New Structural Materials Technologies: Opportunities for the Use of Advanced Ceramics and Composites

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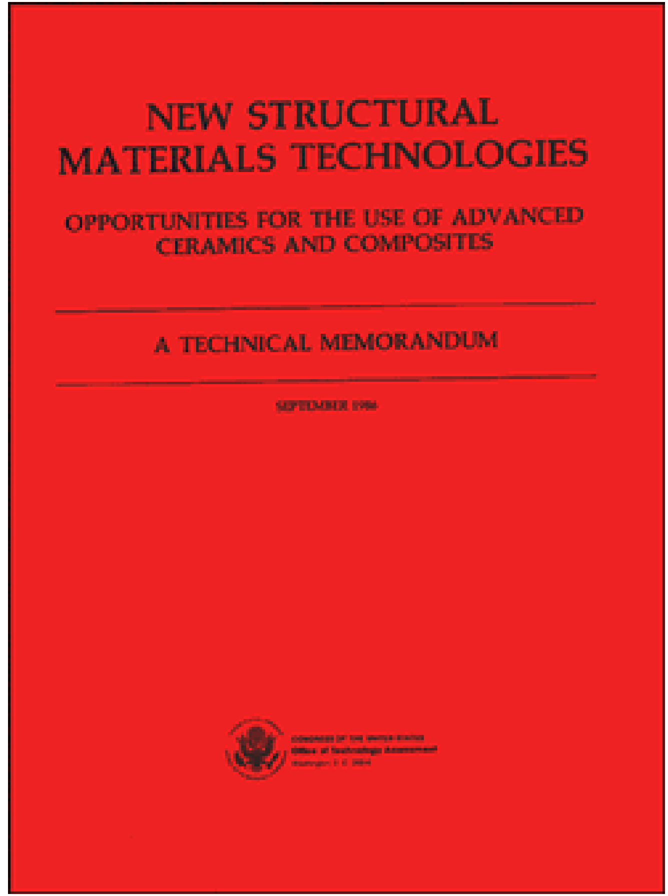

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Foreword

This technical memorandum responds to a joint request from the House Committee on Science and Technology and the Senate Committee on Commerce, Science, and Transportation to analyze the military and commercial opportunities presented by new structural materials technologies and outline the Federal research and development priorities which are consistent with those opportunities. This memorandum is part of a larger assessment which will address the impact of advanced structural materials on the competitiveness of the U.S. manufacturing sector, and offer policy options for accelerating the commercial utilization of these materials.

New structural materials—ceramics, polymers, metals, or hybrid materials derived from these, called composites—open a promising avenue to renewed international competitiveness of U.S. manufacturing industries. There will be many opportunities for use of the materials in aerospace, automotive, industrial, medical, and construction applications in the next *25* years.

In recent years, several excellent studies have been carried out on both ceramics and polymer matrix composites. This memorandum draws on this body of work and presents a broad picture of where these technologies stand today and where they are likely to go in the future.

OTA appreciates the assistance provided by the contractors, advisory panel, and workshop participants, as well as the many reviewers whose comments helped to ensure the accuracy of the report.

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OVERVIEW

The past 25 years have witnessed remarkable developments in structural materials technologies; new nonmetallic materials, such as ceramics and polymer matrix composites, are replacing metals in a wide variety of applications, ranging from cutting tools to tennis rackets. The new materials represent both an opportunity and a challenge for U.S. manufacturing industries. In an era of concern about the long-term economic viability of the manufacturing sector, they open a promising avenue to renewed international competitiveness, new industries, and employment opportunities,

By the year 2000, large markets for ceramic and composite products will be found in military, aerospace, automotive, medical, and construction applications, However, these opportunities cannot be taken for granted. The United States does not enjoy a comfortable lead (indeed it often lags) in new structural materials technologies; key advances continue to come from abroad. Moreover, through well-coordinated government-industry efforts, several countries have succeeded in bringing ceramic and composite products to the market years in advance of comparable U.S. products. Japan in particular has initiated aggressive programs to commercialize its evolving materials technologies, In order to realize the promise represented by the new materials, a consensus is developing in the materials community that U.S. policymakers in government, universities, and industries will have to come together to define feasible goals and materials applications, coordinate research and development efforts toward these goals, and, especially, focus on reducing the barriers to commercial introduction of advanced ceramic and composite products.

This technical memorandum assesses the opportunities for the use of structural ceramics and polymer matrix composites in the next *25* years, outlines the research and development priorities implied by those opportunities, and concludes with a discussion of some key prerequisites for their realization. A parallel treatment of metal matrix composites, as well as a discussion of public policy options for accelerating the development and commercialization of advanced structural materials, is deferred until the final report. [1]

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SUMMARY

In the past *25* years, new structural materials, such as ceramics, polymers, and composites, have brought a revolutionary change to the field of engineering. Never before have engineers had a comparable opportunity to design the materials they use as well as the structures they build. In fact, with advanced ceramics and composites, the very concepts of materials and structures merge together, joined by the new concept of integrated design. Such designs consolidate discrete parts and functions into a single, multifunctional structure, leading to highly efficient use of materials and lower overall costs.

In the future, new structural materials will provide a powerful leverage point for the manufacturing sector of the economy: not only can ceramic and composite components deliver superior performance, they also enhance the performance and value of the larger system in which they are incorporated. When this multiplier effect is taken into account, the impact of advanced structural materials on the gross national product (GNP), balance of trade, and employment could be dramatic. All of the industrialized countries have recognized the opportunities and are competing actively for shares of the large commercial and military markets at stake.

The Federal Government plays two important roles in the research and development of advanced ceramics and composites: one military, and the other nonmilitary. The Department of Defense funds some 35 percent of Federal R&D on structural ceramics and about *70* percent of that on polymer matrix composites. The military and nonmilitary agencies have very different funding goals and materials requirements.

In the case of the military, the government is the customer for materials technology and hardware. It has an interest in securing stable, domestic sources of material supply. Although materials cost is an important consideration, typically the performance advantages obtained are more important. Military applications often provide a first "window" for the use of advanced materials; however, the technologies may or may not be "spun off" into commercial applications. Because of the emphasis on high performance and the fact that production volumes are typically low, often neither the materials nor the production methods are appropriate for commercial applications. For national security reasons, restrictions are placed on the dissemination of DOD-funded research results in scientific publications and at meetings; export controls may also be placed on shipments of the materials abroad. These restrictions tend to further discourage the commercial utilization of materials technologies developed by the military. In the future, demand for high performance materials in such applications as aircraft, missiles, and space-based weapons systems will increase, making these among the fastest growing applications of structural ceramics and composites.

About half of total Federal spending for advanced ceramics and polymer matrix composites R&D is nonmilitary in nature, including most of that funded by the Department of Energy, the National Aeronautics and Space Administration (NASA), the National Science Foundation, the National Bureau of Standards, and the Bureau of Mines. These agencies generally do not act as the procurers of hardware, but instead fund materials research ranging from basic science to technology demonstration programs, according to their mission objectives. Where appropriate, they openly seek to transfer materials technology to the private sector. For a variety of reasons, the success rate of these efforts has been low: the technology may require significant further development prior to utilization; the market opportunities for the technology may be too long-term or poorly defined; or key decisionmakers within the receiving company may not be committed to commercializing the technology. Federal nonmilitary materials R&D clearly represents a resource that can be exploited more effectively by U.S. companies in the future.

An important policy objective for the future will be to encourage industrial investment in research, development, and commercialization of ceramic and composite materials. Factors discouraging these investments include: fragmentation of industries and markets, which precludes

any one segment from undertaking the necessary research; concerns that R&D investments cannot be protected because of the high transferability of the technologies; and the relatively high cost of capital in the United States compared with competitor nations such as Japan. Federal efforts to facilitate collaborative R&D arrangements between industries, universities, and government laboratories, to tighten patent protection for industrial products and processes, and to articulate policy clearly on export controls and on product liability issues, are likely to be very important. Ultimately, however, a strong U.S. competitive position depends on a judgment on the part of manufacturers that the new materials offer cost and performance advantages in the marketplace.

Introduction

Structural materials may be classified as ceramics, polymers, metals, or hybrid materials derived from these, called composites, Wood and oyster shells are examples of composites that have been exquisitely engineered by nature to perform their unique functions. Similarly, manmade composites are engineered materials whose properties can be tailored to match the design requirements of a particular structure. The most common composites consist of a host (matrix) material which is reinforced with particles, whiskers (short single crystals), or fibers of a second material; thus, there are ceramic matrix composites, polymer matrix composites, and metal matrix composites.

Although ceramics, polymers, and metals generally have complementary combinations of properties, there are many applications in which designers can choose from several alternative materials. A new structural material must therefore demonstrate cost or performance advantages (often both) if it is to be chosen over a more familiar material. Very often, ceramics and composites are competing with well-characterized alloys of aluminum, titanium, steel, and high-temperature superalloy, Furthermore, new alloys are being developed and metal processing methods are continually improving. Thus, the minimum cost and performance requirements which must be satisfied by a ceramic or composite are becoming more stringent. This competition among different materials has two important corollaries. First, the characteristics of structural ceramics and composites make them more suitable for some applications than others; it is important for government and industry policymakers to identify the opportunities correctly. Second, the many technical and economic factors which could tip the balance in favor of one material or another make the market penetration of ceramics and composites difficult to predict.

Ceramics

Ceramics encompass such a broad class of materials that they are more conveniently defined in terms of what they are not, rather than what they are. Accordingly, they may be defined as all solids which are neither metallic nor organic. Compared with metals, ceramics have superior wear resistance, high-temperature strength, and chemical stability; they also generally have lower electrical and thermal conductivity, and lower toughness. The low toughness of ceramics (brittleness) causes them to fail suddenly when applied stress is sufficient to propagate cracks which originate at microscopic flaws (e.g., cracks, voids, or inclusions as small as 20 micrometers) in the material. The actual stress level at which this occurs can be very high (e.g., 300,000 psi, or 2,069 MPa) and theoretically could be much higher, if flaw sizes could be reduced. Unpredictable failure caused by poor control over flaw populations is the most serious handicap to the use of structural ceramics in load-bearing structures.

Several approaches have been taken to improve the toughness of ceramics. The most satisfactory is to design the microstructure of the material to resist the propagation of cracks. Ceramic matrix composites, which contain dispersed ceramic particulate, whiskers or continuous fibers, are an especially promising technology for toughening ceramics. A different approach is the application of a thin ceramic coating to a metal substrate. This yields a component with the surface properties of a ceramic combined with the high toughness of metal in the bulk.

Most advanced structural ceramics are fabricated by consolidation of a compact of pure, finely divided oxide or nonoxide powders in a furnace at high temperatures. However, another class of ceramics, called chemically bonded ceramics, develops its strength at room temperature, typically through chemical reactions involving the uptake of water. Traditional cement pastes and concretes fall in this category. Because these materials normally contain large flaws which limit their strength, they are not ordinarily considered "advanced." However, in recent years the properties of chemically bonded ceramics have improved dramatically as new processing methods have reduced the strength-limiting flaws. The low cost and flexible fabrication methods of chemically bonded ceramics could permit them to displace plastics and metals in a wide variety of applications.

Market Opportunities for Ceramics

Market demand for structural ceramics is not driving their development in most applications at the present time. In 1983, the world market for advanced structural ceramics was estimated as $250 million, primarily in heat- and wear-resistant applications. Projections to the year 2000 place the U.S. market variously between $1 and ***$5*** billion, spread among many new applications discussed below. The larger estimates assume substantial utilization of ceramics in automotive heat engines, long predicted to be the most important application of structural ceramics. The analysis below indicates that significant use of ceramics in automotive heat engines is not likely by the year *2000*. However, large near-term opportunities are available in other products, such as medical devices.

Japan is the principal competitor to the United States in advanced ceramics technology. Japanese companies have made a long-term commitment to the development of advanced ceramics which looks beyond the current weak market demand. They have mounted a well-coordinated effort which includes: increasing the quality and availability of raw materials; optimizing fabrication processes; installing the most advanced processing and quality control equipment; initiating manufacturing development; and aggressive marketing of evolving materials. This commitment to the future of ceramics is likely to give Japanese companies the early lead in capturing the large near-term markets.

Current Production

Ceramics such as alumina, silicon nitride, and silicon carbide are in production for wear parts, cutting tools, bearings, and coatings. The market share for ceramics in these applications is generally less than 5 percent, but substantial growth is expected, and the U.S. markets for the ceramic components alone could be over $2 billion by the year 2000. Research and development funding is currently being provided by industry and is driven by competition in a known market.

