Distribution Category:
General Energy Research
(UC-400)

ANL-89/3
CONF-8806303

ANL--89/3

DE89 008190

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ADVANCED MATERIALS IN THE MANUFACTURING REVOLUTION

Proceedings of the Conference held at
Argonne National Laboratory
June 14, 1988

Editors:
Michael V. Nevitt
Norman D. Peterson

February 1989

MASTER

Work supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Science, under Contract W-31-109-ENG-38.

PREFACE

The conference, "Advanced Materials in the Manufacturing Revolution," was held at Argonne National Laboratory on June 14, 1988. Organized as the first of a series of Argonne "technology impact" conferences, this meeting sought to provide the leadership of manufacturing industries a broad perspective on:

- How new materials--metals and alloys, ceramics, polymers, and their composites--are invading the domains of conventional mill-product materials, and
- How new materials strategies are needed for manufacturing systems and products in order to provide competitive cost, performance and quality.

Emphasis was placed on small and medium-size manufacturing industries situated in the Midwest region surrounding Argonne National Laboratory. Co-sponsoring the conference were four local and regional associations with broad, diversified manufacturing constituencies: The Illinois Manufacturers' Association; the Tooling and Manufacturing Association; MIMA, the Management Association; and the Chicago High Tech Association. These organizations publicized the conference extensively within their member communities and provided advice in structuring and staging the activity.

One hundred and eighty-five persons attended, representing thirteen states and Canada. The majority of the participants were from the Milwaukee, Chicago, Rockford, South Bend crescent.

Roughly half of the participants were chief executive officers, presidents, vice-presidents and other manufacturing and R&D executives. The other half of the attendees were staff scientists and engineers, consultants, educators, planners and investment specialists.

Seven speakers covered topics and points of emphasis in morning and afternoon sessions that provided approximately equal coverage of two areas:

1. Management issues and initiatives involved in adapting technological advances in materials and manufacturing methods and exploiting these advances to gain competitive advantage. Donald N. Frey, Joel A. Goldhar and Robert P. Clagett emphasized this area in their presentations.
2. Specific trends in the development and commercial availability of advanced metallics, ceramics, polymerics, and their composites. The impacts of these new, high performance materials and their processing on manufacturing methods and products were covered by Arden L. Bement, Jr., James C. Williams, John P. Riggs and John B. Wachtman, Jr.

Alan Schriesheim, Director of Argonne National Laboratory, provided a brief keynoting statement of the Laboratory's motivations for hosting this and future technology impact conferences.

Discussion periods capping the morning and afternoon sessions and facilitating speaker-participant exchanges were led by Paul T. Sullivan, Executive Director, Purchasing and Transportation Services, Ford Motor

Company and by Charles W. Liedtke, General Manager, Signal Plastics Division, T. L. Swint Industries. Information and points of view brought forward in these discussions were assimilated by the speakers into the written versions of the presentations that follow.

Pamela A. Dalman provided indispensable help in preparing the manuscripts for publication.

The support of the University of Chicago and the U.S. Department of Energy is gratefully acknowledged.

Michael V. Nevitt
Norman D. Peterson

EDITORS

CONFERENCE DIRECTOR

Michael V. Nevitt, Argonne National Laboratory

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Abstract

A conference at Argonne National Laboratory for senior executives of small and medium-size manufacturing companies covered technical and managerial issues involved in adapting advanced materials and new manufacturing methods. Seven speakers discussed how high performance metals, alloys, ceramics, polymerics and their composites are replacing conventional mill-product materials and how these new materials are impacting manufacturing methods and products.

Keynoting Remarks

Alan Schriesheim
Director, Argonne National Laboratory
Argonne, IL 60439

The topic of this conference and the speakers were chosen to help manufacturing industry leaders gain a broader awareness of the advances in materials and processes that are currently underway. While we at Argonne would be very pleased if some participants found specific solutions to materials and manufacturing problems that relate directly to their businesses, a more realistic hope on our part is that participants have located some directions in which solutions can be found and some people they can talk to in order to identify those directions. The measure of success of the conference from the viewpoint of those who attended is mainly in terms of the broadened knowledge and new contacts that were taken away at the end of the meeting.

We also hope that the participants have expanded their knowledge of the process by which new ideas coming from research--especially federally-funded research--find their way into the market place, and have gained some ideas on how to get back in touch with Argonne people and with the speakers in order to follow up on some of the thoughts and ideas that came out of this meeting.

From Argonne's point of view, the assembly of talent brought together is only the start of the process represented by this conference. For more than a year we have been seeking to develop some special means of interacting in a focused way with industry, and especially with the small-business segment. We desire interactions that will benefit private companies and utilize the expertise that is available at this Laboratory.

Why does Argonne seek this role? The most important reason is we, as a national laboratory, and the nation are engaged in a competitive struggle that involves the globalization of innovation and technology. This struggle impacts the American business and financial climates. Argonne National Laboratory is one of the major federally supported laboratories in the U.S. and represents probably the largest technical resource in this section of the country. Therefore, we are a resource that can be applied to the issue of national competitiveness. We take that obligation seriously.

A second reason is that Argonne has one of the most aggressive and effective technology transfer centers in the national laboratory system. Argonne and the other national laboratories, some of which were represented at this conference, have internal organizations dedicated to transferring technology from the laboratory to industry. We're anxious for this conference to generate interactions between key people in industry and in our Laboratory. These interactions can be channeled through our technology transfer operation and also through one-on-one informal exchanges. Still another motivation is that, while we are a national laboratory, we are in fact located in this particular Midwest region and it's important for those businesses situated in this region to understand what kind of a resource

Argonne can be. These factors combine to give Argonne a strong desire to develop a continuing and stronger dialog with its industrial neighbors.

The topic of advanced materials is particularly appropriate, we believe. Argonne has one of the largest and strongest materials science groups within the national laboratories. It is in fact the largest operation within Argonne. Materials and the processes by which they are fabricated are the common denominators in a broad array of manufacturing operations, and there are advances being made in materials that will revolutionize manufacturing processes. Many of the small firms represented at the conference do not have large R&D departments, and they cannot in the normal course of business keep track of breakthroughs in materials and materials processing other than those that directly relate to their product line. Thus, it is important that there are meetings to display that information so that businesses can assimilate it quickly.

This conference represents the fulfillment of an assignment we at Argonne gave ourselves many months ago, and in its planning, organizing and staging we had much valuable advice and help. A Conference Advisory Board, the membership of which has been listed earlier in this proceedings volume, gave us important guidance in the selection of topic, emphasis, and speakers. Many members of the Board attended the conference.

We were fortunate in having enthusiastic and supportive co-sponsors. A substantial measure of the success we had in attracting a large and diversified group of conference participants is due to the endorsements and publicity provided by the cooperating industrial associations: The Illinois Manufacturers' Association, the Tooling and Manufacturing Association, MIMA, The Management Association, and the Chicago High Tech Association. The support of the University of Chicago and the U.S. Department of Energy was also essential.

We plan to develop follow-up meetings dealing within a conceptual framework of technology forecasting. Drawing on our own scientists and engineers and on expertise external to Argonne, we hope to put together discussions of various breakthroughs in science and technology and projections of how they can be applied to manufacturing processes and other major industrial activities. High temperature superconductivity is such a recent breakthrough. We are deeply involved in this exciting field and have begun to ask ourselves, for example, "What impacts will this new development have on manufacturing?"

This conference and subsequent ones, it is hoped, will sharpen our focus and industry's focus on how interactions can be made most productive. We look forward to that prospect.

THE PROCESS OF PROCESSING: HOW TO COMMERCIALIZE IT ALL

Donald N. Frey
Chairman Emeritus, Bell and Howell Company
and
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This discussion, carrying the admittedly whimsical caption, "the process of processing," will treat several topics that appear central to the subject of new materials and the manufacturing revolution:

- The origins and driving force for the revolution;
- The role of advanced materials; and
- The relationship to technology transfer.

The Manufacturing Revolution and How It Started

It is fair to say that the movement we call the manufacturing revolution started very simply: the wolf was at the door; we were getting clobbered. Strategic shifts in business usually start because there is trouble. The manufacturing sector of our economy ran into bad times caused primarily by the increased share of world trade acquired by our two principal competing nations, Japan and Germany. The revolution was also fueled by growing consumers' complaints about the lack of quality of American-manufactured products, particularly consumer goods such as automobiles and television sets, when compared with the stellar, high quality performance of foreign-made products. Japan and Germany also had some price advantages for a time, caused by distorted dollar-yen and dollar-deutchmark relationships, but at the root was the fact that our competitors had started eating our lunch in some of the heartland businesses of America: consumer electronics, automotive, machine tool and steel.

The inroads made by Germany and Japan have been selective, because the central technologies of these two major competitors differ substantially. Germany has not been a particularly strong player in world markets in modern electronics, while Japan has, of course, led the world in consumer electronics. Germany has been preeminent in precision machinery--metalworking, textile and the like, supported by a strong mechanical engineering base. The Japanese have not been as strong in this area, although they are moving in this direction, driven in part by their growing strength in digital machine control systems. There has been a degree of commonality between Japan and Germany with respect to automobile manufacturing, although it is now clear that Japan dominates the mass market, while Germany specializes more in high precision, high quality vehicles. In the course of this discussion some useful comparisons with our two major international competitors will be made. Japanese practices will be emphasized, but equally revealing examples could have been taken from recent German experience.

After starting in a miserable state immediately after the second World War, and as they rebuilt their country, the Japanese steadily mastered quality control, particularly process control in manufacturing. Despite the endless number of seminars and books and speeches and newspaper articles about their quality miracle, the Japanese didn't do it with mirrors, or with anything else that was startlingly new. They did it by devotion to the infinite number of details in their manufacturing operations. Japan had at work in a wide variety of its manufacturing industries a cadre of experienced engineers and recent engineering graduates who were highly proficient in manufacturing and process methods. These professionals applied principles of quality control and process control that were also well known in this country. We had the tools available to us if we wanted to use them. We didn't.

A force that has recently added further momentum to the manufacturing revolution in America is the realization that increasingly innovative foreign products--Japanese in particular--are invading the marketplace. These new products enable Japanese manufacturers to take larger shares of new markets--markets in which they had not earlier established a leadership role. The Japanese are now doing a more effective job of commercialization of R&D, frequently using U.S. basic science and technology. Simply put, they have learned how to commercialize U.S. research results and sell them back to us, adding to our trade imbalance, causing the turmoil in the exchange markets and the like.

Another major contribution to the revolution is our realization, at last, that direct labor in our manufacturing plants doesn't count for much anymore. Direct labor--blue collar, on-the-shop floor labor--averages not more than 15 percent of the cost of goods manufactured. Failing to understand this, we have run our manufacturing companies wrongly in the last decade. Concentrating on direct labor, we have been working on a smaller and smaller fraction of the total cost of the value-added chain, and we have been ignoring the issues associated with overheads and downstream costs. We assumed we were still in the mass production business, which is less and less the mode in major industrial countries. Manufacturing has become more and more customized.

Fifty years ago in this country a normal manufacturing plant mass producing goods such as steel or cars operated with an overhead that was perhaps 40 percent of the direct labor cost. In this country today overhead averages 300 percent of the direct labor cost. Thus, in concentrating on direct labor we have been chasing the wrong thing. In the overheads are all the issues and cost components that are driving the manufacturing revolution: engineering costs; material handling costs; purchasing costs; quality costs; sometimes marketing costs. There are other downstream costs such as customer warranties, and to them must now be added the cost of establishing and maintaining the innovative capability of the company, a matter that we will discuss in more detail later.

Far-thinking manufacturing companies now realize that outdated accounting processes have been a source of their manufacturing problems. In some large, cutting-edge manufacturing companies today, effective accounting practice defocuses the direct labor component and focuses on the elements of overhead enumerated above. These are the drivers today in determining the bottom line.

Unfortunately, many management teams do not yet realize what outdated accounting practices are doing to them. Most small companies, and many large companies, are having a difficult struggle in modernizing their manufacturing operations because there are large capital costs connected with acquiring modern equipment and traditionally these costs have been justified in terms of the savings in direct labor costs in the manufacturing processes. This assumption is too limiting in most cases, and as a result these companies are unable to get adequate bank loans because they can't make a case. In many cases the purchase of capital goods for a manufacturing company can be paid for by reduction of working capital--the work-in-process, the inventories on the floor. While it doesn't make any difference on the balance sheet whether it is a dollar of working capital or a dollar of capital investment, it does make a difference from the viewpoint of modern manufacturing practices and the working capital reduction can be permanent if you continue to run the plant right. Thus, faulty accounting practices get in the way of the manufacturing revolution.

Bad accounting practices have also been one of the sources of quality problems in the U.S. The trouble with quality, as it relates to a manufacturing company, is that it is not an issue of the hour in the same way as direct labor or overhead costs. Quality issues come downstream and their costs are soft costs in the short term, although you do see them eventually. Quality--or more precisely the lack of quality--ends up as a cost to a supplier because his customer doesn't come back and buy goods from him. But since that is a downstream cost, it is harder to measure, and, given the aforementioned problems with traditional accounting, companies normally do not deal with it. Or at least it has not been dealt with in the past, and that is one of the reasons we've gotten into the quality trap.

Chasing the wrong issues in manufacturing, as discussed above, has also almost automatically mitigated against innovation in this country. Innovation means change, and if one is dealing with fixed capital investments, change is not desired. In a plant with old, hard automation there is limited flexibility; changes can't be made until the present equipment has been paid off. The net result is that the short term behavior of American manufacturing companies has been antithetical to innovation, and this behavior has predominated too long.

The Japanese, and the Germans as well, have a much shorter time horizon for investment and a lot longer time horizon for innovation. Their capital structures require much less return in the short run, and in both countries the shareholder-to-management relationship in a company is one in which the shareholder's return is given much less consideration. So companies in both nations have been able to reach out in time and use patient capital to invent and apply.

The Role of Advanced Materials

We are relearning that innovation is market driven, not technologically driven. The subject matter of this conference is relevant to this point. New materials with improved performance and quality are key sources of innovation, but we must remember that these new materials must ultimately appear in consumer products--we don't sell steel or advanced ceramics directly to consumers. So unless market-driven forces dictate the innovative requirements or usage of the new material, its commercial success will be limited no matter how technologically advanced it may be.

A prime example of a successful market-driven materials innovation is the low-alloy deep-drawing steel with high strength, which is moving into the automotive industry. The industry decided for many reasons, including legislative pressure, to improve the fuel economy of cars by, among other things, reducing their weight. Lower weight requires lighter construction, and since the bulk of an automobile is steel, a higher performance steel was required to have the same section moduli and other properties with less weight. Inland Steel Company, for example, mounted a major development effort on a low-alloy deep-drawing steel with high tensile strength, so that the same stiffness can be obtained in an automotive component at less weight. Very sophisticated research on a very common material, steel, was prompted by the fact that the automobile industry said, "We want stronger steels for equivalent weight, or less weight for equivalent strength." The result is clearly a market-driven innovation, driven in this case by demand for lighter-weight, fuel-efficient cars. Incidentally, the profit margin on the high performance steel is higher than that on a plain carbon steel, so the steelmaker gets a premium for his efforts.

The high-strength low-alloy steel development is one example of very important technological advances in materials now being made on a broad front. We are finally achieving the possibility--indeed the probability--that materials can be tailored to the application at hand; that is, materials can be matched to the demand of the innovation of the hour. The design of task-specific metallic and nonmetallic materials, the matching of their properties to the demands of the operating environment and the development of closely coupled processing methods will have profound effects on the manufacturing revolution. Advanced materials represent upstream capabilities that are needed in the downstream innovation process.

The Technology Transfer Relationship

Innovation requires technology transfer. The usual simplistic scenario for technology transfer involves a group of researchers and scientists seated on one side of the table who have or could have some technology of interest while on the other side sit a group of industrialists who say, "We're here to be helped and guided." Unfortunately, this model is not realistic and it doesn't work very well. These two groups of people respond to different reward systems. The researcher has a reward system that relates to his or her peer group: publications, honors, medals, and awards in the scientific or technical community. The industrialist and his employees respond to the bottom line, which is expressed in stock price, profits and all the other financial criteria used to measure the success of a public or private company. In addition to a reward system difference, there is a language difference. It is very difficult for research people to gain *ab initio* an understanding of a business problem because businessmen, unless they are technically oriented, cannot express their problems in technical terms. The scientists, unable to understand what the businessmen are talking about, can't formulate solutions to business problems. The process of getting through the cultural and language barriers requires a willingness on the part of both groups to spend considerable time at the table learning to understand each other's motivations and language.

Another point with respect to technology transfer needs to be clarified. Although technology transfer is frequently associated with small start-up companies, spin-offs, venture capital, and the like, the real economic leverage lies in the application of high tech to our existing economic structure. Argonne's project on the application of advanced technology to steel making, a very old industrial process, is an exemplary example, which, it is hoped, will have a high payoff. It represents the application of high tech to the existing industrial infrastructure, upgrading it and moving it forward, along with the stimulation of downstream areas of innovation and quality and the like.

Summary

The Viennese economist Joseph Schumpeter pointed out long ago--and we are learning it all over again--that for any country the driving economic force is the ability to innovate. All of the rest of it is caretaking--maintenance of the capital base which provides no growth and does not create economic progress or competitiveness. We are in the midst of a manufacturing revolution. Advanced materials will have a large impact to the extent that they affect the major needed driving force, which is the innovative capabilities of our manufacturing industries. We must tackle the as yet unsolved technology transfer problem, and we must break away from obsolete manufacturing concepts and methods that have hobbled us in the past.

DEVELOPING A NEW PRODUCT: DISCONNECTS THAT EXIST BETWEEN DESIGN, MATERIALS SELECTION, MATERIALS PERFORMANCE AND MANUFACTURING

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Introduction

There is general agreement today that the United States has been the leader in developing innovations, but has not been a leader in bringing them to market. The latter capability, which is more managerial than technical, has for many years now been seen to be a particular Japanese strength. It is essential for us to explore this issue, because our ability to exploit the use of new high performance materials together with advanced manufacturing techniques will not make us an effective worldwide competitor unless we can bring our products to market on a timely schedule and at an attractive price. In this paper we will use several comparisons of American and Japanese practices as a route for our exploration, recognizing that this path is not the only one we could follow, and that America's future competitive strength does not simply depend on copying some other national approach, Japanese or otherwise.

We will first characterize the differences in the American and Japanese managerial approaches, differences that we must condense and simplify given our limitations in time and space. Then, having cited these differences and made the (sometimes invidious) comparison of the two approaches, we will suggest some adaptive changes in the American approach that arise from the comparison. When appropriate, materials-related cases and examples will be cited for emphasis.

The differences between American and Japanese management styles lie in five areas:

1. The degree of emphasis on teamwork;
2. The insistence on continuing iterative exchanges between participating groups;
3. The intensity of the commitment to minimizing organizational barriers;
4. The level of attention to customer needs from the pre-design to full-production;
5. The extent of input from all relevant technologies.

There is a kind of holistic character to these five areas that makes them easier to deal with collectively than individually and sequentially. We will therefore use a collective treatment.

Product Design, Manufacturing and Marketing: In Series or In Parallel?

In larger U.S. corporations there is a tendency to develop the specifications for a new product as part of the marketing function. The market, the performance requirements and quite often the concepts of the design, including price, are formulated by the marketing group. Marketing then passes the (prematurely) complete package to the design group, which becomes involved for the first time. And thus begins the continuing "over the wall" scenario, as depicted schematically in Figure 1.

The design group adds its own concept of the latest technology that will make this product better--usually at higher cost--and hands it over the next organizational wall either directly to manufacturing or to the production engineering team preceding manufacturing. Each new recipient has been largely incommunicado up to the transfer point.

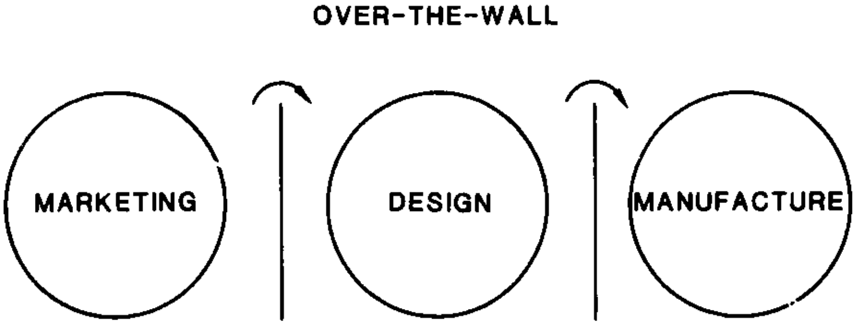

Fig. 1. The "over the wall" path for a new product

The ultimate response of the manufacturing organization is a predictable one: "There is no way we can make it to those specs. We don't have the needed equipment on the shop floor, so we will have to invest a huge amount of money in new gear to make it. There is no way we can absorb those costs."

This is a familiar story. An example based on the author's experience and involving the introduction of a new material will serve to illustrate this syndrome. The manufacturing organization received from the design group a new product design involving an electrical terminal in which the designer needed to create a nest that would have a conductor in it. The conductor at one end was to be a wire-wrapped copper terminal, while the other end was supposed to function as a spring. The design group had performed some materials research leading to the selection of a beryllium-copper alloy for the piece. The assertion was made that there had been sufficient testing to show that it was a good design, and tolerances had been placed on all parts of the design. It turned out that the beryllium-copper component was indeed a good conductor, but it really wasn't an adequate spring. Having the original design completed essentially in isolation and passed to manufacturing "over the wall" produced a major slowdown in introducing the product. It then took a very long time to develop a product that would do both, and it was not the original design.

This approach, "design in series," is shown in simplified form in Figure 2(a). It does not represent good teamwork, it does not provide timely interactions between responsible groups and it tends to accept and solidify--rather than soften--the organizational barriers that exist. This approach yields a product that is not optimized, may have quality problems, may be over budget and, importantly in today's climate, takes a longer time to produce.

