tools. In: Proc. Sys. Eng. Conf., p. 25, 6-8 Nov. 1974, Minneapolis, Minn.
3. R. I. King and J. G. McDonald. Product Design Implications of New High-Speed Milling Techniques. Paper No. 76-DE-22, Trans. ASME, J. Eng. for Industry, Apr. 1976.
4. R. I. King. High-Speed Production Milling of Non-Ferrous Materials, Proc. 4th North Amer. Metalworking Res. Conf., p. 334, Soc. Manuf. Eng., Dearborn, Mich., May, 1976.
5. R. L. Vaughn. Ultrahigh Speed Machining. AMC TR60-7635(1), June, 1960.
6. L. V. Colwell and L. J. Quackenbush. A Study of High-Speed Milling, Part II -- High-Speed Milling of Titanium Alloys, Rep. No. 05038-2F, Dec. 1962, Off. of Res. Admin., Univ. of Michigan, Ann Arbor, Mich.
7. J. F. Kahles, M. Field, and S. M. Harvey. "High-Speed Machining - Possibilities and Needs," paper presented at the 28th General Assembly of the College of International Production Research, Eindhoven, The Netherlands, Aug., 1978.
8. P. K. Wright and E. M. Trent. Met. Tech., 1:13, 1974.
9. N. H. Cook. Trans. ASME, J. Eng. for Industry, p. 931, 1975.
10. A. Bhattacharyya and I. Ham. Trans. ASME, J. Eng. for Industry, p. 790, 1969.
11. I. Ham and H. Narutaki. Trans ASME, J. Eng. for Industry, p. 951, 1973.
12. T. C. Hsu. Trans. ASME, J. Eng. for Industry, p. 652, 1969.
13. G. Barrow. Tribology, p. 22, 1972.

METAL DEFORMATION PROCESSING

Howard A. Kuhn, (Panel Chairman), Frank J. Fuchs, and Harry C. Rogers

Introduction

Materials processing, in its broadest context, includes all the processes for transforming raw materials into finished products. A general classification of the processes includes: refining raw materials into a pure form; consolidating the pure material into a solid state; working the solid material into final shape; and finishing the worked material.

In metals processing, the deformation (working) processes are particularly significant because of their flexibility. Deformation not only produces the final product shape, but it has large, controllable effects on metallurgical structure, and hence, on product properties.

Metal deformation processes involve primarily metal flow and do not depend on long-term rate processes, which permits automated high-speed production of products having reproducible shape and properties. These features place deformation processing at the core of modern mass production, upon which much of this country's international competitive position depends.

From another point of view, deformation processing is worthy of attention because of potential material, energy, and cost savings. Formed parts, in some cases, may be produced near the final desired shape and surface finish, reducing or eliminating the need for finishing steps and the material loss due to machining or trimming. Forming product shapes in the solid state (deformation processing) is much less energy-intensive than casting from the liquid state because lower temperatures are involved and the deformation energy is negligible relative to the thermal energy required.

Furthermore, control of product structure by deformation processing provides the capabilities for property enhancement. Such improvements may eliminate the need for costly, energy-consuming heat treatment steps, as well as provide property combinations and, hence, applications that were previously unattainable.

The surface has just been scratched in exploration of the potential of deformation processing for improving productivity in our metals processing industries. Gaps in knowledge, however, hamper expansion of deformation processing toward realization of its full benefits. Relative to the importance of the subject, too few people in industry, government, and universities, are involved in the research necessary to increase our understanding of deformation processing and accelerate expanded and improved use of the processes. These are the problems addressed by this workshop panel.

Current Technology and Limitations

Deformation processes involve a complex interaction between the forming machine, tooling, and workpiece material through a frictional interface between the tools and workpiece. Plastic deformation during the process causes a change in shape, surface, and metallurgical structure of the material. A prime objective of the process is to produce a product having a net shape, i.e., the final required shape and dimensions without defects. A further desirable objective is that the surface produced be a net surface, i.e., have an acceptable finish, devoid of defects, and not require finish grinding. Finally, it is advantageous to produce a net structure by the deformation process, i.e., a metallurgical structure requiring no further heat treatment to obtain the desired properties. Although these objectives are clearly out of reach in many cases, incremental progress toward these ultimate ends has been accomplished. Such successes, combined with the potential payoff for further success, provide the impetus for continued investigation.

Deformation processing is still very much an art. Process development normally occurs by trial-and-error and process design, for example, it may be entrusted to the experience of a die designer. Such procedures are both time-consuming and unreliable, particularly when using the newer, hard-to-work alloys.

Rational process design procedures require much greater knowledge of the process expressed in the form of predictive equations or tabular data. These would include the interrelationships between plastic metal flow, the frictional interface, and the material structure. Successful development of rational design procedures would heighten confidence in expanding deformation processes to new materials and products, and would decrease the time required for successful development of the process.

The current state of affairs in deformation processing, its potential and limitations, are best illustrated through two examples. Extrapolations from these cases to other processes will show the generality of the problem and help define the science bases required for further develoment.

Forging

Forging is a widely used process for production of parts and components for commerce, industry, and defense. It enhances strength of the material, produces somewhat complex shapes, and reduces scrap loss relative to the process of machining from barstock.

Existing procedures, however, limit the benefits derived from the process. Complexity and detail of forged shapes is limited by lack of understanding of metal flow in localized regions such as fillets and corners. With existing practice, metal cannot readily be forced into small fillets and recesses of the die. Similarly metal flow around sharp corners often leads to defects in the metal surface as well as excessive wear of the die corner. To combat such limitations, it is conventional practice to fabricate the forging dies with large corner radii and large fillets. This, in turn, requires an excess layer of metal on the forged part. Final processing of the forged part, then, involves machining away the excess layer of metal to produce the sharp corner and fillet radii required in the finished part. Such finishing steps not only extend the time and cost of producing the finished part, but involve material loss through the machining chips removed.

Cracking is another limiting condition in forging, particularly in newer alloys that exhibit higher strength. Concomitant with the higher strength is a lower inherent ductility and greater likelihood of fracture during a deformation process. This effect is accentuated by the parallel trend toward forming more complex shapes. Increased complexity of the forged shape increases the amount of metal flow such that the ductility limit of the metal may be reached. Formed parts containing cracks, of course, must be discarded, so the entire volume now becomes scrap rather than just the metal machined away, as in the previous case.

Progress toward forging a net shape and avoidance of defects is based largely on accumulated experience, intuition of specialists, and considerable trial-and-error experimentation. Such efforts result in alterations of procedure, such as preforming, lubrication, die design, temperature, and strain rate. The fact that such measures are effective implies that the response of the material is reproducible and predictable. Establishing the techniques for such predictions constitutes a major part of the needed science base for metal deformation processing.

The situation illustrated above for forging is similar to that in other metalworking processes. Sheetforming processes inherently involve an unavoidable scrap loss in material remaining after blanks are cut from the sheetstock. Defects, however, are a major problem in striving for the production of more complex shapes by sheetforming. Similarly, bar and section rolling involves the sequential reduction of a simple shape to a more complex shape, such as an I-beam, through a series of roll grooves. Again, the metal is expected to flow into sharp roll grooves (equivalent to die corners and fillets in forging) without forming cracks. Extrusion of complex shapes without defects is a further example of a deformation process that is limited in application because of lack of predictive capability in metal flow. Thus, establishing the rational techniques for metal flow analysis and process design in one process opens up the possibility of their extrapolation to other processes.

Controlled Rolling

The pursuit of increased strength of materials has captured the focus of a substantial fraction of metallurgical research in recent decades. The various mechanisms of strengthening include solute strengthening, workhardening, transformations, precipitation, and grain refinement; but the most effective of these require post-forming treatments. To avoid the additional manufacturing and energy costs associated with post-forming treatments, it would be desirable to incorporate significant strengthening effects into the deformation process.

Controlled rolling of high-strength low-alloy (HSLA) steel sheet is an example of such metallurgical control during deformation. Hot rolling and passage through the austenite-to-ferrite transformation produces a fine-grained ferritic material having greater strength than conventionally hot-rolled steels, approaching that of heat-treated steels.

Controlled rolling requires refinement of grain size after austenization followed by repression of recrystallization during finish rolling. Concurrently, precipitation of fine carbides and carbonitrides occurs, which tends to prevent subsequent recrystallation. Presently, knowledge of such reactions and interactions is limited and process development for controlled rolling is based on trial-and-error efforts and experience. Comprehensive, in-depth understanding of precipitation kinetics and interactins between precipitation and recrystallation are essential for rational design of alloy compositions and rolling schedules to develop the strengthening effects during controlled rolling to their highest level. This constitutes another major area of necessary science base for metal deformation processing.

As in the case of metal flow analysis cited in the forging example, an increase in knowledge of precipitation and recrystallization interations in HSLA steels can lead to applications in other processes and alloys. Precipitation in copper alloys and aluminum alloys could be used to greater advantage as well as development of fine grain size in processes other than strip rolling.

The basic concept of controlling microstructure and properties through deformation processing can be extended to two-phase materials. Titanium alloys serve as a prime example where such investigations may be useful. An Air Force program has been initiated to develop the necessary data base and process analysis for forging of a component such that it has one set of structural characteristics in one region and another set of characteristics in another region.

Science Base

In general terms, the overall objectives of deformation processing are to produce a product as close as possible to net shape, net surface, and net structure. As described previously, any deformation process involves a complex interaction between the forming tooling and workpiece material through a frictional interface. In-depth understanding of these interactions would provide the necessary predictive equations or relationships necessary for development of new processing methods or improved control of existing processes towards the ends of net shape, surface, and structure.

Despite the complex interactions between tooling, workpiece, and interface in deformation processing, it is useful to consider separately, at least initially, the fundamental phenomena involved. These include: deformation modeling, friction and lubrication, and structure changes. The working group on deformation processing was subdivided into these three categories to consider the science base requirements in each area.

Their conclusions were many and varied, but three major areas of particular importance emerged. These areas reflect the interdependence of tooling, workpiece, and interface considerations in deformation processing.