Ceramics are also in limited production (in Japan) in discrete engine components such as turbochargers, glow plugs, and precombustion chambers. Current military applications include radomes, armor, infrared windows, and heat sources.

Near-Term Production

Near-term production (next 10 to 15 years) is expected in advanced bearings, bioceramics, construction applications, heat exchangers, electrochemical devices, discrete components in automobile engines, and military applications. The technology feasibility has generally been demonstrated, but scale-up, cost reduction, and design optimization are required. Large markets are at stake: especially promising are bioceramics for dental and orthopedic implants, and chemically bonded ceramics for construction applications. Wisely directed government funding will be required to solve the remaining problems and achieve a production capability competitive with foreign sources.

Long-Term Applications

Long-term applications (beyond 15 years) are those which require solution of major technical and economic problems. These include an advanced automotive turbine engine, the advanced ceramic diesel (although ceramics could be used in military versions of these engines at an earlier date), some electrochemical devices, military components, and heat exchangers. A variety of other turbine engines, especially turbines for aircraft propulsion and for utility-scale power generation, should also be categorized as long term. In general, the risks are perceived by U.S. industry to be too high to justify funding the needed research. Advances in these applications are likely to be driven by government funding.

Research and Development Priorities

The following hierarchy of R&D priorities is based on the technical barriers that must be *over*come before ceramics can be used in the applications discussed above.

Very Important

Processing Science .—This is the key to understanding how processing variables such as temperature, composition, and particle size distribution are connected to the desired final properties of the ceramic.

Environmental Behavior.—In many applications, ceramics are required to withstand high temperature and corrosive or erosive environments. Information on the long-term behavior of ceramics in these environments is essential to predict the service life of ceramics in those applications.

Reliability .—The reliability of advanced ceramics and ceramic composites is the single most important determinant of success in any application. Progress requires advances in brittle materials design, process control, nondestructive evaluation, understanding crack growth processes, and life prediction.

Ceramic Composites.—These novel materials offer an exciting opportunity to increase the strength and toughness of ceramics.

Important

Joining. -Joining of ceramics to metals, glasses, and other ceramics is necessary when ceramic components are incorporated into larger systems. The principles developed in joining research can also be applied to coating technology.

Tribology.—This is the study of friction, wear, and lubrication of surfaces in relative motion. It is especially relevant to understanding the degradation of ceramic wear parts, bearings, and the lubrication requirements of high-temperature ceramic engines.

Standardization and Testing.—Although standards exist for ceramic refractories and brick, at present there is a lack of standards for advanced ceramics, whether for testing procedures, compositions, or processing history. Such standards are a prerequisite for confident design and industry acceptance of ceramics.

Desirable

Chemically Bonded Ceramics.—These materials, which include advanced cement pastes and concretes, represent an outstanding potential for low-cost, net shape fabrication of ceramic structures. The cost savings associated with the use of improved concretes in highways and bridges are likely to be very large compared with the research investment required.

Polymer Matrix Composites

Polymer matrix composites are organic polymers which have been reinforced with a variety of short or continuous fibers to provide added strength and stiffness. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement. The amount of reinforcement and its geometry can be varied across the structure, resulting in highly efficient use of material, consolidation of parts, and weight savings.

Polymer matrix composites are often divided into two categories: reinforced plastics and “advanced composites. ” The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-strength glass fibers; they have been in use for 30 or 40 years in applications such as boat hulls, corrugated sheet, pipe, automotive panels, and sporting goods. Advanced composites, which are used primarily in the aerospace industry, consist of fiber and matrix combinations which yield superior strength and stiffness, They are relatively expensive and typically contain a large percentage of high-performance continuous fibers (such as high-strength glass, graphite, aramid, or other organic fibers). In this technical memorandum, market opportunities for both reinforced plastics and advanced composites are considered.

Chief among the advantages of polymer composites is their light weight coupled with high stiffness and strength along the direction of the reinforcement. This combination is the basis of their usefulness in aircraft, automobiles, and other moving structures. Other desirable properties include corrosion and fatigue resistance. One generic limitation of polymer matrix composites is temperature; an upper limit for service temperatures with present composites is about ***600°*** F (316° C). With additional development, temperatures above 8000 F (4270 C) might be achieved.

In addition to their superior physical and mechanical properties, polymer composites offer many design and manufacturing advantages. Perhaps the most important of these is the opportunity to consolidate a large number of parts into one, thus reducing assembly costs. This capability has already been demonstrated in aircraft and automotive applications. For example, it has been estimated that the 1,500 structural parts in an automobile could be reduced to a few hundred using composites, resulting in major savings in tooling and manufacturing costs.

Most advanced composites today are used in the aerospace industry. They are fabricated by a laborious process called "lay -up." This typically involves placement of sequential layers of polymer-impregnated fiber tapes on a mold surface, followed by heating under pressure to cure the lay-up into an integrated structure. Although automation is beginning to speed up this process, production rates are still too slow to be suitable to high-volume, low-cost applications such as automotive production lines. New composite fabrication methods which are much faster and cheaper will be required before composites can successfully compete with metals in these applications.

Market Opportunities for Polymer Matrix Composites

Fiberglass composites have been in use since the 1940s, and about 85 percent of the materials used in the reinforced plastics/composites industry today are glass fiber reinforced polyester resins. Less than 2 percent of the materials are "advanced" composites such as those used in aircraft and aerospace. Worldwide sales of advanced composites have been projected to grow by 15 percent annually for the remainder of the century, increasing from a 1985 value of $1.4 billion to nearly $12 billion by the year 2000. The industry continues to be driven by aerospace markets, with defense applications likely to grow by as much as 22 percent per year in the next few years.

Current Production

Aerospace applications of advanced polymer composites account for about 60 percent of current sales. Sporting goods, such as golf clubs and tennis rackets, account for another 20 percent. The sporting goods market is considered mature, with projected annual growth rates of 3 percent. Automobiles and industrial equipment round out the current list of major users of advanced composites, with a 15 percent share.

Near-Term Production

Composites were introduced into the horizontal stabilizer of the F-14 fighter in 1970, and have now become the baseline materials in high performance fighter and attack aircraft. The next major challenge for composites will be use in large military and commercial transport aircraft. Composites currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757, but could eventually account for more than 65 percent. No technical barriers are foreseen which might prevent this scenario, although design and certification databases for civil applications need to be established. Since fuel savings are a major reason for the use of composites in commercial aircraft, continued low fuel prices could delay their exploitation.

The largest volume opportunity for polymer composites is in the automobile. Composites currently are in limited production in body panels, drive shafts, and leaf springs. By 1995, composite unibody frames could be introduced in limited production. The principle advantage of a composite unibody would be the potential for parts consolidation resulting in lower assembly costs. If composites were to be used extensively in unibodies, the effects on the way automobiles are designed, built, and serviced would be dramatic.

However, production methods some 10 times faster than current methods will have to be developed in order to take advantage of this opportunist y.

Additional near-term markets for polymer composites include medical implants, reciprocating industrial machinery, storage and transportation of corrosive chemicals, and military vehicles and weapons.

Long-Term Applications

Beyond the turn of the century, composites could be used extensively in construction applications such as bridges, buildings, and manufactured housing. Realization of this opportunity will depend on development of cheaper materials and on designs which take advantage of compounding benefits of composites, such as reduced weight and increased durability. In space, a variety of composites will be used in the proposed aerospace plane, and composites are being considered for the tubular frame of the space station. Composites of all kinds, including metal matrix, ceramic matrix, and polymer matrix, will be a central feature of space-based weapons systems such as those under consideration for ballistic missile defense.

Research and Development Priorities

Polymer matrix composites have achieved an excellent service record and experience indicates that reliable composite structures can be fabricated. However, in many cases the technology has outrun the basic understanding of these materials. In order to generate improved materials and to design and manufacture composites more cost-effectively, the following needs should be addressed.

Very Important

Processing Science.—Development of new, low-cost fabrication methods will be critical for composites. An essential prerequisite to this is a sound scientific basis for understanding how process variables affect final properties.

Impact Resistance.—This property is crucial to the reliability and durability of composite structures.

Delamination.—A growing body of evidence suggests that this is the single most important mode of damage propagation.

Interphase.—The poorly understood interracial region between the fiber and matrix has a critical influence on composite behavior.

Important

Mechanical Properties.—Better scientific understanding and modeling in the following areas would permit development of better materials and improved designs: strength, fatigue, and fracture.

Environmental Effects.—The environments to which composites are subjected can have a deleterious effect on their long-term reliability. Investigation of the effects of moisture and temperature are particularly important.

Reinforcement Forms and Hybrid Composites.—Innovations in both of these areas would provide opportunities to improve properties and reduce costs. The large number of variables makes a purely empirical approach very inefficient.

Test Methods.—Lack of standardized test methods contributes to the considerable variability in reported property values.

Desirable

Viscoelastic and Creep Properties.—Deformation resulting from sustained loading can have an adverse effect on structural performance. A greater database is required, especially for compressive loading.

General Prerequisites for the Use of Advanced Structural Materials

Education and Training

At present, the demand for scientists and engineers trained in ceramics and composites technologies outstrips the supply. Education may be the most effective tool available to government for accelerating the development of advanced materials in the long run. Several aspects should be considered. Undergraduate introductory courses in ceramics and composites should be offered to engineering majors. Undergraduate courses specializing in design with these materials should also be available to all students in applied mechanics, including mechanical and civil engineers. Provision should be made through seminars and short courses for continuing education of engineers in other areas who want to learn more about ceramics and composites. Also, education of designers, planners, managers, and the general public through newspapers, magazines, and television will be especially important in creating demand for products made from these high-technology materials.

Multidisciplinary Approach

In recent years there has been an increasing appreciation of the fact that many problems in science and technology are most effectively solved through the combined efforts of specialists from a variety of disciplines. In no case is this more apparent than with advanced materials. The nature of ceramics and composites is such that the process which transforms the raw materials into the finished product integrates the discrete steps of design, manufacturing, and testing into a coherent whole. The familiar distinctions between the product and the material from which it is made become blurred, in a way which is qualitatively different from our experience with traditional materials. This integrative property implies that a multidisciplinary team of experts is more likely to solve the problems associated with the development and application of advanced materials than an alternative approach involving individual researchers.

Integrated Design

The outstanding opportunities presented by ceramics and composites do not lie in part-for-part replacement of metal in current designs; rather, new designs which incorporate many parts and functions into one are made possible. These new structural shapes and systems for carrying loads may not look at all like metal designs. Such a design capability will require the development of sophisticated software for computer modeling and analysis, as well as an extensive database on materials properties. Perhaps the most important requirement is for a better scientific understanding of how the properties of the microscopic constituents determine the overall behavior of the structure. Many of the research and development priorities above are aimed at providing this information.

Systems Approach to Costs

High cost is often cited as the largest barrier to the use of advanced ceramics and composites. Indeed, on a dollar-per-pound basis, today's ceramics and composites often cost several times as much as the materials they would replace. Although costs can be expected to decline as production volumes increase and manufacturing technologies mature, the baseline costs per pound of many ceramics and composites may always be higher than those of steel and aluminum. However, rather than a barrier, cost may in fact be a potential advantage of the new materials, if the "system costs," including materials, manufacturing, and life cycle of a structure, are all taken into account. Like multidisciplinary research and integrated design, a systems approach to costs is implied by the holistic nature of advanced materials.

In conclusion, advanced structural materials represent evolving technologies which will dramatically affect the U.S. economy. The near-term markets for these materials are large, and the long-term opportunities are just beginning to be recognized. Although the United States faces stiff international competition for the developing world markets, the United States does possess several natural strengths which should enable it to excel in this competition. These include a strong university system, a well-developed computer and software industry, and the largest domestic market for materials in the world. The challenge to national policy makers is to define a Federal role which facilitates the maximum exploitation of these natural strengths. The most important policy issues and options for addressing them will be explored in the final report.

INTRODUCTION

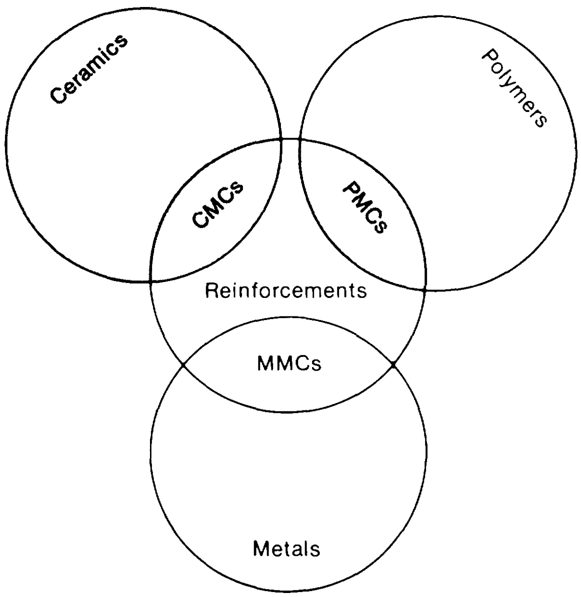
The past 25 years have witnessed an unprecedented explosion of new structural materials available to the designer and engineer. Polymers, ceramics, and composites promise to bring a revolution in the performance of a wide variety of engineering components and structures, and in the way those structures are designed and fabricated. Today the pace of technological change in this field is rapid, and the scope of the opportunity presented by the new materials is only beginning to be recognized.