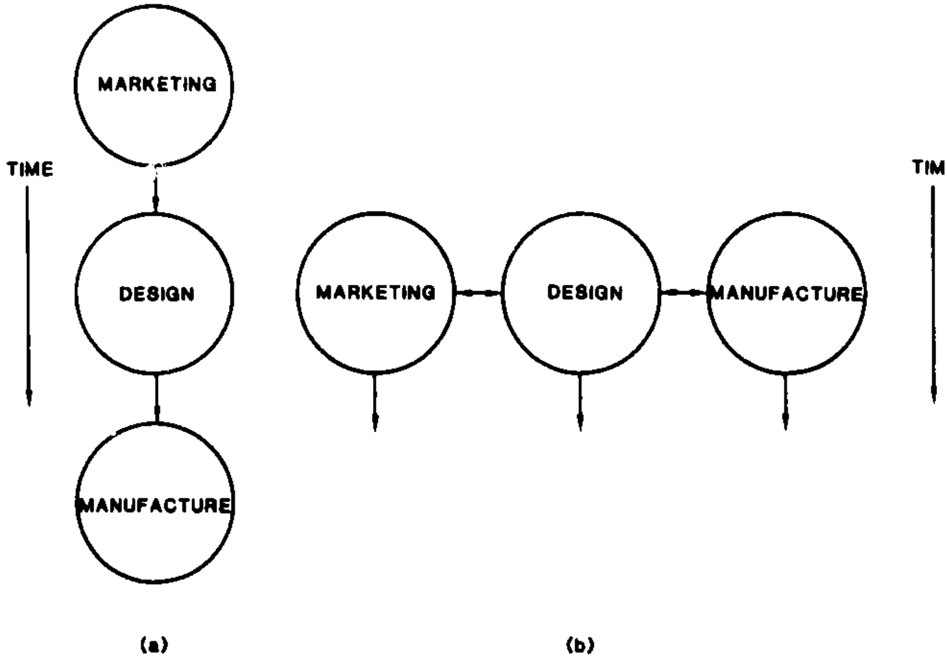

Fig. 2. (a) Design in series vs. (b) design in parallel

In general, the Japanese have a totally different system. Theirs is a parallel approach to the introduction of a new product in which marketing, design, manufacturing and the other responsible teams work collectively and interactively throughout the development and manufacturing cycle, as shown in oversimplified form in Figure 2(b).

The extent to which the chart of Figure 2(b) underplays the broad range and level of Japanese organizational involvement is made clear in Figure 3, which is an adaptation of the new-product flowchart of the Telecommunications Group of the OKI Electric Company. The chart is a matrix. The horizontal grid is composed of most of the organizational units at OKI, starting with the office of the president and proceeding through quality assurance, engineering (design in the U.S.), production engineering, production, marketing and sales and finally the service center, or warranty, organization. Along the vertical grid are the functional tasks and responsibilities that are required in creating a new product, starting with information collection, and proceeding through product specifications, quality assurance planning, design, prototype, pre-production, production, and so on.

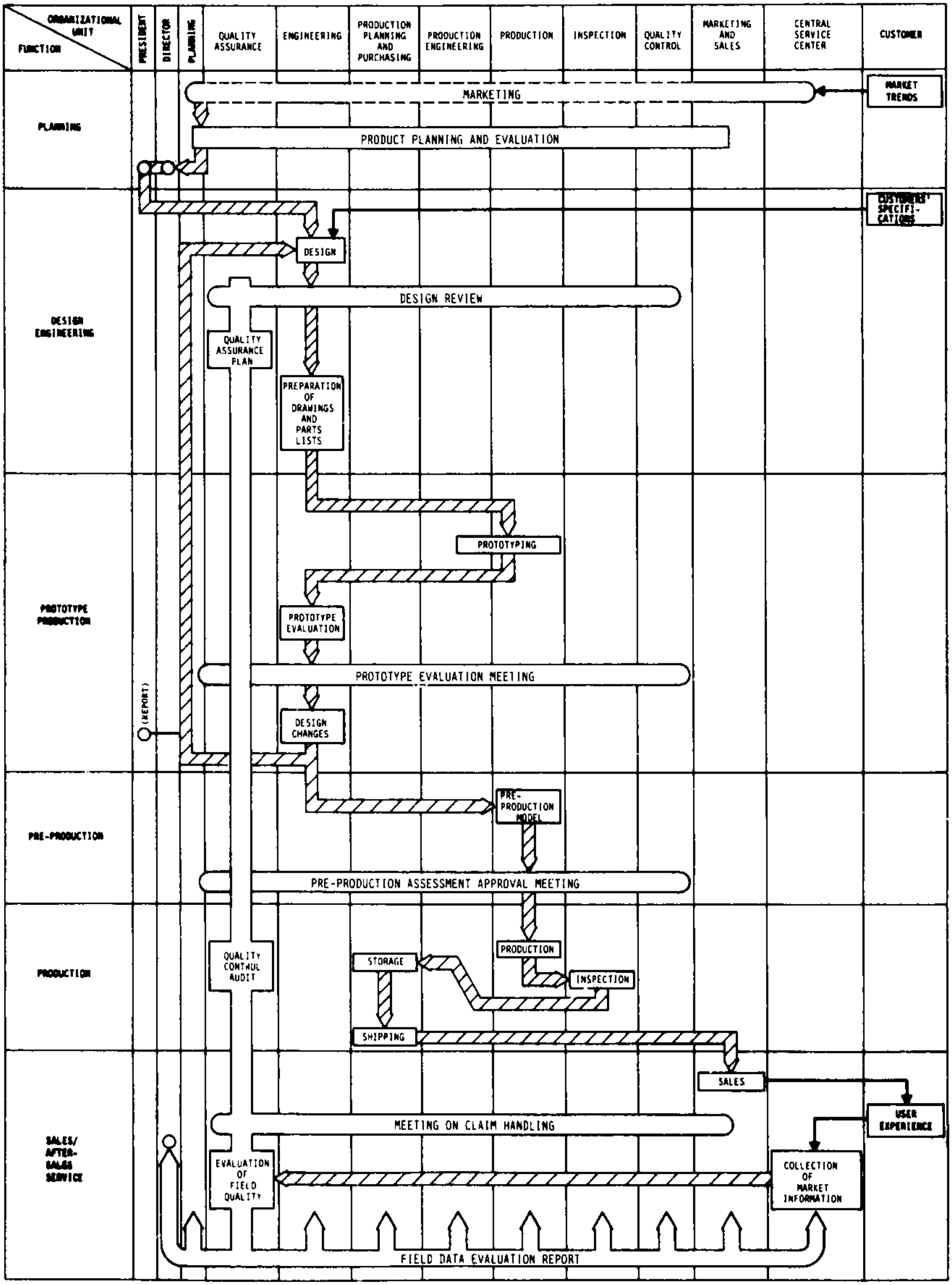

Fig. 3. New-product flowchart for OKI Electric Company

Responsibilities, assignments, and materials flow through the matrix on the conventional path, but the unique Japanese feature is the involvement of extensive, repetitive, company-wide feedback and team play at many stages. Starting at the information-collection and product-planning stage, meetings and discussion sessions (denoted by the open horizontal bar) involving every organizational unit from the office of the president to the warranty group are held to discuss the purpose of the new product, how it will be created, and its required quality. Close attention is paid to information coming back from the distributor network concerning customer needs. Only after these detailed discussions are complete is an assignment made to the engineering/design department to perform the original design work, incorporating the input from quality assurance, manufacturing, marketing, warranty and other parts of the company.

The repetition of the open horizontal bars down the matrix grid indicates how this iterative, interactive process continues. After the initial design is completed, and before a prototype is produced, all of the organizations come back together to discuss the design, critique it, make suggestions on production, and so forth. After a prototype is created there is another company-wide critiquing session, and yet another at initial production.

Finally, the plan calls for still another checkpoint meeting about six months after full production has started. This discussion is led by the warranty organization, which provides information back from the field as to the reception the new product is receiving and the kinds of warranty claims or quality problems that are being encountered. Customer feedback tells the company whether they have the product right and they modify the product substantially if they don't have it right.

It is interesting to note that OKI entitles the new-product flowchart from which Figure 3 was derived a "quality assurance program," asserting that the whole process of determining what product the customer wants, what quality level he wants and how to design and build that product to that quality level is basically the company's quality assurance plan.

The Japanese inclination to collaborate across all parts of the corporation, and not to separate into smaller groups, derives in large part from a cultural heritage that emphasizes the values of the strong family unit. This ingrained family loyalty carries over to corporate cooperation and togetherness. In the absence of that strong cultural inheritance in the U.S., other techniques have to be used.

Team Play in the Large Manufacturing Company

One approach that has sometimes been successful in this country is to create or nucleate in a large corporation a small entrepreneurial unit which, lacking the conventional organizational barriers that cause the over-the-wall chain response, can create a new product and get it to market much faster.

The creation of the IBM PC was accomplished through the use of this technique. When the PC was first proposed in IBM, it met with much resistance. It was not perceived by the majority of the corporate leaders as a favorable product direction for IBM; they were and they expected to continue to be mainframe specialists.

If it had not been for the fact that one of the corporate officers, supported by an engineering team, championed the PC development, the project probably would not have been started. One-year funding was provided (reluctantly). That was probably the best thing that could have happened. A small group was formed, much like an entrepreneurial company, and in one year a PC was created, largely with components from other manufacturers. The small group, unhampered by the customary organizational barriers, conceived the product, reviewed how they were going to make and market it, thrashed out the quality level needed, and, most importantly, talked about customer needs. And they got it to market quickly. That approach was so successful that IBM now works most of its operations in business units like the PC project team.

Another approach employed by many companies is to set up project teams. For this old concept to work, the team must comprise members from all of the relevant corporation units and have an interdisciplinary character. Each team member needs to have familiarity with organizational units other than his own. It is important for the designer, for example, to know what goes on in manufacturing and what kinds of equipment are available, so he or she can build current factory capabilities into the design and take into account the manufacturing problems that may be associated with a particular design. This familiarity can be developed in the initial stage of a new engineer's employment through training-period assignments and maintained in later stages of his or her career by relatively brief, well-defined transfer assignments.

In Japanese management practice, a new engineering employee is considered to be a long-term investment, so considerable time is spent in the beginning in training and orienting him or her to the products and processes of the Japanese company. A new graduate assigned to a design group does not begin design work for at least a year. The new employee spends about six months in manufacturing. A similar amount of time is spent in some part of the service or warranty group working with customers and dealers in order to imbue the employee with the need to be customer sensitive. All of this takes place before he or she is allowed to start working on a design problem.

In many large American companies, on the other hand, a comparable kind of orientation period is not routinely employed because, driven by high starting salaries for new engineers, the company moves to make the young person immediately productive. He or she is most likely to be assigned immediately to design work, for example, probably without having an opportunity to learn much about manufacturing, and certainly without a chance to view the dealer or customer end of the business.

The most effective teams are interdisciplinary. If a problem is perceived to be a mechanical problem and a mechanical engineer is assigned to it, it is assured that a mechanical solution will be arrived at. If, on the other hand, an interdisciplinary team is assigned to the problem, a team that includes materials experts, physicists and chemical engineers, some unique solutions will be generated and at the same time the organizational barriers that we have discussed will be reduced.

There are many cases in American manufacturing where a wisely chosen project team has been successful in the timely, cost-effective creation of a new product. One example will suffice to illustrate the point. At the time the research group in the Bell Laboratories was still working on the materials problems associated with their method of creating ultra-pure glass by depositing pure silica from a gas inside a quartz tube, the AT&T Engineering Research Center (ERC) in Princeton, NJ, was working on process problems. The ERC had been set up explicitly to work with Bell Labs--the designer--and Western Electric--the manufacturer--on new processes. A team was formed from Bell Labs, ERC and the Atlanta Works where production facilities would be located. By the time BTL had stabilized the design and materials requirements, ERC had developed the process equipment for the factory and the factory engineers were well along in floor layout and equipment requirements. It is estimated that the parallel, team approach saved three years in bringing the product to market over the series, hand-off from one group to the next, approach.

The points that have been made here, and the several examples given to illustrate technical management problems and solutions in manufacturing, all move in the same direction. Whether the issue is creating a new product, introducing a new material into an existing product, or using a new material to generate a performance in a product that isn't presently realized, the way to get that product to market effectively and quickly is by working all of the participating groups in parallel. Many U.S. companies will need more sustained concentration in this area if they are going to stay in parity with world competition in exploiting the many opportunities for using advanced materials to produce products that are of either better quality, better performance, better cost, or a combination of these.

The Innovation Path from Laboratory to Product Line

Not covered in the discussion thus far are the problems an innovation encounters in its path from the R&D laboratory into the other parts of the organization and ultimately into the company's product line. This is a classic case of technology transfer. The present author's experience as a research worker and ultimately as director of an R&D organization with the responsibility of transferring new technology to manufacturing has shown that there is a built-in proclivity to NIH (Not Invented Here) in most organizations and this response is a barrier in the path of new product development. Each engineering organization in a large company tends to feel that it is best and therefore it is the one that understands the problem and is the keeper of the technology responsibilities. Many companies have a hard time overcoming this problem and quite often fail in the timely introduction of a new product.

One way to make an effective transfer of technology out of the R&D center is to have a member of the using organization (manufacturing, for example) involved temporarily in the research and development work before it is complete, so that the user identifies with the solution. And the reciprocal involvement is almost as important: transferring temporarily a member of the R&D team to the manufacturing team helps the users to feel that the development team is still there and working to make the project a success.

The temporary assignment should not exceed about six months in length. If the assignment lasts longer, the person involved is no longer an effective transfer agent because now he or she is looked upon by the parent organization (manufacturing, say) as part of the R&D team.

The use of the human agent as the technology transfer medium is an essential technique. Put another way, when a design or R&D group, working in isolation from the manufacturing team, develops a solution and then goes looking for the problem, you will be guaranteed that it won't be used. As an example, the AT&T Engineering Research Center developed a more aggressive solder flux to use in wave soldering and then took it to locations to solve soldering problems. They could interest no users. Later, a quality and assembly team was formed between factory engineers and ERC researchers and the flux was used in conjunction with other methods in improved procedures.

The U.S. has a strong competitive edge in the innovation of new high performance materials, but that edge can be lost after the completion of the development by not getting the innovation into the product and not getting the product into production fast. Thus, the increasing use of new materials will place great demands on the process of transforming innovation into competitive market-place reality in a timely, efficient way. Even with the current use of more conventional materials, this process needs to be improved in American industry. New materials and new manufacturing technology will accentuate this need.

Summary

Drawing on U.S. experience and comparing U.S. and Japanese practice, we can in summary suggest several steps:

- To make the innovation-to-product process work, all groups of the corporate team must pull together and work in parallel. A better product will be achieved at a rate three times faster.
- Customer needs must be thoroughly examined before the design is started. This is true even if the product is technology driven. Technology provides an opportunity for a new product; it does not yield a new product.
- All the relevant technologies must have an input, especially materials technology.
- Iterative critiquing and discussing by all the participating groups in the organization should occur throughout the creation and initial production of the new product.
- Organizational walls and barriers should be broken down by whatever means are appropriate to the particular company. The creation of business centers, the development of interdisciplinary project teams and the short-term transfer of personnel between the participating teams are some of the managerial techniques for making this happen.

EXPLOITING NEW MATERIALS FOR COMPETITIVE ADVANTAGE

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This topic is a broad one which could be addressed from a number of important dimensions. In the present discussion, we will focus on the following major themes:

- The changing global scene,
- Industry responses,
- Emerging materials technologies,
- Opportunities for new materials in design and production,
- Managing the technology selection and acquisition process, and
- Lessons learned.

The Changing Global Scene

During the period 1973 to the present, increasing national concern has focused on our trade relations and growing interdependency with other nations of the world. Whether the Arab oil crisis of 1973 should be categorized as an "energy crisis" or an "energy annoyance" is debatable. However, it did bring home to every American a strong awareness of our growing dependence on the rest of the world for energy resources and raw materials.

The fraction of the world's technology generated by the United States has declined during this period not so much because we have been contributing less but because the rest of the world has been contributing considerably more. Other nations have not only increased their technological capabilities to compete with the United States for global markets but have also become better able to pursue American markets. Until the beginning of this period, the United States market, the biggest in the world, was relatively captive--we owned it. Now, increasingly, other nations are making major inroads.

Looking ahead, the decade of the 90's will be a period of uncertainty, during which people will have multiple options and will exercise them with intelligence and creativity. There will be greater challenges for industry, organized labor, investors, and law makers to be more forward-looking in analyzing the future, anticipating change, and mitigating the traumas of change. We must break the habit of looking at the future as an orderly extension of the past. As one wag expressed it, "The future is not what it used to be."

Today, as well as in the future, we can expect that advanced materials will create new sources of influence and strength. Federal investment in materials technologies will have high leverage because it creates demands for new machine tools and inspection equipment. Japan will continue to become superior to the United States in many materials technologies, and these technologies will continue to provide manufacturing industries with increasing opportunities for competitive advantage.

Western European countries, both independently and through the European Economic Community (EEC), are making significant investments in advanced materials technologies in order to enhance their competitiveness in global markets. Although the materials technologies being emphasized vary from country to country, four general categories of materials technologies are being particularly emphasized: polymers, ceramics, composites, and rapidly-solidified metals. One can also find advanced metal working technologies, such as precision forging, stamping, and net-shape forming technologies being developed in Eastern European countries, especially in USSR, East Germany, Czechoslovakia, and Poland.

Developing and newly industrialized countries (NIC's) alike, especially those which have abundant raw materials, are aggressively pursuing the establishment of higher value-added manufacturing industries in order to increase their exports and thereby obtain the foreign currency needed for reinvestment in advanced technologies. By liberalizing their policies for attracting production operations of multinational corporations, they are systematically increasing the skill level of their workforce and acquiring the know-how needed to produce "world-class," high-quality products.

A factor of increasing importance for small and large companies alike is the export control listing of many dual-use advanced materials technologies considered critical to defense applications, such as metal-matrix composites and advanced ceramics. Re-export license requirements imposed on our trading partners have also resulted in the delisting of some U.S. sources of supply for these advanced materials. Because of the high transaction costs in applying for and tracking export licenses through the review process, many small and medium size specialty materials companies have difficulty in competing for civilian export markets.

Our ability as a nation to exploit new materials technologies is also directly related to our cost of capital. The United States can be characterized as a "high-cost-of-capital" society, primarily because of our high national debt, our emphasis on consumption, and our lack of incentive for savings. Unfortunately, the cost of money in the United States after tax is three-fold higher than it is in Japan. This difference has a dominating influence on relative technology development cycles and investment opportunities for plant modernization.

The cost of capital also influences those technologies that industry will invest in, based on discounted cash flow. Analysts and commentators often criticize the short-term focus of U.S. management, especially where technology investment is concerned, without appropriately relating cause and effect.

Obviously, with a cost of capital of 6 to 7% the average development cycle in the United States before payback must be much shorter than in Japan with their relatively low cost of capital. As a result, technical investments in the United States tend to be skewed more toward advanced software and electronic devices which have relatively short development and product cycles as compared with, for example, advanced materials which often require five or more years of development for market introduction.

A low cost of capital has also permitted Japanese companies to follow parallel paths in their research and development more readily and thereby increase the number of attempts to a successful solution. U.S. companies have generally had to work in a more normative fashion and become more sophisticated in their R&D management methods. Reaching a major barrier or a dry hole often requires abandoning the project because of the inability to fulfill expectations for market introductions or return on investment. There is much less margin for second chances. In many such instances a fast follower strategy may be the superior strategy for new product and process developments. There may also be a need to change the mindset of those R&D managers who have an aversion to looking outside for new technology and in licensing technology from abroad.

Because of the factors described above, the roles of the national laboratories and the universities in working the national competitiveness agenda are beginning to shift. There is growing recognition that these important research institutions must devote more of their attention to materials processing technologies and becoming much more knowledgeable about production systems and industry's needs than they have in the past.

This conference exemplifies the leadership that Argonne National Laboratory is exerting to develop a closer relationship with small and medium size companies and make available to them research capabilities that can address their long-term technology requirements. Two examples of materials processing research underway at Argonne that can provide very high benefits to industry if they are properly exploited are:

(a) The application of novel processing techniques to fabricate conductor configurations from the new, highly-brittle, high-temperature superconducting ceramics, and

(b) The applications of nuclear magnetic resonance to monitor binder burnout and to characterize porosity and cracks in ceramic preforms.

These and other such developments cannot achieve their application potential unless they are actively pulled on by industry and exploited in the marketplace.

Industry Responses

In the face of global competitive forces, U.S. industries have been forced to take an intensified global view in conducting R&D, gathering information, forecasting technologies, planning markets, developing new businesses, and finding materials sources. This has required taking a much more open stance when it comes to sourcing technology and recognizing that no matter how much technology a company has under its control, there will be much more outside.

Companies around the world are now facing shorter product life cycles and lead times for new technology insertion that cannot be satisfied alone by internal development. As a consequence, many U.S. companies are decentralizing their R&D laboratories and either replacing or complementing bench scientists with "hunter-gatherer" technologists. U.S. companies are also augmenting internal developments with alliances, collaborations, and partnerships of various kinds around the world in order to exploit superior sources of technology wherever they exist.

U.S. companies are becoming much more sophisticated in developing technology acquisition strategies linked to their business plans. Such strategies include longer-range requirements definition, more detailed make/buy analyses, a more conscious pursuit of "fast follower" strategies, global licensing of superior technologies, and the adoption of more explicit patent policies which better delineate the relative advantages of intellectual properties and proprietary know-how in achieving competitive advantage.

There are several forms of technological knowledge needed by a company to compete in global markets. The first type is factual knowledge which is fundamental, reproducible, and subject to the test of scientific methods. The second is procedural knowledge or technological know-how which is needed to translate factual knowledge into added value. The third is managerial knowledge or the ability to plan and execute the applications of factual knowledge and know-how to systems of development, production, marketing, and distribution. A company must achieve a relatively high proficiency in applying all three forms of knowledge to be competitive in global markets.

Unfortunately, many of our industrial companies have been too compartmentalized and overly specialized. Many have in the past organized around a distinct innovation system (to include R&D, product development, and design), a distinct production system, and a distinct management system. Top recruits brought into one of these three systems often remain there throughout most of their careers. Furthermore, many business schools have in the past prepared their graduates with the philosophy that an understanding of management principals alone is sufficient to the task of managing diverse and specialized systems.