Deformation Modeling

Improved accuracy in modeling the flow behavior of metal during deformation processes continues to be the major objective of researchers in plastic deformation mechanics, and such improvements are largely dependent on more accurate constitutive relations of plastic flow along with more accurate characterization of the interface frictional shear distribution. This is part of the longer-term problem, however, of modeling of flow and temperature in three-dimensional detail in selected localized regions.

Some progress has been made in identifying the local conditions of stress state, strain state, temperature, and strain rate leading to defect formation in a variety of materials. Use of this information in predictive techniques for achieving net shape products by deformation processing will depend on availability of methods for accurate representation of the stress state, strain state, temperature, and strain rate in critical locations of the material. This might involve improved finite element techniques or the use of physical modeling and grid measurements, and most likely both approaches.

Interface Phenomenon

More accurate measurement and representation of interface shear distribution for deformation modeling is the focus of much attention in tribology for metalworking, but increased concerns for product surface integrity and tooling wear strongly influene the future direction of such research. All aspects of the interface problem could be incorporated in a comprehensive model of the complex chemical and physical interactions between the workpiece, tooling, and lubricant at the interface. The model must necessarily treat thin-film and molecular layer cases as well as the common thick-film case. It must consider rheology of the fluid, adhesion, chemical interactions, and thermal aspects. Results of such a model would be constitutive relations for the interface frictional shear, prediction of workpiece surface characteristics, and prediction of tool wear. Aside from improving the interface boundary condition input for deformation modeling, these results would contribute toward achieving a net surface in products of deformation processes.

Structural Behavior

Incoming material structure influences material behavior during a deformation process and the process itself affects the resulting product structure. The first set of effects is embodied in constitutive equations and is required for deformation modeling, while the second set of effects is required for rational alloy and process design to achieve desired structures. Modeling of deformation structure interactions serves the long-term needs of both aspects. Existing constitutive equations relate flow stress to strain, strain rate, and temperature, but the effects of material structure are, at best, represented through coefficients or exponents in the equations. Including structure as an independent variable would enhance the use of the equations in deformation modeling. Since the progressing deformation modifies the material structure, extension of the same modeling techniques would provide the relationships between deformation characteristics and product structure. Such models would necessarily focus on deformation-temperature-recrystallation-precipitation interactions and would involve micromechanical models as well as physical modeling and test techniques. The outgrowth of such a model would contribute to development of processing methods for net structure in a wide range of processes.

Potential Applications and Priorities

Because of the breadth of the field, a complete list of potential applications, including expected payoffs and recognized science needs would be unwieldy. This section first presents in some detail one attractive application, that of high pressure metal forming technology. Second, the problems and potential payoffs in the areas of processing materials with unstable microstructures, sheet metal forming, and new process development are presented in outline form in Table 1. Additional information is given in Appendix III which contains the reports of five working groups.

A Detailed Example

One metal-forming field that seems to offer maximal potential both for exploring the advantages of using a science base approach and producing new and useful results is high-pressure metal forming technology. This field is relatively new and not yet widely understood or used. The difficulties in the high-pressure methods are the very conditions that would afford the most rewarding research results.

High-pressure forming can be characterized as those processes, batch or continuous, that make use of sufficiently high hydrostatic compression stress on the workpiece so as to produce the Bridgman effect. Very large deformations can be used to produce a sound product, sometimes with much enhanced physical properties. The very fact of deliberately induced high surface pressures vastly accentuates the changes in lubricants and surfaces during the forming operation. Also, because of the large deformations possible, instantaneous heat produced in the material is a much more significant factor. Taken as a whole, it seems clear that the opportunities for attaining the goal of developing a science base in a "window" that can provide worthwhile results and benefit from industrial and academic participation are present in high-pressure metal forming.

Work has been done in this field for the most part by industry and in some measure at government laboratories. Most of the work has been exploratory in nature and has used laboratory equipment that in many cases was not suitable for the extensive use required by production or even lengthy research programs.

In recent years, however, some very exciting developments have produced high-pressure equipment designs that can be utilized both by industry and academic reseach organizations. Pioneering work (Western Electric Engineering Research Center, Princeton, New Jersey) has produced dependable high-pressure shell-forming equipment, automatic hydrostatic billet-extrusion machinery, and

Table 1. Three additional examples

I. Problems in processing of unstable microstructures
   A. Interaction of precipitation and recrystallation
   B. Extension of room-temperature yield loci work in hexagonal close packed (HCP) metals to high temperatures
      1. Processing of HSLA steels [controlled rolling]
      2. Processing of α/β Ti alloys (Extend to Cu alloys, Al(Cu) alloys)
   C. Payoff
      Improved materials (particularly strength/weight) for automotive and aircraft industries)

II. Sheet metal forming
   A. Constitutive equations must be developed that include:
      1. Rate dependence
      2. Effects of stress reversal
   B. Failure processes must be more clearly defined
      1. Shear localization and plastic instability not well understood
      2. Void nucleation growth, and coalescence-ductile fracture -- much improvement in understanding needed.
      3. Interaction of defect development and plastic instability not clear.
   C. Leads to:
      1. Improved prediction capability
      2. Better input for computerized die design and selection of process variables
   D. Payoff
      1. Large production runs (e.g., automotive industry): reduce scrap, reduce design lead time
      2. Small production runs (e.g., Air Force) reduced lead time, a major impact.

III. New Process Development
   Virtually impossible to pre-analyze <u>any</u> new process (e.g., high-pressure metalworking processes).
   A. Need data base giving flow and fracture behavior materials of commercial interest as a function of rate, stress state, and temperature.
   B. Better (and more) friction and wear data (for specific tool material and lubricants)
   C. Payoff
      1. Lead time reduced
      2. Reduce waste of cut-and-try methods.

continous hydrostatic extrusion machines. Organizations are interested in using the processes and equipment to produce their own commercial products.

Earlier work using the Western Electric approach (Princeton Metal Systems Company) was probably more interesting to the Air Force from the standpoint of providing a window for needed technology. It involved production of titanium tubing at much reduced cost and with considerably improved mechanical properties and microstructure. Given some science base assistance from the academic world, it is reasonable to assume that this process would now be the best way to manufacture low-cost titanium tubing and shapes. The difficulties of determining optimal lubrication, tool materials, temperature control, and other process parameters was only empirically approached. However, those efforts resulted in a base on which a very effective project can now be built, and the availability of some very sturdy and efficient machines.

In addition to the work on billet extrusion of titanium tubing, Western Electric has developed continuous extrusion equipment to produce aluminum and copper wire. Those designs have been proven operational at pressures over 300,000 psi. Such equipment would undoubtedly be useful to produce titanium and refractory metal wire and shapes. Again, only empirical studies and limited analytical work have been done in the science base problems of lubrication, heat effects, surface metallurgy, and flow stresses. Limited constitutive equations involving some gross assumptions with regard to several of these parameters have been developed. To expand this effort to suitably predict and optimize the process to make titanium, refractory metal, or superconductive materials, a concerted study of process parameters would have to be made.

The potential for academic-industrial cooperation in this field is impressive. Since the continuous hydrostatic extrusion method provides a unique way to measure temperature, friction, strain rate, and extreme pressure effects in real time, it is probably the ideal vehicle to study the benefits of the science-base approach to metal forming. In addition to providing an immediately usable superior process for products now difficult to manufacture, the extreme ranges of the parameter data that will be obtained can be quickly applied to other metal-forming processes.

One such process which probably would be a useful window is the hydrostatic-pressure forming of shells. Two useful areas of application to the government are cartridge shells and grenade shells. Although the formation of these products cannot be done continuously, they do require extreme pressure and have lubrication and tool-part interface effects almost as extreme as hydrostatic extrusion. High-pressure shell forming techniques have been invented and used at the Western Elecric Company to produce commercial parts similar to those mentioned above. However, the science base research in the surface, metallurgical parameters, and constitutive equation areas has yet to be done before wide application can be expected. Here again, the equipment designs for pursuing hydrostatic-pressure forming research are now available.

Recommendations

The level of academic research in deformation processing is very low. However, it is only from this sector that the needed science base for deformation processing can arise. This will require a steady and increased level of funding to bring new creative workers into the area. This must be done in such a way that true interdisciplinary interactions are achieved. It must also be done with meaningful industrial interaction so that academic researchers work on basic aspects of relevant problems.

The research topics discussed above are achievable long-term goals only if the academic community can be brought to bear on deformation processing research in a meaningful way. The specific recommendations for research are:

1. Realistic constitutive equations for describing plastic flow in all regimes of deformation processing must be developed. Workability and/or fracture criteria must be extended to the high temperature region. Continued work on numerical analysis of large-scale plasticity should be encouraged. These three thrusts should be merged to provide an enhanced level of deformation process modeling.

2. Sustained long-term interdisciplinary research is needed on mathematical and physical modeling of interface friction in deformation processing. This should aim at better understanding of interface shear stress distributions and of methods for predicting workpiece surface characteristics and the wear of tooling.

3. A major effort should be given to integrating the physical metallurgy of hot deformation (recrystallization, strain-induced precipitation and transformation) in a quantitative way into process modeling. This has a goal of introducing structure into the constitutive relations for flow and of developing quantitative descriptions for the interactions between deformation-temperature-recrystallization-precipitation. The long term payoff of this ambitious undertaking would be greatly increased utilization of the benefits of thermo-mechanical processing.