In addition to changing the engineering landscape, advanced structural materials have also altered the boundaries of traditional policy concerns relating to materials. Historically, the Federal interest in materials has centered around the problem of shortages of supply of certain "critical" minerals. For example, the United States is dependent on foreign sources for virtually all of its chromium, manganese, cobalt, and platinum group metals. These metals are important ingredients in a variety of steel alloys and superalloy. To a limited extent, ceramics and composites, which are made from plentiful raw materials, can alleviate this problem through substitutional However, the potential of the new materials goes far beyond simple substitution; they provide performance advantages in both military and commercial applications which cannot be achieved with metals. Ceramics and composites are now considered to be "critical" in their own right, both for national defense and future economic competitiveness. Therefore, the appropriate Federal role in accelerating the development and commercialization of these materials is likely to be a subject of active debate in the years ahead.

Advanced materials are often ranked with microelectronics and biotechnology as the three most promising "high-tech" industries of the future. Many countries around the world have recognized the exceptional promise of these materials and have targeted them for priority development, with the result that the United States, having pioneered many of the basic technologies, now finds itself in a heated race with Japan and several countries in Europe to supply the growing world markets. Fundamental advances in these technologies are now being made overseas, so that the United States cannot afford to be complacent if it intends to be competitive. It is important to note that in most cases ceramic and composite structures do not stand alone, but are instead components that enhance the performance of much larger systems, such as automobiles or aircraft. Thus, the materials have a significance to the economy extending far beyond the value of the materials themselves.

Structural materials may be classified as ceramics, polymers, or metals, as shown in figure 1. Two or more of these materials can be combined together to forma composite having properties superior to those of the constituents alone.

Figure 1.— The Family of Structural Materials



The family of structural materials includes ceramics, polymers, and metals. Reinforcements added to these materials produce ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Materials in the shaded regions are discussed in this report.

SOURCE: Off Ice of Technology Assessment

[1] U. S. Congress, Office of Technology Assessment, *Strategic Materials: Technologies To Reduce U. S. Import Vulnerability*, OTA-ITE-248 (Washington, DC: U.S. Government Printing Office, May 1985).

The most common form of composite is a host material (matrix) which is reinforced with particles or fibers of a second material. Composites are classified according to their matrix phase; thus, there are ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Wood, jade, and oyster shells are natural composites which display remarkable strength and durability. A common manmade composite is glass fiber reinforced plastic (FRP), which combines the strength of the glass with the toughness and corrosion resistance of plastic,

Each type of structural material has its own advantages and disadvantages. For example, metals are strong, tough, inexpensive, and readily formable, but are also heavy, chemically reactive, and limited to service temperatures below about 1,900° F (1,038° C). Ceramics are hard, chemically stable, and useful at high temperatures, but are also brittle and difficult to fabricate. Polymers are light and easy to fabricate, but are relatively weak and restricted to service temperatures below about 600° F (316° C).

Frequently, composites offer an excellent opportunity to eliminate some of the undesirable properties while retaining the desirable ones. Metals can be reinforced with ceramic fibers to extend their useful strength to higher service temperatures; ceramics can be reinforced with ceramic fibers to reduce their brittleness; and polymers can be reinforced with ceramic or organic fibers to make them, pound for pound, the strongest materials known. The great value of composites is that the reinforcement type and geometry can be varied to optimize the performance and minimize the cost of the overall structure.

In the face of the challenge from ceramics and composites, metals technologies have not remained static. New steel and aluminum alloys and new processes such as rapid solidification and powder metallurgy techniques have been developed. Metal matrix composites promise to increase the hardness and service temperature of metals without requiring a large investment in new manufacturing plant and equipment. Also, various coatings and surface modification techniques can be used to protect the metal so that it will not deteriorate in hostile environments.

The diversity of structural materials available today offers many options to the designer. Typically, a given structure can be fabricated from any of a variety of candidate materials. Only rarely will the performance requirements dictate a single choice. Nor does the challenge to the primacy of metals come only from the most "advanced," most expensive composites or ceramics: unreinforced engineering polymers such as nylons or polyamides, and chemically bonded ceramics (high performance cements) offer an inexpensive and effective alternative to metals in many applications. This capacity for materials substitution also complicates the task of projecting the future shares of materials in various markets. However, one can predict with confidence that the properties and manufacturing advantages of ceramics and composites will make them as familiar in the 21st century as metals are today.

CERAMICS

Ceramics may be defined as nonmetallic, inorganic solids. By far the most common of terrestrial materials, ceramics in the form of sand and clay have been used for many thousands of years to make brick, pottery, and artware. Modern structural ceramics bear little resemblance to these "traditional" materials; they are made from extremely pure, microscopic powders which are consolidated at high temperatures to yield a dense, durable structure.

The Advanced Structural Ceramics Industry

The world market for advanced structural ceramics in 1983 was only $250 million. [2] Of this, the Japanese market made up nearly half. These ceramics were primarily used in heat- and wear-resistant applications. The limited current markets for ceramics do not exert a strong "market pull" on the technology; at present, the situation is characterized by "technology push. " In the next 10 to 15 years, however, the market opportunities for structural ceramics are expected to expand rapidly (table l), such that by the year 2000 U.S. markets are projected variously between $1 billion and $5 billion.[3] This estimate reflects only the value of the ceramic materials and components, and does not include the value of the overall systems in which they are incorporated. When this multiplier effect is taken into account, a recent study has indicated that the country which leads in the development of advanced ceramics will reap large benefits in the form of jobs and economic expansion.[4]

2G.B. Kenney and H .K, Bowen, "High Tech Ceramics in Japan: Current and Future Markets, " *American* Ceramic Society *Bulletin* 62(5):590, 1983.

Table 1.—Some Future Applications of Structural Ceramics

Application	Performance advantages	Examples
Wear parts seals bearings valves nozzles	High hardness. lowfriction	Silicon carbide, alumina
Cutting tools	High strength, hot hardness	Silicon nitride
Heat engines diesel components gas turbines	Thermal insulation, high temperature strength, fuel economy	Zirconia, silicon carbide, silicon nitride
Medical Implants hips teeth joints	Biocompatibility, surface bond totissue, corrosion resistance	Hydroxylapatite, bioglass, alumina, zirconia
Constructlon highways bridges buildings	Improved durability, lower overall cost	Advanced cements and concretes

SOURCE Off Ice of Technology Assessment

Properties of Ceramics

The properties of some common structural ceramics are compared with those of metals in table 2. In general, ceramics have superior high-temperature strength, higher hardness, lower density, and lower thermal conductivity than metals. The principal disadvantage of ceramics as structural materials is the sensitivity of their strength to extremely small flaws, such as cracks, voids, and inclusions. Flaws as small as 10 to 50 micrometers can reduce the strength of a ceramic structure to a few percent of its theoretical strength. Because of their small sizes, the strength-controlling flaws are usually very difficult to detect and eliminate.

The flaw sensitivity of ceramics illustrates the importance of carefully controlled processing and finishing operations for ceramic components. However, even with the most painstaking efforts, a statistical distribution of flaws of various sizes and locations will always exist in any ceramic structure. Even "identically prepared" ceramic specimens will display a distribution of strengths, rather than a single value. Design with ceramics is therefore a statistical process, rather than a deterministic process, as in the case of metals. The situation is illustrated in figure 2.

The curve on the right of figure 2a represents the distribution of strengths in a batch of identically prepared ceramic components. The curve on the left is the distribution of stresses to which these

3Greg Fischer, "Strategies Emerge for Advanced Ceramic Business, " *American Ceramic Society Bulletin* 65(1):39, 1986.

4Larry R. Johnson, Arvind P.S. Teotia, and Lawrence G. Hill, "A Structural Ceramic Research Program: A Preliminary Economic Analysis, " Argonne National Laboratory, ANL/CNSV-38, 1983.

Table 2.—Comparison of Physical and Mechanical Properties of Common Structural Ceramics With Steel and Aluminum Alloys. SiC: silicon carbide; Si_3N_4: silicon nitride; ZrO_2: zirconia

Material	Density[a] (g/cm³)	Room temperature strength (M Pa)	Strength[a] at 1,095" C (M Pa)	Hard ness[b] (kg/mm²)	Thermal conductivity 250/1 ,100° (W/mC)
Various sintered SiC materials	3.2	340-550 (flexure)	340-550 (flexure)	2,500-2,790	85/1 75
Various sintered Si_3N_4 materials	2.7-3.2	205-690 (flexure)	205-690 (flexure)	1,366	17/60
Transformation toughened ZrO,	5.8	345-620 (flexure)	—	625-1,125	1.713.5
Steels (4100, 4300, 8600, and 5600 series)	7-8	1,035-1,380 (tensile yield)	useless	450-650	43
Aluminum alloy	2.5	415-895 (tensile yield)	useless	***100-500***	140-225

NOTE. 1 MPa = 145 psi = O 102 Kg/mm [Y],

SOURCES: [a]R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design, " *Materials* Science *and Engineering 71 '227-249, 1985.*
[b]Elaine P Rothman, "Ultlmate Properties of Ceramics and Ceramic Matrix Composites, " contractor report for OTA, December 1985

components are subjected in service, The overlap between the two curves, in which the stress in service exceeds the strength of the ceramic, determines the probability that the part will fail.

There are several ways to reduce the probability of failure of the ceramic. One is to shift the strength distribution curve to the right by elimination of the larger flaws (figure 2b). A second approach is to use nondestructive testing or proof testing to weed out those components that have major flaws. This leads to a truncation of the strength distribution, as shown in figure 2c. Although proof testing of each individual component is expensive and can introduce flaws in the material which were not there originally, it is widely used in the industry today.

A third approach is to design the microstructure of the ceramic to have some resistance to fracture (increased "toughness"), and hence, some tolerance to defects. Toughness is a measure of the energy required to fracture a material in the presence of flaws. For a ceramic component under stress, the toughness determines the critical flaw size which will lead to catastrophic failure at that stress. In fact, the critical flaw size increases with the square of the toughness parameter; thus, an increase in the material toughness of a factor of 3 leads to a ninefold increase in the flaw size tolerance. Reduction in the flaw sensitivity of ceramics is especially important for applications involving a hostile environment which can introduce strength-degrading defects, and thus negate all efforts to ensure reliability by identifying or eliminating the largest preexisting flaws. Three recent developments have been shown to improve the toughness of ceramics: microstructure design, transformation toughening, and composite reinforcement.

Microstructure Design

The toughness of monolithic ceramics can be improved considerably by refinement of the polycrystalline grain size and shape. The presence of elongated fibrous grains, especially in ceramics based on silicon nitride, has been shown to increase toughness by as much as a factor of 2 over other monolithic ceramics, such as silicon carbide and aluminum oxide.[5] Numerous mechanisms have been proposed to account for the observed toughening: crack deflection, microcracking, residual stresses, crack pinning, and crack bridging. It is likely that several of these mechanisms operate simultaneously in these materials. The high toughness is accompanied by high strength, both of which result from the modified microstructure. Commercial activity in the silicon nitride-based materials is projected to expand rapidly by 1990 and many new applications should be established by 1995.