Japanese companies, in contrast, have a much stronger focus on production as a totally integrated system. Engineering graduates usually start their careers on the manufacturing floor learning operations. They are subsequently cross-trained in marketing, sales and product design. Such cross-training pays dividends in their mid-career when they are tapped for management development. As a result of this career progression, Japanese managing directors are much more aware of how value is created on the shop floor. They are more focused on creating value rather than managing value.

Fortunately, these lessons are now being taken to heart by U.S. companies focused on improving their competitiveness. Concurrent engineering, cross-training and longer-term career planning and development are gaining in importance. Also, many company chairmen are rediscovering that value is created by the production system not by Wall Street.

Because of the increasing need for industry to link up with universities and national laboratories to exploit new technical concepts at a more upstream stage of risk reduction, greater attention has been given to technology transfer as a competitive strategy. However, attention is generally focused on only the acquisition stage of technology transfer. Relatively little attention is given to the technology adaptation and integration stages, which usually involve the longest lead times and incur the greatest costs Technology is not fully transferred until the product is sold, so better incentives are needed for sustaining relationships between providing and receiving parties throughout the acquisition, adaptation, and integration stages of the transfer process.

Industries also have many opportunities to transfer technology along their extended value chain, which includes both customers and suppliers. These relationships have always existed in the past, but are being strengthened to better work common quality strategies and to share development costs in the interest of becoming more competitive. Particularly pertinent to the theme of this conference are the linkages now occurring between materials users and materials suppliers in order to couple the processing know-how of the materials supplier with the product design, marketing, and manufacturing know-how of the materials user. An example of such a linkage is the joint venture between the Norton Company and TRW to develop ceramic components for heat engines.

Finally, transnational companies, generally the primary conduits for international technology transfer, are seeking ways of making their technology strategies more compatible with technology policies within the countries they operate in order to better profit from their R&D programs.

Emerging Materials Technologies

An examination of the field of materials science and engineering will show that it is advancing at an accelerating pace. It is now generally recognized as one of the key emerging technology fields propelling our world societies into the 21st century. The driving forces for this revolutionary pace are social, economic, political, and technological. Major changes in materials processing and use patterns are creating requirements for new materials developments, substitutions, and associated processes. Never before have materials engineers been able to offer so many options to design engineers in assisting them to reconcile conflicting ideals of efficiency, economy, functionality, durability, and aesthetics.

The materials engineer, with a deep fundamental understanding of structure-property relationships; an increasing selection of materials synthesis, processing and joining techniques; modern computer methods; and advanced characterization instrumentation, is more than ever "plugged in" at all steps along the "value-added chain" from engineering development to design and to manufacturing. However, the substitution of advanced materials is not likely to occur in a revolutionary way unless they are inserted as a part of the new design concept.

For example, engineered polymers and composites offer new flexibilities for achieving modular designs and integrated "smart" structures with improved overall performance and simplified designs. In TRW, for example, we are finding new opportunities for introducing these materials in automotive linkages, rubber-bonded ball joints, modular front-end assemblies, supplemental passenger restraint systems and such satellite components as "smart" struts, which self dampen when vibrated, and adaptable apertures.

Unfortunately, the lead in many important materials technologies is shifting away from the United States. For example, Japan with its longer R&D horizons and greater emphasis on processing R&D has already achieved or is in the processing of achieving world leadership positions in such materials technologies as diamond films, fine ceramics, high temperature superconductors, tribological coatings, advanced composites, intermetallic compounds, magnetic materials, optical materials, and advanced semiconductors. New federal technology policies and closer couplings among industries, universities, and national laboratories will be required to stem this tide.

Future materials substitutions will threaten existing businesses, and the potential of becoming blindsided by global developments will intensify. For these reasons companies will need to invest more in technology forecasting and intelligence gathering. An effective strategy for surveying world technology is to develop special relationships with key university and national laboratory investigators whose international reputation is based, in part, on their ability to keep current on leading developments in their specialty throughout the world.

In addition, there will be an increasing demand for materials generalists who can rationalize the biases among materials specialists in selecting an optimal mix of materials for a new or improved design. In most instances these decisions need to be made in concert with customers and suppliers to anticipate and overcome design, manufacturing, and quality problems.

Opportunities for New Materials in Design and Production

Most U.S. companies have been actively pursuing a number of business strategies in order to improve their competitiveness relative to Japan and Western Europe. These strategies include facilitating just-in-time principles, reducing the cost of quality, improving quality-to-the-customer, installing manufacturing cells to improve manufacturing flow and employee involvement, investing in in-line measurement and control systems, and emphasizing concurrent engineering. Many of these strategies involve the innovative use of existing technology and the application of improved management and control principles in addition to investments in new technology.

The broadening combinations of properties afforded by advanced engineered polymers and composites, especially those that can be woven and braided into two-dimensional and three-dimensional shapes, is providing increasing flexibility in designing highly-integrated modules and subassemblies. For example, TRW has developed a one-piece composite suspension spring for recreation vehicles and heavy trucks. This module is an illustration of the increased design flexibility provided by advanced composites. Also, the greater computerization of engineering databases, incorporating materials properties data, is facilitating concurrent engineering and the greater use of modeling, simulation, and fast prototyping to prove out designs in ways that greatly reduce the costly testing and evaluation practices of the past.

Increasingly, procurement strategies by highly-conscious companies recognize the need to be tough buyers but also to help suppliers better tune their production schedules to meet tougher quality and performance specifications. These strategies are now being applied globally to find sources for the highest quality materials. Trends are to measure the success of these strategies more on total production and life cycle cost benefits than on least cost on delivery. Where these measures are applied effectively, it will be easier to justify materials substitutions and the premiums requested for higher-quality materials.

Considerable focus in recent years has been given to the implementation of net-shape manufacturing strategies to reduce the number of manufacturing and finishing steps, to conserve costly materials, and especially, to minimize metal cuttings and grinding swarf which are costly to handle, reclaim and dispose of. Processing developments for many advanced materials are focussing on casting, sintering, or injection molding in order to facilitate near-net-shape fabrication. Fortunately, there is also a growing number of emerging automatic contact and non-contact measuring techniques for verifying the achievement of net-shape in both two and three dimensions.

Among the greatest bottlenecks in a manufacturing flow system are heat treatment and metal plating departments. These usually impede optimally configuring a plant into manufacturing cells. In order to minimize heat treatment, many companies are now substituting high-strength, low-alloy steels for heat-treatable steels where high surface hardness is not a critical requirement. Other major benefits of the use of microalloyed steels are the ability to maintain precise tolerances and minimize distortions that must be subsequently removed. Also, some furnace heat treatment departments are being replaced with in-line induction and laser heat treating to simplify manufacturing flows.

The emergence of a number of advanced surface modification technologies, such as chemical vapor deposition, plasma deposition, ion plating, and ion implantation, provide a number of new options for producing surfaces with desired levels of hardness and corrosion resistance that again can substitute for off-line metal plating and heat-treating operations.

The growing family of toughened ceramics which can better withstand wear, impact, and thermal shock is increasing the number of potential applications for ceramics in cutting tools and dies, especially where the ceramic can be confined in compression. Benefits in the use of ceramics for tools, such as extrusion dies, include longer die life, reduced shutdown time for die replacement, and greater tolerance control. Also, the increasing use of hobs, drills, end mills, taps, and dies coated with super-hard thin films, such as titanium nitride, is significantly increasing tool life, improving tolerance control, and reducing set-up time.

Modern steel-making practice involving continuous casting, vacuum pouring, improved deoxidation practice, ladle processing, and better in-line inspection and control is providing not only cleaner steels but also ultra-clean steels for wire drawing, upsetting, and precision forging applications. These cleaner steels are facilitating the transition from hot-working to warm, and in some cases, cold-working operations. Substantial cost savings from this transition can result from reductions in energy, finishing, and quality costs. In many cases, the premium paid for higher-quality steel is more than made up for by these savings as well as reductions in warranty and liability costs.

Recent modifications in manufacturing cost accounting, necessitated by just-in-time and manufacturing cell strategies, can also facilitate the application of advanced materials to manufacturing operations. The trend is away from standard-hours accounting and toward a total manufacturing cost structure that will improve management's ability to separate out key manufacturing costs of the total product. For example, tracking the costs of expendable materials by product can often help identify where important materials technology improvements can have a big payoff.

These examples point out that the best way to identify where new materials can be applied to improve quality, reduce inventory costs, and increase thoughput is through a more-integrated engineering approach along the entire value chain and through innovation by all individuals in the workforce.

Managing the Technology Selection and Acquisition Process

The number of technological options that must be analyzed in a modern manufacturing enterprise is increasing dramatically and will continue to increase in the future. Managing the process of option selection will require that many steps be taken simultaneously and done well. Key among these are smart internal and external leveraging, a clear definition of customer needs and trends, and focusing on the highest-leverage opportunities.

The ability to bring into a company from the outside important "must-have" technologies and adapting these for use through internal know-how and innovation is key to achieving competitive advantage. This strategy can offer the best combination of shortened lead time and proprietary advantage.

Nearly all the steps in the process of managing technology derive from a clear, explicit definition of requirements based on customer needs and long-term market trends. The process of defining these requirements requires a multi-functional team effort to examine all factors along the value chain.

Of the various methods proposed in recent years for prioritizing technology investment, a useful one employs a figure of merit derived from the ratio of summed opportunity factors to summed risk factors, suitably weighted. Typical opportunity factors include value of the potential market, pervasiveness of the technology, leverage, simplicity, cost, and duration of impact. Risk factors include technical, operational, and business risks, and costs of investment in the manufacturing base and in replacing research and development at some future date. One can further weight this figure of merit with time deltas which represent, respectively, the projected product life cycle, the time span from proven technical feasibility to proven commercial feasibility, and the time span from technical availability to optimal introduction into the market place.

An appropriate balance and weighting of the various business, technical and operating risk factors should be made. Forecasting requirements should be done far enough into the future to guard against becoming blindsided from potentially destabilizing technology developments. One must also insure that capital investments will provide for systematic technology insertion over time in order to make sustained evolutionary product improvements.

These assessments and planning operations are carried out more in parallel than sequentially, and they all feed interactively into the development of the goals and objectives which will drive the acquisition and development efforts. The end product is a superior strategy for acquiring and using high-leverage technologies that will achieve sustained, strategic, competitive advantage.

Lessons Learned

Most of the manufacturing operations in TRW, the company with which the present author is associated, are carried out in plants of from 200 to 300 employees, which are contained in relatively self-standing divisions of a scale of $50 to $100 million annual sales. TRW as a matter of corporate philosophy and practice pushes down to the divisions nearly all the R&D and engineering development assets to effectively integrate them with manufacturing and marketing operations. These small and medium size operations in TRW operate in a manner not unlike separate stand-alone businesses. The lessons being learned from these emerging principles should therefore be generally applicable. Among these are:

(a) To a large degree the direction and timing of technology evolution can be anticipated.

(b) Technology changes and external competitive position can be analyzed.

(c) Competitiveness in many businesses is paced by advances in materials and process technologies. Elastomers, advanced composites, net- and near-net-shapes, advanced surface modification and smart measurement and control technologies will have particularly high leverage.

(d) Most technology needs are developed on the outside; upgrading the global knowledge base of these emerging "must-have" technologies is a continuous requirement.

(e) Strengthening technology management skills and practices is critical, with the greatest emphasis needed in long-term technology forecasting, planning and requirements definition.

(f) External alliances and collaborations in a focused and selective manner can provide a number of benefits to include shorter development lead time, avoidance of surprise, better returns on investment, and stronger international competitiveness.

Small and medium size companies can especially benefit from the greater flexibility, control, and employee involvement that can be achieved from relatively small manufacturing operations. Economy of scope rather than economy of scale may be the key to competitiveness in these operations. Finally, looking outside the company for upstream technologies can provide advantages if effective technology acquisition, adaptation, and integration strategies are employed. This may require expanded capabilities in fast prototyping and engineering modeling and analysis in order to minimize lead time in critical product and process development. It is here that the overall skill and competence of the technical director or engineering manager can have the greatest payoff.

Conclusions

The U.S. industrial enterprise, its ability to innovate, and its enormously strong national research infrastructure can provide us with the major weapons we need for future global competition. The growing interest of universities and national laboratories in establishing closer relationships with industry gives us every reason to expect that the United States can be a major technological force in global markets well into the future. The critical element, however, is learning better how to leverage these technical resources to our best advantage.

AN ASSESSMENT OF NEW ENGINEERED METALLIC MATERIALS

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Introduction

This paper provides a perspective on a group of metallic materials that are considered "new" because they are not yet in wide use, and "engineered" in the sense that they have unique performance characteristics imparted by value-adding steps taken during production. Emphasis will be placed on the intimate association of properties, processing and design, and their coupled influence on the manufacture of metallic products and components that can be attractive in world markets. This paper takes the view that tailoring materials to specific applications holds one of the most important keys to competitiveness, and that a critical step lies in producing a confluence of design and manufacturing.

After providing a general definition of an engineered material, we will develop a generic model of such a material. Following that, we will show the close coupling to processing methods and cite several examples. We will then treat the complementary design issue. Throughout this discussion and in summary fashion at the end, we will describe several particularly important and promising new engineered metallic materials.

The Engineered Metallic Material

We start with a definition. A material which has a higher performance because of higher value which is added during its production can be termed an engineered material. It is important to recognize that the added value may be the result of higher value components. Some of the expensive metallic alloys, and composites containing very high-value fibers, are examples. But the added value may also be the result of more sophisticated processing; some of the rapidly solidified products qualify on this basis.

A generic model of an engineered material, one that has been frequently used in the recent past, is one whose properties are built around what is called a "designer microstructure." Such a structure is conceived by deciding what constituents are needed in a material to impart a specific set of properties. It goes without saying that it is much easier to concoct a designer microstructure on a computer than it is to produce it in a factory. That is one of the problems with engineered materials.

A designer microstructure for high temperature applications, depicted in Figure 1, might have a matrix consisting of a brittle intermetallic compound. If it is to have high creep strength, it may be desirable to put in

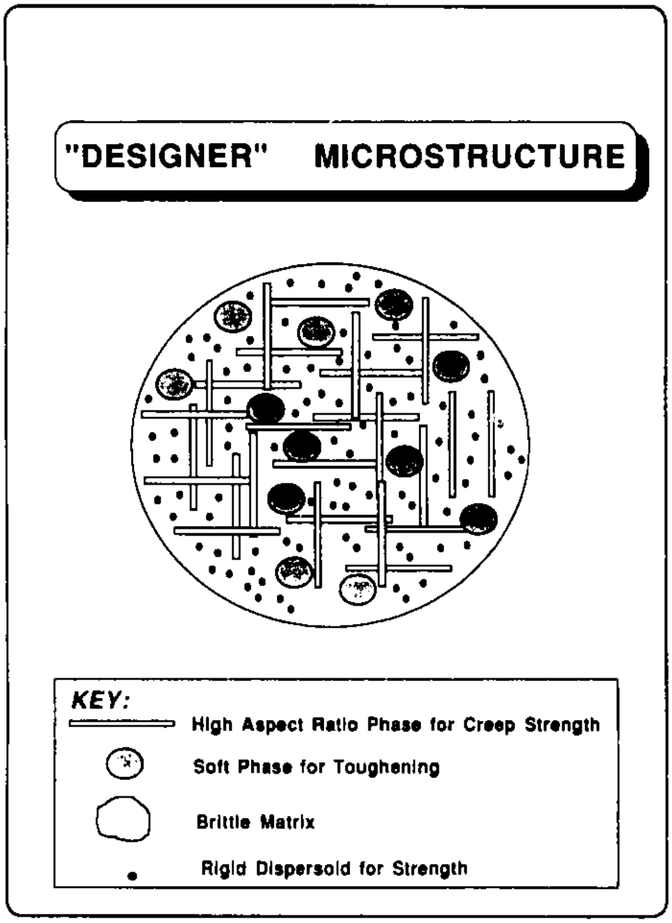

Fig. 1. A designer microstructure for high temperature applications

some phases in the form of particles with a high aspect ratio, which are known to impart good creep properties. Since the matrix is an intermetallic compound, it is probably not very ductile, so in order to be safe, one might wish to put in a soft phase as a toughening agent. Finally, if the strength of the material is at issue, a rigid dispersoid may be added to improve the strength, because most of the intermetallics are not intrinsically very strong.

The essence of this process, highly idealized in the foregoing model, is to take what is known about creep, fracture toughness, and strengthening, and design a material which can be produced from specific components and which will respond to needs related to each of those properties. This option, if it is available to us, is superior to taking what nature gives us.

Processing Considerations

The ingress of new engineered materials is having a large impact on processing technologies and, in fact, is making it clear that considerations of structure, properties, performance, and processing are largely inseparable. Some entirely new processing methods are moving in, but, at least as frequently, existing techniques are being upgraded and modified to meet new demands.

Relevant technologies involved in the processing of engineered materials are shown in Table I.

TABLE I

EXAMPLES OF NEW TECHNOLOGIES IN MATERIALS PROCESSING

- **P/M Methods**
- **Thermomechanical Processing**
- **Hot Die Forging**
- **Superplastic Forming**
- **Rapid Solidification Processing**
- **Artificial Intelligence/Expert Systems**

- Powder metallurgy methods have begun in recent years to show particular promise. All the high-performance turbine discs in aircraft engines now are made by powder metallurgy methods.
- Thermomechanical processing, both for near-term commodity materials such as high-strength low-alloy steels and for newer materials such as titanium alloys and nickel-based alloys, is an essential means of controlling microstructure and producing a better set of properties for a given composition than was previously thought possible. Hot-die forging, one of the thermomechanical processing techniques, allows a greater degree of flexibility and control over the working process and is an important recent contribution to forging technology.
- Superplastic forming, which has been around for a long while, has recently come into its own. Superplastically formed titanium sheet-metal components and, more recently superplastically formed high strength aluminum alloys, are now beginning to show up on the scene.
- Rapid solidification processing (RSP), which started about ten years ago, has substantial promise. RSP basically allows the microstructures of a wide range of materials to be tailored in ways that are not possible with conventional ingot metallurgy methods. For example, RSP Al alloys look promising at temperatures up to about 500°F.

The application of artificial intelligence and expert systems is a new option that will enable us to take rules of thumb that are generated from experience-based activities and encapsulate them in computer-based systems. We may then use such systems to control processes and make them reproducible, even when we do not explicitly understand them.

It seems likely that we are going to see more improvement in materials performance by learning how to improve the processing of existing materials than in developing new compositions. Upgrading of a materials processing method, which allows us to improve the properties of an alloy or material that has already been qualified for a particular application, is a more attractive way to get significant improvements in performance than is starting with a new composition, which will require a complete requalification. The latter option is a long and very expensive process, the payoff for which must, of necessity, be substantially larger.

Designing with Advanced Materials

As we begin to produce materials with specific capabilities, we are going to have to learn how to design them efficiently if we are going to capture the added value that comes with these more expensive and valuable constituents. An additional issue is the reluctance of designers to incorporate life cycle cost into their materials selection process. This naturally places higher initial cost materials at a competitive disadvantage. A worthy design goal is to model cost of ownership of a structure rather than initial cost only.

These considerations take us to the subject of materials by design, or theory-assisted engineering of materials. We will consider this new approach against the backdrop of materials development as it is now practiced. The traditional approach has been to start with a large matrix of alloy options. Compositions are placed on this matrix, yielding perhaps a 20 x 20 array, with 400 different possible compositions. All of these are made and tested. The better ones are selected, a smaller matrix is constructed, and the selection process is repeated. This approach has been successful but it is not very sophisticated; it basically has a terminal case of the "too's": It takes too long and it is too expensive. A more intelligent approach, exploiting our rapidly growing base of understanding of materials, is to employ a flowchart, such as that shown on Figure 2, which is based on the theory-assisted engineering concept.

With an application in mind and with property goals clearly set, the materials experts and the designers first work out a path that can converge on what is needed and possible. This initial homing-in exercise puts some bounds around the problem and defines a three-pronged attack:

- Materials research people, using recently developed scientific concepts that include phase stability calculations based on thermodynamics and electron theory, provide qualitative guidance. A narrowed-down set of compositions can be chosen on the basis of this guidance.
- Micromechanics experts, employing the designer-microstructure concepts, guide the choice of the constituents needed and the required microstructure.

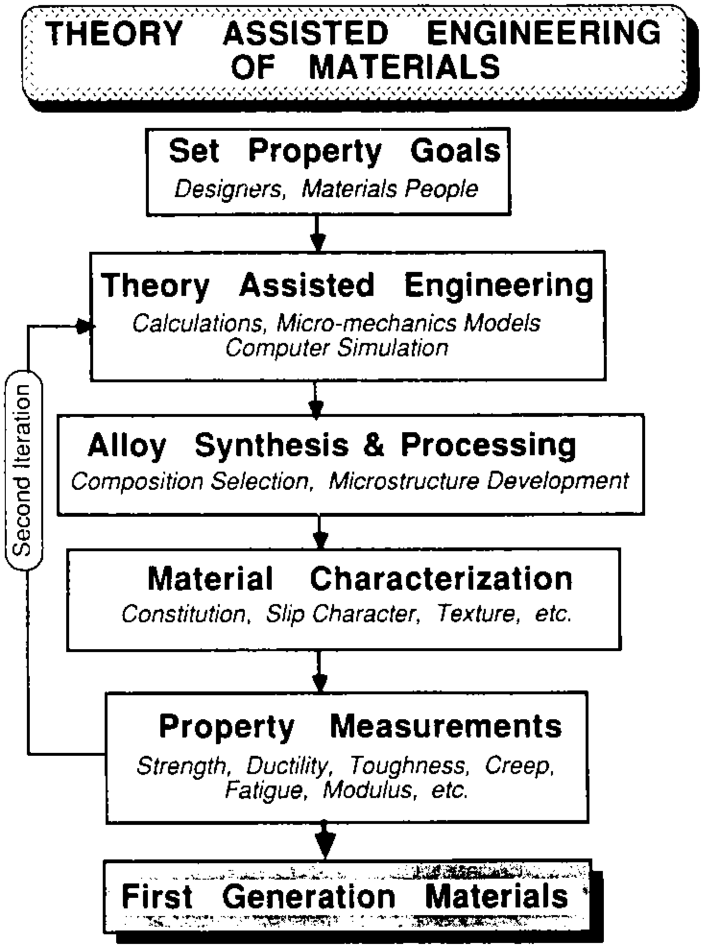

Fig. 2. A materials-development flowchart based on theory-assisted engineering

- Computer modeling methods can simulate the performance response of each of the candidate compositions.