ADVANCED COMPOSITES

Bryan R. Noton (Panel Chairman)

Introduction

Composite Applications

The defense and commercial applications of advanced composite materials with polymeric matrices are steadily increasing. Besides the well-documented defense applications, for example, to the Air Force's F-15 and F-16 aircraft and the Navy's F-14 and F-18 aircraft, many opportunities are rapidly developing in commercial markets. In addition to established commercial applications, such as brake linings, cutting wheels, gasoline tanks, pipelines, and pressure vessels, the following are examples of production applications of advanced composites. They are not intended to provide a complete overview:

- Civil aircraft--control surfaces, vertical and horizontal stabilizers, floor beams, and posts
- Lightweight automobiles--drive-shafts, push-rods, suspension springs, crashworthy body-beams, hybrid trunk-lids, and door hinges
- Cables--balloon and buoy tethers, deck pendants, and electromechanical cables
- Textile equipment--heddle frames, picker sticks, driving arms, reciprocating combs, oscillating rolls, serpentine rolls, and wet bearings
- Engines--fan-blades and static structures, e.g., ducting, thrust beams, and shrouds
- Leisure products--ski poles, fishing rods, tennis rackets, golf clubs, and javelins
- Medical engineering products--splints, prostheses, wheelchairs
- Energy storage--flywheels
- Electrical equipment--solid-state actuated switches
- Concrete Construction--concrete casting molds
- Chemical storage--large vessels
- Data processing equipment--print heads, tape drives
- Paper box machines--cross-register bars, feed drive drums
- Photocopying machines--scanning, traversing, and paper handling mechanisms; squeeze rollers; paper transport shafts; and bale mechanisms.

Some of the above applications, such as in the leisure area, have already achieved production status and the markets are growing. Although most of the current attention is directed at graphite fibers, alumina fibers may also find use. In a number of these applications, hybrid composites will be necessary where the graphite fibers are strategically or selectively utilized with lower-cost glass-fiber reinforcements for cost-competitive products. There is also some potential for reinforcing stainless steel films and fibers.

It is important to appreciate that in the realization of high-volume, commercial applications, such as energy-efficient, light-weight automobiles, some important developments are required. Examples are the development of new automated manufacturing technologies and also fibrous material forms which lend themselves to these high-volume manufacturing processes. Complex trade-offs are required between materials and manufacturing technology. In future years, one can expect a two-way flow of technology between defense and commercial industries. Methods of analysis, design techniques, serviceability experience, and testing methods are examples of the well-develped technologies that flow from aerospace to commercial industries. However, it is likely that manufacturing technology developed in commercial markets will, in due course, benefit the fabrication of discrete parts and assemblies in lower volume defense applications of composites. It is well known that the impact of these higher-volume applications on the cost of the advanced composite constituent materials will be significant and will, therefore, promote even wider applications in defense industries.

Manufacturing Technology Development

The composite manufacturing technology currently available was developed by the interaction between the materials and process engineering, manufacturing technolgoy and tooling engineers, and also material suppliers.

The methods developed were generated empirically using experience acquired with glass-fiber reinforced plastics, autoclave cycle development, a limited amount of polymer chemistry background, and trial and error.

A sophisticated scientific approach is now required to improve the consistency and effectiveness of composites processing, to reduce costs, to widen the spectrum of materials that are routinely processed in production, and to increase the usage of composites to enhance the performance of engineering systems in both defense and commercial markets.

Advanced composites technology has experienced a transition from the early stages which were characterized by high materials cost, direct substitution in design, manual labor-intensive operations, limited material forms, limited application to structures, weight savings, and cost savings seldom achieved.

Today it is characterized by material prices in the $30-50/lb range (for graphite/epoxy unidirectional tape);* innovative design configurations, innovative manufacturing technology approaches, trend toward automated manufacturing processes, variety of material forms available, application to secondary and primary structures, and weight and cost savings achieved.

While one can expect newer forms of materials such as those identified in the recommendations of this panel, the following are examples of the forms available today:

Form	Form Type
Unidirectional monofilament	Tape and broadgoods
Woven	Tape, broadgoods, and oriented
Chopped	Random
Continuous cross-ply filaments	Sheets
Combination continuous and chopped fibers	Sheets
Random and oriented spunbonded and melt-blown	Sheets and webs

A number of manufacturing processes have been developed to fabricate composite structures, but as identified by the panel, problems still exist with some of these methods.

The state-of-the-art manufacturing methods are:

- Autoclave processing
- Oven/vacuum bag
- Injection molding
- Matched die molding
- Filament winding (fiberglass and Kevlar)
- Compression molding
- Automated tape-wrapping/laying
- Braiding (nongraphite)
- Automated ply cutting/trimming
- Drum-wound broadgood sheets
- Integrally-heated tools.

Manufacturing methods expected to enter production in the near future are listed below.

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* With increasing demand, the price of graphite fibers may come down to $10/lb, and prepegs with epoxies, unsaturated polyesters, and even bismaleimides may reach prices in the range of $12-15/lb.

Accepted for production hardware within 3 years:

- Filament winding (graphite prepegs and wet-winding)
- Compression molding with continuous fiber prepegs (SMC)
- Thermoplastic matrix structural composites -- continuous roll forming, vacuum forming, extrusion, press-molding
- Oriented, preplied, high modulus composite sheets
- Pultrusion
- Simplified automated-ply placement
- Multidimensional oriented fabrics (more than bidirectional)
- Unitized construction (e.g., stitched joints).

Accepted for production hardware in 3- to 10-years:

- Rapid curing resins and prepegs
- Advanced automated ply placement
- CAM-operated processing steps
- Rapid, more efficient, automated nondestructive evaluation
- Computer collection and analysis of nondestructive investigation (NDI) data
- Tailored matrix and fiber properties within a single component
- More durable nonmetallic tooling
- Nonmachined, contoured metal tools
- Computer fiber placement to fabricate complex parts such as stiffeners, brackets, etc.
- Transfer molding of graphite fiber components.

Project Selection Criteria

The solution of the scientific problems identified in the processing of advanced composite materials will have significant economic impact for both commercial and defense markets.

The specific objectives of the panel, "Science Base for Processing of Advanced Composite Materials", were to identify processes that would most benefit from an improved science base; science areas that require emphasis for future progress in advanced composites processing; methods of stimulating greater academic participation in interdisciplinary endeavors focused on advanced composite processing; and methods of stimulating cooperative or coupled university/industry endeavors in advanced composite processing. Each objective was addressed by the panel.

Future benefits expected from the proposed science base programs include improved conservation and utilization of materials and energy; increased rate of production of structures with assurance of quality, reproducibility, and durability; reduced or avoided factors that raise costs in advanced composite hardware fabrication; reduced influence of manufacturing processes on structures because of minimized deficiencies introduced by these processes; and more rapid introduction of basic science into processing practices by cooperative, interdisciplinary science programs in academia and industry.

Science base projects should be selected in consideration of the technical aspects -- visibility and impact on funding agency, criticality of need, breadth of expected utilization, tractability of the problem, viability of approaches, availability of appropriate skills, availability of adequate fundings; whether the project is short-term (less than 3 years) or long-term (3-10 years); the project's appropriateness to a university and how the technology transfers (participation of potential user); and the adequate funding and cooperation regarding its commitment.

Recommended Categories of Science Base Programs to be Addressed

In the development of composite hardware, the designer is not only concerned with raw material forms and the distribution and orientation of the reinforcing fibers in the polymeric matrices, but also with the complex interaction between materials, design configuration, analysis, manufacturing technologies, joining methods, nondestructive evaluation, etc. The science base areas of investigation recommended by the Panel cover a number of these important considerations; research needs have been prepared by the panel in each of the following areas:

- Raw material variability at start of processing cycle
- Scatter of physical property data needed for modeling processes
- Relationships between microstructure, processing, and properties
- Modeling and control of fiber dispersion and orientation in molding
- Material forms required for high-speed processes
- Rapid curing techniques (thermosets)
- Rapid curing and fabrication techniques related to thermoplastics

- Automated fabrication of thermosetting resin composites
- Automated fabrication of thermoplastic resin composites
- Thick laminate processing
- On-line process control methodology
- Process-flaws-failure interaction
- Fiber degradation
- Tooling for composites
- Bagging for tool closure
- Joining of composites
- Machining of composites

Problem Areas and Research Needs

Raw Material Variability at Start of Processing Cycle

Key parameters for fiber finishing control and documentation of downstream effects must be identified, and the special role of continous and short fiber-matrix adhesion on composite performance defined. A third research need is to eliminate parametric tests, such as resin flow, which do not adequately relate to prepreg conditions and which are not precise to the degree required for raw material process control. Procedures and "fingerprinting" standards for tests that can adequately measure resin advancement should be established using techniques such as gel permeation chromatography (GPC), liquid phase chromatography (LPC), and Fourier transform infra-red analysis (FTIR).

Scatter of Physical Property Data Needed for Modeling Processes

To deal with modeling processes, correlations between specific independent variables (temperature, viscosity, gel time, mixing inhomogeneities, resin chemistry variability, fiber aspect ratio, etc.) and the resulting part properties (degree and uniformity of cure, degree of fiber wetout, fiber agglomeration, shrinkage, etc.) must be developed. Independent correlations (perhaps empirical) between resulting part physical properties and part performance mechanical properties must also be developed, as must quantitative characterization schemes for appropriate families of resins.

Examples of problem areas are:

- Temperature-viscosity data
- Gel time-temperature relations
- Physical mixing inhomogeneities
- Stoichiometry balance
- Degree and uniformity of cure
- Degree of fiber wet out

- Thermodynamic/rheological/kinetic relationship
- Fiber orientation and agglomeration
- Shrinkage
- Temperature profile
- Matrix resin variability (chemical)
- Nature, amount, and effect of impurities
- Fiber density and geometry variations
- Fiber aspect ratio

Relationships between Microstructure, Processing, and Properties

Classification of these relationships necessitates identification of the influence of matrix resin chemistry, fiber type and form, and processing conditions on composite microstructure. This involves applying chemical kinetics and chemorheology to the curing process, and monitoring development of microstructures and related physical properties during the cure and subsequent post-cure, annealing, etc.

The relationships for stability of microstructure and engineering properties must be determined in chemical, thermal, and mechanical environments, for both fiber and matrix, as well as at the interface.

Quantitative chemical, mathematical, and mechanical models must be developed that will relate starting chemical structures, fiber type and form, through processing to final microstructure including fiber orientation, and engineering properties. Both theoretical and empirical approaches should be pursued. It should be emphasized that processing-microstructure modeling and properties-microstructure modeling can be pursued independently. But at some future time, they should be integrated.

Real-time process monitoring techniques must be advanced and used for adaptive automated processing. To accomplish a real-time monitoring, correlations between measurable transient parameters or combinations thereof and the associated real models must be determined.