Transformation Toughening

Transformation toughening is a relatively new approach to achieving high toughness and strength in ceramics and has great potential for increasing the use of ceramics in applications requiring wear resistance. The key ceramic material is zirconium oxide (zirconia). Zirconia goes through a phase transformation from the

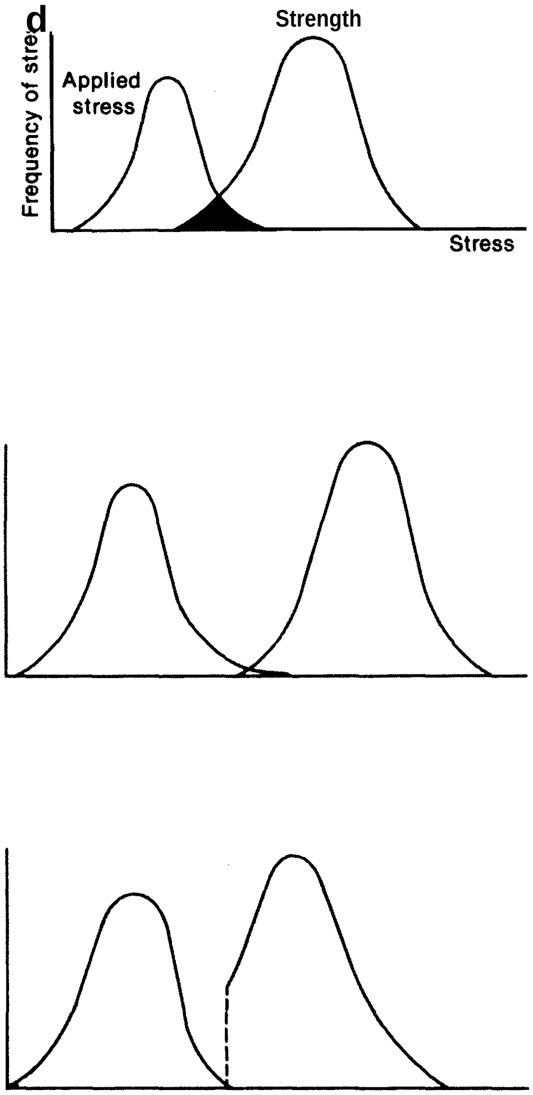
'*Nitrogen Ceramics,* F.L. Riley (ed,) (Boston and The Hague: Martinus Nijhoff Publishers, 1983).

Figure 2.— Probability of Failure of a Ceramic Component

a)

b)

c)



The probability of failure of a ceramic component is the overlap between the applied stress distribution and the material strength distribution, as shown in (a). This probability can be reduced by reducing the flaw size (b), or truncation of the strength distribution through proof testing (c).

SOURCE R Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," Materials Science *and Engineerfrig 71:227.249, 1985*

tetragonal to the monoclinic crystal form while cooling through a temperature of about 1,1500 C (2,102°F). This phase transformation is accompanied by an increase in volume of 3 percent, similar to the volume increase that occurs when water freezes. By control of composition, particle size, and heat treatment cycle, zirconia can be densified at high temperature and cooled such that the tetragonal phase is maintained down to room temperature. When a load is applied to the zirconia and a crack starts to propagate, the high stresses in the vicinity of the crack tip catalyze the transformation of adjacent tetragonal zirconia grains to the monoclinic form, causing them to expand by 3 percent. This expansion of the grains around the crack tip compresses the crack opening, preventing the crack from propagating. The result is a ceramic that is both tough and strong.

Ceramic Matrix Composites

A variety of ceramic particulate, whiskers (high-strength single crystals with length-to-diameter ratios of 10 or more), and fibers maybe added to the host matrix material to generate a composite with improved fracture toughness. The presence of these additives appears to frustrate the propagation of cracks by at least three mechanisms. First, when the crack tip encounters a particle or fiber which it cannot easily break or get around, it is deflected off in another direction. Thus, the crack is prevented from propagating cleanly through the structure. Second, if the bond between the reinforcement and the matrix is not too strong, crack propagation energy can be absorbed by "pullout" of the fiber from its original location. Finally, fibers can bridge a crack, holding the two faces together, and thus preventing further propagation.

Table 3 presents the fracture toughness and critical flaw sizes (assuming a typical stress of ***700*** MPa, or about 100,000 psi) of a variety of ceramics and compares them with some common metals. The toughness of monolithic ceramics generally falls in the range ***3*** to 6 MPa-m’ ^{1}, corresponding to a critical flaw size of 18 to 74 micrometers. With transformation toughening or whisker dispersion, the toughness can be increased to 8 to 12 MPa-m’ ^{2}(critical flaw size 131 to 294 micrometers); the toughest ceramic matrix composites are continuous fiber-reinforced glasses, at 15 to 25 MPa-m’ ^{1}. It is important to note that in the latter composites the strength appears to be independent of preexisting flaw size, and is thus an intrinsic material property. Metals such as steel have toughnesses above 40 MPa-m^{1}(some al-

Table 3.—Fracture Toughness and Critical Flaw Sizes of Monolithic and Composite Ceramic Materials Compared With Metals.[a]
A12O3: alumina; LAS: lithium aluminosilicate; CVD: chemical vapor deposition

Material	Fracture toughness (MPa. m’/^{2})	Critical flaw size (micrometers)
Conventional microstructure:		
Al_2O_3	3.5-4.0	25-33
Sintered SiC.	3.0-3.5	18-25
Fibrous or interlocked microstructure:		
Hot pressed Si_3N_4.	4.0-6.0	33-74
Sintered Si_3N_4.	4.0-6.0	33-74
SiA10N	4.0-6.0	33-74
Particulate dispersions:		
Al_2O_5-TiC	4.2-4.5	36-41
SiC-Ti B_2.		
Si_3N_4-TiC.	4.5	41
Transformation toughening:		
ZrO_2-MgO	9-12	165-294
ZrO_2-Y_2O_3.	6-9	74-165
A1203-zro2	6.5-15	86-459
Whisker dispersions:		
Al_2O_3,-SiC	8-10	131-204
Fiber reinforcement:[b]		
SiC in borosilicate glass .	15-25	
SiC in LAS	15-25	
SiC in CVD SiC	8-15	
Aluminum[c].	33-44	
Steel[c].	44-66	

aAssumes a stress of 700 MPa (- 100,000 psi).
bThe strength of these composites is independent of preexisting flaw size.
cThe toughness of some alloys can be much higher.

SOURCES David W. Richerson, “Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites, ” contractor report for OTA, December 1985, and Elaine P. Rothman, “Ultimate Properties of Ceramics and Ceramic Matrix Composites,” contractor report for OTA, December 1985

loys may be much higher), more than 10 times the values of monolithic ceramics.

The critical flaw size gives an indication of the minimum flaw size which must be reliably detected by any nondestructive test in order to ensure reliability of the component. Most NDE methods cannot reliably detect flaws smaller than about 100 micrometers, corresponding to a toughness of about 7 MPa-m$^{1/2}$. Toughnesses of 10 to 12 MPa-m$^{1/2}$ would be desirable for most components.

Ceramic Coatings

The operation of machinery in hostile environments (e. g., high temperatures, high mechanical loads, or corrosive chemicals) often results in performance degradation due to excessive wear and friction, and productivity losses due to shutdowns caused by component failure. Frequently, the component deterioration can be traced to deleterious processes occurring in the surface region of the material. To reduce or eliminate such effects, ceramic coatings have been developed to protect or lubricate a variety of substrate materials, including metals, ceramics, and cermets (ceramic-metal composites).

The coating approach offers several advantages. One is the ability to optimize independently the properties of the surface region and those of the base material for a given application. A second advantage is the ability to maintain close dimensional tolerances of the coated workpiece, since very thin coatings (of the order of a few micrometers) are often sufficient for a given application. Further, cost savings are obtained by using expensive, exotic materials only for thin coatings and not for bulk components. This can contribute to the conservation of strategically critical materials. Finally, it is often cheaper to recoat a worn part than to replace it.

In view of these advantages, it is not surprising that ceramic coatings have found wide industry acceptance. For example, coatings of titanium nitride, titanium carbide, and alumina can enhance the useful life of tungsten carbide or high speed steel cutting tools by a factor of 2 to 5.[6] In 1983, annual sales of coated cutting tools reached about $1 billion.[7] Ceramic coatings are also finding wide applications in heat engines. Low thermal conductivity zirconia coatings are now being tested as a thermal barrier to protect the metal pistons and cylinders of advanced diesel engines. In turbine engines, insulative zirconia coatings improve performance by permitting combustion gas temperatures to be increased by several hundred degrees (F) without increasing air-cooled component metal temperatures or engine complexity.[8] Ceramic coatings have also been used to provide an oxidation barrier on turbine blades and rings.

[6]David W. Richerson, “Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites, ” contractor report prepared for the Office of Technology Assessment, December 1985.

[7]U. S. Department of Commerce, Bureau of the Census, Census of Manufacturing, Fuels, and Electric Energy Consumed, 1984.

[8]Tom Strangman, Garrett Corp., personal communication, August 1986.

Progress in the use of ceramic coatings in these and other applications suggest that further research on new coatings and deposition processes is likely to yield a high payoff in the future.

Design, Processing, and Testing of Ceramics

It is in the nature of advanced structural materials that their manufacturing processes are additive rather than subtractive. They are not produced in billets or sheets which are later rolled, cut, or machined to their final shape. Rather, the goal is always to form the material to its final shape in the same step in which the microstructure of the material itself is formed. Because of the severity of joining problems, the designer is always conscious of the need to consolidate as many components as possible together in a single structure. To be sure, these goals are not always realized, and expensive grinding or drilling is often required. However, to a great extent, the promise of the advanced materials lies in the possibility of net shape processing, thereby eliminating expensive finishing and fastening operations.

Ceramics Design

Designing with ceramics and other brittle materials is much different from designing with metals, which are much more tolerant of flaws. In practice, ceramic structures always contain a distribution of flaws, both on the surface and in the bulk. Ceramic designs must avoid local stress concentrations under loading which may propagate cracks originating at the flaws.

Two serious barriers to the use of ceramics are the lack of knowledge among designers of the principles of brittle material design, and the poor characterization of ceramic materials of interest. Greater emphasis needs to be placed on brittle materials in college curricula. Courses at the college level and minicourses for continuing education on design for brittle materials should be offered and publicized.[9]

The characterization of commercially available ceramics for design purposes is generally poor. The poor quality of the data is due to the fact that mechanical, thermal, and chemical properties of ceramic materials vary with the method of manufacture as well as test method. Both carefully controlled and documented processing procedures and standard test methods will be required to give designers the confidence that consistent properties at a useful level can be obtained at a predictable cost.

Computer-aided design (CAD) techniques have become essential to the design process, particularly in the analysis of mechanical stresses, thermal stresses, and life prediction of the part in service. Sophisticated software to calculate mechanical and thermal stresses is available; however, these programs require detailed data on properties such as thermal expansion coefficient, heat capacity, and elastic modulus, which often are not available. Current techniques for predicting the service life of ceramics are limited by lack of data on the behavior of these materials in various environments of interest. These techniques are especially unreliable in high temperature, high stress regimes where several failure mechanisms are operating simultaneously.[10]

It is not particularly unusual that there should be a lack of reliable design data in a field like structural ceramics, which is very new and which is constantly producing new materials. It can even be argued that the imposition of codes and specifications would be premature, given that there is no consensus on the best materials or processes. Although there is a danger in narrowing the field too soon, there is also a danger in keeping it general for too long. It may be appropriate to choose one or two materials which seem most promising and concentrate on producing uniform, high-quality components from these. Silicon carbide and silicon nitride would be two possible candidates, because they have already received a large amount of research funding over the years for heat engine applications. These materials have a broad range of potential uses, but designers cannot compare them or use them without a reliable data-

[9] Specific proposals to improve ceramics education are given in the Report of the Research Briefing Panel on Ceramics and Ceramic Composites (Washington, DC: National Academy Press, 1985).

[10] R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," *Materials Science & Engineering 71*;227-249, 1985.

base on standard compositions having specified properties.

Processing of Ceramics

The production of most ceramics, including traditional and advanced ceramics, consists of the following four basic process steps: powder preparation, forming, densification, and finishing. The most important variations on these steps are given in table 4.

Powder Preparation.—Although the basic ceramic raw materials occur abundantly in nature, they must be extensively refined or processed before they can be used to fabricate structures. The entire group of silicon-based ceramics (other than silica) does not occur naturally. Silicon carbide, silicon nitride, and sialon (an "alloy" of silicon nitride with aluminum oxide in which aluminum and oxygen atoms substitute into silicon and nitrogen lattice positions, respectively) compositions must all be fabricated from gases or other ingredients. Even minerals which occur naturally, such as bauxite, from which alumina is made, and zircon sands, from which zirconia is derived, must be processed before use to control purity, particle size and distribution, and homogeneity.

In recent years, the crucial importance of powder preparation has been recognized. Particle sizes and size distributions are critical in advanced ceramics to produce uniform green (unfired) densities, so that rearrangement can occur to produce a fully dense, sintered, ceramic part.