The next step is to select several compositions based on the guidance coming from the calculations, the micromechanics, and the computer simulations. Processing considerations are incorporated from the beginning so that the variables involved in optimizing the performance can include processing parameters. A first generation of candidate alloys is prepared and property measurements are made to confirm that the logic path is valid. These samples are probably not optimal. Further iterative selecting, modifying, and testing is almost always required, but theoretical studies can make a large contribution in contracting the time and the cost of the development cycle.

A point that warrants repeating is that it is critical to incorporate processing technologies into the way that designers think about shaping components. Advanced materials are going to be more expensive to make and buy. Therefore, if the leverage sufficient to justify the increased initial investment is to be gained, the design effort must be commensurately better. Moreover, the material selection process, which will have to begin at the design stage, will become an increasing challenge. Engineered materials will become more unique and specialized, and the designer, who is probably a mechanical, aeronautical or civil engineer, is likely to become less qualified to make proper and thoughtful decisions about them. One way around this dilemma may be to provide computer-based expert systems that encode at least the basic expertise of a materials expert, which the designer can bring on line to act as a functioning and constantly available materials expert. Another approach is to develop and deploy smart data bases, which not only provide the data in tabular form but also incorporate interpretive guidance that helps the designer to understand the pitfalls associated with bare tabular information. The early use of computer simulation to model materials and explore how they are going to perform is another sensible option.

Engineered Metallic Materials: Monolithics and Composites

A few examples of engineered metallic materials will now be briefly reviewed.

- Advanced intermetallic compounds can be expected to be used in the next generation of aircraft engines--more extensively if the national aerospace plane or some other hypersonic vehicle comes into reality. Probably the most pressing problems in the use of advanced intermetallics is low-temperature brittleness. Ni_3Al, Ti_3Al and TiAl (the latter two in particular), exhibit essentially zero percent tensile elongation at room temperature in their binary form, a property that is of course, unacceptable to the designer. Recent effort to control the microstructure by alloying additions has improved the room temperature ductility of the materials to a point where they begin to look attractive. However, adding a ternary or quaternary component mars the intrinsic beauty of a binary intermetallic compound, which is a single-phase material and thus free of the problems associated with multiphase materials such as high temperature rafting of gamma-prime (in nickel base superalloys), stress-induced grain coarsening and sigma phase formation. The ability to process and adapt materials that are as brittle as advanced intermetallics is a major challenge because brittleness affects the cost and yield, and in the limiting case determines whether or not the intermetallic can be used in a particular application.

Maximum temperature capability for intermetallics continues to be pushed up through the use of single-crystal alloys. Alloying additions to strengthen grain boundaries are unnecessary because, by definition, single crystals have no grain boundaries. The solidus temperature is higher, the maximum service temperature as determined by creep is raised, and the gamma-prime solvus is often raised as well. These property improvements allow the material to be used at a higher operating temperature with an acceptable life.

- Aluminum-lithium alloys depend on the addition of lithium to reduce the density and increase the elastic modulus. They are made by ingot metallurgy, so they do not require particularly sophisticated processing. For the aircraft designer the two most significant properties are the density at a given strength level and the elastic modulus at a given density. Aluminum-lithium alloys now are being introduced into the McDonnell Douglas

MD11 and are beginning to find their way into limited applications in the next generation of Boeing aircraft. If the Advanced Tactical Fighter aircraft becomes a reality, aluminum-lithium alloys will be used in substantially greater amounts.

Property comparisons and trade-offs are tricky. Table II presents a comparison of three classes of related materials: conventional titanium alloys, titanium aluminides, and conventional nickel base superalloys. Moving from left to right toward the titanium aluminides, the density decreases and the elastic modulus increases, trends that are very helpful. The creep temperature and other capabilities also improve, but unfortunately, the room temperature ductility falls rather dramatically. It is important that the designer not look up Ti_3Al in a handbook, be frightened by the low room temperature ductility (which can be improved through processing and alloying), or be attracted to the 1500°F creep temperature, without understanding clearly that there are a number of penalties and a number of potential risks associated with other factors such as environmental degradation. Data such as these show why it is necessary to stay in close communication with the designer and make sure that he or she understands the difficulties in using newer materials.

TABLE II

Aluminides vs. Ti Alloys & Superalloys

Property	Ti	Ti_3Al	TiAl	Ni-Base
Density (# / in^3)	.16	.152	.136	.30
Stiffness (10^6 psi)	16	21	25.5	30
Max. Temp. - Creep (°F)	1000	1500	1650	2000
Max. Temp. - Oxidation (°F)	1100	1200	1750	2000
Ductility - Room Temp. (%)	≈20	2 - 4	1 - 3	3 - 10
Ductility - Operating Temp. (%)	high	5 - 12	5 - 12	10 - 20

- Advanced composites comprise a group of new metallic materials that merit special attention. Table III contains a representative list, divided into three classes: long fiber composites, having essentially continuous fibers or whiskers in them; short fiber composites containing more randomly oriented fibers; and particulate composites containing one or more phases as essentially equiaxed particles in the metal matrix. The last-mentioned class has not yet demonstrated particular performance advantages; it will not be discussed further in this paper.

TABLE III

ISSUES IN ADVANCED COMPOSITES

- **Long Fiber Composites**
  - **Fiber type and coating**
  - **Whiskers - quality, availability and cost**
  - **Fiber/Matrix Interaction**
  - **Fabrication/Processing of Brittle Matrix Materials**
- **Short Fiber Composites**
  - **Blending**
  - **Properties**
- **Particulate Composites**
  - **Particulate Stability**
  - **Particulate size and volume fraction**
- **Toughness & Ductility**

Long fiber composites tend to have very anisotropic properties because the fibers are aligned in a unidirectional fashion. Actual structures are typically made by cross plying or 45 degree plying of layers of these materials to improve the isotropy while maintaining the benefits. The difficulties involved, at least in high temperature composites, are the narrow range of fiber types that are available, the complications related to fiber-matrix compatibility, and the necessity to coat the fibers so they will have an enhanced compatibility with the matrix, and/or will have the particular interface characteristics that impart the desired physical properties to the material. Whiskers are important because they are the strongest type of reinforcement phase, but the quality, availability, and cost are major barriers to their widespread use. The limited quantity of whisker material that is being used during the development period has not yet provided sufficient incentive for the investment of the necessary capital to insure adequate production.

Fiber-matrix interactions can degrade the performance of the composite and represent a problem that is particularly serious during high-temperature service. The fabrication and processing of composites using brittle matrix materials can be extremely challenging. For example, the silicon carbide fiber-TiAl matrix composites are prone to matrix cracking during the fabrication because of the difference in thermal expansion of the two components, which puts the matrix in tension.

Short fiber composites are made by blending, compacting, and sintering or hot isostatic pressing of particulate constituents. A difficulty arises in achieving a uniform distribution and a random orientation when spherical metal powder particles are mixed with high aspect ratio fibers. The properties of short fiber composites are typically less attractive than those of the long fiber composites.

Standing in the way of the utilization of most of these composite materials are questions of toughness and ductility. An apparent paradox concerning toughness and ductility is illustrated in Figure 3 which shows the fracture resistance as a function of the volume fraction of reinforcing phase for metal matrix, intermetallic matrix, and ceramic matrix composites. For the metal matrix composite the ductility sinks as the volume fraction of the reinforcing phases increases, dropping dramatically above 20 percent. Conversely in ceramic matrix composites, as the volume fraction of reinforcement phase is increased the toughness or fracture resistance rises. The reason for this contrasting behavior is now understood. In metal matrix composites, voids forming at the fiber-matrix interface are sources of ductile fracture in the matrix. On the other hand, in a ceramic composite the matrix cracks at low strains, but the fibers, which remain intact, tend to bridge the crack and load the crack tip. The resulting effect is to improve the fracture resistance.

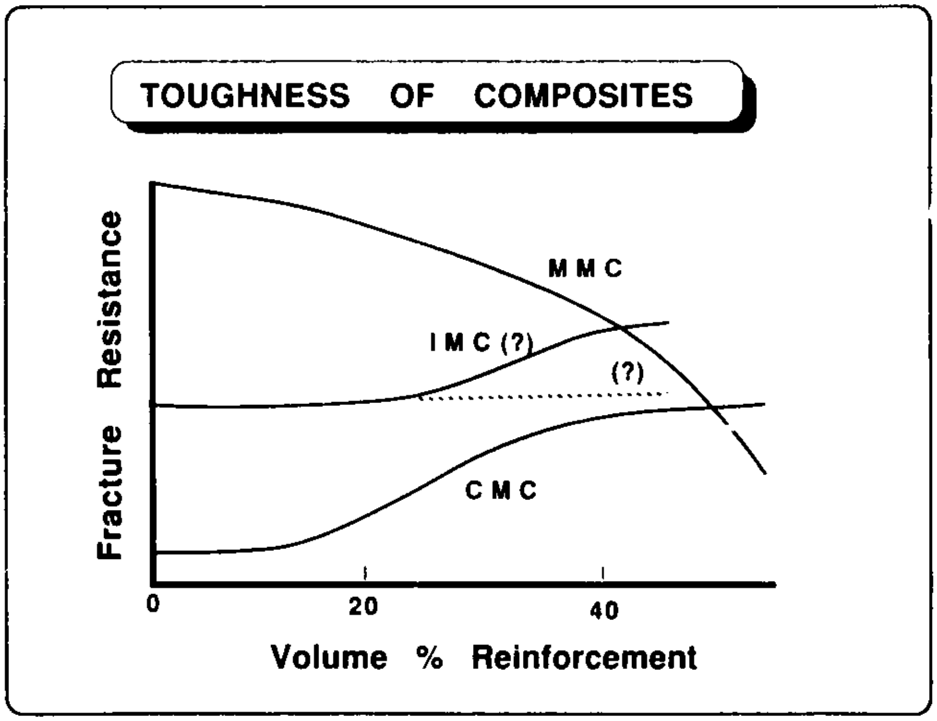

Fig. 3. Fracture resistance vs. volume fraction of reinforcing phase for various composites. (MMC - metal matrix composite; IMC - intermetallic matrix composite; CMC - ceramic matrix composite).

The unanswered question is--what happens in intermetallic matrix composites, which for many high temperature applications may be the most interesting materials in the next five or ten years. There has not yet been enough work done to determine whether the toughening benefit found in a ceramic composite will be observed. It seems likely that it will, as projected in Figure 3, because an intermetallic does not fracture in a ductile manner. Uncertainties concerning toughness remain very prominent issues pacing the development of advanced composites.

Engineered Structural Materials Versus Other Newer Materials

At this point it is important to make an explicit distinction--one that has been implicit thus far--between the engineered structural materials that are the subject of this paper and an array of other "newer materials" that are being developed for electronic, photonic, and magnetic applications. In principle, there should be cross flow of processing and production technologies between engineered structural materials and the newer materials. However, this transfer is in fact limited by the greatly different scales of production for the two classes of materials. Both structural materials and these newer materials are important to national security and to the competitive manufacturing base in this country. However, it seems increasingly clear that there is a tension between them, and that the newer materials may be getting preferred attention for R&D outlays, for capital investment for their production, and as targets for entrepreneurial and startup activities. There may be two possible bases for this preference. Newer materials have a shorter development cycle than structural materials and this discourages investment in the latter. Also, production of newer materials seems to be less capital intensive. Whatever the reasons or perceptions, this apparent tilt needs to be examined and an effort made to generate a more balanced distribution of effort and capital expenditure. Unless the technology, production, and use of advanced engineered structural materials is pursued aggressively and widely in the next several generations of manufactured goods, our products will be increasingly less competitive in world markets.

Summary

Engineered structural materials will be an important part of the future of manufacturing in the United States. As new materials and new products are conceived, new design methods must develop at the same time because design is at least as important to the overall performance, cost, and competitiveness of a product as manufacturing. This issue has not yet received the attention it needs.

In the near term the new engineered materials that show up in manufactured goods are likely to be those produced by advanced processing methods. Advanced materials based on entirely new compositions will require longer development times.

Engineered materials will be more expensive in terms of initial cost, but may be very attractive in terms of total cost which incorporates improved performance and reduced fuel consumption. We must work toward evaluating materials on a total cost basis.

A stronger effort will be required to balance the attention paid to structural materials vis-a-vis newer materials developed for photonic, electronic, and magnetic applications.

DEVELOPING TRENDS AND CHARACTERISTICS OF HIGH PERFORMANCE POLYMERS AND COMPOSITES: MANUFACTURE, SUPPLY AND USE

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Introduction and Background

This paper will provide a broad perspective--from both a technological and a business development viewpoint--of the current growing role of polymeric based materials in demanding applications. In the structural area, which is the principal focus here, metal replacement is the main determinant for growth. The intent is not to provide technical detail but to give an accurate picture of where polymers are playing, what the future potential is, and what is likely to happen.

Specific objectives for the presentation are as follows:

1. To provide a view of advanced materials as a technical and business development discipline in itself, and the characteristics that differentiate it from other areas.
2. To take a look at trends in metals substitution by polymers and composites, and to provide a view of the overall impact of polymer-based materials in the advanced materials arena; in particular, to give an appreciation for the breadth of the cross-cutting impact accompanying the growing and broader use of polymers on the growth of new technologies and emerging industries.
3. To examine the critical aspect of processing and manufacturing development and needs--and the problems and opportunities this presents.
4. To take a look at market projections, and in this context specific materials types and selected applications, considering future materials development and availability and the interaction with process and manufacturing development.
5. To provide an integration of the issues and general trends associated with these areas.

Advanced materials can be defined as materials with unique mechanical, thermal, optical, electrical, or magnetic properties, and combinations of these, purchased for function and for added value derived from use.

Encompassing in its full range an extraordinary scope and intensity of activity, the area of advanced materials is an internationally targeted development effort regarded as a key part of the base for the next generation of industries. As was stated by the president of NEC at a recent international advanced materials conference, "Those who control materials, dominate technology," and there is no enterprise working harder on this than Japan.

Among the characteristics in the practice and use of advanced materials that differentiate it from other activities, the following are particularly prominent:

- It is highly interdisciplinary, and its successful conduct demands an environment that encourages and facilitates creative interactions in both technical and business development.
- There is a unique impact of processing and fabrication. The end use characteristics of essentially all kinds of materials (organic and inorganic, metallic and non-metallic) are related to structural factors (such as crystallinity, grain size, morphology, orientation, fibrillarity) that can be manipulated and controlled by process parameters. These features dictate that timely introduction and cost-effective use of new materials are dependent on early exploration and definition of process/structure/property interactions. The optimal use of many new materials will require early parallel development of new or modified fabrication and manufacturing approaches; processing innovations are highly significant. Moreover, a knowledge of the implications of new materials use beyond that of a single component replacement, i.e., an appreciation for systems impact, is necessary.
- The implementation of new advanced materials into practice, particularly in structural applications, has had very long and costly development cycles. Perhaps the major obstacles to this timely introduction have been delays in the developing effective fabrication technologies for end use conversion, in understanding the potential cost impact on the total system, and in defining standards to help sort out what is becoming a rather confusing array of new materials options. There are many reasons for these delays, including cost and timing constraints associated with replacing or modifying installed capital, inherent conceptual difficulties in devising new or modified fabrication concepts, and inadequate early research into fabrication and manufacturing implications. These constraints have been compounded by education gaps that have resulted in a lack of awareness of materials, process and design advances that have been and are being made. In total, this can lead to a strategic framework in business and in technology development and practice that gives short shrift to the innovation engine.

All of this points to a clear-cut set of needs. There must be faster implementation--in view of the international effort, this is an increasingly important competitive aspect--and an early focus on processing. An improved understanding and use of modeling, analysis and numerical simulation techniques is required, starting at the molecular level and continuing through process design and simulation to component and system analysis. Furthermore, there must be database development in the areas of markets, performance gaps, manufacturing cost, and inter-materials competition. This activity would seem to be a particularly fruitful area for the application of knowledge based systems, i.e., expert system technology.

We will now focus on high performance polymers and composites in comparison to metals and on the broader area of structural and functional materials. Figure 1 projects the extent of dollar volume penetration of the metals market by polymeric based structural materials as a function of time [1]. The comparatively small penetration to date, resulting from well

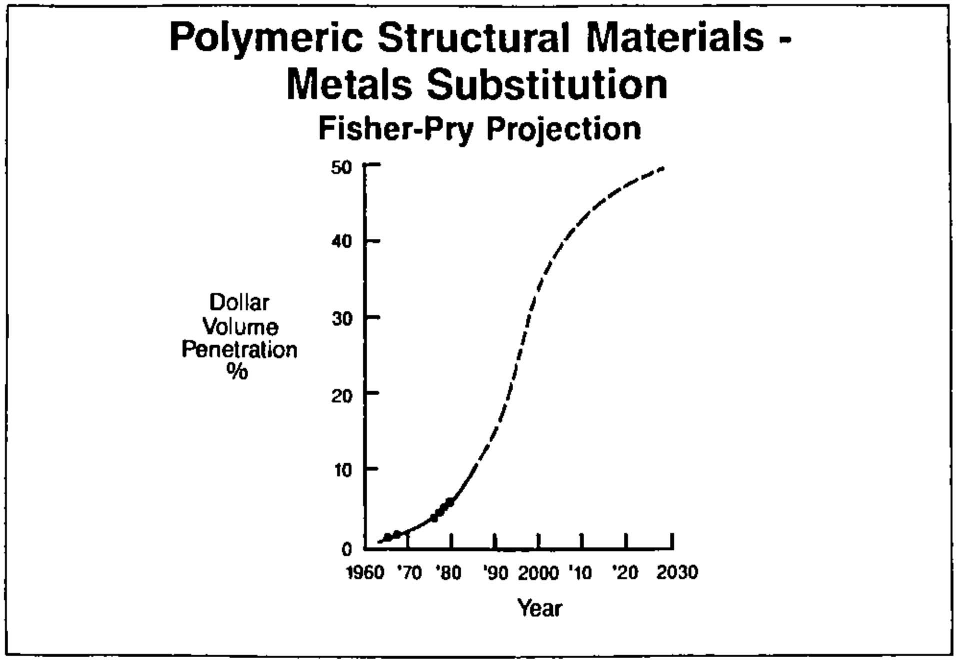


Fig. 1. Penetration of the metals market by polymeric based structural materials as a function of time. (After Lees, 1987[1]).

over thirty years of activity, has been based on engineering plastics developments, most of which are injection molding applications with relatively low performance requirements. Only a tiny portion has resulted from the use of higher performance polymers and composites. However, we are entering a rapid growth phase driven by a growing recognition of the cost, performance, design, manufacturing, and life-cycle advantages afforded by the more advanced polymeric based materials and the capability to use these advantages.

Polymeric materials, i.e., plastics, in particular those often referred to as commodity thermoplastics, continue to have a broad impact on current industrial technology and the economy, with uses familiar to all of us: clothing, furniture and furnishings, packaging of all sorts, and construction and building applications. But polymers are also playing a critical role in new advanced materials developments, with cross-cutting impact on the growth of a range of new technologies and emerging industries. These include high performance structural polymers with applications dominant in automotive/transportation and aircraft/aerospace industries, polymeric materials for electrical applications, polymeric-based gas and liquid membrane separation uses, biopolymers, and--the newest area of impact--polymer materials for optical applications including both passive and active devices and components in telecommunications, data communications, information storage, and other areas.

Figure 2 positions the overall role of advanced polymeric based materials in relation to metals and other inorganics in the total structural and functional arena, showing that over 60% of the high performance materials application area is based on polymers. The structural component evaluated independently shows the same type of balance of polymeric vs. non-polymeric materials use. Total dollar volume associated with structural materials is projected to grow from $10-15B in 1985 to $25-30B in 1995, of which almost $20B would--or could--be polymeric based, with the highest growth areas being in higher performance polymers (18% compound average growth rate) and advanced composites (12-15% compound average growth rate).

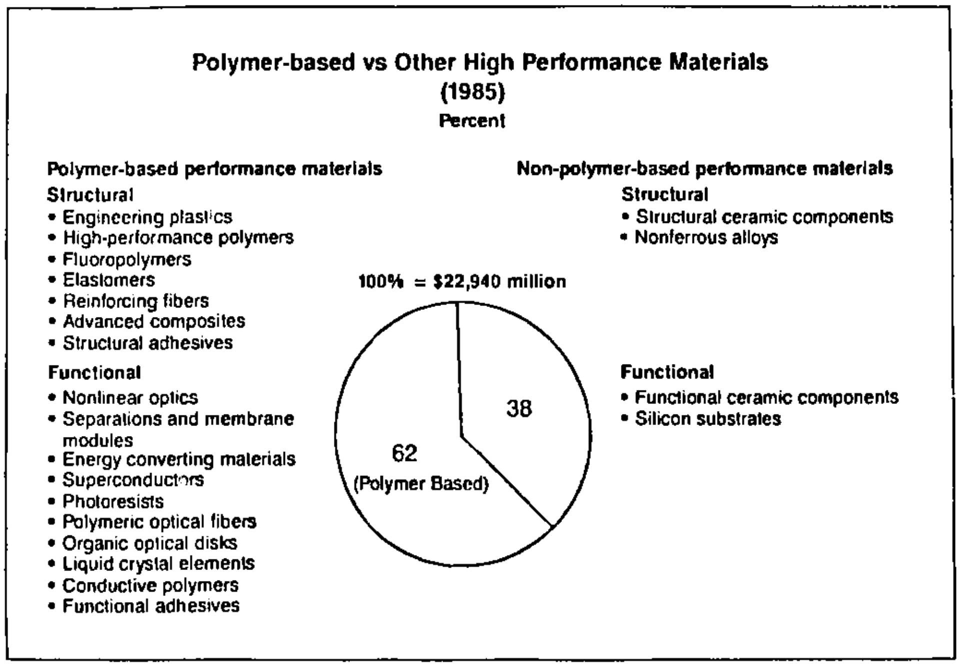


Fig. 2. Market values of high performance materials based on polymers and on certain nonpolymerics. (1985 data; ferrous materials excluded).