Tools and techniques that identify the chemical and physical microstructure of composite materials should be developed and used. At the molecular level these techniques should identify crosslink density and distribution; gradients; molecular orientation, crystalline and amorphous regions; and domains. At the super-molecular level they should identify phase distribution; voids, cracks, crazes; fiber orientation; and at the interphase, fiber (microstructure in the outermost layers), matrix (microstructure within 1000A of the interface), and interlamina (microstructure at the juncture of lamina, i.e., polymer-rich area).

Modeling and Control of Fiber Dispersion and Orientation in Molding

Here we must develop correlations between specific independent rheological parameters and resulting orientation distributions. For example, for injection molding, what is the effect of gate geometry, other variables being constant, on the resulting fiber orientation distribution? For compression molding, what is the effect of charge pattern on fiber orientation distribution? We must also develop constitutive relationships for effects of major processing variables on fiber orientation distribution for injection and compression molding.

Material Forms Required for High-Speed Processes

Research needs in materials development are: the evaluation of sheet molding compounds (SMC); the evaluation of SMC with the addition of continuous fiber hybrids; the development of materials with less exotherm susceptibility than the current epoxies; and development of bulkier fiber tows/prepreg systems, required to improve utilization economics.

Rapid Curing Techniques (Thermosets)

Progress in rapid curing techniques demands evaluation and demonstration of resins other than state-of-the-art epoxies (i.e., vinyl-esters, newer epoxies). A chemical understanding of the rapid cure mechanisms must be attained, and essentially complete crosslinking with no distortion, must be demonstrated. Energy sources that provide uniform energy exposure and cure, independent of part thickness and geometry must be developed.

Rapid Curing and Fabrication Techniques (General)

Research in this area requires development of new reinforcing forms; study of kinetics during processing; rheology of thermoplastic polymers, and internal stresses due to processing; determination of the effect of processing on fiber orientation; and development of techniques of resin/fiber ratio control in rapid filament winding processes. Particularly problematic are: reinforced reaction injection molding (RIM), including controlled fiber distribution and fiber/resin interaction; pultrusion, including high pulling forces, slow pull rate, and orientation limit; and high-pressure molding, including poor control of fiber orientation.

Automated Fabrication of Thermosetting Resin Composites

Primary needs are studying the relationship between reliability and production automation; incorporating and/or eliminating secondary operations in the automated process; and identifying suitable constitutent composite materials for automation, such as resins or reinforcement forms. Design throughout the process to automation must be furthered.

Heating efficiency -- method, uniformity, effect on materials and on processing -- must be studied.

Methods of process control that include pressure application, viscosity/temperature controls, fiber orientation controls, inspection, and composition control are to be developed.

Especially problematic is that product volume is insufficient for specialized equipment development. Excessive high-cost secondary operations also are required, such as, sanding, trimming, and deflashing. Furthermore, knowledge of materials and/or processes to specify parameters for automation is insufficient, particularly regarding pressure development and viscosity control.

Automated Fabrication of Thermoplastic Resin Composites

Research needs are the development of methods for rapid sheet stock lamination, improved forming equipment, improved tooling concepts, and solvent resistant polymers; rheology of polymers; study of the fiber-resin interface, including wetting, failure mechanisms, and coupling agents; determination of the effect of processing on polymer structure/morphology; and investigation of the influence of processing on properties. Problem areas are poor fiber wetting, poor solvent resistance, unavailable materials forms (sheets, prepreg, etc.), and high-process temperature and related parameters.

Thick Laminate Processing

Important here is the development of material form for net resin/tight tolerance prepreg (approximately 1 percent on resin), and of cure cycle control with uniformity throughout with a possible need for integrally heated tooling. This could present a special problem for parts of variable thickness. Throughout the thickness, thermal gradients and gel transients must be eliminated, and porosity and ply compaction/thickness controlled. In addition, ply waviness must be eliminated.

On-Line Process Control Methodology

We must determine the most sensitive and rapid indicators of degree of cure. Potential methods include dielectric loss, electrical conductivity, acoustical modulus. To be developed are: interfacing between the technique and rapid computer-controlled feedback process control; rapid, efficient means for monitoring temperature profile information, such as thermography; models for predicting heat-transfer characteristics of processes; on-line monitoring of volatiles and out-gassing during cure and the correlation with mechanical and chemical changes in the resin during cure and processing; computer techniques for determining pressure and temperature profile for optimum curing of different preimpregnated materials. Lastly, the effects of prepreg age, storage conditions, and history on processing and composite properties require definition.

Problem areas for on-line process control are summed up in the questions: How is the degree of cure monitored? How should temperature distribution be monitored? What is the fiber concentration and orientation? What sensing techniques should be utilized?

Process-Flaws-Failure Interaction

Process flaws include the following: voids, impurities, fiber kinking and misorientation, unreacted species, thermal (residual) stresses, residual solvents, delamination, inclusions, microcracking, inhomogeneity of fiber distribution, molecular degradation, poor fiber-matrix bond (debonding), and fiber variability.

Research is required to develop analytical descriptions and experimental verifications of the effects of flaws on static strength and fatigue behavior for various performance stress states. Particularly, there is a need to determine the relative significance of various flaws. For proven critical flaws, we need to develop sufficiently sensitive detection techniques.

Specific processes through modeling must be optimized in order to minimize critical flaws introduced during the process cycle; for example, microcracking, fiber kinking, and thermal stresses.

For compression molding processes, we must develop correlations and constitutive models for the influence of rheological parameters (such as temperature, viscosity, charge pattern, tool geometry) on the formation of flaws (such as resin-rich areas, thermal stress concentrations, knit lines, fiber disorientations). Similarly, for injection molding processes involving short fiber systems, we must develop correlations and constitutive models to describe the effects of rheological parameters (time, temperature, viscosity, flow rates, gate and runner geometry, mold geometry, pressure, etc.) on void formation, volume fraction of fibers, fiber aspect ratio, degradation, fiber disorientation, etc. And for continuous fiber lamination processes, we must develop models for the effects of cure cycle variables on formation of residual stresses, microcracks, delamination, etc.

Fiber Degradation

Overcoming fiber degradation problems requires that we develop models and theories to resolve molding problems with chopped fiber compunds, as well as encourage interaction between structural mechanics and textile engineers to develop optimized fabrics and mats. We must come to understand the interface between fiber and resin so that finishes can be developed which protect the fiber during subsequent processing, as well as increasing the properties of the composite product.

Especially problematic are fibers damaged and poorly distributed. These limit properties in various molding processes--injection, mat and die, extrusion of chopped fibers. Weak spots in fibers limit properties. Fiber strengths are increasing, but composite properties are seldom equivalent to those predicted by the rule of mixtures. Compared with tape, woven and mat preforms give lower properties due to fiber waviness, shorter length, and process damage.

Tooling for Composites

Research needs require the development of: integral tools that use novel techniques to apply heat and pressure; analytical techniques for designing better nonmetallic tools; improved plating, electroforming, plasma spraying, or other processes to make a contoured surface from a model without machining; better elastomeric materials for tools that retain their shape, e.g., do not suffer from compression set; metal alloys that can be more easily machined and with higher expansion coefficients for internal molding thereby facilitating removal; and finite element heat transfer analysis of materials and molds for uniform cure.

The interface with autoclave and presses causes facility problems due to size restrictions, high energy costs, and investments. Steel and aluminum tools pose problems such as excessive weight, uneven heat transfer, being costly to machine, and requiring long lead-times. Plastic tools have durability and material variability problems as well as poor heat transfer rates and uniformity. And rubber tools have poor dimensional stability, uneven pressure distribution, and poor heat transfer rates and uniformity.

Bagging for Tool Closure

A coating that can be sprayed over the layup and bleeder assembly to form an air-tight, thermally stable, extensible bag should be developed, as should extensible, high elongation, thermally stable films that can be stretched over the assembly, and then made to seat snugly by vacuum.

Problems are that nylon film is costly to install on complex shapes to obtain constant pressure; it may bridge, and it may fail. The problem is magnified for complex integral structures. Tooling required to make preformed rubber bags is troublesome. Brush-on bags made from silicone resin and solvent often do not meet Occupational Safety and Health Administration (OSHA) requirements. Would-be suppliers have limited R&D capability.

Joining of Composites

The joining of composites will be advanced by the development of: stronger, tougher adhesives to eliminate bolts; novel joining methods--plastic welding, plastic fusion processes using thermoplastics; less process-sensitive adhesives; methods to introduce three-dimensional effects into layups before cure, using, for example, stitching; and innovative methods for joining both thermoplastics and thermosetting resins.

This area is costly because of the need for titanium fasteners and hole preparation, and bonding with attention required to cleanliness, environmental control, heat/pressure cycle, and fit-up problems. Joints impose structural penalties, and the types of integral structure that can be made are limited.

Machining of Composites

Here we must develop mathematical models to relate composite properties to cutter loads that can be safely applied, i.e., breakout is a failure in block tension and interlaminar shear. Metallurgical advances are needed for cutters to ensure that they remain sharp and dimensionally acceptable for longer periods with abrasive composites. We must develop feedback electronics to control cutter feed and speed, to control loads on the workpiece, to prevent damage, but to maintain optimum operating efficiency. And we must develop nontraditional methods such as improved and faster diamond wire cutter and ballistic machining.

Some problems are that diamond tools are costly to buy (but can be reclaimed); metal tools, e.g., carbide, high-speed steel, have limited life; breakout and delaminations occur; and a science base in previous studies is lacking.

Potential Payoff

Advanced composite materials, frequently of hybrid design, are being utilized to an increasing extent in defense aircraft. The Air Force, Army, and Navy commitments to advanced composites in production of aircraft have increased over the past 10 years from 1 to 3 percent, representing mainly horizontal and vertical stabilizers and dive-brakes, to the main load-carrying structures of wings and fuselage sections, including wing-carrythrough sections, representing from 12 to 17 percent in structural weight. In some current advanced aircraft, the use of composites on a weight basis now compares with that of titanium. The payoffs and benefits in the utilization of advanced composites in military aircraft are frequently projected as follows:

- weight savings--20-35 percent
- cost savings--20-30 percent
- life extension--200-300 percent
- corrosion resistance--75 percent
- reliability--100 percent
- maintainability--75 percent.