Table 4.—Common Processing Operations for Advanced Ceramics

Operation	Method	Examples
Powder preparation	Synthesis	SiC
	Sizing	Si_3N_4
	Granulating	ZrO_2
	Blending	
	Solution chemistry	Glasses
Forming	Slip casting	Combustors, stators
	Dry pressing	Cutting tools
	Extrusion	Tubing, honeycomb
	Injection molding	Turbocharger rotors
	Tape casting	Capacitors
	Melting/casting	Glass ceramics
Densification	Sintering	Al_2O_3
	Reaction bonding	Si_3N_4
	Hot pressing	Si_3N_4, SiC, BN
	Hot isostatic pressing	Si_3N_4, SiC
Finishing	Mechanical	Diamond grinding
	Chemical	Etching
	Radiation	Laser, electron beam
	Electric	Electric discharge

SOURCE Off Ice of Technology Assessment

Various dopants or sintering aids are added to ceramic powders during processing. Sinterability can be enhanced with dopants, which can control particle rearrangement and diffusivities. These dopants allow sintering at lower temperatures and/or faster rates. Dopants are also used to control grain growth or achieve higher final densities. The use of dopants, while providing many beneficial results, can also influence the material's properties. Segregation of dopants at the crystalline grain boundaries can weaken the final part, and final properties such as conductivity, strength, etc., may differ significantly from those of the "pure" material.

Forming.—Ceramic raw materials must be formed and shaped before firing. The forming process often determines the final ceramic properties. The processing variables in the forming step affect particle shape, particle packing and distribution, phase distribution, location of pores, shrinkage, and dry and fired strength.

Forming processes for ceramics are generally classified as either cold or hot forming. The major cold forming methods include slip casting, extrusion, dry pressing, injection molding, tape casting, and variations. The product of cold forming techniques is called a "green body, " which may be machined before firing. The homogeneity of the cold formed part determines the uniformity of shrinkage during firing.

Hot forming methods combine into one step the forming and sintering operation to produce simple geometric shapes. These techniques include hot pressing and hot isostatic pressing.

Densification.— Sistering is the primary method for converting loosely bonded powder into a dense ceramic body. Sintering involves consolidation of the powder compact by diffusion on an atomic scale. Moisture and organics are first burned out from the green body and then, at the temperature range where the diffusion process occurs, matter is moved from the particles into the void spaces between the particles, causing densification and resulting in shrinkage of the part.

Combined with forming techniques such as slip casting, sintering is an economic method for producing intricate ceramic components. Its drawback lies in the need to use additives and long sintering times to achieve high densities. The complications introduced by the additives have been noted above in the discussion of powders.

Finishing.—These techniques include grinding and machining with diamond and boron nitride tools, chemical etching, and laser and electric discharge machining. The high hardness and chemical inertness of densified ceramics make the finishing operations some of the most difficult and expensive in the entire process. Grinding alone can account for a large fraction of the cost of the component, In addition, surface cracks are often introduced during machining, which reduce the strength of the part and the yields of the fabrication process.

Near Net Shape Processing (NNSP).—This describes any forming process which gives a final product that requires little or no machining. Typically, ceramics shrink to about two-thirds of their green volume upon sintering. This shrinkage makes it extremely difficult to fabricate ceramics to final net shape. However, if the green ceramic is machined prior to densification, a near net shape part can be obtained. Hot isostatic pressing and ceramic coatings also yield parts which do not require subsequent machining.

Near net shape processes which are currently used for metals include powder metallurgy and advanced casting techniques. Since metals are in direct competition with ceramics in many applications, near net shape processing of ceramics will continue to be a high priority research area which will be critical to their cost competitiveness,

Ceramic Matrix Composites

Ceramic matrix composites may consist of continuous fibers oriented within a ceramic matrix, ceramic whiskers randomly oriented within a ceramic matrix, or dissimilar particles dispersed in a matrix with a controlled microstructure. The potential benefits of ceramic composites include increased fracture toughness, hardness, and improved thermal shock resistance. Processing methods for particulate-reinforced composites are similar to those for monolithic ceramics.

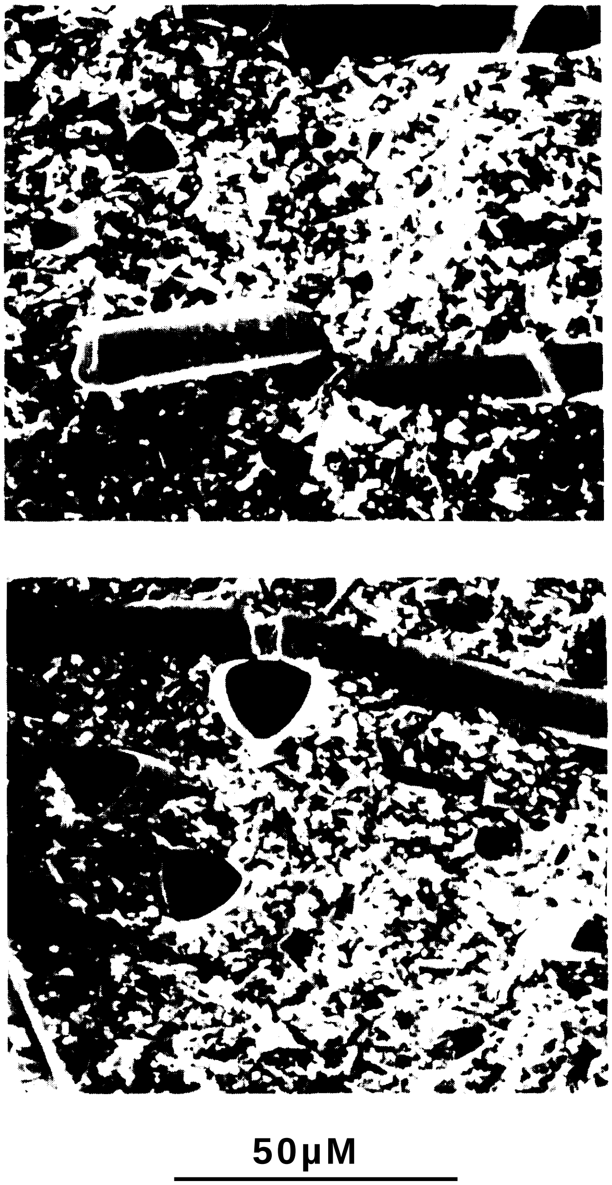


Photo credit: Los Alarnos Nafional Laboratory

Fracture surface of a composite formed by hot-pressing silicon nitride powder with 30 percent by volume silicon carbide whiskers.

Whisker Reinforcement.—Ceramic whiskers are typically high-strength single crystals with a length at least 10 times the diameter. Silicon carbide is the most common whisker material. Current dispersed whisker composites are fabricated by uniaxial hot pressing, which substantially limits size and shape capabilities and requires expensive diamond grinding to produce the final part. Hot isostatic pressing (HIP) has the potential to permit fabrication of complex shapes at moderate cost, but procurement of expensive capital equipment and extensive process development are required.

Continuous Fiber Reinforcement.—The primary fibers which are available for incorporation into a ceramic or glass matrix are carbon, silicon carbide, aluminum borosilicate, and mullite. Currently, glass matrix composites are more developed than their ceramic analogs. These composites are far tougher than unreinforced glasses (t a b l e 00 to **1,3000** F **(593°** to **704°C).** Service temperatures up to 2,0000 to 2,2000 F (1,093 o to 1,2040 C) may be obtained with "glass-ceramic" matrices which crystallize upon cooling from the process temperature.[11] Carbon matrix composites have the highest potential use temperature of any ceramic, exceeding 3,5000 F (1,927° C). However, these composites oxidize readily in air at temperatures above about 1,100° F (s930 C), and require protective ceramic coatings if they are to be used continuously at high temperature.[12]

[11]Karl M. Prewo, J .J. Brennan, and G.K. Layden, "Fiber-Reinforced Glasses and Glass-Ceramics for High Performance Applications," *American Ceramic Society Bulletin* 65(2):305, *1986.*

[12]Joel Clark, et al., "Potential of Composite Materials To Replace Chromium, Cobalt, and Manganese in Critical Applications, " contractor report prepared for the Office of Technology Assessment, 1984.

Photo credit' United Technologies Research Center

Tensile fracture surface for Nicalon SiC fiber-reinforced glass-ceramic

Fabrication of continuous fiber ceramic composites is currently of a prototype nature and very expensive. Several approaches are under development:

- The fibers are coated with ceramic or glass powder, laid up in the desired orientation, and hot pressed,
- Fibers or woven cloth are laid up, then are infiltrated by chemical vapor deposition (CVD) to bond the fibers together and fill in a portion of the pores,
- Fibers are woven into a three-dimensional preform, then infiltrated by CVD.
- A fiber preform is infiltrated with a ceramic-yielding organic precursor, then heat treated to yield a ceramic layer on the fibers. This process is repeated until the pores are minimized.

Considerable research and development will be necessary to optimize fabrication and to decrease the cost to levels acceptable for most commercial applications.

Ceramic Coatings

Many different processes are in use for the fabrication of ceramic coatings and for the modification of surfaces of ceramic coatings and of monolithic ceramics. Table 5 lists some of the more important techniques. The choice of a particular deposition process or surface modification process depends on the desired surface properties. Table 6 lists some of the coating characteristics and properties which are often considered desirable. Additional considerations which can influence the choice of coating process include: the purity, physical state, and toxicity of the material to be deposited; the deposition rate; the maximum temperature which the substrate can reach; the substrate treatment needed to obtain good coating adhesion; and the overall cost.

For most coating processes, the relationships between process parameters and coating properties and performance in various environments are poorly understood. Coating providers tend to rely on experience gained empirically. Work is in progress to establish these relationships for certain processes, e.g. ion beam- or plasma assisted-physical vapor deposition. However, in view of

Table S.—Selected Processes for the Production of Ceramic Coatings and for the Modification of Ceramic Surfaces

Process category	Process class	Process
Ceramic coating processes:		
Low gas pressure ('(vacuum") processes	Chemical vapor deposition (CVD)	Pyrolysis Reduction (plasma assisted) Decomposition (plasma assisted) Polymerization (plasma induced)
	Physical vapor deposition (PVD)	Evaporation (reactive, plasma assisted) Sputtering (reactive, plasma assisted) Plasma-arc (random, steered) Ion beam assisted co-deposition
	Low pressure plasma spraying	Plasma discharge spraying
Processes at elevated gas pressures	Plasma spraying Flame spraying	Plasma arc spraying Combustion flame spraying
Liquid phase epitaxy processes	Wetting process	Dip coating (e.g., Sol-Gel) Brush coating
	Spin-on coatings	Reverse-roller coating
Electrochemical processes	Electrolytic deposition	Cation deposition
	Electrophoretic deposition	Charged colloidal particle deposition
	Anodization	Anion oxidation in electrolytes
	Electrostatic deposition	Charged liquid droplet deposition
Processes for the modification of ceramic surfaces:		
Particle implantation processes	Direct particle implantation	Energetic ion or atom implantation in solids
	Recoil particle implantation	Recoil atom (ion) implantation in solids
Densification and glazing processes	Laser beam densification and glazing	CW-laser power deposition Pulsed-laser power deposition
	Electron beam densification and glazing	Energetic electron beam power deposition
Chemical reaction processes	Gaseous anodization processes	Ion nitriding Ion carburizing Plasma oxidation
	Disproportionation processes	Deposition of molecular species Formed in gas phase
Conversion processes	Thermal diffusion	Diffusion of material from surface into bulk of substrate
Etching processes	Chemical etching	Acidic solutions; lye etching
	Ion etching	Sputter process
Mechanical processes	Grinding Peening Polishing	

SOURCE: Manfred Kaminsky Surface Treatment Science International, Hinsdale. IL

the current widespread use of coated machinery components, and projected future requirements for components with advanced coatings, research in processing science for ceramic coatings remains an important priority. In addition, improved deposition processes are required, particularly for the coating of large components or those having a complex shape.

Chemically Bonded Ceramics

Hardened cement pastes and concretes fall in the category of chemically bonded ceramics (CBCs), because they are consolidated through chemical reactions at ambient temperatures rather than through densification at high temperature. Due to their low strength compared with dense

Table 6.—Characteristics and Properties of Ceramic Coatings Often Considered Desirable

Good adhesion
Precise stoichiometry (negligible contamination)
Very dense (or very porous) structural morphology
Thickness uniformity
High dimensional stability
High strength
High fracture toughness
Internal stresses at acceptable levels
Controlled density of structural defects
Low specific density
High thermal shock resistance
High thermal insulating properties
High thermal stability
Low (or high) coefficient of friction
High resistance to wear and creep
High resistance to oxidation and corrosion
Adeauate surface topography

SOURCE Manfred Kaminsky, Surface Treatment Science International, Hinsdale, IL.