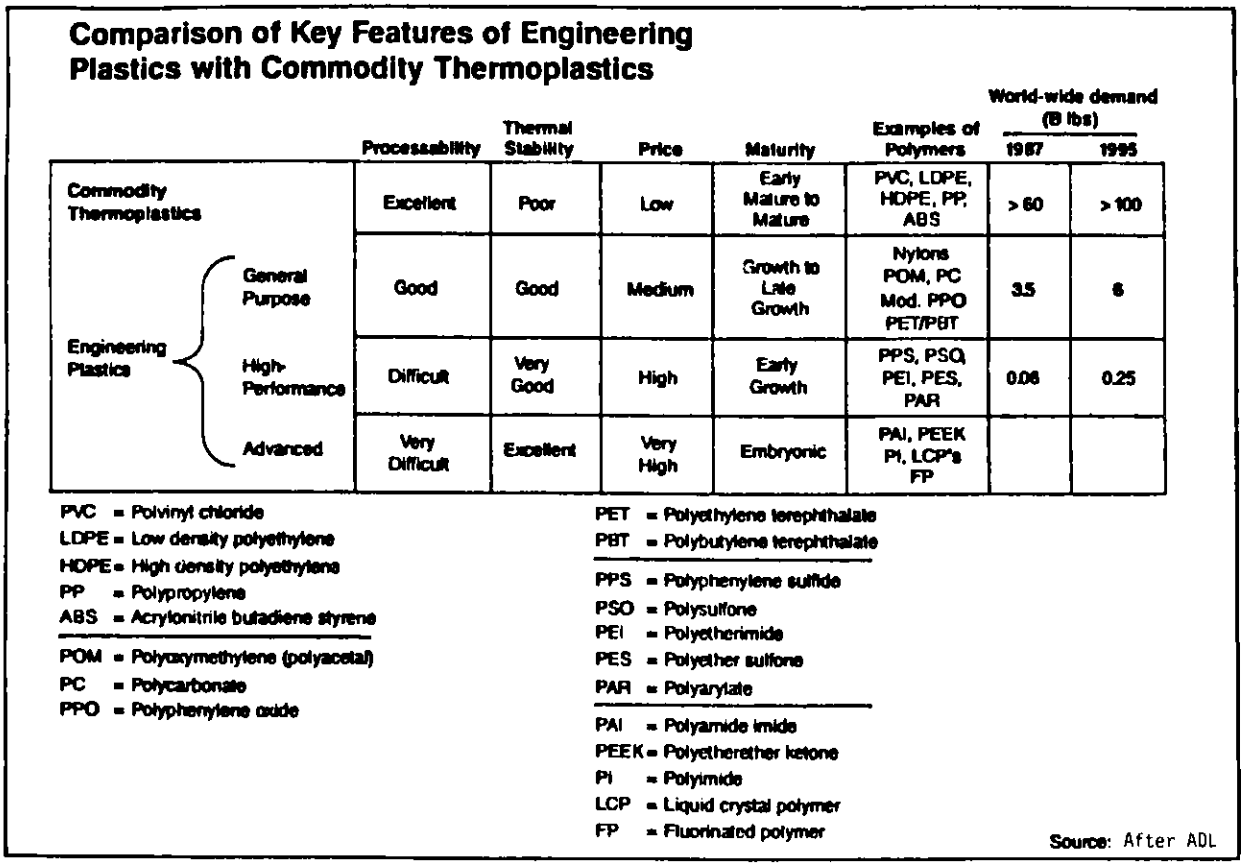
Polymeric Structural Materials by Class: Engineering Plastics and Composites

We now look in more detail, first at the area of polymers for higher performance structural applications--generally called engineering plastics--and second at composite materials.

Engineering plastics can be conveniently divided into three categories, general purpose, high performance, and advanced, depending on performance. General purpose engineering plastics, such as nylons, polycarbonate, polyacetal, and various polyesters, have been widely accepted into use because of advantages in weight and relatively high strength-to-weight ratio, toughness, manufacturing and processing cost advantages and flexibility, good electrical properties and increased design freedom along with aesthetic characteristics. The higher performance polymers are extending these characteristics to provide better thermal, chemical, and oxidative resistance along with higher mechanical properties, i.e., more metal-like performance. It should also be noted that all of these materials are used not only as neat resin, but also extensively as short, chopped, random glass fiber filled molding compounds. The glass provides additional stiffness, usually higher thermal performance and, in some instances, increased toughness.

Table I provides a broader comparison of the key features of the three classes of engineering plastics, along with a comparison to the commodity thermoplastics. Along with improvements in other performance characteristics as noted previously, increasing performance brings with it improved thermal stability with a decrease in the ease of processing and what can be sharply higher materials costs (hence, applications are often driven by a cost benefit associated with the total system). The differences in the stages of market development are significant; the high performance and advanced materials still very much in emerging and embryonic phases with total current worldwide volume at 60 million pounds, a factor of 1000 less than the commodity materials.

TABLE I



Comparison of Key Features of Engineering Plastics with Commodity Thermoplastics

		Processability	Thermal Stability	Price	Maturity	Examples of Polymers	World-wide demand (B lbs)	
							1987	1995
Commodity Thermoplastics		Excellent	Poor	Low	Early Mature to Mature	PVC, LDPE, HDPE, PP, ABS	> 60	> 100
Engineering Plastics	General Purpose	Good	Good	Medium	Growth to Late Growth	Nylons POM, PC Mod. PPO PET/PBT	3.5	6
	High-Performance	Difficult	Very Good	High	Early Growth	PPS, PSO, PEI, PES, PAR	0.06	0.25
	Advanced	Very Difficult	Excellent	Very High	Embryonic	PAI, PEEK PI, LCP's FP		

PVC = Polvinyl chloride
LDPE = Low density polyethylene
HDPE = High density polyethylene
PP = Polypropylene
ABS = Acrylonitrile butadiene styrene

POM = Polyoxymethylene (polyacetal)
PC = Polycarbonate
PPO = Polyphenylene oxide

PET = Polyethylene terephthalate
PBT = Polybutylene terephthalate

PPS = Polyphenylene sulfide
PSO = Polysulfone
PEI = Polyetherimide
PES = Polyether sulfone
PAR = Polyarylate

PAI = Polyamide imide
PEEK = Polyetherether ketone
PI = Polyimide
LCP = Liquid crystal polymer
FP = Fluorinated polymer

Source: After ADL

It is useful to look at the current effect of increased thermal performance characteristics on materials cost. Figure 3 shows that an increase of 50-100°C in resistance to heat distortion under pressure can result in an increase in cost of $30-40/kg ($15-20/pound). This illustration also demonstrates the all-too-prevalent chicken and egg situation where higher volumes would bring down price but use is hindered by cost.

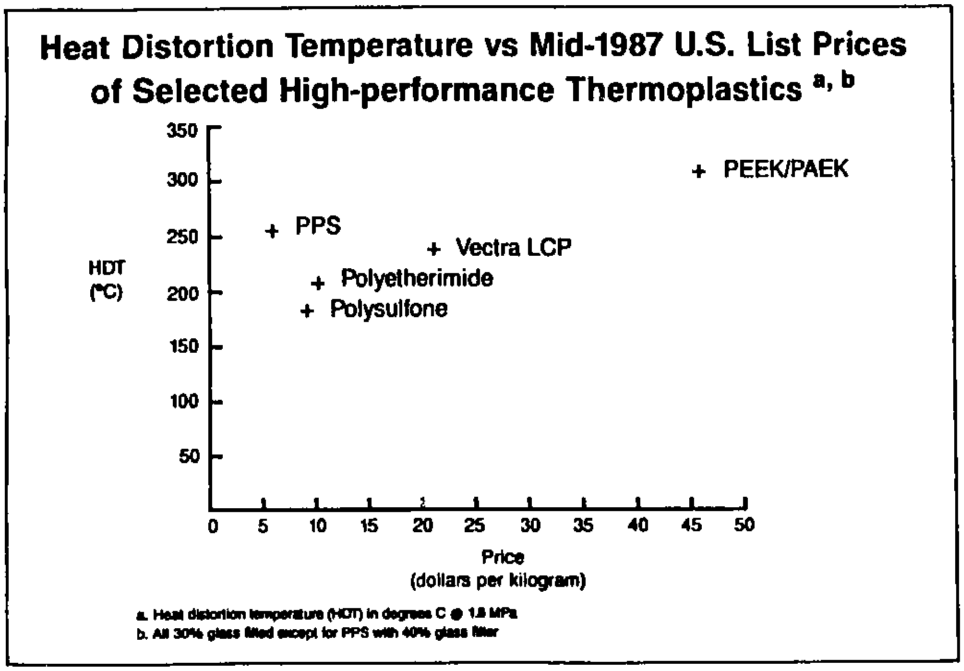
A more detailed breakdown of the estimated demand for the various engineering plastics is shown in Table II. In the right-hand columns is given an overall summary of the increase from 3.5 billion to 6 billion pounds in the 1987-1995 timeframe, with the highest volumes in the nylons, polycarbonate, and the acetals. Individual market growth rates range from 4%/year to 8%/year. The higher performance plastics are projected to quadruple in volume to a level of 250 million pounds, growing at an average rate of 18% (and individually ranging from 11% to 40%). The growth of a number of these, shown in the left-hand columns, is dominated by materials such as polyphenylene sulfide, polysulfone, polyethersulfone, and polyetherimide.

In concluding this discussion on high performance polymers, or engineering plastics, it is useful to summarize a number of the general characteristics of the business and some developing trends. High performance polymers are produced primarily by large companies having extensive polymer experience and the manufacturing processes are technically sophisticated and often highly capital intensive. Marketing is technically intensive and oriented towards product performance. Technology is a key element of strategy; assisting fabricators with applications development and processing technology is important. However, there is some tendency for the major materials developers to move downstream into fabricated products, either through joint technology or business ventures, acquisitions or independent development to capture more of the value!

Aerospace, automotive, and electrical/electronics will continue to be the most important markets. There will be less emphasis on new polymers and more on polymer blending, alloying and compounding as a more rapid and less costly route to new products. Polymer fabrication and processing methods will continue to be improved through efforts in both equipment and process design and polymer blending, the latter trading some performance for easier processability. There will be increasing inter-materials competition between various types of polymers and polymer blends, including, on the high end, competition with composites.

Composites, or more precisely advanced composites, will now be discussed. The focus will be on advanced resin-based composites with fibrous reinforcements, continuous or discontinuous, that are oriented in some organized pattern. Random, short-fiber reinforced molding compounds are thus excluded. The fibers can be embedded in thermoset or thermoplastic matrix materials, and constitute at least 60% by volume of the composition.

This configuration is shown schematically in Figure 4. Here a selection of reinforcing filament and matrix resin is made, an intermediate product form (here depicted as a pre-impregnated tape) is generated, and the tape is then fabricated into some type of laminated structure where the individual laminae are placed with the fibers in different degrees of



a. Heat distortion temperature (HDT) in degrees C @ 1.8 MPa
b. All 30% glass filled except for PPS with 40% glass filler

Fig. 3. Influence of increased thermal performance on cost of polymeric materials. PPS - polyphenylene sulfide; LCP - liquid crystal polymer; PEEK/PAEK - polyetheretherketone. Source: SRI.

TABLE II. WORLDWIDE DEMAND FOR THERMOPLASTICS, 1987 TO 1995

High-Performance and Advanced Engineering Thermoplastics (millions of pounds)	1987*	1995	Growth (%/year)
Polyphenylene sulfide (PPS)	28.0	86	15
Polysulfone	18.0	46	11.5
Polyarylate	3.6	18	22
Polyether sulfone (PES)	3.8	33	31
Polyetherimide (PEI)	3.0	32	40
Liquid crystal polymers (LCPs)	4.5	15	25
Polyetheretherketone (PEEK)	0.6	4	26
Others	1.5	12	30
Total	63.0	246	18.5

Source: ADL

Engineering Thermoplastics (millions of pounds)	1987*	1995	Growth (%/year)
Polyamides	1,450	2,200	5
Polycarbonate	770	1,410	8
Polyacetals	575	795	4
Modified polyphenylene oxide (PPO)	400	680	7
Thermoplastic polyesters	325	615	8
High-performance and advanced engineering thermoplastics	63	246	18.5
Total	3,583	5,946	6.5

*Estimated for 1987

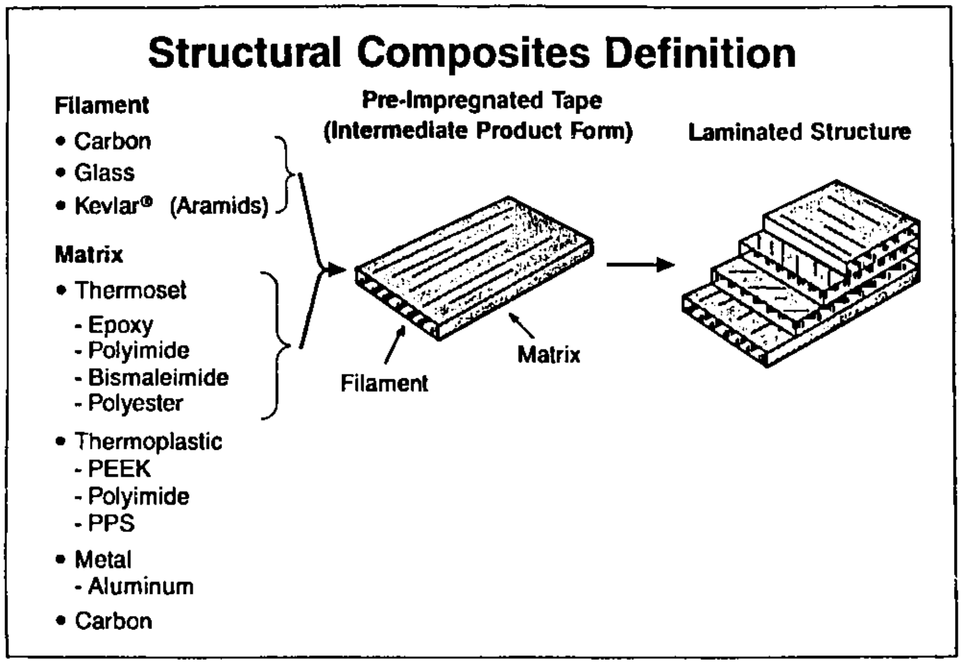
orientation. The fibers primarily affect mechanical properties and are the basis of the truly unique physical properties, such as strength and stiffness-to-weight, fatigue resistance, vibration damping, and low thermal expansion. The matrix binds the reinforcing fibers together, forming a coherent structure, and providing a medium by which to transfer applied stresses from one filament to the next. The matrix material affects high temperature mechanical properties, transverse strength, i.e., strength in directions other than along the length of the fiber, and moisture resistance. The matrix is also a key factor in toughness, shear strength, and oxidation and radiation resistance. Moreover, the matrix also strongly influences the fabrication process and associated parameters for forming composite materials into intermediate and final products. This latter point, along with improved composite toughness, has become a key reason for the expanding efforts on developing thermoplastic matrix materials. It should also be evident from Figure 4 that there are some inherent fabrication problems and that the composite product is highly anisotropic, posing a combination of design opportunities and problems and directional performance characteristics much different than those for isotropic metals. The potential combinations of materials, along with control of fiber direction, leads to the possibility of a multiplicity of tailored products.

The drivers for switching to composites have been known and demonstrated in principle for some time. Depending on choice of fiber and resin, combinations of performance characteristics can be acquired with composite constructions that cannot be attained by other means. Increased systems efficiency can be achieved through both productivity and life cycle effects and reduced systems costs can be effected through a variety of routes including the demonstrated potential for substantially reduced manufacturing costs.

For all their promise, the rate of substitution of composites into use has, to date, been disappointingly slow, even in the aircraft and aerospace industry, where the performance, weight and life cycle advantages are very large. The factors that have impacted the substitution rate by composites include:

- Development of low cost, high volume manufacturing processes;
- Matrices improved for performance and processability;
- Development of materials and design methodology for maximum effectiveness with anisotropic materials;
- Resolution of problems in joining and bonding dissimilar materials;
- Development of effective and relatively rapid, non-destructive testing techniques; and
- Better understanding of performance characteristics and failure modes. Composites fail differently than metals. The failure mode can be strongly influenced by characteristics of the fiber reinforcement used.

Figure 5 illustrates one of the aspects that has been delaying composites substitution. It compares, using stiffness and fracture toughness as criteria, the performance of different fibers, resins and different resin based composites vs. metals. The ready effect of increasing stiffness with reinforced thermosets is clear--but at a serious penalty in

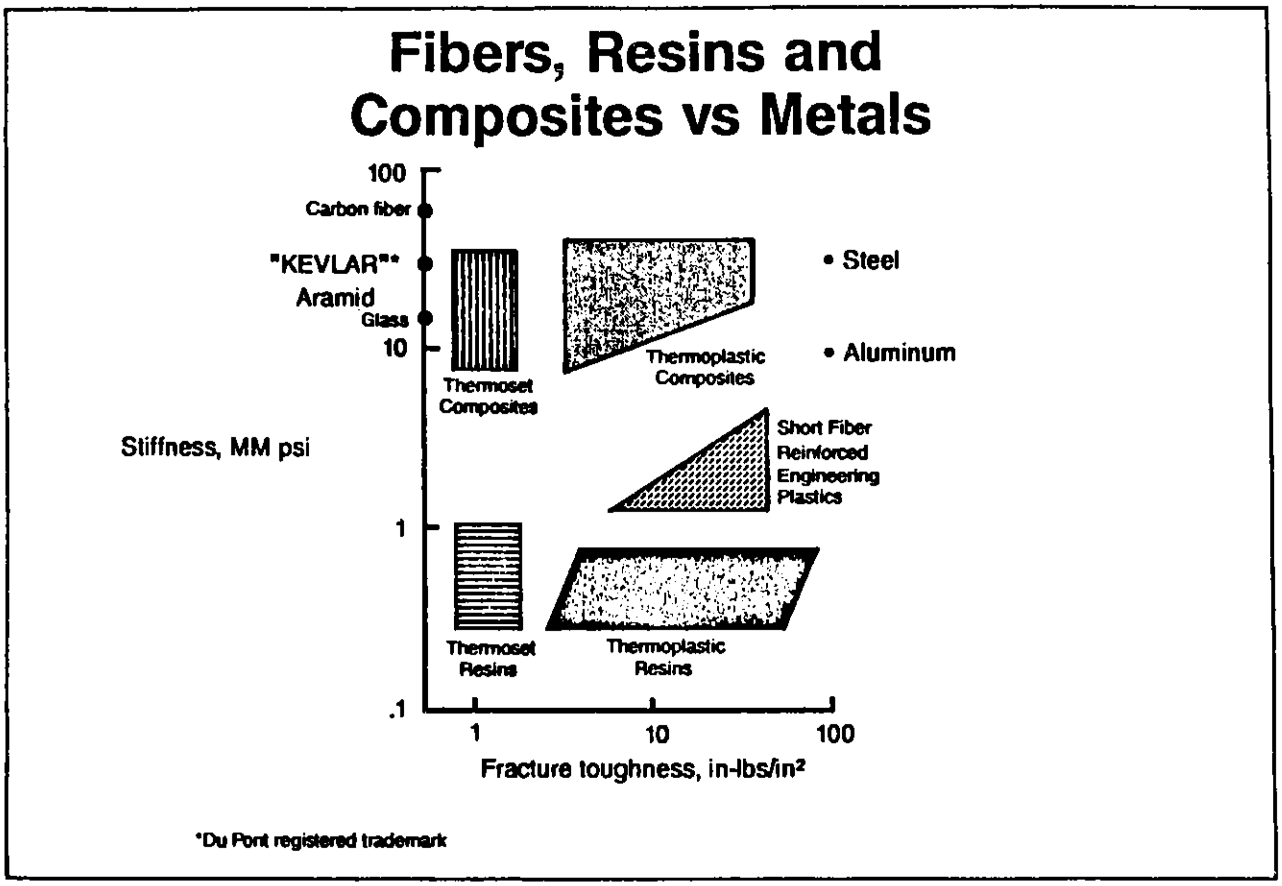


Structural Composites Definition

Filament
- Carbon
- Glass
- Kevlar® (Aramids)

Matrix
- Thermoset
  - Epoxy
  - Polyimide
  - Bismaleimide
  - Polyester
- Thermoplastic
  - PEEK
  - Polyimide
  - PPS
- Metal
  - Aluminum
- Carbon

Fig. 4. Schematic construction of an advanced composite



Fibers, Resins and Composites vs Metals

*Du Pont registered trademark

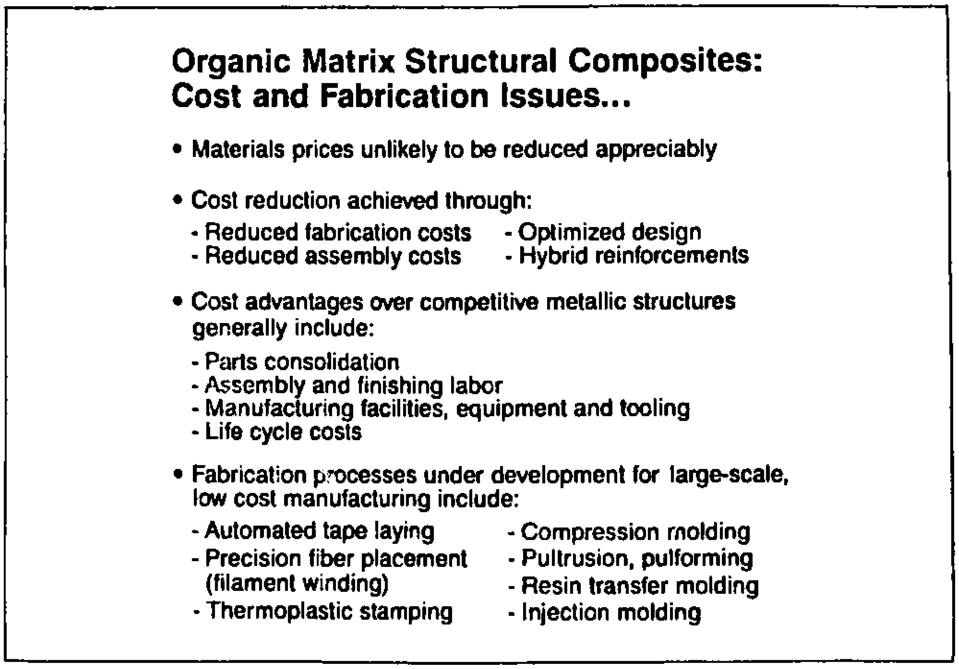
Fig. 5. Stiffness vs. toughness relationship for various composites and for metallic materials. (After Lees, 1987 [1]).

toughness. With the use of thermoplastic matrices and better tailored fibers, the potential for achieving, cost effectively, a combination of stiffness and toughness approaching that of metals is evident, and there is substantial effort in this area.