Conceptual and preliminary designers are studying the utilization of advanced composites for major primary structures to exploit innovative aerodynamic configurations with canards and double-delta and trisonic hybrid wing planforms, in which the benefits of composite materials on aircraft sizing and configuration would be fully exploited with this window.

The innovative manufacturing techniques under current development and referred to in the recommendations of this Panel will simplify fabrication flow and reduce costs. The fabrication of essentially all-composite aircraft has been shown to be both feasible and cost-effective, and design verification components indicate that full-scale aircraft will be produced with confidence. Although metalworking technology is highly advanced, aircraft production costs are high due to the large number of complex discrete parts which must be produced and delivered on schedule. The assembly flow is further complicated by the installation of countless factors as the discrete parts and subassemblies are integrated. A philosophy of the all-composite aircraft is, therefore, to significantly reduce the number of parts and fasteners. An example is co-curing of large assemblies to reduce the tooling, fastening, and production tracking costs.

The development of essentially all-composite aircraft is critical to the effectiveness of the Air Force, Army, and Navy. The pursuit of the science base areas recommended by the panel on advanced composites will enable research results to be applied with greater confidence and will enable a more systematic approach to many of the manufacturinq concepts currently being considered to achieve the ultimate objective of the essentially all-composite aircraft operating cost-competitively and cost-effectively through its life-cycle.

Although the initial successes in the use of advanced composites were mainly in aircraft, applications to small- and medium-sized boats should also be mentioned. There is also qreat interest in the use of advanced composites in lightweight armor for tanks and armored troop carriers, as well as in selected civilian applications.

HIGH-MODULUS POLYMERS

Paul C.D. Han (Panel Chairman) and Paul H. Lindenmeyer

Background

It has long been recognized that the theoretical modulus of a polymer chain in tension should approach that of steel.[1] Until about a decade ago, such theoretical estimates were generally dismissed as being unrealistic and highly unlikely ever to be achieved since the moduli of all available polymeric materials were at least two orders of magnitude lower. This low modulus results because the typical polymer molecule in the solid state has a conformation such that an applied stress produces rotations about the carbon-carbon bonds. The force constant for bond rotation, as determined from spectroscopy on an isolated molecule, is approximately two orders of magnitude lower than that for bond bending and about three orders of magnitude lower than for bond stretching. Consequently it follows that if all molecules were in a fully extended conformation, the modulus parallel to the molecular axis would be increased by one to two orders of magnitude.

The need for polymeric materials with improved thermal and oxidative stability led to the synthesis of polymers that contained aromatic and heterocyclic rings as well as dual chain or "ladder" structures. Although these polymers possessed the desired oxidative and thermal stability, they could not be melted without decomposition, and they possessed limited solubility even in rather drastic solvents (e.g., hydrofluoric or sulphuric acid). Consequently, they could be processed into useful items only with great difficulty. Nevertheless, some of these polymers[2] have been processed into fibers that have a Young's modulus in excess of 25 million psi, which indicates the validity of the earlier theoretical estimates. One class of these polymers, the aromatic polyamides, now termed aramids, is being manufactured commercially on a limited scale. Patents on these materials indicate that successful processing requires first producing an anisotropic solution followed by spinning using an "air-gap" between the spinnerette and the coagulation bath--a technique also known as dry-jet wet-spinning. Other polymers with a limited number of rotatable bonds have been processed into fibers having a high modulus without first going through the anisotropic liquid state.[3] These fibers did not attain a high modulus until they were drawn by the conventional fiber-forming technique.

At the other extreme, one of the most flexible polymers, polyethylene, has been processed into fibers having a substantially increased modulus either by drawing from a dilute flowing solution,[4] by extruding a supercooled melt,[5] or by drawing in the solid state under carefully controlled conditions.[6]

With this evidence at hand, the Air Force Materials Laboratory considered that it might be possible to find the necessary processing techniques which, when applied to certain types of molecules, could produce structural materials whose moduli are comparable to metals but whose densities are substantially lower. Such a material would be extremely valuable to the Air Force, and probably useful elsewhere in the economy, depending upon its cost. A related suggestion[7] is a molecular composite in which some of the molecules are fully extended to form the "fiber" and others in the more usual coiled conformations form the matrix.* It should be possible, at least theoretically, to vary the properties of such a molecular composite all the way from those of present commercial polymers up to the theoretical limit. It has also been suggested[7] that if the extended polymer chains were oriented parallel to one another, the modulus in one direction might approach that of steel; if they were oriented randomly in a plane, the modulus might approach that of titanium; and if extended in all three directions might be that of aluminum. How one might accomplish these ends is a matter of contention including the belief by some that a three-dimensional high-modulus polymer is impossible even in principle. The interest in this field is illustrated, for instance, by a recent book on the subject.[8]

Status of Science and Technology

In spite of divergent opinions on how to accomplish these ends, the panel did agree on the following two points:

- It is at least theoretically possible that non-reinforced polymeric materials having a high modulus in one or two dimensions can be made.
- There exists enough experimental evidence to expect that this theoretical possibility is achievable if "high modulus" is defined as one in excess of 5 million psi. (Poly(p-hydroxybenzoic acid) has been forged to give a high-modulus material (2.3×10^6 psi) that is isotropic in the plane.[9])

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*Other materials of interest are the segmented copolymers and the interpenetrating networks.

It should perhaps be emphasized that the only polymers now commercially available that can be considered to be nonreinforced high modulus structural materials are the aramid fibers. Other materials (e.g., from Tennessee Eastman) are available in experimental quantities, but most of the more promising materials must still be custom-synthesized. Thus the processing research needed to produce a non-reinforced high modulus structural material must still be closely coupled with the design of molecules expected to yield the best combination of inherent properties and processability.

Although these materials may be some time from realization as viable products, the potential importance of materials that might replace metals or reinforced plastics and offer substantial weight and/or cost savings led the panel to recommend that the science base for processing such materials be expanded.

Science Base for Processing High Modulus Polymers

As mentioned earlier, there was an understandable divergence of opinion on the panel as how best to proceed toward accomplishing these ends. Consequently there was not unanimous agreement on the relative importance of various areas of science. Nevertheless, it was generally agreed that basic information on the following six items would provide the knowledge necessary to establish the technological base. In particular, a fundamental understanding is needed of:

- the structure of the anisotropic fluid state whether this anisotropy arises from the inherent properties of the molecule, from the imposed flow, or by other means;
- the rheology of the anisotropic fluid state, and the effect of type and rate of deformation upon the molecular order;
- the solidification of anisotropic fluid in both the dynamic and quiescent states;
- the chemical, physical, and microstructural changes that occur during post-solidification processing, e.g., heat treatment and drawing;
- the microstructure of the product, the processing condition that influences it, the means of measuring it, and its relation to molecular and physical properties; and
- the molecular design required for optimizing processing and ultimate properties.

The panel recognized that this was an all-inclusive list which does not establish the priorities necessary to make this a useful report. In subsequent voting on priorities, it was clear that a majority of the panel believed that the third item, the understanding of the solidification process, was the most critical and the one most likely to yield valuable results. Also, many considered the last item to be an essential point but one that might be considered as materials selection rather than processing research.

Key Objective (or Window)

To establish a technological base for the development of nonreinforced, high modulus, polymeric structural materials that might find applications in much the same areas where fiber reinforced materials are now used is the objective. Attaining this objective offers the following advantages: increased modulus to weight ratio; no interface problems; possible easier fabrication; possible economic advantage.

Specific Recommendations

- It is recommended that additional support be given for the basic understanding of the solidification of anisotropic fluids as well as the other items listed in the science base for processing.
- It is also recommended that further attention be given to develop processing science for producing items other than fiber.

REFERENCES

1. F.C. Frank. Proc Roy Soc A319:127 (1970).
2. John C. Halpin. Polym Eng Sci 15:132 (1975).
3. W. Bruce Black and J. Preston (eds.). High-Modulus Wholly Aromatic Fibers. Marcel Dekker, Inc., New York, 1973.
4. A.J. Pennings. J. Polymer Sci, Part C 59:55 (1977).
5. R.S. Porter, J.W. Southern, and N. Weeks. Polym Eng Sci 15:213 (1975).
6. G. Capaccio and I.N. Ward. Polym Eng Sci 15:219 (1975).
7. P.H. Lindenmeyer. Polym Eng Sci 15:236 (1975).
8. A. Ciferri and I.M. Ward, eds. "Ultra-high Modulus Polymers," Applied Science Publishers, London, 1977.
9. J. Economy, R.S. Storm, V.I. Matkovich, S.G. Cottis, and B.E. Nowak. J. Polymer Sci (Polymer Chem Ed) 14:2207 (1976).

INSTITUTIONAL BARRIERS TO INDUSTRY-UNIVERSITY INTERACTION

Raymond W. Fenn, Howard A. Kuhn,
Bryan R. Noton, and Paul C. D. Han

Background

Most of the advances in materials processing achieved during the last several decades in the United States have been largely the results of empirical developments, with little or no scientific input. The workshop wrestled with many difficult questions related to this problem. Since the potential value of progress in the science base for material processing has been demonstrated by several impressive examples in the United States, and since it is being pursued so effectively in West Germany and other countries, why has none of the mechanisms identified and implemented in the United States to foster processing science been fully effective in a self-sustaining mode? Why does it appear that the major ARPA program between Martin-Marietta and the University of Denver on Hi-Rate Forming did not result in a more lasting industry-university coupling? Why did the Processing Research Institute at Carnegie Mellon University close when the National Science Foundation (NSF) money ran out? If progress in this area is potentially so rewarding, why don't the major manufacturers pursue it more vigorously?

A major cause, apparently, is that, in the United States, research on materials processing is not accepted in academic circles as a first-class research endeavor; another cause is that little or no funding is available for this purpose (the Department of Defense supports only short-term, applied work in this area, while NSF apparently gives a very low priority to materials processing research); still another cause is that many practitioners in this field are so far removed from basic research that they do not know how to reduce to practice the findings of the few who carry out basic studies in these areas.