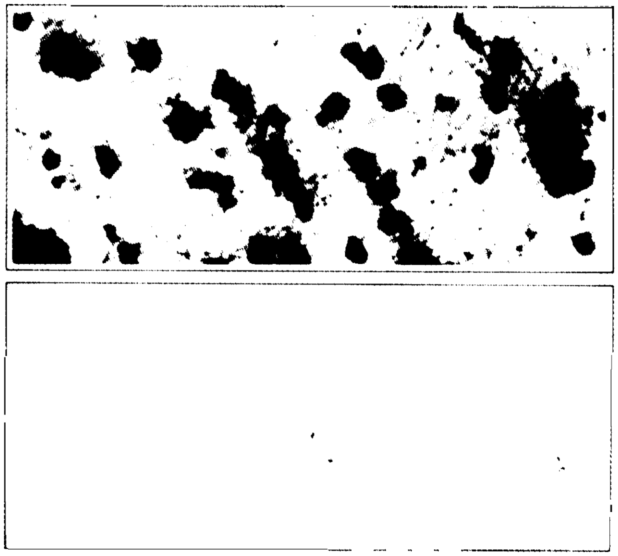


Photo credits" *Imperial Chemical Industries PLC*

Top photo: Conventional Portland cement paste microstructure, showing large flaws (pores). Bottom photo: Advanced cement paste microstructure, illustrating the absence of large pores (magnification x1OO).

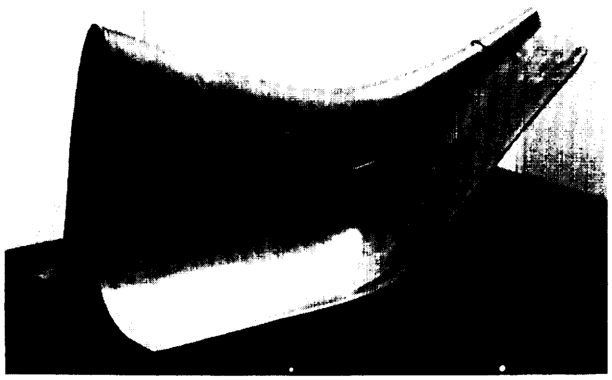


Photo credit" CEMCOM Research Associates, Inc

This tool, made from a cement-based composite, is used for autoclave forming of a fiber-epoxy jet engine component.

ceramics, concrete and other cementitious materials are not normally considered "advanced. " However, in recent years, new processing methods have led to significant improvements in the strength of chemically bonded ceramics, and further development will provide additional improvements. In fact, the ultimate limits on tensile and compressive strength have not yet been approached.

Cements.—Cements are chemically active binders which may be mixed with inert fillers such as sand or gravel to form concrete. Cement pastes containing minor additives such as organic polymers can also be used as structural materials. By far the most common cement used in making CBCs is portland cement. Portland and related cements are hydraulic; i.e., they react with water to form an relatively insoluble aggregate. In hydraulic cements, excess water is usually added to improve the working characteristics, but this causes the hardened structures to be porous (the minimum porosity of fully hydrated cements is about ***28*** percent)[13] and of low strength. In a recent advance, a high-shear processing technique together with pressing or rolling are used to remove pores from a low-water calcium aluminate cement paste containing 5 to 7 percent by weight organic polymers to improve workability. The dense paste, which is sometimes called macro-defect-free or MDF cement, has the consistency of cold modeling clay, and can be molded or extruded by techniques similar to those used for plastics. The hardened cement paste has a strength approaching that of aluminum (table 7) and much lower permeability than ordinary portland cement paste.[14] Although MDF cement pastes cost 20 to

Richard A. Helmuth, Portland Cement Association, personal communication, August 1986.

[14]According to product literature supplied by Imperial Chemical Industries, "New Inorganic Materials. "

Table 7.—Comparison of the Mechanical Properties of Various Cements and Aluminum

Material	Density (g/cm^3)	Flexural strength (psi)[a]	Compressive strength (psi)	Fracture energy (J/m^2)
Portland cement paste	1.6-2.0b	725-1,450	4,000-5,000[b]	20
Cement/asbestos	2.3	5,075		300
Advanced cements[c]	2.3-2.5	14,500-21,750	22,000-36,000	300-1,000
Aluminum	2.7	21,750-58,000	42,000	10,000

[a]1 MPa = 145 psi.
[b]According to information supplied by the Portland Cement Association
[c]The advanced cement has the following composition. 100 parts high alumina cement; 7 parts hydrolyzed Poly (vinylacetate), 10-12 parts water
SOURCE Imperial Chemical Industries.

30 cents per pound compared with portland cement paste at 3 cents per pound, they are still significantly cheaper than metals and plastics.

Processing of hydraulic CBCs is very cheap, since it involves only adding water, mixing, casting or molding, and allowing the material to set at room temperature or slightly elevated temperature. Very little dimensional change occurs during the set and cure, so that parts can be made to net shape. Due to the low processing temperature, a wide variety of reinforcing fibers can be considered, including metal fibers. Further work is needed to improve the long term stability of these materials, and the presence of organics makes them unsuitable for use above about **2000** F ***(93° C).***

Concrete.—As chemical additives, such as organic polymers, have improved the properties of cement pastes, chemical and mineral additives have had a similar effect on concrete. Minerals such as fly ash and microscopic silica particles help to fill in the pores in the concrete and actually improve the bonding in the cementitious portion. This results in greater strength and reduced permeability. In a recently developed concrete, molten sulfur is used as a binder in place of cement. Sulfur concrete has superior corrosion resistance in acidic environments and can be recycled by remelting and recasting without loss of the mechanical properties.

The compressive strength of typical concretes today is around *5,000* psi (34 MPa), although concretes with strengths of 10,000 to 15,000 psi (69 to 103 MPa) are becoming common. Under laboratory conditions, compressive strengths of at least 45,000 psi (310 MPa) have been achieved, and there is no indication that the ultimate strength is being approached. [16] In concrete highrise buildings, the higher compressive strengths permit use of smaller columns, with consequent savings in space and materials.

Two deficiencies in concrete as a structural material are its low tensile strength and low toughness. A typical concrete has a tensile strength below 1,000 psi *(7* MPa). Steel reinforcement bars are added to the concrete to provide tensile strength. In prestressed concrete, high strength steel wires under tension are used to keep the concrete in a state of compression. To improve strength and toughness, a variety of reinforcing fibers, including steel, glass, and polymers, have been tried, with varying degrees of success. Fiber reinforcement can increase the flexural strength by a factor of 2.5 and the toughness by a factor of 5 to 10 above unreinforced materials. [18] This technology, which dates back to the straw-reinforced brick of the ancient Egyptians, requires fiber concentrations which are sufficiently low (usually 2 to 5 percent by volume) to preserve the flow characteristics of the concrete, and a chemically stable interface between the fiber and the concrete over time. Asbestos fibers served this function for many years; however, because of the health hazards, new fibers are being sought. A fully satisfactory reinforcing fiber for concrete has yet to be discovered.

Nondestructive Evaluation (NDE) of Ceramics

Nondestructive evaluation refers to techniques for determining properties of interest of a struc-

“W. C. McBee, T.A. Sullivan, and H.L. Fike, “Sulfur Construction Materials, ” Bulletin 678, U.S. Department of the Interior, Bureau of Mines, 1985.

[16]Sidney Mindess, “Relationships Between Strength and Microstructure for Cement-Based Materials: An Overview’, ” *Materials Research Society Symposium Proceedings*, 42:53, *1985.*

[17]Ibid.

[18]American Concrete Institute, “State-o-the-Art Report on Fiber-Reinforced Concrete, ” Report No. ACI 544.11 <-82, 1982.

ture without altering it in any way. NDE has historically been utilized for flaw detection in ceramic materials to improve the reliability of the final product. In the future, NDE will be utilized for defect screening, material characterization, in-process control, and lifecycle monitoring. These techniques will be applied to the starting materials, during the process, and to the final product.

A key goal for the future will be the evolution of NDE techniques amenable to automation and computerization for feedback control. Powder and green body characterization will be critical for materials processed from powders. For in-process characterization, the relation between measurable quantities, obtained through the use of contact or noncontact sensors, and desired properties is crucial. This will require developments in sensor technology as well as theories which can quantitatively relate the measured NDE signal to the properties of interest.

In the past, a great deal of emphasis has been placed on the sensitivity of an NDE technique, i.e., the size of the smallest detectable flaw. A more relevant criterion for reliability purposes is perhaps the size of the largest flaw that can go undetected. There has been very little emphasis on the reliability of NDE techniques, i.e. the probability of detecting flaws of various sizes. Experience has shown that most quality problems result not from minute flaws, but from relatively gross undetected flaws introduced during the fabrication process.[19]

[19] R Nathan Katz and Alfred L. Broz, "Nondestructive Evaluation Considerations for Ceramics and Ceramic Matrix Composites, " contractor report prepared for the Office of Technology Assessment, November 1985.

Cost of production estimates for high performance ceramic components typically cite the inspection costs as approximately *50* percent of the manufacturing cost .[20] Successful NDE techniques for ceramic components should meet two major criteria: they should reliably detect gross fabrication flaws to ensure that the material quality of the component is equal to that of test specimens, and they should be able to evaluate the quality of a complex-shaped component in a practical manner. No single NDE technique for ceramics completely satisfies these criteria. However, those which could be cost-effective for production level inspections are described in table 8.

Health Hazards

The most serious health hazard associated with ceramics appears to be associated with ceramic fibers. Studies carried out at the National Cancer Institute have indicated that virtually all durable, mineral fibers having a diameter of less than 1 micrometer are carcinogenic when introduced into the lining of the lung of laboratory rats.[21] The carcinogenicity drops with increasing diameter, such that fibers having diameters greater than 3 micrometers do not produce tumors. Recent studies on commercially available aluminosilicate fibers suggest that animals exposed to the fibers develop an increased number of lung cancers over time compared with a control group .22 No data on the effects of ceramic fibers on humans are available, and no industry standards for allowable fiber concentrations in the workplace have been estab-

[20] Ibid.
[21] Mearl F. Stanton, et al., *Journal of the National Cancer Institute* 67:965-975, *1981.*
[22] Philip J. Landrigan, M. D., The Mount Sinai Medical Center, personal communication, August 1986.

Table 8.—Comparison of Some Possible Production-Level NDE Techniques for Structural Ceramics

NDE technique	Detected flaw type	Sensitivity	Adaptability to complex shapes	Extent of development required for commercialization
Visual (remote)	surface	fair	good	none
Dye penetrant	surface	good	good	none
Radiographic	bulk	1-20/0 of specimen thickness	excellent	none
Ultrasonic	bulk and surface	good	poor	some
Holographic	surface	good	fair	large
Thermographic.	surface	poor	excellent	some
Proof test	any	good, but may introduce flaws	excellent	none

SOURCE: Office of Technology Assessment

lished. Until such data become available, the animal studies suggest that these fibers should be considered carcinogenic, and treated in a manner similar to asbestos fibers.

Applications of Structural Ceramics

Figure 3 shows an estimated timetable for the introduction of ceramic products in various categories. It shows that some advanced structural ceramics are in production, others have near-term potential for production, and some are far away from production.

Current Production

Ceramics such as alumina, silicon nitride, and silicon carbide are already well established in production for many structural applications in the categories of wear parts, cutting tools, bearings, and coatings. The ceramics portion of the market is currently small (generally less than 5 percent) .[23] Substantial growth in ceramics production is expected to occur over the next *25* years by growth of the overall markets, by achieving an increase in the market share, and by spin-off applications.

Ceramics are also in limited production (in Japan) in discrete engine components such as turbochargers, glow plugs, and precombustion chambers. Current military applications include radomes, armor, infrared windows, and heat sources.

Funding for known near-term markets is currently being provided by industry. Much of the funding is directed toward development of new or improved ceramic or ceramic matrix composite materials. Key objectives are to achieve improved toughness, higher reliability, and decreased cost. Development of silicon nitride, transformation toughened ceramics, and composites has yielded materials with enhanced toughness and reliability, but costs are still high and reliability remains a problem. Progress in resolving these limitations is occurring, and large increases in the market share for ceramics are projected.

The United States is competing with other countries, especially Japan, for the growing markets. Japan has a well-coordinated effort which includes: increasing the quality and availability of the raw materials; conducting material fabrication process optimization; installing the most advanced processing and quality control equipment for prototype and production facilities; and aggressively marketing their evolving materials.

Near-Term Production

Near-term production is projected in advanced construction products, bearings, bioceramics, heat exchangers, electrochemical devices, isolated components for internal combustion engines, and military applications. The technology feasibility has generally been demonstrated, but scale-up, cost reduction, or design optimization are required. Although much of the feasibility demonstration has occurred in the United States, foreign industry and government-industry teams, particularly in Japan, have more aggressive programs to commercialize the near term applications. Large markets are at stake; for example, the world market for all biocompatible materials has been projected to be as much as *$6* billion by the year 1995[24]; ceramics could capture *25* to *30* percent of this. 25 Foreign dominance of these markets would adversely affect the U.S. balance of trade. Government, industry, and universities need to team together in focused programs to solve the remaining problems and achieve production capability competitive with that of foreign countries.