Cost and Fabrication Considerations

Our final discussion will focus on some of the cost and fabrication issues. Materials prices are unlikely to be reduced appreciably. Cost reduction, achieved through a variety of routes that will be discussed, will combine with various performance characteristics to provide cost advantages over metallic structures in a number of important areas. Furthermore, progress is being made in adapting fabrication processes for large-scale, low cost manufacture. Table III summarizes these points.

TABLE III

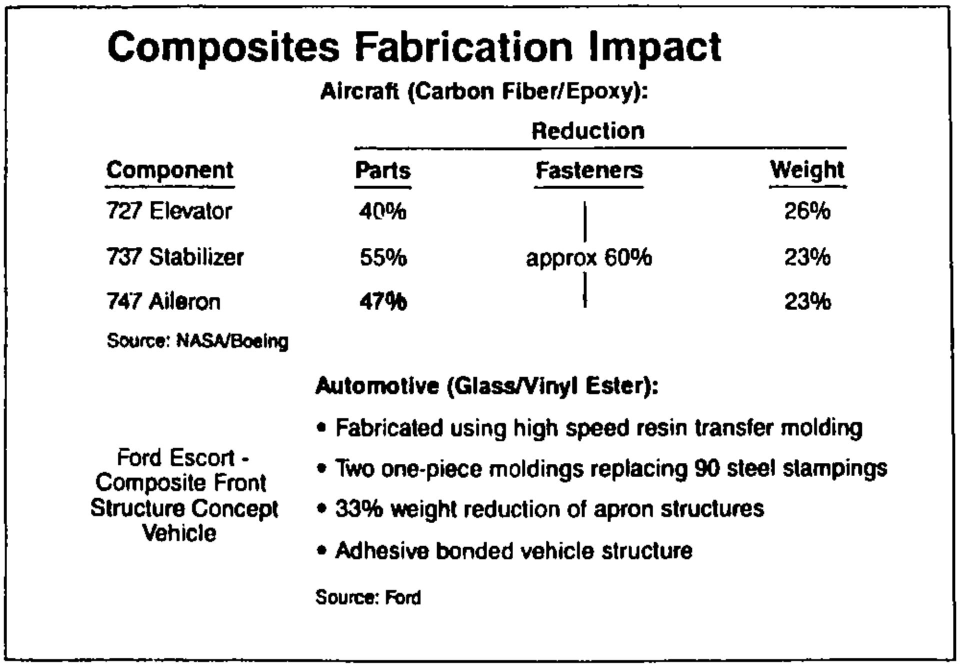


Organic Matrix Structural Composites:
Cost and Fabrication Issues...

- Materials prices unlikely to be reduced appreciably
- Cost reduction achieved through:
  - Reduced fabrication costs
  - Reduced assembly costs
  - Optimized design
  - Hybrid reinforcements
- Cost advantages over competitive metallic structures generally include:
  - Parts consolidation
  - Assembly and finishing labor
  - Manufacturing facilities, equipment and tooling
  - Life cycle costs
- Fabrication processes under development for large-scale, low cost manufacturing include:
  - Automated tape laying
  - Precision fiber placement (filament winding)
  - Thermoplastic stamping
  - Compression molding
  - Pultrusion, pulforming
  - Resin transfer molding
  - Injection molding

The impact of some of the most important elements--assembly, parts consolidation and hybrid reinforcements--will be illustrated. In Table IV are examples of both aircraft and automotive applications. Very early on, various aircraft components fabricated using carbon fiber/epoxy materials showed a reduction in the number of individual parts per component ranging from 40 to 55%, a 60% reduction in the number of fasteners required and this was accompanied by a substantial weight reduction. A more recent example is given for prototypic automotive component application using a lower cost glass and vinyl ester composite and a high speed fabrication process (resin transfer modeling). This option demonstrates the replacement of 90 steel stampings with two one-piece moldings and provides potentially a 33% weight reduction. Such prototype demonstrations are moving

TABLE IV



Composites Fabrication Impact

Aircraft (Carbon Fiber/Epoxy):

Component	Reduction		
	Parts	Fasteners	Weight
727 Elevator	40%	approx 60%	26%
737 Stabilizer	55%		23%
747 Aileron	47%		23%

Source: NASA/Boeing

Automotive (Glass/Vinyl Ester):

Ford Escort - Composite Front Structure Concept Vehicle

- Fabricated using high speed resin transfer molding
- Two one-piece moldings replacing 90 steel stampings
- 33% weight reduction of apron structures
- Adhesive bonded vehicle structure

Source: Ford

closer to production reality and driving a projected, expanding use of composites in automotive and other land transportation applications. The recently announced pre-competitive, joint development effort in composites among the big three automotive companies in the U.S. can be expected to increase prototype activity such as this.

Figure 6 illustrates the advantages of a hybrid materials approach for both product and process. As noted earlier, the ability to make changes in the orientations of the reinforcing fibers as well as in the basic strength and modulus characteristics of these fibers, along with selecting different matrix systems, provide unique capabilities in the design and tailoring of composite structures. In addition, different fibers can be used in the same composite system (hybrid composites) to achieve major cost/performance advantages. These systems combine the best attributes of the fiber components as well as taking advantage of optimal geometric placement and orientation of the different fiber reinforcements. In the schematic on the left the high performance fiber (in this instance, carbon fiber) is positioned in low weight ratio as a unidirectional face sheet on a chopped glass core, with the overall resulting materials cost being very competitive to higher performance engineering plastics, and the basic mechanical performance being much higher. The challenge is how to make this rapidly in a controlled, reproducible fashion. The process on the right illustrates a variety of ways of forming an in-situ thermoplastic (TP) matrix composite preform, such as a TP powder infiltration, a plied matrix, a co-woven fabric, and commingled yarns, which take advantage of thermoplastic characteristics and preserve a number of processing options. Intermediate product-form hybrids such as these are very important to developing cost-effective fabrication technologies that employ thermoplastic matrices. They are currently under active and extensive development.

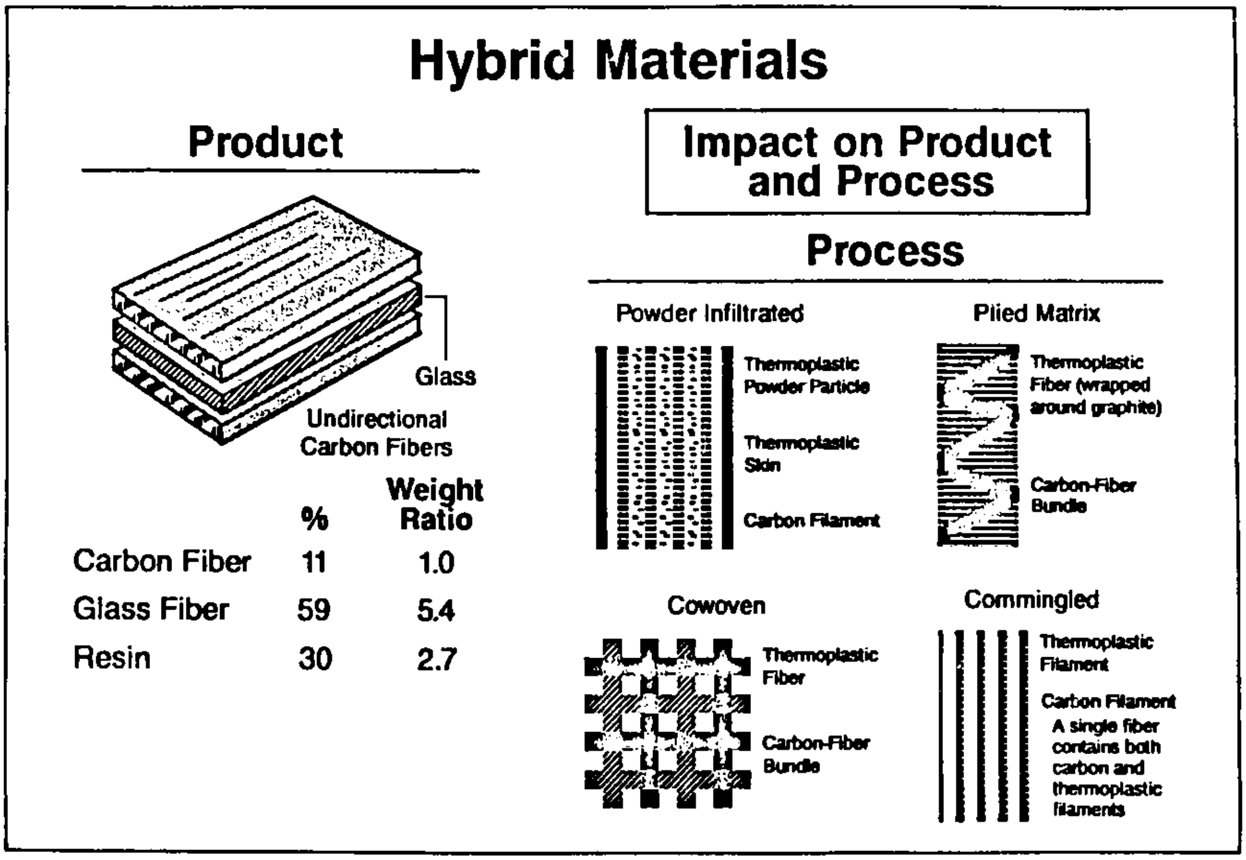
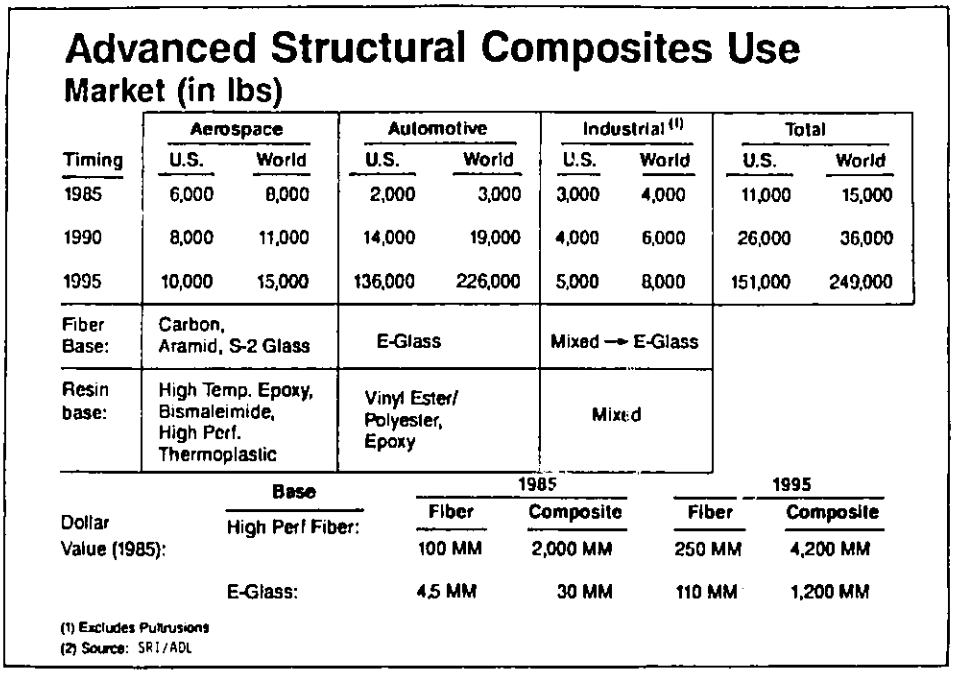


Fig. 6. Various forms of hybrid composites shown schematically: at left a product form; at right various processing approaches. (After Klein, 1987 [2]).

Moving now to a consideration of markets, Table V summarizes market development aspects by major market area--aerospace, automotive, industrial--in the timeframe 1985-1995. There is expected to be a market transition from an aerospace dominated volume activity in 1985 to an automotive dominated market in 1995. Aerospace has, and will continue to, dominate the high performance segment of composites usage, and currently composite use in this sector also dominates all applications, accounting for about 55% use worldwide. This is projected to change rapidly by the mid 1990's when low cost composite materials used in automotive based applications will prevail. Over the next ten years automotive applications of composites are expected to grow significantly. There is a corresponding variation in fiber base among the three markets, the aerospace market using the high performance fibers such as carbon, aramids and the S-glasses, automotive using E-glass and hybrid combinations, and the industrial market initially using mixed products but moving largely to the lowest cost base in the future. The table also shows a similar difference in resin usage for the three markets, i.e., the high performance applications are based on the higher performance thermoset and thermoplastic resins; automotive will likely use mostly lower cost vinyl ester, polyester, and epoxy thermosets, although it would seem that a properly adapted thermoplastic base could also be quite important; and the industrial market will use a mix of products.

TABLE V



Advanced Structural Composites Use

Market (in lbs)

Timing	Aerospace		Automotive		Industrial[1]		Total	
	U.S.	World	U.S.	World	U.S.	World	U.S.	World
1985	6,000	8,000	2,000	3,000	3,000	4,000	11,000	15,000
1990	8,000	11,000	14,000	19,000	4,000	6,000	26,000	36,000
1995	10,000	15,000	136,000	226,000	5,000	8,000	151,000	249,000
Fiber Base:	Carbon, Aramid, S-2 Glass		E-Glass		Mixed → E-Glass			
Resin base:	High Temp. Epoxy, Bismaleimide, High Perf. Thermoplastic		Vinyl Ester/ Polyester, Epoxy		Mixed			

Dollar Value (1985):	Base	1985 Fiber	1985 Composite	1995 Fiber	1995 Composite
	High Perf Fiber:	100 MM	2,000 MM	250 MM	4,200 MM
	E-Glass:	4.5 MM	30 MM	110 MM	1,200 MM

(1) Excludes Pultrusions
(2) Source: SRI/ADL

Finally, Table V shows an estimate of the dollar volume (in $ millions) associated with the high performance fiber and E-glass applications, breaking down the revenues into fiber and value added composite components. Important to note is that the composite value is almost a factor of 20 higher than the fiber component. Also, the high performance fiber and composite values reflect the 15-20X higher materials costs for the higher performance composite systems, compared to E-glass.

Overall, as Table VI shows, the market can be seen to be progressing from a high performance, high cost aerospace and aircraft segment today, to a moderate performance demand and higher volume in the mid '90's based on automotive and industrial applications and to a high performance and high volume usage well into the next century. Referring to the metals substitution trend depicted in Figure 1, this would represent about a 70-year development cycle for the broad-use introduction of structural composites.

The trends and industry characteristics for organic matrix structural composites can be summarized as follows: the market structure has been quite complex, and will continue to be for some time, with very different supplier/customer relationships in different market segments. There are currently a large number of materials suppliers and fabricators and a relatively small number of customers. On the materials supply side, a shakeout has been in progress for some time and the number is likely to decrease further. The customer base will remain relatively concentrated for some time and as a result customers control procurement. And they can control price.

TABLE VI

ADVANCED COMPOSITES

MARKET DEVELOPMENT...

TODAY	1995-2000	2020-2030
AEROSPACE/AIRCRAFT	LAND TRANSPORTATION/SELECTED INDUSTRIAL	CONSTRUCTION AND GENERAL USAGE
HIGH PERFORMANCE HIGH COST	MODERATE PERFORMANCE HIGHER VOLUME	HIGH PERFORMANCE HIGH VOLUME
PERFORMANCE ADVANTAGES PROCESSING AND MANUFACTURING - COST - ADVANTAGES	→	

There are very large differences in performance requirements, cost structure and customer knowledge among different markets--essentially aerospace vs. all others. High performance composites have become well-accepted in the aircraft/aerospace market; the growth rate of use is declining in the U.S. but growing in the rest of the world. Materials usage in this sector is dominated by carbon and aramid fiber and high performance epoxy resins, but with a growing use of high performance thermoplastics. Rapid growth, accounting for very large volumes of structural composites, is expected in the automotive industry. Materials usage will be dominated by much lower cost glass fiber and epoxy and polyester/vinyl ester thermoset resins, with the probable introduction of some hybrid fiber and thermoplastic matrix based systems.

Summary and Conclusions

General conclusions regarding developments in high performance polymers and composites can be summarized as follows:

- Metal replacement is the main determinant for growth and, although penetration to date has been very small, a rapid growth phase is developing.
- There is a somewhat confusing array of materials options available--in many respects materials product development, to date, has greatly outpaced the ability of many manufacturers to incorporate new materials. In this context, the recently announced pre-competitive joint R&D program among GM, Ford and Chrysler to develop composite materials (as mentioned previously) should go a long way towards standardizing materials and processes and defining specific products.

- There is likely to be a growing overlap in performance and use among a variety of materials currently under development.
- The major shortcomings of advanced polymeric based materials are in the areas of elevated temperature performance (particularly in the presence of moisture or solvents), relatively high materials cost and processability. All of these are currently the focus of extensive development efforts.
- The engineering plastics business will continue rapid development with the highest growth rates for the higher performance segments.
- Modification of existing materials through filling/blending/reinforcing/alloying will continue to be a key direction for technological development--reflecting cost advantages in materials development and more specificity in tailoring products.
- Fabrication and processing are critical issues and this has a number of implications; design capability, quality control, and cost will become important competitive factors; in the non-aerospace markets, design is likely to become a key competitive factor for composite component fabrication; processing must become more automated to reduce labor content and cycle time; and materials supply, design and fabrication are becoming more integrated.
- The role of the materials supplier is changing and broadening. The expanded role will involve more emphasis on: supplying a range of materials; becoming involved in design and component fabrication--both final and semi-finished; establishing a more integrated approach in disciplines and technologies, including various types of partnerships and alliances; and, in some instances, forward integration to capture more of the value associated with process innovation and end-use components.

References

1. J. K. Lees, Materials and Society, 11 (1987), pp. 143-160.
2. A. J. Klein, Advanced Composite, 2 (1987), pp. 36-48.

THE MATERIALS EFFECT IN THE MANUFACTURING REVOLUTION: EMPHASIS ON ADVANCED CERAMICS

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Introduction

There is considerable excitement over a wide variety of high performance ceramic materials, which go under the general name of advanced ceramics or high technology ceramics or fine ceramics. Many, but not all, of these so-called advanced ceramics are made in a way very similar to that used for conventional ceramics. However, they all differ in having substantially higher performance than traditional ceramics. This performance sets stringent requirements on phase composition, purity, and microstructural control. The requirements demand, in turn, sophisticated and highly reproducible processing. The result is a family of high-value-added materials generally at a much higher cost per pound than traditional ceramics.

The field of advanced ceramics includes a wide diversity of materials. Such ceramics can be organized into categories by the functions which they perform. These functions, given with examples in Table I, depend upon the special properties which can be designed into ceramics, properties which in turn depend ultimately on the fundamental characteristics of the chemical bonding. A central theme of this paper is that properties achievable in ceramics often make them the material of choice despite the fact that they have some limitations as well as desirable features. We will first discuss the functions which ceramics can perform in a unique way and then treat specific ceramic materials that provide these functional requirements.

Advanced Ceramics by Function

Chemical processing functions include coal gas filters for sulphur removal, high temperature or corrosion resistant membranes for chemical processing and chemical sensors. Thermal functions are one of the oldest roles of ceramics and continue to be important for severe thermal environments. It is noteworthy that materials possessing the lowest thermal conductivity and the highest are both ceramics. Applications include fibrous super refractories, such as the space shuttle tile, thermal barrier coatings, such as linings on combustor cans for jet engines, and high heat conduction paths. The use of a ceramic as a temperature sensor is another thermal function.

Advanced ceramics that serve in electronic and electromechanical functions represent the most rapidly growing category and enjoy the largest current market. These functions derive directly from the mixed ionic and covalent chemical bonding, which makes most ceramics good electrical insulators but allows for modification into semiconductors, conductors, and superconductors. Electrical insulators make up a large category of uses including the complex three dimensional electronic substrate wiring arrangements widely used with electronic chips. Ceramic dielectrics ar

TABLE I. ADVANCED CERAMICS BY FUNCTION - SOME EXAMPLES

- FOR CHEMICAL/PROCESSING FUNCTIONS
  - Coal gas filters for sulfur etc. removal
  - Membranes for chemical processing
  - Chemical sensors
- FOR THERMAL FUNCTIONS
  - Fibrous super refractories
  - Thermal barrier coatings
  - High heat conduction paths
  - Temperature sensors
- FOR ELECTRONIC FUNCTIONS
  - Insulators
  - Electronic Substrates
  - Dielectrics for capacitors
  - Semiconductors
  - Filters
  - Absorbers of RF
  - Electron emitters
  - Over-voltage protection
  - Solid electrolytes
  - Electrodes
  - Superconductors
- FOR ELECTRO-MECHANICAL FUNCTIONS
  - Transducers
  - Micropositioners
  - Pickups
- FOR MAGNETIC FUNCTIONS
  - Soft magnets
    - Recording heads
    - Magnetic tape
  - Hard Magnets
  - Motor parts
- FOR OPTICAL FUNCTIONS
  - Light sources
  - Light guides
  - Light detectors
  - Reflectors
- Memory systems
- Shutters
- Frequency doublers
- FOR MECHANICAL FUNCTIONS
  - Cutting tools
  - Engine parts
  - Pump parts
  - Dies
  - Valves
- FOR TRIBOLOGICAL FUNCTIONS
  - Bearings
  - Seals
  - Guides

used extensively in capacitors; production is measured in terms of 10^9 units per year. The semiconducting capability of ceramics is the basis for various specialized sensors and devices such as high frequency filters for signal selection and absorbers of radio frequency energy for stealth applications. High intensity electrical sources for electron microscopes employ ceramic electronic emitters. Over-voltage protection devices are composed of strongly nonlinear ceramic materials. Solid ceramic electrolytes form the basis of fuel cells and high performance batteries, while electrodes for severe chemical and thermal conditions utilize special conducting ceramics.