A general conclusion of the workshop was that this state of affairs leads to inefficiencies in the development of new processes or in the utilization of materials requiring new processes. Another general conclusion was that the situation could not be corrected unless an agency such as NSF would make a major, serious commitment to the funding of research aimed at providing the science base for materials processing. Each of the four panels reached various conclusions, which are presented separately below.

High-Speed Metal Removal

The problems associated with the ultimate commercial implementation of high-speed machining are complex and demand an interdisciplinary management and application approach. A polling of panel participants indicated that this objective could best be achieved through a cooperative effort involving industry, government, and university personnel. Methods for accomplishing this were not made entirely clear, although, it was generally concluded that sufficient long-term funding would have to be made available for such an enterprise to succeed. Several suggestions voiced by individual panel members included the establishment of a national high-speed machining center(s) for performing fundamental studies on all metal-cutting processes. Such studies would be coordinated through an industry/university metal removal advisory board, which would assist in the planning and guidance of the work and the eventual implementation of beneficial process developments. It also was suggested that construction and operation of the machining facility might be derived from governmental and industrial funding in which the latter would receive tax credits for its participation. University involvement might be encouraged by governmental support of graduate students pursuing careers in high-speed metal removal and ensuring that individual professors receive publication privileges and appropriate recognition leading to the attainment of university tenure.

Metal Deformation Processing

Advancing the science base for deformation processing of metals will require the development of sophisticated models of structural change during plastic deformation and of interface phenomena, as well as improved techniques of mathematical analysis of metal flow. The nature of these phenomena involves techniques and methods of analysis from a variety of disciplines, including plasticity, mathematics, metallurgy, surface chemistry, heat transfer, and fluid flow.

Perhaps it is this diversity of requirements that has been the major drawback to progress in deformation processing. The various phenomena involved are treated within various academic disciplines in universities, but there is little intradisciplinary transfer of knowledge. As a result, fundamental developments in other areas of study do not find their way to application in metal deformation processes.

An approach to correcting this situation academically is to develop manufacturing as a viable, self-sustaining, autonomous academic discipline. Then the various necessary fundamental studies would be directed specifically to metal deformation processes. Increased funding for manufacturing research would develop improved respectability for the subject as an area of academic study among young professors, instigate courses in manufacturing, and promote a positive image of the subject for students.

Another difficulty with the current dominance of discipline-oriented research in academic circles is the sterility of specialization. Extremely detailed and sophisticated studies are performed, but very often they are directed to material systems or deformation modes that are irrelevant to the materials, processes, and problems of industrial importance. It is mandatory that researchers take a problem-oriented approach to research in deformation processing.

In short, the problem of supplying the necessary science base for deformation processing might be better served, not by itemizing and rationalizing the needs, as in the previous sections, but by promoting academic programs in the subject. Then the needs would be obvious to those involved and there would be sufficient numbers of researchers to address those problems. A proper academic environment for deformation processing would assure a steady supply of well-educated engineers who are receptive to the introduction of science into manufacturing. In the long run, this would bring about the necessary changes in attitudes toward manufacturing as these engineers reach management positions.

From the point of view of the industries, the competitive position of materials processing industries is seriously hampered by the relatively low regard for the subject. The high-technology industries are reasonably competitive because of large amounts of government R&D monies. In these industries there is also a keen awareness of the importance of new developments, and technology transfer is not difficult. The low- and medium-technology industries, on the other hand, suffer from highly fragmented R&D in diverse manufacturing industries.

Advanced Composites

Compared with metals processing, processing of advanced composite materials is in its infancy, and, therefore, as expected, a large number of problem areas and programs aimed at solving these problems were identified by the panel. To successfully address many of these programs, there are significant advantages in establishing cooperative efforts between industry and the universities. However, for such industry/university programs to be successful, a number of important factors must be considered. Those suggested during the deliberations of the panel are as follows:

- Geographical proximity
- Government-funded program stipulating interaction
- One program manager for programs with more than one person involved at each facility in the team
- Definition of goals of each partner and central awareness of each other's unique needs
- Mutual dedication to objectives
- Availability of facilities and talent
- Freedom to publish research results based on careful definition of problems
- Agreement on patent treatment
- Cooperative attitude between individuals involved
- Long-term funding commitment
- Visiting scientist/resident scholar-type exchanges between universities and industries.

High-Modulus Polymers

In this particular field, where processing is still intimately connected with materials design and selection, it becomes still more difficult to get a meaningful cooperation between academe and industry. The only examples of such cooperation occur in the United States when government is supporting both the industry and the university on the same project. It should be noticed, however, that this is not necessarily true in other countries. Close university-industry coupling has proven very fruitful abroad in accelerating the reduction to practice of advanced, sophisticated science and technology. Well-known examples are those of Prof. Natta with Montecatini, Prof. Ziegler with Ruhrchemie, and Prof. Kasimir with Philips.

Implementation

Since increased progress in providing an expanded science base for materials processing is potentially so rewarding, and since a key requirement to achieve this goal is to provide more effective industry-university interaction, what can be done to foster this interaction? Reasons why past efforts to achieve such a coupling have had only limited success have been discussed in earlier sections of this report. It is clear that optimal coupling between the basic research at the universities and the applied processing development in industry requires effort, dedication, and commitment on both sides. Such coupling is time consuming, and the benefits do not become apparent for a long time. Perhaps some of the past disappointments were due to unrealistic expectations: on the one hand, the results of basic research usually are not felt in the marketplace for a long time; on the other, academic recognition for such research does not accrue until such major scientific and engineering advances have been achieved that they attract the attentiuon of leading scientists and engineers in the academic community at large. In order for major academic programs in the materials processing area to become self-sustaining, federal funding must be assured for a long enough period of time to achieve such recognition. Enough scientists and engineers with a deep knowledge of this science base must become available for employment in industry to allow the effective translation of the science base into applied practice.

The workshop concluded that the potential benefits are sufficient to justify an immediate increase in the federal funding available for this area. This funding should be provided by a mechanism which would encourage industry-university coupling; for instance, contracts and grants could be structured so that the federal funds would flow from the ultimate user -- industry -- to those who carry out the basic research -- the universities. Thus, grants or contracts should be made by the federal agencies to industrial organizations, with the provision that the bulk of the funds would be subcontracted to universities. Industry should preferably retain none of the funds, or at most, a small amount required for work in direct support of the universities. As a condition of the subcontracts the universities should send their students to work for limited periods of time in the laboratories of the principal industrial contractor, and a commitment should be made to exchange senior personnel between industry and university for a limited time. Such a mechanism would guarantee that the programs will have relevance to the industrial sector and that industry will be sufficiently motivated to apply the results of university research to its technological needs. While the participants at the workshop recognized that this and other suggested approaches may not be the ultimate solution, the consensus was that an early start was critically needed and that it should not wait for the conclusion of the recommended national study aimed at identifying the optimum industry-university mechanisms.

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Science Base for Materials Processing

SEPTEMBER 27-28, 1978

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

PROPOSED PROGRAM

WORKSHOP ON SCIENCE BASE
FOR MATERIALS PROCESSING

SEPTEMBER 27, 1978

9:00
GOALS OF THE WORKSHOP
George E. Dieter, Jr.—Workshop Chairman
University of Maryland

KEYNOTE SPEAKERS

9:10
Status of Processing Science Research in the U.S. and Europe
Harris Burte
Air Force Materials Laboratory, Wright Patterson AFB

9:50
Science Base Program to Design a Dual Property/ Microstructure Compressor Disk
Harold Gegel
Air Force Materials Laboratory, Wright Patterson AFB

10:30
COFFEE BREAK

10:45
Institutional Barriers to Industry—University Interaction in Materials Processing
George E. Dieter, Jr.
University of Maryland

11:30
LUNCH

12:30
INDIVIDUAL WORKSHOP PANEL SESSIONS

Metal Deformation Processing
Howard P. Kuhn, *University of Pittsburgh, Chairman*

Requirements for High Speed Metal Removal
Raymond W. Fenn, Jr., *Lockheed Missiles & Space Co., Chairman*

Processing of High Modulus Polymers
Paul C. D. Han, *PINY, Chairman*

Processing of Advanced Composites
Bryan Noton, *Battelle Columbus Laboratories, Chairman*

5:00–6:00
SOCIAL HOUR
(Evening workshop sessions may be arranged at the discretion of the panel chairmen)

SEPTEMBER 28, 1978

8:00
WORKSHOP PANEL SESSIONS (*continued*)

11:30
LUNCH

PLENARY SESSION

12:30
Report by the Panel on Science Base for Metal Deformation Processing

1:00
Report by the Panel on Science Base Requirements for High-Speed Metal Removal

1:30
COFFEE BREAK

1:40
Report by the Panel on Science Base for Processing High Modulus Polymers

2:10
Report by the Panel on Science Base for Processing Advanced Composites

2:40
GENERAL DISCUSSION

3:10
OVERALL SUMMARY
Francis L. VerSnyder, Rapporteur

3:30
ADJOURN

PURPOSE AND SCOPE

Progress in creating advanced materials for structural applications depends critically on improved basic understanding of materials processing. There are three principal drivers in this direction:

- Controlled materials synthesis by fine-tuning processing to create new structures with enhanced properties.
- Net shape processing to reduce manufacturing costs.
- Improved processing to reduce energy consumption.

The needs in these areas have increased, but the science base to provide for attainment of significant advances does not exist.

The objective of this workshop is to assemble knowledgeable people from industry, universities, and government to:

- Identify areas of materials processing where increased science base could be expected to have a major impact on improved processing technology or processing economics.
- To define the needed science which must be performed for each process to achieve the anticipated technological and economic improvements.
- To explore the institutional problems which must be overcome to achieve greater academic participation in processing science and to develop long-lasting procedures for effective industry-university interaction.

It is expected that the conclusions and recommendations of this workshop will form the basis for long-term federally funded programs to achieve the above objectives, which will greatly enhance the science base for processing in this country.

This workshop will deal with the processing of both metals and polymers. Attention will be focused primarily on processing which enhances the structural properties or improves the economics of structural parts.