Long-Term Applications

Some potential applications of ceramics require solution of major technical and economic problems. These high risk applications are categorized as long term (greater than 15 years away). The ultimate payoff may be large, but it is not possible to predict confidently that the problems will be overcome to achieve the benefits.

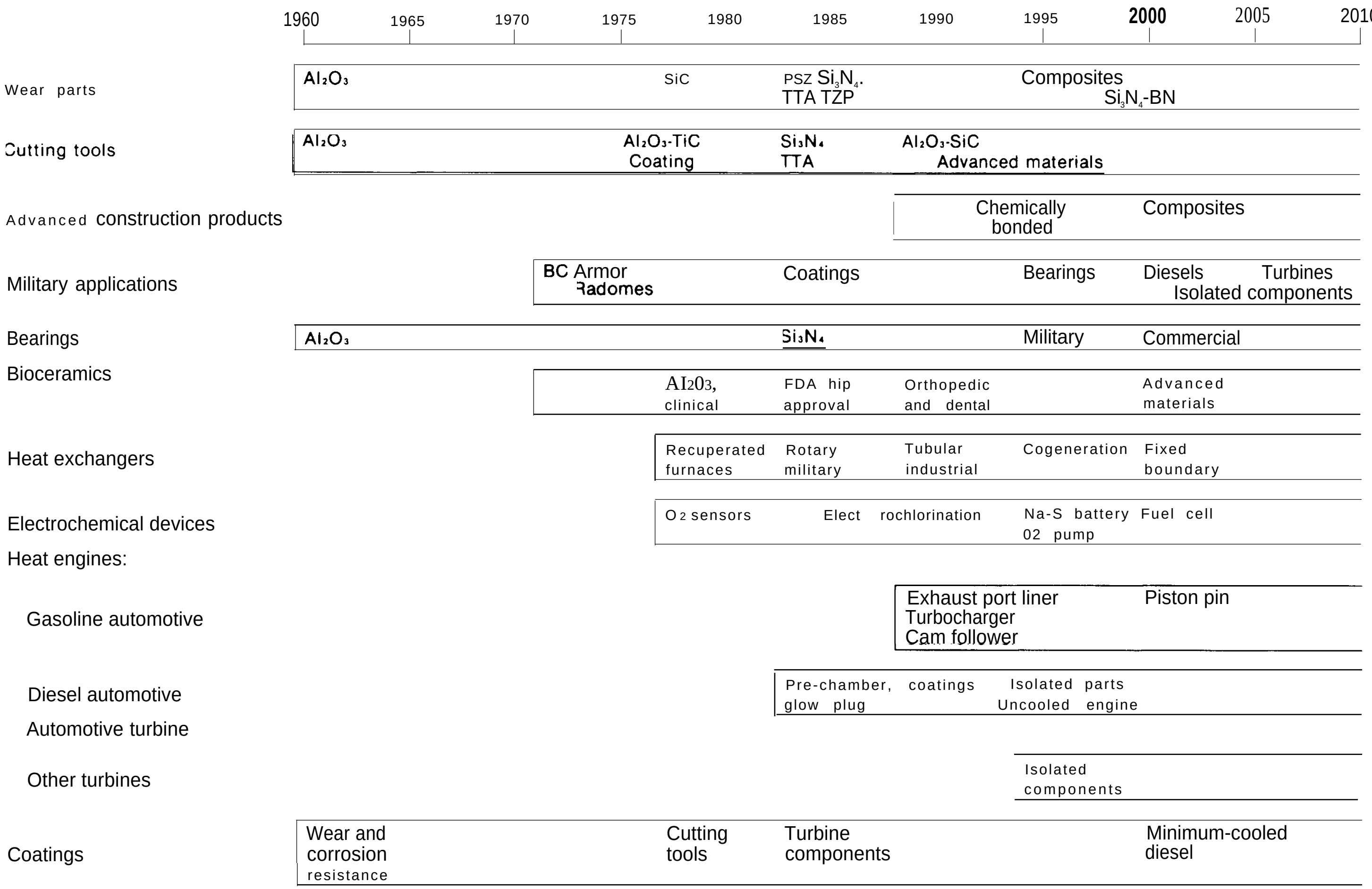
Long-term applications include the automotive gas turbine engine, the advanced diesel, some elec-

[23] U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry* (Washington, DC: U.S. Government Printing Office, March 1984), pp. 38-39.

[24] Larry L. Hench and June Wilson, "Biocompatibility of Silicates for Medical Use," *Silicon Biochemistry*, CIBA Foundation Symposium No. 121 (Chichester: John Wiley & Sons, 1986), pp. 231-246.

[25] Larry L. Hench, University of Florida, personal communication, August 1986.

Figure 3i.—Estimated Scenario for Implementation of Ceramic Components in Structural Application Categories



SOURCE: David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985.

trochemical devices such as fuel cells, some heat exchangers, and some bearings. A variety of other turbines, especially those for aircraft propulsion and utility scale power generation, should also be categorized as long term.

Substantial design, material property, and manufacturing advances are necessary to achieve production of applications in the long-term category. In general, risk is perceived by industry to be too high and too long range to justify funding the needed developments. Advancement will likely be driven by government funding. In many of these categories, military use will predate commercial use.

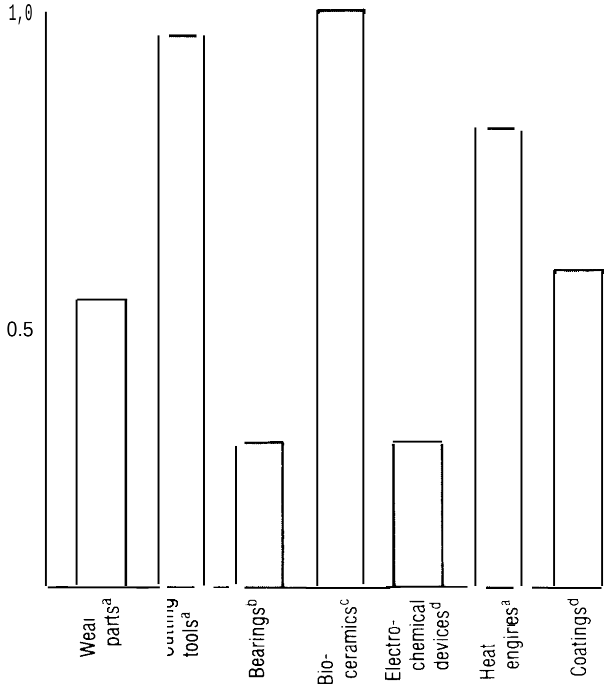
Markets for Advanced Structural Ceramics

Estimated U.S. markets in the year 2000 for several of the categories listed above are shown in figure **4.**

Wear Parts.—Wear parts include such applications as seals, valves, nozzles, wear pads, grinding wheels, and liners. The Department of Commerce has estimated that by the year ***2000*** ceramics could capture roughly ***6*** percent of the wear parts market, currently dominated by tungsten carbide cermets, and specialty steels. With the total market estimated at $9 billion, the ceramic portion would be ***$540*** million.[26]

Cutting Tools .—Ceramics have demonstrated a capability as a cutting tool, especially in competition with tungsten carbide-cobalt cermets (ceramic-metal composites) as inserts for metal turning and milling operations. The advantage of ceramics compared with carbides is retention of high hardness, strength, and chemical inertness to temperatures in excess of 1,000° C ***(1,8320*** F). This allows use of the ceramics at much higher machining speeds than can be tolerated by carbides. However, the ceramics have lower toughness than the carbide materials, and have only been used successfully in the limited operations of turning and milling. A further impediment to the use of ceramics, especially in the United States, has been equipment limitations. Much of the production metal machining equipment does not have the rigidity or speed capability to utilize ceramics.

Figure 4.— Projected U.S. Markets for Structural Ceramics in-the Year 2000 (billions of dollars)



SOURCES aU.S. Department of Commerce, "A Competitive Assessment of the U.S. Advanced Ceramics Industry" (Washington, DC, U S Government Printing Office, March 1984)
[b]High Technology, March 1986, P. 14.
[c]Larry L. Hench and June wilson, "Blocompatablility of Silicates for Medical Use, " CIBA Foundation Symposium 121, pp. 231-246 (Chichester, John Wiley & Sons, Publishers, 1986) Ceramics are as. sumed to capture 30°/0 of the estimated $3 billion U S blomaterials market
[d]David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Com. posites, " contractor report prepared for the Off Ice of Technology Assessment, December 1985

In spite of the current limitations of ceramics and equipment, an assessment by the Department of Commerce estimates steady growth of ceramics for cutting tool applications. It projects a growth of the total U.S. shipments from $2.2 billion in 1980 to $8 billion in the year ***2000,*** with the growth of the ceramics portion from $45 million *(2* percent) to ***$960*** million (12 percent) .2'

[26]U.S. Department of Commerce, Op. cit. , March 1984, p.35.

[27]Ibid.

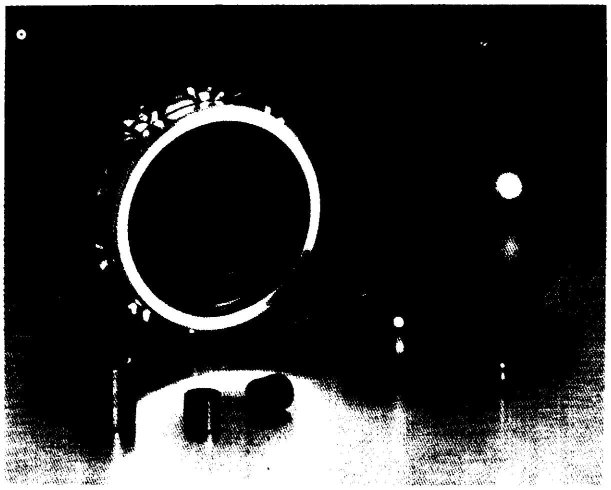


Photo *credit: Norton Co*

Silicon nitride anti-friction bearing components offer improved wear resistance and fatigue life compared to most bearing steel.

Bearings

High-performance ceramic bearings have been developed for military applications such as missiles. The primary candidate material is hot pressed silicon nitride. Ceramics offer resistance to low temperature corrosion, high temperature stability, low density, and the ability to operate for a moderate length of time with little or no lubrication. Hot isostatic pressing (HIP) is being developed to improve properties and to decrease cost by allowing near-net-shape fabrication.

The military developments will yield a technology base that can be applied to commercial products such **as** instrumentation bearings, hydraulic and pneumatic activator systems, and ceramic coatings on the foils in gas bearings. Potential ceramic bearing markets have been estimated to be $300 million per year.[28]

Coatings

Ceramic coatings provide a variety of benefits, including abrasion resistance, thermal protection, corrosion resistance, and high-temperature lubrication. Applications include ultrahard coatings for cutting tools, thermal insulation and lubricating coatings for adiabatic diesel engines and cooled gas turbines, and bioactive glass coatings for metal orthopedic implants. The list could be expanded to include other sectors such as mining (e.g., drills), utilities (e.g., turbine-generator sets, heat exchangers), agriculture (e. g., plows and tillers), and aerospace (e. g., bearings, power transfer assemblies, and actuator drive systems).

The availability of advanced ceramic coatings is expected to be a significant benefit to the U.S. economy. The value of the market for ceramic coatings is not easily assessed, because the range of applications is so wide. One estimate is for a $1 billion market worldwide for all coating materials, about *60* to *70* percent of which is domestic.[29] This estimated market includes jet engine, printing, chemical, textile, and tool and die applications. As we have seen, this list could be greatly expanded to include wear parts, bearings, biomaterials, heat exchangers, and automotive components in the future. Ceramic coatings should be considered an extremely important technology for extending the performance of metal components, and, in some cases, coated metal structures may be an excellent alternative to monolithic ceramics.

Advanced Construction Products

Potential applications of advanced cement-based materials include floors, wall panels, and roof tiles, in addition to pipes, electrical fittings, and cabinets. The cements can be laminated with wood or foam to form hard, decorative, and protective surfaces.so Advanced cement pastes cost *20* to *30* cents per pound compared with 75 cents to 2 dollars for metals and plastics, and could displace them in the future in many common uses.