In parallel with thermal conductivity, the complete extremes of electrical conductivity are available in ceramics--ranging from some of the best insulators known to superconductors with the highest known critical temperature. Ceramic superconductors represent an entirely new technological advance. Ceramic transducers, micropositioners, and pickups represent electromechanical functions ranging from the serious use in submarine warfare to the scientific cutting edge in scanning tunneling microscopes to light-hearted consumer products such as singing birthday cards.

Magnetic and optical functions also derive from the fundamental chemical bond characteristics, which provide the ability to tailor ceramic structures and compositions to specific magnetic or optical properties. Small magnets, many of them made of ceramics, are ubiquitous in our lives, as exemplified by recording heads, magnetic tapes, and motor parts. Optical functions are an exploding technology with revolutionizing consequences for the fields of information handling and communication. Most ceramics have the kind of distribution of electron energies that make them transparent and give them vital roles as laser light sources, optical wave guides and light detectors. Their applications as reflectors include, not only special devices, but also a whole new generation of residential windows, which transmit visual light, but reflect infrared light, for more thermal efficiency. The coming generation of optical memory systems with enormous storage capacity--many of these employing ceramics--will make a qualitative difference in information handling.

Mechanical and tribological functions comprise another important category. Ceramics are having several impacts on machining. First, ceramic coatings on cobalt-bonded tungsten carbide have greatly increased cutting speeds and tool life. Typical coatings are TiC and TiN as well as multilayer coatings, such as TiC/Al_2O_3, and $TiC/TiN/Al_2O_3$. Typical cutting speeds have increased from 500 ft/min for cemented carbide to 1000 ft/min for coated cemented carbide. Today about 85% of the carbide tools used in the United States are coated.

Second, monolithic ceramic cutting tools are also coming into increasing use. The older families of ceramic cutting tools are based on Al_2O_3 and are used mostly for cutting cast iron. The newer families involve either whisker reinforcement (typically with SiC whiskers) and alternate matrix materials (typically silicon nitride or sialon). Cutting speeds as high as 10,000 ft/min are foreseen for silicon nitride composites.

Third, great advances in the use of diamond in cutting and grinding are occurring. Several technologies are coming together to offer real breakthroughs. The new methods for synthesizing diamond by chemical vapor deposition now offer synthetic diamond coatings at reasonable cost. Fine diamond crystals can now be made on a simple torch using a cooled substrate from which the diamonds are then removed. Another exciting advance is the development of cast-iron bonded diamond grinding tools. Nakagawa of the University of Tokyo and his collaborators have demonstrated material removal rates up to 100 times previous practice in the grinding of hard materials such as silicon nitride. This is important because previous grinding costs have been a serious obstacle to wider use of hard ceramics as parts in machinery and other devices. The new grinding tools are made by a process for sintering cast iron containing diamonds which does not cause the diamonds to convert into graphite and which yields dense, strong compacts.

The combination of good strength, relatively low density, high hardness, and good corrosion resistance makes ceramics useful for many applications such as engine parts, pump parts, dies, and valves, while their good friction and wear properties give them high potential for use in bearings, seals, and guides where the conditions are especially demanding.

Ceramic Materials Providing Functional Requirements

We now consider several of the actual materials of greatest interest as advanced ceramics. Most of them are compounds--typically oxides, nitrides, carbides, borides, or oxinitrides. Many are complex multi-component compounds in which the composition and microstructure must be accurately controlled. An especially exciting family of ceramics is the emerging group of ceramic-ceramic composites. An example is the newly developed and highly-successful cutting tool insert which is a composite of aluminum oxide reinforced with silicon carbide whiskers. A key to its success is the special processing technique, pressure assisted sintering, which is used to compact the material at high temperature. These ceramics have high toughness compared to unreinforced ceramics and retain high hardness to high temperatures. This combination of properties gives high tool life in demanding machining conditions. Table II lists a representative number of specific advanced ceramic materials.

For chemical processing functions, microporous material such as alumina (Al_2O_3) and zirconia (ZrO_2) are involved as filters for hot gases and liquid metals. Figure 1 shows a high temperature chemical processing application, a monolithic ceramic honeycomb used extensively in automobiles as the catalyst carrier for emission control. This material, shown in several configurations, is cordierite (magnesium aluminum silicate) which has a low thermal expansion coefficient giving it good thermal shock resistance. The honeycomb is made by extruding a mixture of powders and organic binders and plasticizers through a die. The material is subsequently made into a ceramic in a carefully programmed heating sequence in which the binder is first removed and the powder is then sintered. The resultant honeycomb, having 400 to 600 channels per square inch of cross section, is the basis for the exhaust catalyst technology universally used in automobiles in the United States. The material is finding other uses such as for high temperature particulate filters. An application for ceramic honeycombs likely to develop strongly in the near future is in the clean-up of coal burning power plant emissions.

For thermal functions, insulation is provided by highly porous structures either in fiber form or as bulk materials; alumina, zirconia, and silica (SiO_2) are among the leading choices. High thermal conductivity, on the other hand, is provided by diamond or beryllium oxide, while temperature sensors include ceramics such as yttrium titanate and barium titanate, both of which have electrical resistance with a positive temperature coefficient.

Figure 2 demonstrates that advanced ceramic materials are providing important advances in an old, traditional application. The fibrous material is a much more efficient thermal insulator and therefore can be used in much thinner sections, allowing the refitting of old furnaces to gain appreciably more interior volume without changing exterior dimensions.

TABLE II. ADVANCED CERAMICS BY FUNCTION - THE ACTUAL MATERIALS

FOR CHEMICAL/PROCESSING FUNCTIONS
- Microporous alumina hot-gas filters
- Zirconia-mullite liquid-metal filters
- Zirconia oxygen sensor

FOR MAGNETIC FUNCTIONS
- Soft magnets
  - Zn-Mn-Fe-O
- Hard magnets
  - Sr-Fe-O

FOR THERMAL FUNCTIONS
- Fibrous silica/alumina super refractories
- Zirconia thermal barrier coatings
- Diamond, BeO high heat conduction paths
- $BaTiO_3$:Y PTC temperature sensors

FOR OPTICAL FUNCTIONS
- Alumina-Cr lasers
- Silica light guides
- Ba-Na-Nb-O IR detectors
- Sn-O reflectors for plate glass
- Pb-La-Zr-Ti-O shutter
- Pb-La-Zr-Ti-O memory systems
- Frequency doublers

FOR ELECTRONIC FUNCTIONS
- Alumina electronic substrates
- Barium titanate dielectrics for capacitors
- SiC semiconductors as heaters
- SnO_2 translucent electrodes
- "123", "2112", etc., superconductors
- Pb-Zr-Ti-O piezo filters
- Mg-Al-Si-O absorbers of RF
- LaB_6 electron emitters
- ZnO over-voltage protectors
- Na-Al-O solid electrolytes

FOR MECHANICAL FUNCTIONS
- Monolithic ceramics
  - Silicon nitride
  - Silicon carbide
- Ceramic composites
  - Transformation-toughened alumina
  - Transformation-toughened zirconia
  - SiC whisker-reinforced alumina
  - SiC fiber reinforced glass-ceramic
  - SiC whisker reinforced iron, aluminum

FOR ELECTRO-MECHANICAL FUNCTIONS
- Pb-Zr-Ti-O transducers
- Pb-Zr-Ti-O micropositioners
- Pb-Zr-Ti-O pickups

FOR TRIBOLOGICAL FUNCTIONS
- Monolithic alumina, silicon carbide
- Carbide, nitride, oxide coatings
- Diamond coatings

This insulating material falls into four basic classes depending on the maximum service temperature: fluxed alumina-silica (1600°F), basic alumina-silica (2300-2400°F), modified alumina-silica (2400-2700°F) and high alumina or metal oxide (2400-3000°F).

For electronic, electromechanical, magnetic, and optical functions, an array of highly specialized, task-specific ceramic materials, mainly oxides, are employed. Each of them is tailored compositionally and structurally to have unique performance-related properties. Not much insight is gained by going down the list in Table II in a cursory, composition-by-composition manner. Instead, we will discuss two of them, chosen not only to illustrate advanced ceramic materials per se, but also to exemplify the kinds of properties and processing considerations and miniaturization concepts that are beginning to dominate this area of multicomponent, device-oriented materials. Both of the examples relate to the theme of this conference. One represents a challenging manufacturing problem; the other exemplifies a sensing device applicable to "smart processing" methods.

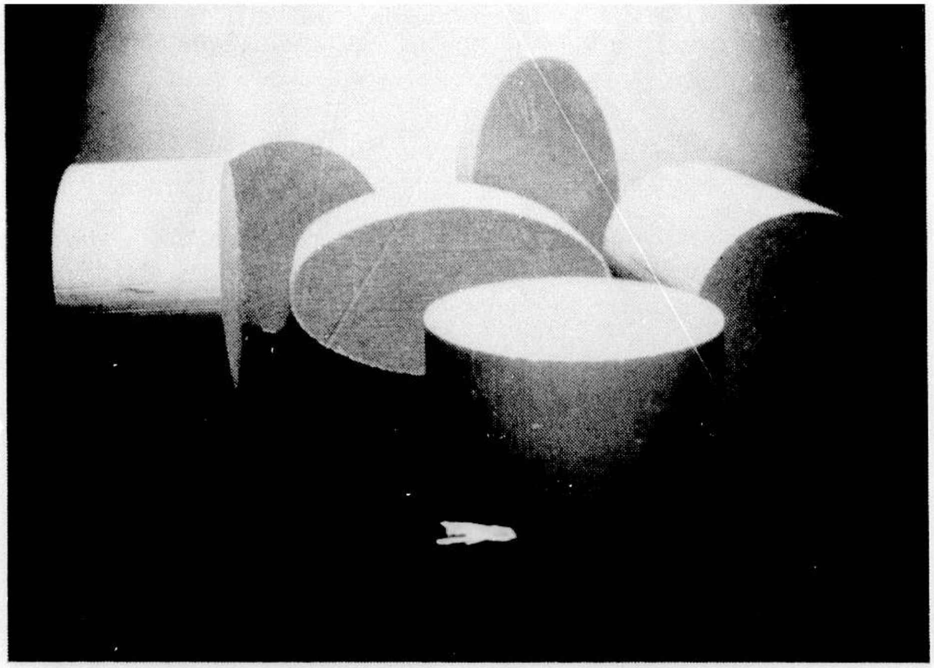

Fig. 1. Monolithic cordierite (magnesium aluminum silicate) honeycomb. (Photograph courtesy of Corning Glass Works, Corning, NY).

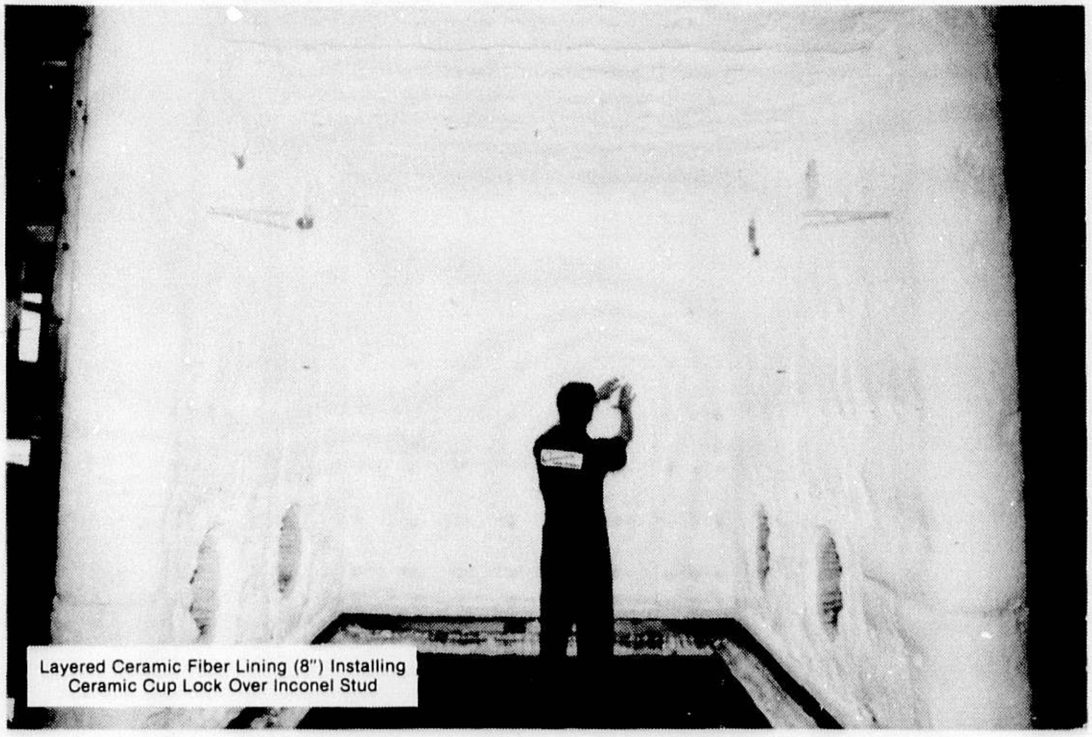

Fig. 2. Large industrial furnace refitted with ceramic fiber layered insulation. Fuel savings over 50% relative to hard brick insulation. (Photograph courtesy of Gas Research Institute, Chicago, IL).

The first example is the multilayer ceramic capacitor, illustrated in Figure 3. This device is fabricated in an intricate, microscale ceramic-metal technology which is being pushed toward an ever smaller dimension. Only a few microns separate the layers in this device, made by powder technology techniques. It can be appreciated, therefore, that there are major processing challenges involved in making this kind of structure and making it reliably in hundreds of million units. To produce such a multilayer structure several steps are involved. First, ceramic powder (typically aluminum oxide for an insulating layer or barium titanate for a high capacity layer) is mixed with binder and tape cast to make a thin, flexible, unfired tape. Second, this tape is cut to desired shape and holes are punched through when electrical connections between layers are desired. Third, a metal-containing ink is screen printed on the surface of the unfired tape to give the desired pattern of conductors, including the conductors through the layer to the one below when desired. Fourth, the tape sections are stacked. Fifth, the stacked tapes are fired to remove binder, sinter the ceramic, and consolidate the electrical conductor. A high level of ceramic technology is necessary to have these processes succeed.

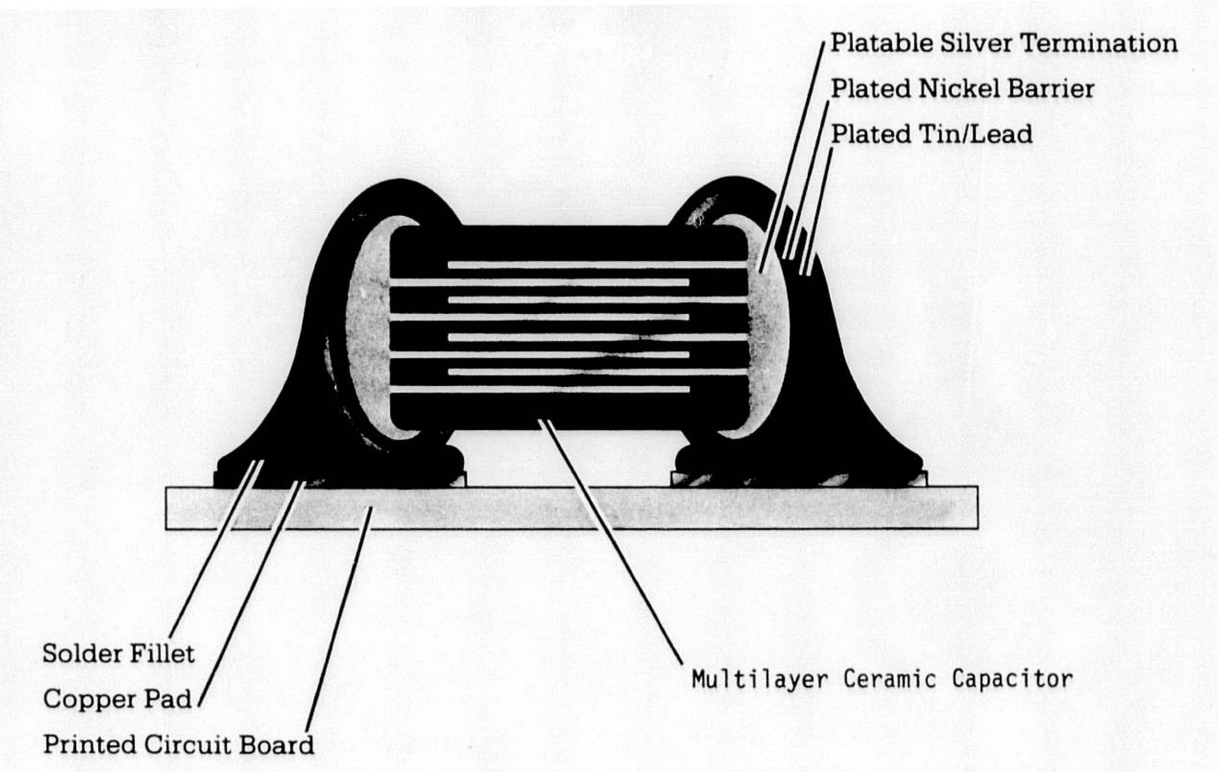

Fig. 3. Microscale multilayer ceramic capacitor. Plate-to-plate separation may be in microns. (Photograph courtesy of Electronic Materials Division, E. I. duPont de Nemours and Co., Wilmington, DE).

The second example is the PZT micro-positioner. This type of micropositioner is made of polycrystalline lead-zirconate titanate (PZT). This type of material is widely used for industrial applications such as nondestructive evaluation with ultrasonic waves and in military applications such as in sonar. A familiar application is in "fish finders" widely used to measure the depth of water under a boat and to reflect the image of a school of fish. The recent use of PZT as a micro-positioner has made possible the scanning tunneling microscope in which a shaped tip is moved in successive steps each of which is only about one-tenth of the diameter of an atom.

For mechanical functions, silicon nitride and silicon carbide are the leading monolithic materials, while transformation-toughened zirconia and alumina and silicon carbide whisker-reinforced alumina are important ceramic composites. Ceramics reinforced with whiskers are typically made in a multistage process. First, a mutual suspension of a ceramic powder and ceramic whiskers is made. This is not a simple process in itself and requires mastering dispersion technology. Second, the suspension is cast into the shape desired but with larger dimensions to allow for subsequent shrinkage. Third, the binder is burned out at a moderately high temperature. Fourth, the resulting porous body is pressed in a graphite die at high temperature to consolidate it and remove the porosity.

For tribological functions--friction reduction and enhanced wear resistance--use is made of monolithic ceramics such as alumina and silicon carbide and coatings composed of carbides, nitrides, and oxides. Figure 4 shows a silicon carbide-titanium boride ceramic part which has been EDM-machined into an intricate shape. Diamond grinding of this component to final shape from a ceramic blank would be a prohibitively expensive process. However, by forming the component to near net shape and building into the ceramic a second phase which imparts some degree of electrical conductivity, it becomes possible to use electric discharge machining, an economical process that permits a precision part to be made in a single "cut."

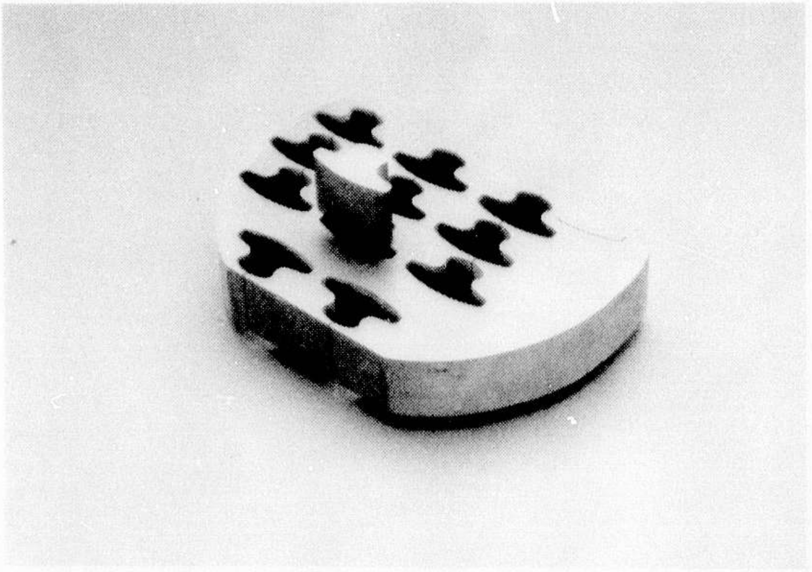

Fig. 4. Rocker arm inserts EDM-machined from SiC/TiB_2 composite. (Courtesy of Ceramic Industry, Solon, OH and Carborundum Co., Niagara Falls, NY).

Ceramics for heat engines offer a potential market comparable in size to the presently large and growing electronic ceramics market. Potential involvement includes friction- and wear-reducing applications, uses where reduced mass is beneficial, applications for high temperature strength, and uses involving heat management. Some uses on an exploratory, low-volume basis in production automobiles include cam-follower pads made of silicon nitride, silicon-aluminum-oxide-nitride (sialon) and zirconia-toughened alumina; turbocharger rotors made of silicon nitride and silicon carbide. Figure 5 shows a silicon carbide prototype turbocharger rotor made as a single part to final shape with no final machining required, except at the joint with the metal shaft. This component is made by powder technology, and therefore shrinkage is involved. The processing of this component is a substantial challenge.

Applications for heat engines now in the stage of laboratory development and expected to come into practical use in the next decade include valve guides, valve seats and valves made of silicon nitride, sialon or zirconia-toughened alumina; piston pins made of silicon nitride or sialon; piston rings made of silicon nitride, sialon or silicon carbide; exhaust system coating made of alumina; and an exhaust manifold liner made of mullite or silica.