Four workshop panels will be constituted in furtherance of this purpose. A brief description of their proposed activities follows.

PANEL ON SCIENCE BASE FOR PROCESSING ADVANCED COMPOSITES

The panel will evaluate the scientific basis for processing advanced composites with polymeric matrices. It will include both short fiber and continuous fiber reinforcements and will concentrate on those processes involved in the final stage of processing hardware. In the case of thermosetting matrices, this will include fabrication of parts utilizing preimpregnated materials and in the case of thermoplastic resins with, for example, short fiber reinforcements, the processing will include the flow, dispersion and orientation of fibers in discrete parts ready for assembly.

The panel will discuss and analyze the basic science which underlies these processes and attempt to pinpoint those areas where increased knowledge will have the greatest influence in (a) improving the properties, (b) decreasing the costs by addressing cost-drivers, and (c) improving the reproducibility of composite structures and the reliability of systems.

PANEL ON SCIENCE BASE FOR HIGH-SPEED METAL REMOVAL

The panel will evaluate the scientific base for high-speed metal removal (machining and grinding) and outline the additional scientific base required to cost-effectively implement high-speed metal removal. Items which will be considered are: material properties, constitutive equations, deformation mechanisms, tool composition and wear, lubricant/additive, tool/workpiece interface behavior, cutting performance as function of process variables, control of system dynamics (machine, tool and workpiece), dynamic data analysis, real time sensing and control, and characterization of machined surfaces.

Recommendations on the required additions to the science base for high-speed metal removal will be made.

Consideration will also be given to methods of stimulating cooperative endeavors between industry and universities to generate the required science base to permit utilization of high-speed metal removal in a cost-effective manner.

PANEL ON SCIENCE BASE FOR METAL DEFORMATION PROCESSING

The objectives of this panel are to identify the processes which would most benefit from an improved science base and to specify the science areas needed for advances in deformation processing. Both massive forming and sheet forming processes will be considered. In addition, attention will be given to methods of stimulating greater academic participation and strong cooperative endeavors between universities and industry in processing science.

Since metal deformation processing involves a multitude of physical phenomena in a complex interaction between the workpiece material and processing hardware, it is useful to subdivide the topic into functional areas of mathematical modeling, material behavior, and tribology. ***Mathematical modeling*** of a given process serves as a conceptual framework around which a systems approach can be used and the complex interactions can be analyzed. Reliable mathematical models can then be carried on to direct application through CAD/CAM methods. ***Material behavior*** is important both in the relationships between incoming material and processing characteristics (flow stress, strain rate effect, workability) and in the relationships between processing and product properties (work-hardening, anisotropy, fibering). The former relationships provide necessary input data for accurate mathematical modeling, while the latter relationships define objectives for the process. ***Tribology*** involves the phenomena at the frictional interface between material and tool. Lubrication due to the interface film, surface finish developed on the workpiece, and wear of the dies are important aspects. In addition to direct application of results to the processes, tribological studies supply values of frictional shear to be used as realistic boundary conditions in mathematical models.

PANEL ON SCIENCE BASE FOR PROCESSING HIGH MODULUS POLYMERS

The panel will be responsible for evaluating the potential for processing polymer molecules into high modulus materials. It has been established both theoretically and experimentally that polymeric materials under some circumstances can be processed in a manner that increases their modulus by orders of magnitude. Polymers with inherently rigid chains have high modulus but can be processed into useful shapes only with extreme difficulty. Polymers with flexible chains can be easily processed into useful shapes but can be made to exhibit high modulus only with extreme difficulty. What combination of inherent chain stiffness and materials processing can lead to useful high modulus polymeric materials? What sciences must be better understood before a breakthrough in materials processing becomes a reality? What basic scientific knowledge is required? What institutional problems must be overcome to obtain this knowledge?

APPENDIX II

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APPENDIX III

METAL DEFORMATION PROCESSING

Working Group Reports

Microstructural Behavior

Categorization of Material Processing Problems.

The working group considered that these could usefully be divided into two broad areas: cold (and warm) processing, and hot processing. The former is categorized by stable microstructures (no recrystallization, precipitation, aging phenomena, etc.), whereas the latter is typified by the presence of unstable microstructures, so that some understanding of metallurgical processes such as recrystallization, precipitation, and aging is required.

Processing Problems in the Presence of Stable Microstructures.

- Work Hardening and Constitutive Relations

When all aspects of the microstructure are stable (except for the dislocation density), the principal problem is the description of the work hardening behavior. Knowledge of this kind is required for the solution of two types of practical problems: plastic instability calculations, and rolling (working) load calculations. The constitutive relation approach addresses itself to this problem within the meaning of a science base and is aimed at specifying how the "hardness state" or internal stress depends on the strain rate and temperature history of the strain path. In this regime of behavior, unloading between processing operations only leads to anelastic (recovery) effects (no recrystallization) and does not affect the hardness state. In this terminology, the Bauschinger effect is also an anelastic phenomenon.

- Texture, Anisotropy, and Yield Surface

When anisotropic materials are being considered (e.g., hcp metals), and particularly when arbitrary strain paths are to be followed (e.g., with respect to the prior rolling direction), the anisotropy of the yield surface must be taken into account. The effect of deformation history on producing "cameos" and bulges in the yield locus also becomes important. This is currently an area of active research in plasticity theory.

- <u>Deformation of Multiphase Materials</u>

Here we restrict ourselves to the characterization of the flow behavior when all the phases are ductile. (The effect of hard second phases, e.g., inclusions, on the cavitation processes is considered to be part of the ductility problem area.) The aim of research in this area is to be able to make quantitative predictions on the basis of knowledge concerning the separate behaviors of the constituent phases.

- <u>Embrittlement and Segregation Effects</u>

The development of modern techniques for the examination of surfaces and grain boundaries has made it possible to determine the effect of trace elements and other impurities on fracture behavior. In cases where metal processing operations are limited by such effects, the tools are now available for the investigation of these phenomena.

<u>Processing Problems at High Temperatures and in the Presence of Unstable Microstructures</u>.

The working group considered a large number of metallurgical phenomena under this heading and decided, for simplicity, to select two groups of these phenomena for investigation to the extent that they are involved in two industrial applications: processing of high-strength low-alloy (HSLA) steels, and processing of α/β titanium alloys.

<u>Processing of HSLA Steels</u>

- <u>Recrystallization Studies</u>

The primary goal of the controlled rolling operation is to produce a fine-grained ferritic material after hot rolling and passage through the γ ---> α transformation. Such a product requires the presence of deformed and unrecrystallized austenite grains prior to the transformation; the deformed unrecrystallized austenite grains prior to the transformation; the deformed grains must also be fairly fine, so that intermediate grain refining operations are required after austenization (which produces a coarse grain size). Thus controlled rolling implies the promotion of recrystallization when required (during roughing) and the inhibition of recrystallization when it is to be avoided (during finishing). The dependence of the recrystallized grain size on the previous strain, strain rate, temperature, and material composition is also important. A considerable data bank has been amassed by the steel industry regarding the above parameters, although they have not been well synthesized into suitable quantitative "laws of recrystallization." Such laws would also be very useful with respect to titanium processing (see below), as well as aluminum alloy processing, copper alloy processing, nickel alloy processing, etc.

- Precipitation Kinetics and the Interaction between Recrystallization and Precipitation

The controlled rolling process involves the prevention of recrystallization during finish rolling by means of the precipitation of fine-alloy carbides and carbonitrides during processing. The kinetics of precipitation of these particles are only known under restricted conditions. Precipitation kinetics should be determined both during deformation and after deformation. The differences in the behavior of the Nb-based, V-based, and Mo-based precipitates must also be known. The rational design of rolling schedules and the scientific selection of alloy compositions both entail a comprehensive research effort regarding determination of the kinetics of precipitation under a wide range of conditions, and development of a synthetic theory for the interaction of precipitation and recrystallization.

An increase in the understanding of this interaction in the HSLA steels can lead to applications in the processing of copper alloys (e.g., Cu_2O precipitation), aluminum processing (e.g., $CuAl_2$ precipitation), etc., and to the possibility of controlling grain size under widely varying processing conditions.

- Effect of Solute Additions on the Recovery and Recrystallization Behavior during Hot Working

A full understanding of controlled rolling (and the capability for the rational design of these processes) requires that the role of solute additions be better defined. There is considerable evidence that the addition of elements such as Mn and Mo can considerably modify both the work hardening (dynamic recovery) and the recrystallization behavior. Thus the metallurgist can inhibit recrystallization not only by promoting dynamic precipitation during processing, but also by the judicious addition of solutes. (The retarding effect of solute addition is indeed necessary to prevent recrystallization until the precipitation process begins to play its role.) A comprehensive research effort regarding controlled rolling would thus have to have three components:

Recrystallization behavior
- Kinetics (ϵ, $\dot{\epsilon}$, T, composition)
- Grain growth studies
- Effect of ϵ, $\dot{\epsilon}$, T, and composition on grain size
- Precipitation kinetics
- Solute effects on recovery and recrystallization

Under the recrystallization heading, the distinct effects of dynamic, post-dynamic, and classical recrystallization would all have to be determined.

- <u>Deformation of "Two-Phase" Materials</u>

The control of grain size is a processing problem that does <u>NOT</u> involve the use of constitutive relations, as outlined above. However, the constitutive relations approach can be useful for the calculation of rolling loads during controlled rolling. Here we assume that the description of work hardening by this means (as a function of temperature and strain rate) is adequate, and that we also know the recrystallization kinetics. Constitutive relations for materials in the partially recrystallized condition could then be devised by considering that <u>two</u> phases are present, one of which is worked (and therefore has a hardness specified by the constitutive relations) and the other of which is recrystallized and therefore annealed. This problem is a special case of the more general problem of the deformation of multi-phase materials to be described below. Once again the successful development of constitutive relations for partially recrystallized HSLA steels would point the way to the development of such relations for other alloy systems.

<u>Processing of α/β Ti Alloys</u>

With respect to the high-temperature processing of titanium alloys, the working group selected three problem areas as being crucial to the improvement of indusrial procedures. These topics were also thought to be of general relevance to other alloy systems (e.g., zirconium alloys).

- <u>Deformation of Multiphase Alloys</u>

The aim of this type of work is to characterize the flow behavior of two-phase systems in terms of the mechanical properties of the individual (ductile) phases and the volume fractions of the various phases. The problem is complicated by the fact that at each temperature in an $\alpha+\beta$) region, for example, not only does the volume fraction vary, but the equilibrium compositions of the α and β phases are also different. Thus a solution to the problem involves the preparation of a series of α alloys over the required strain rate and temperature range. A suitable method must then be found for the description of the overall flow behavior in terms of the proportions and characteristics of the individual phases.

- <u>Deformation of Materials Containing Unstable Microstructures</u>

The commonly used titanium alloys contain such non-equilibrium microstructures as the Widmanstatten and martensitic structures. During high temperature forming, these microstructures are coarsened and modified, leading to a decrease in the hardness level. Systematic research should be carried out regarding:

> determination of the geometric features of the unstable microstructures which are responsible for the high temperature strength; and
> investigation of the rate of modification of these microstructures over the range of strain rate, temperature, and composition of industrial interest.

The general results applicable to titanium alloys would also be valid for the zirconium alloys, and in a qualitative way would apply to steel and other alloys sytems.

- <u>Texture and Anisotropy Effects at Elevated Temperatures</u>

During high-temperature forming, texture and anisotropy effects tend to be less important than in cold or warm forming. This is because of the much greater freedom of dislocations to choose an appropriate glide plane at elevated temperatures. Nevertheless, in hexagonal metals such as α-titanium and zirconium, crystallographic anisotropy can affect the successful accomplishment of forming operations. There is a clear need for extension of the type of yield-locus work done at room temperatures to the temperature ranges involved in hot forming.

Interface Phenomena

The term lubrication is not sufficient to describe the nature of interface control required for the success of modern metalworking processes. The function of a substance applied to or existing at the interface is to provide a means for achieving acceptable surface finish with a process that minimizes tool wear and avoids galling. Friction control rather than friction minimization is frequently required.

• <u>Windows</u>

Several examples can be cited of processes that show substantial cost benefits if the state of the art in interface control is to be advanced. First, in warm working (processing at temperatures below the lower critical temperatures) successful interface control substances simply are not available. If they were, an enormous material (and therefore energy) savings would be attained through reduction in input billet weight and the reduced machining requirements in components such as gears, bearings, and the like.

Second, high-speed strip rolling is an established manufacturing process, e.g., for steel and aluminum sheet. Industry in concert with lubricant manufacturers, has been working to achieve better interface control in their operations in view of the enormous cost benefit inherent in small process improvements. The improvements are slow to come, however, mainly because of our lack of fundamental understanding of the mechanisms of interface control.

Third, precision isothermal and conventional hot-forging processes are excellent ways to conserve strategic and energy intensive alloys such as those of titanium and aluminum. Net-shape processing is required for these, however, and surface conditions are critical in the finished part. The surface condition involves more than root mean square (RMS) roughness and includes a layer of material in the workpiece adjacent to the interface. This layer is critical to performance and properties in the finished component and therefore must be completely controlled by the process control variables, especially interfacial substances.

Other examples can be cited in metalworking including steady-state processes such as wire drawing and extrusion or nonsteady processes such as cold forging, and therefore it is obvious that a generic approach to understanding interfacial features that affect increased productivity, material conservation, and reduced lead time will improve our science base. Process modeling itself cannot succeed without realistic boundary condition input, however complex, of a form that simply does not exist today.

• <u>Approved Philosophy</u>

The following describe several problem areas in tribology under plastic deformation conditions. The approach to success in this field is necessarily a systems approach, and one that combines analytical methods with experimental techniques. No purely abstract notions will suffice and a totally empirical formulation is inadequate.

The basic system can be represented in the following way:

- **Recommended Research Topics**

  - To assess the state of the art in tribology with a view to its application to metalworking
  - Basic property determination: rheometric studies and heat transfer properties, etc., under pressure
  - Model studies -- analysis and experiments on simple deformation processes such as, ring compression, plane-strain compression for nonsteady processes, and strip drawing for steady state methods.

Additional validation by axisymmetric billet "nosing" and Hill's "bar side-pressing" methods may be useful but calibration methods are lacking currently.

  - Characterization of deformed surfaces and relation to interface condition.
  - Analysis and experimentation on real process.
  - Innovative ways of measuring the shear stress in the deformation zone.

- **Benefits Anticipated**

The final output from an improved science base for interface control is of two types:

First, a qualitative model can emerge that in itself will lead to better process control, improved surface quality, and reduced variability.

Second, a quantitative model can be formulated that will fit directly into advanced CAD process models and fully implement these techniques toward control of component definition and properties in alloys wherein the final structure cannot be determined by post processing heat treatment. Increasing concern with factors such as fatigue, stress corrosion cracking, and oxidation behavior--all factors influenced by the interface-adjacent zone--can be better approached. Increasing realization that residual stress, texture, and localized plastic deformation are strongly interface-regulated must be defined with a more science-based technique.

Identification of tribological regimes based on film thickness and surface roughness considerations is a significant missing portion of our data bank.

The continuous nature of thick film lubrication has been recognized for years, but lubrication mechanics in "thin" film regions, wherein the coating thickness is of the order of the surface roughness, is less well understood. Two further regimes can be identified as thickness decreases: namely, the ultrathin regime in which asperity contact becomes significant and the molecular regime in which chemical effects predominate. Any one or all of these regimes may be present in a single metalworking operation. For example, in a gear forging, a balanced degree of tooth-form extrusion and bulk-metal movement must be achieved to avoid lubricant entrapment in the thick-film region since, otherwise, an "egg shell" or "orange peel" surface condition can result.

A mathematical formulation designed as a useful process model must be able to predict lubricant thickness distributions if valuable output is to be obtained.

Sheetforming

In regard to sheetforming, there is little knowledge of the actual process itself and there is little predictive capability.

The goal for sheetforming is to model metal flow for application to computerized die design and selection of process variables. The benefit for large production runs, would be reduced scrap and reduced design lead time; for small production runs it would be reduced lead time. Warm forming versus superplastic forming -- better prediction of material behavior could allow forming at lower temperatures and/or higher rates leading to considerable energy savings.

Deformation at High and Low Temperatures.

- Constitutive equations

The influence of stress reversal on constitutive equations is unknown. This prevents us from, as an example, predicting flow stresses under drawbead-forming conditions, as well as predicting residual stresses and springback after forming. Furthermore, existing equations cannot predict stress as a function of arbitrary strain, strain-rate, temperature, or strain path anisotropy. Nor can existing constitutive equations handle changes in microstructure reflected by recrystallization, precipitation, aging, and other effects. Constitutive equations must include rate dependence, initial structure and structural evolution, strain history, and multiaxiality.

- Failure processes

The actual nature and size of imperfections (material, geometric or otherwise) leading to failure have not yet been established experimentally.

Not yet fully understood are:

- loss of plastic stability and necking behavior -- a proven model to predict forming limit is required;
- the process of shear localization;
- void nucleation, growth, and coalescence during fracture processes; and the
- extent of cavitation or structural damage tolerable in service of formed parts -- therefore the forming limit in such cases is unknown.

Bulk Forming Processes

- <u>Recommended Research Topics</u>

To develop a functional relationship between stress and strain which can be used to predict flow stress as a function of:

- temperature -- from just below recrystallization
- temperature to well into the temperature range normally associated with recovery and recrystallization
- strain rate -- from 10^{-5} sec $^{-1}$ to 10^{3} sec^{-1}
- strain range -- at least to a true strain of 1.0 but to a true strain of 5-10 as well
- initial material -- microstructural conditions -- cast, wrought, and particulate materials including microstructural variables such as grain size, strengthening, second phases

To develop failure criteria models for deformation limits determined by phenomena such as cavitation, micro fracture (create flaws), and macro fracture (separation into two pieces), and as a function of:

- temperature -- recovery and recrystallization;
- strain rate -- from 10^{-5}-10^{2} or 10^{3} sec^{-1};
- stress state; and
- microstructure -- such as:
    - second phases
    - grain boundaries
    - segregation
    - grain size
    - slip behavior

To determine causes for the development of dead zone formation.

To develop modeling techniques that would permit evaluation of flow behavior and deformation limits for materials normally processed at elevated temperatures by using low-strength materials at room temperature.

To determine a real-time system to quantitatively define microstructure:

- high-temperature microstructures
- anisotropy
- grain size
- second phases

nondestructive sensors

To determine defect formation as in:

- Effect of inclusion and interface and grain boundary on defect and microcrack formation as function of processing variable, $\dot{\epsilon}$, T, ϵ, in materials of engineering interest, for specific prior microstructures;

- Effect of microstructure on flow behavior of the matrix;
- Reduction in energy consumption;
- Reduction in scrap-improve utilization of materials;
- Improve reliability of products;
- Higher production rates;
- Decrease time for putting new processes on line;
- High strength-to-weight ratio;
- Apply the information to:
  - Build new mills at higher rolling speeds
  - Roll pass design - plate, sheet, shape, tube, rounds
  - Preform design in hot forging - closed die forging titanium and steel
  - Reducing number of dies in forging or stands in rolling sequence
  - Tube Piercing
  - Hollow Forging

To establish central source of material behavior data.

Deformation Modeling

Research needs for deformation modeling center around the following:

- Constitutive equations for room temperature deformation are satisfactory, except for materials exhibiting high crystallographic anisotropy. For high temperature deformation, however, no acceptable constitutive equations exist.
- Present analytical techniques (energy of deformation, slab, slip-line, upper bound) should be applied to complex geometries.
- Methods must be developed for evaluation of the effects of temperature gradients on flow gradients, with particular application to shear defects.
- Mathematical simulation of metal flow in the nonsteady state processes is required; it would aid preform design in forging.
- Data bank is recommended on properties for deformation processing using standardized measurement techniques.
- There is a long-range need for reliable large-strain, three-dimensional, elastic-plastic finite element and finite difference programs.