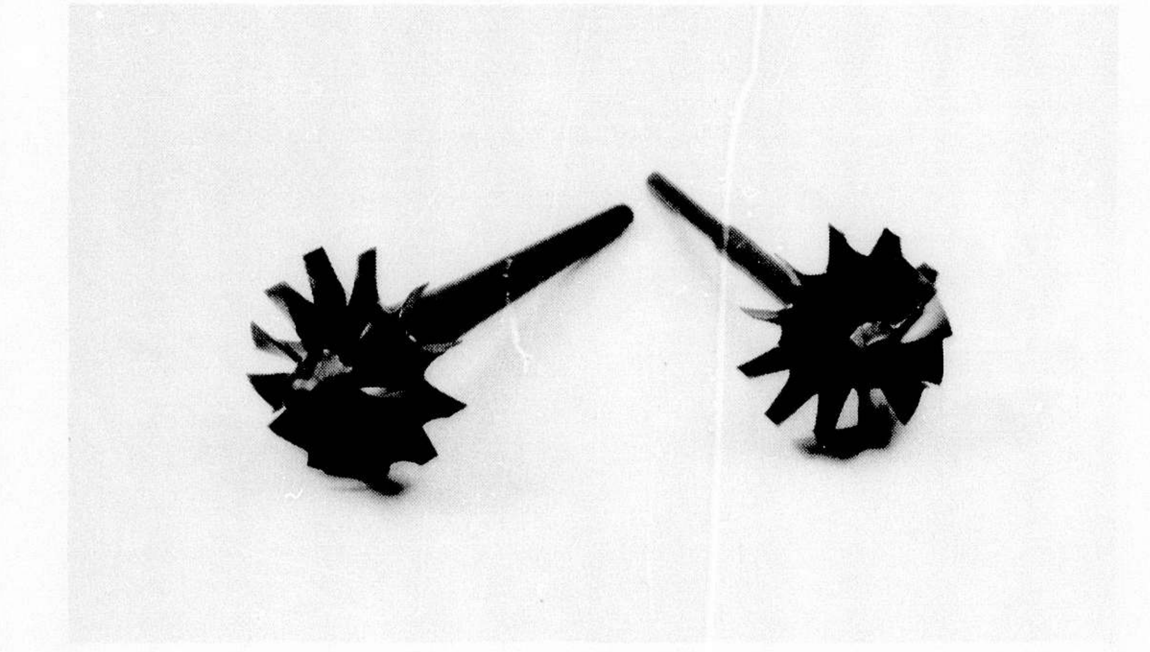

Fig. 5. Prototype silicon carbide turbocharger rotor made as a single part by powder technology. (Photograph courtesy of Carborundum Co., Niagara Falls, NY).

Processing and Design Considerations

Ceramics constitute an enabling technology--under the right circumstances a ceramic material gives a performance enhancement which makes it a required component in achieving competitive performance. At the same time ceramics can have a high performance leverage. The amount of ceramic needed for a performance improvement is often only a small portion of an overall device or system. However, the introduction of an advanced technology sometimes brings difficulties and risks requiring careful management. This is certainly the case in the use of advanced ceramics, where an incautious attempt simply to substitute ceramic parts without understanding their special characteristics can lead to trouble. The properties can vary with processing effects associated with changes in the size of the part. Ceramics are typically brittle, and can fail catastrophically because of their sensitivity to the presence of tiny structural defects. Also, ceramics present special joining problems because they are sensitive to high local contact stresses arising from thermal-expansion differences.

In order to benefit from the good properties of ceramics, very careful attention to processing and design variables is important. Much further work is required in three areas:

- Improved ceramic processing is needed to increase reliability by reducing structural defects and reducing costs.
- Improved design practice is required to exploit their good properties while minimizing their limitations.
- Basic materials engineering principles are needed in order to design optimized compositions and microstructures for improved properties.

Among the developments now proceeding at a rapid pace are these:

- Production of ceramics with finer grain sizes extending even to sizes below one micron is well along, motivated by a need for property improvement and to facilitate the making of microscale pieces. Fine grain size is important because the strength of ceramics is dependent on flaw size which usually correlates with the size of the grains. Fine grain size material can give higher strength if the processing is carefully controlled. The lower the sintering temperature, the finer the grain size, and this leads to advantages in processing.
- Ceramics are being systematically designed as multiphase composites. For example, a new family of ceramic composites composed of cordierite (magnesium aluminum silicate) and mullite (magnesium aluminate) is being developed for electronic substrate applications by IBM, DuPont, and others. The composite offers an advantage over the conventional alumina substrate in having a better thermal expansion match to silicon and a lower dielectric constant. The composite offers new processing challenges because a multi-component suspension must be used and because sintering in two-phase systems presents problems of compatibility of deformation.
- New chemical routes and better control of the chemistry of conventional processing routes is leading to better properties and better quality control. The new chemical routes include the sol-gel route in which a metal-organic precursor is reacted with water to form a partially polymerized oxide. The resulting structure is typically on a very fine scale (tens of Angstroms) and can typically be sintered at temperatures hundreds of degrees below the sintering temperatures for normal powders. The process presents problems in the stage of making the unsintered shapes, however, because of the large shrinkage on drying which often

causes cracking. An approach with some overall similarity but distinct differences in detail is the synthesis of very fine powders of uniform size by careful control of nucleation and growth.

- An overall systems approach to ceramic processing is leading to increased reliability.
- The use of computer modeling permits the optimization of a set of properties rather than a single property. Most applications require a set of properties, including some not thought of during early design iterations.
- The areas of surface phenomena, joining, and tribological behavior are being attacked on a more scientific basis. Metal-ceramic joining typically is done at high temperatures and leads to high stresses due to thermal expansion differences. This is an old problem but progress is being made through a combination of several approaches. One approach is to modify the composition of either or both of the ceramic and the metal to promote wetting and chemical bonding during partial liquid formation at high temperatures. A second approach is to use a buffer layer with intermediate thermal expansion. New developments include carbon-copper composites which can be made with a gradient of thermal expansion. A third approach involves computer modeling of the stresses which arise and modification of the geometry of the joint to minimize stress concentrations.

  Tribology (study of friction and wear) of ceramics is of growing importance as ceramics are increasingly considered for parts in engines. Ceramics have generally been developed to give the highest strength and toughness. The microstructures which are optimum for this purpose are not necessarily the best for wear resistance. Also, lubricants have generally been optimized for metals rather than ceramics. Consideration of the dominant wear mechanisms in ceramics and development of the best microstructures and lubricants to minimize wear of ceramics is at an early stage.

Market Considerations

Table III shows the projected Japanese market for high technology ceramics, as seen by the Japan Fine Ceramics Association. It indicates that a substantial market for electronic ceramics already existed in 1983 and is in the process of growing to a very large market by the year 2000. Thermal and mechanical ceramics for heat engines made up a much smaller market in 1983; this market is forecast to be on a significant growth curve by the year 2000, with the major use coming later. This long planning horizon has not deterred the Japanese from making a national effort in this field. Other especially promising areas are the fields of chemical, medical, and optical uses. Japanese estimates of world markets for high technology ceramics in 1983 and in the year 2000 are also shown in Table III. Enormous growth is projected for the year 2000. It's important to realize that achieving these markets depends on success in ceramic design, in cost effective processing, and improved quality and reliability.

It must be appreciated that several quite different types of markets exist. Three examples typify the differences. For optical wave guides, very small parts can play a very critical role so that a cost figure of

TABLE III

(a)

JAPANESE MARKET FOR HIGH-TECH CERAMICS
(JFC estimates by permission of S. Saito)
$ BILLION

	1983	1990	2000
Elect and Mag Ceramics	2.9	8.4	18.8
Mechanical Ceramics	0.2	0.5	1.0
Thermal/Mech Ceramics	0.1	1.4	4.5
Chem and Medical Ceramics	0.1	1.0	2.0
Optical Ceramics	0.1	0.8	3.2
Other (Nuclear, etc.)	<0.1	0.5	1.1

(b)

REGIONAL MARKETS FOR HIGH-TECH CERAMICS
(JFC estimates by permission of S. Saito)
$ BILLION

	1983	2000
N. America	7.0	62.4
W. Europe	6.5	59.7
Japan	3.5	30.6
Other F Asia	0.4	14.7
SW Asia	0.3	4.6
S. America	0.7	9.2
Oceania	0.3	3.0

$4,000 per pound may be acceptable. For parts in aircraft engines, $400 per pound may be acceptable. However, for use in automobiles, a price figure in the range of $4-$10 per pound seems more realistic if large-scale applications are to occur.

Summary Comment

Simon Ramo has stated that, "It is becoming possible to produce a vast array of materials that do not appear in nature and to specify their properties in advance." The first part of this statement is certainly true of ceramics, and we are moving toward an ability to achieve the latter. Ceramics are in competition with other classes of materials, or can be combined with them for the optimum choice. Use of the best materials--ceramics, metals, polymers, and combination of these--will be required in the manufacture of competitive products. This is a moving target and expert guidance is needed.

Editors' note: The earlier papers in these proceedings have stressed innovation and the role of materials, the flexible integration of product and process, and the coupling of materials design, engineering, and manufacturing. Joel D. Goldhar points out how modern information and control technologies permit these new thrusts to be dealt with and exploited on the factory floor.

MANUFACTURING FLEXIBILITY FOR COMPETITIVE ADVANTAGE . . . THE STRATEGIC IMPERATIVE FOR CIM

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Introduction

Traditional factories built with mechanical engineering-based technologies, industrial engineering organizing concepts, and human brain/paper archive information systems exhibit economic and operating characteristics that encourage us to trade off innovation in favor of productivity. As a product moves from introduction to maturity, the increase in volume requires a standardization of the product design and a migration from labor intensive to capital intensive production facilities in order to maintain low-cost operations. The strategic cost is in terms of reduced flexibility and slower response time. "Proper" traditional engineering and management practice results in a rigid factory that does its "job" very efficiently but is unable to respond effectively to changes in market demand [1].

The business strategies that go with this traditional factory are designed to accommodate its constraints and limitations. They include outsourcing, "repositioning" the product, off-shore manufacturing, price competition, and imitation/follow-the-leader approaches. These policies will usually result in increased short term efficiencies. They also result in the creation of a product design umbrella that invites counterfeiters and clones; and a mature industry with low profits and high exit costs. This situation leads managers to a correct reluctance to invest in new product innovation in light of the trend to increasingly truncated life cycles. As illustrated in Figure 1, doing a good job of process innovation results in a factory that becomes a barrier to the next round of new product development.

In the 1955-1975 time period--one in which many of our senior managers were trained and/or had their most successful experiences as middle managers--industry could afford to use this limited flexibility production approach. This was a period of relatively long product life cycles, leisurely rates of technological change, domestic markets and competition, mechanical process technology and geographical market segments. Business was based upon long-range planning and "scientific management" and the traditional factory was an appropriate response.

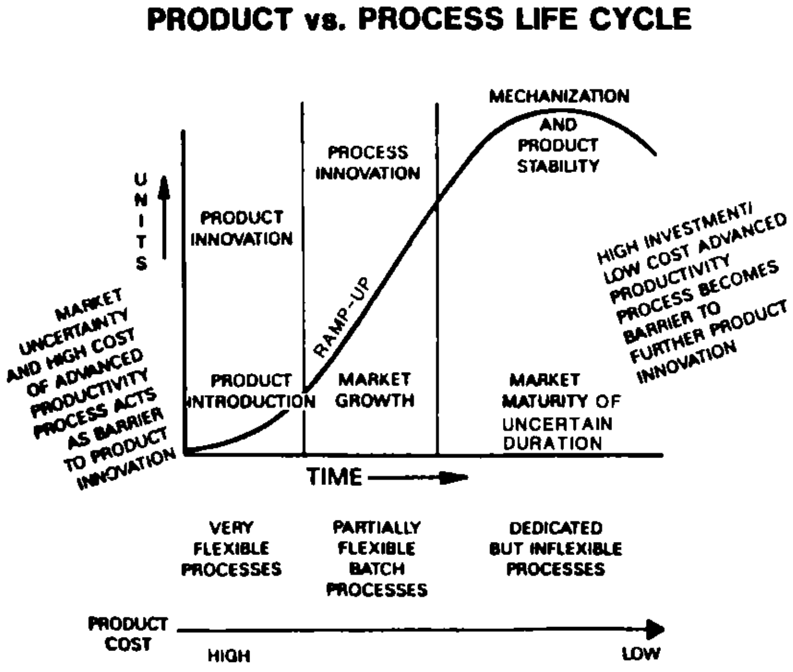

Fig. 1. The product vs. process life cycle

Since 1980 we see evidence of increasingly shorter product life cycles and faster product development cycles, global markets and competition, fragmented markets, and sophisticated customers. The traditional factory will not be a satisfactory response to these demands. Fortunately, the recent efforts to apply digital electronic technology to all aspects of design and manufacturing allow us to design a factory that is both responsive and efficient, that can deliver high variety at low cost with short production cycles. The use of digital electronics in the form of computers and communications links creates the efficiency of high degrees of integration without the rigidities created by mechanical integration.

This is the key to computer-integrated manufacturing (CIM), which is a combination of computer-aided design (CAD), computer-aided manufacturing (CAM) and flexible manufacturing systems (FMS) including robotics. The Factory of the Future is essentially a computer system with flexible machines and robots as the output devices in place of printers, disc packs, and plotters.

However, creating and benefiting from the new technology will necessitate new business strategies, different organizational forms, revised administrative policies, and a top-down strategic approach. And, most of all, it requires an effort to understand the details and the potentials of

CIM technology and a change in managers' mind-sets about the role of manufacturing as a force for sustainable competitive advantage.

Understanding CIM

To understand the implications of advanced manufacturing technology, two basic ideas require consideration. The first is that the new manufacturing technology is fundamentally different--in design, operation, and capability--from the equipment, process, and technology that we are accustomed to in traditional factories. The new technology is smarter, faster, integrated, optimized, and flexible. The new factory not only does traditional tasks differently, it can perform tasks not possible in the traditional factory. This means that many of the opportunities that we face, the management styles we need to use, the strategic options that are available to us, and the production decisions that we have to make, are going to be contrary to the experiment of past successes.

Secondly, manufacturing is rapidly becoming a science-based activity with high potential for revolutionary change well beyond what is considered, even today, as the state of the art. The level of scientific and technical knowledge required to understand how to design, manage, and optimize the kinds of factories we are discussing is beyond what most currently college trained manufacturing engineers possess. Trends in materials science, control theory, and artificial intelligence, combined with the application of computers, communications technology, and information science techniques, will lead to a new concept of manufacturing that is orders of magnitude more powerful than anything in our experience.

Computer-integrated manufacturing (CIM) embraces fully integrated, close-coupled, high variety, continuous-flow systems in which lead times for new product introductions or improvements will be drastically reduced. Work-in-progress inventories will practically disappear; costly final-goods inventories, used to buffer the factory from the uncertainties of the market place, will not be as necessary; and both direct and indirect labor will be substantially reduced.

The CIM factory is a paperless factory. It combines smart computer-controlled hardware, with knowledge work capabilities that allow us to manage large amounts of information in real time, to handle variety, to accommodate quick change, and to take advantage of the true power of new factory hardware. One without the other is not sufficient. Quick-change hardware without an information system that can keep track of variety will cause trouble, and a fancy information system, which is faster than the production hardware can change, is not going to deliver its full value. A word of warning is appropriate, however. The new technology is a computer-aided way to do the things we always recognized as necessary to run an effective factory. But if management is not running an effective and efficient factory now, no amount of computer automation will help.

We need to rethink most of our traditional concepts of factory organization, plant layout and location, choice of process technology and equipment, production planning and control, and the degree of standardization of product designs. Similarly, we should review the means for introducing new technology into existing systems, the ways to measure productivity and performance, and the kinds of training and skills needed by managers and professionals. Everything is up for reappraisal. That is not to say that everything is going to change. It is to say that everything has to be looked at with a fresh eye to find out whether or not it has to change.

We are developing a better understanding of the scientific underpinnings of production. This comes from better knowledge of the behavior of solid materials under various process conditions. As an analogy, we might ask why chemical companies have been willing to invest hundreds of millions of dollars in relatively unproven new process technology plants. It is because we know enough about the behavior of matter in the fluid state to be able to design and optimize a new process on paper and in the computer, and to build a test-scale pilot before companies make large-scale investments. We do not have many pilot plants for mechanical-based technologies; nor do we have a sense of confidence in our scale-up factors. But we are getting there. We certainly know more now about the behavior of the materials that we are using in products and in manufacturing systems. We are beginning to learn more about how to simulate factory operations and to use better analytical tools. Control theory, artificial intelligence, measurement and sensing capabilities are all advancing at a very rapid rate.

We are switching from an era in which we produced large volumes of standard products on specialized machinery to systems for the production of a wide variety of similar products in small batches--even one at a time--on technology that is standard but multimission, flexible, and tailored to the particular design through software. When information is in machine-readable form, rather than built into conveyors or pipes or cams and gears, we have the flexible manufacturing capabilities that will allow U.S. industry to respond to the global market pressures of the future.

Economy of Scope, Factory Operations and the New Meaning of Productivity

The key to understanding the opportunities presented by CIM-based flexible manufacturing is a set of production economics concepts called economy of scope. Economy of scope allows for low-cost variety of output. This means that the cost of producing a bundle of different product configurations on a particular piece of multimission equipment is the same as, or less than, the cost of producing the same number of pieces of identical design on specialized equipment designed for that particular product configuration [2].

The best example is a simple numerical control machine tool or CNC machining center. Such a tool can equally well make 12 of one product design in a row, or one each of 12 different designs in random order, provided those 12 different designs have been incorporated into its software. Essentially, this moves the fixed cost per design away from the plant floor and back to the engineering stage--and leads us to some generalizations on the design and characteristics of the factory of the future. A factory based on economy of scope rather than of scale will require a switch in management emphasis from minimum cost to maximum effectiveness and profitability. It will entail a very real change in both the way we define productivity and in the role and style of the factory manager.

Variety will have no cost penalty, at least on the production floor, but revenue and profit will be very sensitive to volume because total costs are essentially fixed. The factory will be capable of high levels of accuracy and repeatability. However, these cost-of-variety advantages will do little good for a company that is locked into a strategy of selling long runs of standard products for an assumed long life cycle. Quality will be built in from the beginning. "Make to order" will replace "make to stock" and product decisions will be based on joint cost rather than marginal cost economics. If the factory is thought of as a computer system, capacity additions will be in relatively small increments. Once the basic computer capability has been built, the software to add another milling machine or another robot cart or another loop on the line can be put in place quickly enough to eliminate any long-range capacity planning concerns.

Management's attention will be focused on extensive and very expensive preproduction activities, rather than on the plant floor. The manufacturing manager of the future will have to shift attention from the traditional narrow focus on productivity, unit material and labor costs to: (1) integration within the factory and integration among R&D, engineering, factory, marketing, and distribution; (2) innovation, both process innovation and product innovation; and (3) strategy for the manufacturing function itself and for the contribution of manufacturing to the strategic thrust of the firm as a whole.

For the old factory, sound operating principles and management techniques consonant with the old assumptions were developed. Centralization, large plants, balanced lines, smooth flow, standard product design, low rate of change, and inventory as a decoupler from the market were all desirable characteristics of the "good" factory.

The new factory will be marked by an entirely different set of desirable operating characteristics: decentralization, disaggregation, flexible operation, responsiveness to innovation, production tied to demand, and closely coupled systems. These represent sharp changes both for practitioners of manufacturing engineering and teachers of manufacturing management. The factory of the future is just as likely to be a high-cost factory (capable of dominating the "fashion" market segment through rapid product design change) as a low-cost price leader. A narrow preoccupation with cost and traditionally measured productivity will not get us where we need to go. However, new strategic options are possible.

Strategies for Maximizing Value in CIM Based Businesses

The changing criteria for manufacturing success lead to a set of strategies for maximizing the value of the factory of the future that are counterintuitive to what we teach in engineering and business schools and also to the things that worked well in the past. It starts with: invest in flexibility--not just in the flexibility of machining or assembly but in the flexibility of the organization as a whole, in research, engineering, marketing and distribution, and strategic planning.

Deliberately truncate the product life cycle. Create a product life cycle that is so short that by the time a competitor has a "knock-off" product, it is clear to the customers that it is not the most advanced product available. If a slightly more advanced, or a clearly newer product, is available at a reasonable cost, people will buy it. A flexible manufacturing system liberates management from the need to trade off newness for low product cost.

Proliferate the range of products to the extent of customizing them one-by-one so that no customer ever has a reason not to go to you for whatever he needs. A reasonable strategy is to deliberately fragment the market into segments so small that they can't support a traditional economy-of-scale based factory. Do the things that prevent competitors from coming in and competing in your market without having to make the same high levels of investment; not just capital investment but the human organizational investment in flexibility [3].

Finally, one can argue for deliberately complicating the product, although it goes against what we learn and teach in value and reliability engineering and production management. If the product is simple, it is easy to copy and there are no barriers to entry and no switching costs. What is really meant by "complicating the product" is to gradually embed the uniqueness of the product more and more deeply into the manufacturing process, so that it cannot be copied except by making that same kind of investment in flexibility, and to continually add value to the product through service and innovation. These are capabilities of the process rather than of the product.

Once you achieve flexibility at low cost, you clearly have to compete broadly across a wide range of market segments and a wide range of products in order to keep the flexible manufacturing system busy 24 hours a day, 7 days a week, because you are working with an almost 100 percent fixed-cost manufacturing system. In turn, this will place tremendous burdens for managing variety and flexibility on the marketing and distribution capabilities of the firm.

Implementation

Achieving this requires a top-down strategic approach. This kind of innovation is not going to "bubble up" from the plant floor. There has to be commitment, starting with the board of directors and implemented across the organization. This means that a firm must have a well-thought-out strategy before it can effectively justify and utilize a factory-of-the-future. We must ask: What business are we in, or what business do we want to be in? And what must we be able to do well to be successful in that business? And then, how can we acquire the necessary skills?

The most important starting point is the realization that low cost (productivity in the traditional definition) is a necessary but not sufficient condition for competitive advantage and sustainable profitability. A so-called "high cost" factory that offers rapid response to customer demand may be the most profitable one. CIM technology breaks the linkage between volume and cost and eliminates the factory as a barrier to rapid product innovation and aggressive customer service relationships. In summary, CIM allows manufacturing to become a "service business."

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1. This point has also been made by C. W. Skinner, Harvard Business Review, 64 (1986), pp. 55-59.
2. See also J. D. Goldhar and M. Jelinek, Harvard Business Review, 61 (1983), pp. 141-148.
3. For a rigorous proof of the desirability of market fragmentation and product proliferation see A. T. Talaysum, M. Z. Hassan and J. D. Goldhar, IEEE Transactions on Engineering Management, EM-34 (1987), pp. 85-91.

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Advanced Materials in the Manufacturing Revolution
Argonne National Laboratory
June 14, 1988

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