The development of a cost-effective, durable, high tensile and compressive strength concrete would have dramatic implications for the infrastructure of the United States. It has been estimated that between 1981 and the end of the century the nation will spend about $400 billion for replacement and repair of pavements, and about $103 billion to correct bridge deficiencies .3' Cost

²⁸*High Technology,* March 1986, p. 14.

[29] Richerson, op.cit., December 1985.

“Imperial Chemical Industries, op. cit.

[31] National Research Council, Transportation Research Board, “America’s Highways: Accelerating the Search for Innovation, ” Special Report 202, 1984.

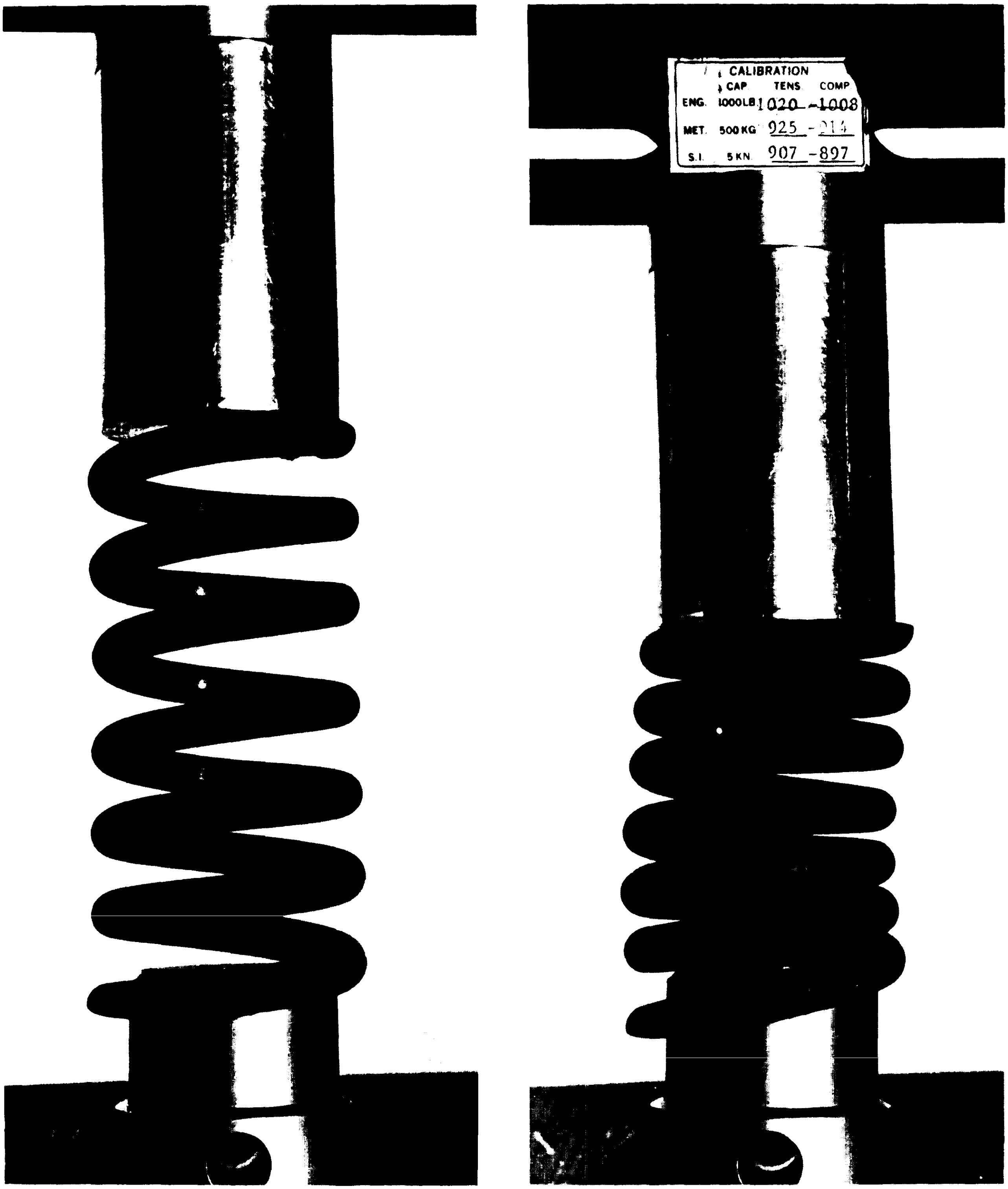


Photo credits" CEMCOM Research Associates, *Inc.*

A spring made from a high-strength cement, formed by extruision processing. Left: natural length. Right: compressed. The spring is not intended for any practical use, but demonstrates the versatility and resilience of the material.

savings of about $600 million per year could result from implementing new technologies .32 In addition to reducing repair and maintenance costs, new materials would provide other benefits. For example, high compressive strength concrete can be used to reduce the number and thickness of concrete bridge girders, significantly reducing the structural weight;[33] in concrete high-rise buildings, its use permits a reduction in the diameter of the columns, thus freeing up additional floor space.

The barriers to the development and implementation of new technologies in the construction industry are high. Some of those most often cited are industry fragmentation (e.g. some *23,000* Federal, State, and local agencies operate the Nation's highway industry), a system which awards contracts to the lowest bidder, and low industry investment in research as a percentage of sales (the steel industry invests ***8*** times more) .[34] The low investment is due in part to the fact that the principal benefits of the use of better materials accrue to the owner of the highway or bridge (the taxpayer) rather than to the cement producer.[35]

Legislation is currently before Congress (the Federal-Aid Highway Act of 1986, S.2405) which would set aside 0.25 percent of Federal-aid highway funds for a 5-year, ***$150*** million Strategic Highway Research Program. The program, which would be administered by the National Research Council, has targeted six priority research areas for support: asphalt characteristics, $50 million; long-term pavement performance, ***$50*** million; maintenance costs, ***$20*** million; concrete bridge components, $10 million; cement and concrete, $12 million; and snow and ice control, $8 million.

Bioceramics

Bioceramics, or ceramics for medical applications such as dental or orthopedic implants, represent a major market opportunity for ceramics in the future. The overall worldwide market for biocompatible materials is currently about ***$3*** billion, and this is expected to double or triple in the next decade .3' Ceramics could account for ***25*** to *30* percent of this market .37

Bioceramics may be grouped into three categories: nearly inert, surface active, and resorbable.[38] Nearly inert ceramics can be implanted in the body without toxic reactions. These materials include silicon nitride-based ceramics, transformation-toughened zirconia and transformation-toughened alumina.

Surface-active ceramics form a chemical bond with surrounding tissue and encourage ingrowth. They allow the implant to be held firmly in place and help prevent rejection due to dislocation or to influx of bacteria. Surface-active ceramics which will bond to bone include dense hydroxy - apatite, surface-active glass, glass-ceramic, and surface-active composites.

The function of resorbable bioceramics is to provide a temporary space filler or scaffold which serves until the body can gradually replace it. Resorbable ceramics have been used to treat maxillofacial defects, for filling periodontal pockets, as artificial tendons, as composite bone plates, and for filling spaces between vertebrae, in bone, above alveolar ridges, or between missing teeth. An early resorbable ceramic was plaster of paris (calcium sulfate), but it has been replaced by trisodium phosphate, calcium phosphate salts, and polylactic acid/carbon composites.[39]

Any new material intended for use in the body must undergo extensive testing before it is approved. Preclinical testing, clinical studies, and followup may take as long as 5 years to complete. 40 However, ceramics have been in clinical use for some 15 years, and are gaining acceptance. Industry interest in bioceramics has increased since 1980; however, no data were available on aggregate R&D spending either in industry or the Federal Government. In contrast, France, Germany, and especially Japan have aggressive programs of government support for the commercialization of

[32]Ibid.
[33]J.E. Carpenter, "Applications of High Strength Concrete for Highway Bridges, " *Public Roads* 44:76, *1980.*
"National Research Council, op. cit., 1984.
[35]Ibid.
36 Hench and Wilson, op. cit., 1986.
[37]Larry L. Hench, University of Florida, persona] communication, August 1986.
[38]J.W. Boretos, "Ceramics in Clinical *Care, "American Ceramics Society* *Bulletin* 64(8):630-636, *1985.*
[39]Ibid.
[40]Eduardo March, Food and Drug Administration, persona] communication, August 1986.

Photo credit' R/chards Medical Co

Total hip system including ceramic femoral head and acetabular cup, with metal femoral stem, The system is manufactured in West Germany and marketed by Richards Medical Co.

bioceramics.[41] All researchers interviewed agreed that the Japanese effort in bioceramics is considerably larger than the U.S. effort.

Heat Exchangers

Ceramic heat exchangers are of great interest because they can utilize waste heat to reduce fuel consumption. Heat recovered from the exhaust of a furnace is used to preheat the inlet combustion air, so that additional fuel is not required for this purpose. The higher the operating temperature, the greater the benefit. Ceramic systems have potential for greater than *60* percent fuel savings.[42]

Ceramic heat exchangers may be used in a variety of settings, including industrial furnaces, industrial cogeneration, gas turbine engines, and fluidized bed combustion. The size of the unit, manufacturing technique, and material all vary depending upon the specific application. Sintered silicon carbide and various aluminosilicates have been used in low pressure heat exchangers because of their thermal shock resistance; however, the service temperature of these materials is currently limited to under *2,200°* F (1,2040 C), Silicon carbide is being evaluated for higher temperatures, but considerable design modifications will be necessary.[43]

Government support has been necessary to accelerate development of the ceramic materials and system technology for heat exchangers, in spite of the design projections of significant fuel savings and short payback time. The material manufacturers, system designers, and end users have all considered the risks too high to invest their own funds in the development and implementation of a system. Specific concerns include: the high installed cost (up to *$500,000* for a 20 MBTU per hour unit), which represents a significant financial risk to the user for a technology that is not well proven; the fact that many potential end users are in segments of industry that presently are depressed; and the fact that designs vary according to each installation, leading the user to want a demonstration relevant to his particular situation.

Many of the ceramic heat exchanger programs were initiated in the 1970s when there was a keen sense of urgency concerning the "energy crisis. " In recent years, declining fuel prices have generally reduced this sense of urgency. If the current low fuel prices persist, this could delay the widespread implementation of ceramic heat exchangers for waste heat recovery.

~ :Richerson, Op, ci t., December 1985.

[42]S.M.Johnson and D.J.Rowcliffe, SRI International Report to EPRI, "Ceramics for Electric Power-Generating Systems, " January 1986.

[43]Richerson, op. cit,, December 1985.

Electrochemical Devices

Though not strictly structural applications of ceramics, devices in this category utilize ceramics for both their electrical and structural properties. Typically, the ceramic, such as zirconia or beta alumina, serves as a solid phase conductor for ions such as oxygen or sodium. Examples include oxygen sensors, oxygen concentration cells, solid oxide fuel cells, the sodium sulfur battery, sodium heat engine, and electrodes for metal winning and electrochlorination cells. As a group, these applications could comprise a market of over *$250* million for ceramics by the year 2000.[44]

Heat Engines

The advantages of using ceramics in advanced heat engines have been widely publicized. These include increased fuel efficiency due to higher engine operating temperatures, more compact designs, and reduction or elimination of the cooling system .45 Ceramics are being considered in three general categories: discrete components such as turbochargers in metal reciprocating engines; coatings and monolithic hot-section components in advanced diesel designs; and all-ceramic gas turbine engines.

A number of sources have predicted that components for heat engines will be the largest area of growth for structural ceramics over the next **25** years. Market estimates have varied widely. Kenney and Bowen stated:

> The potential demand for ceramic engines could reach $9 billion in Japan and $30 billion world wide. If ceramics are used only to partially replace metals as hot parts in the engine, the demand would be from $1 to $5 billion.[46]

The Department of Commerce has estimated more conservatively a U.S. market of $56 million by 1990 and $840 million by 2000.[47] A study by Charles River Associates estimates U.S. consumption of ceramic heat engine parts at $25 to 45 million in 1990 and $920 million to $1.3 billion by ***2000.***[48] Some structural ceramic components are already in limited production for heat engines. Ceramic precombustion chambers and glow plugs for diesels, and ceramic turbochargers, are now in production in current model Japanese cars. These markets will grow, but not to a level that will account for the projected $1 billion sales for heat engine components in the year 2000. Growth to this level would require material and design technology breakthroughs, as well as manufacturing scale-up and cost reduction. In view of these technical and economic barriers, the more conservative estimates are likely to be be the more accurate.

Gasoline Engines.—The automotive internal combustion engine offers a vast market for materials. Total sales for 1985 of cars and trucks in the free world have been estimated at 38.7 million units.[49] Any part replacement or new part would represent a volume market with substantial sales, even if the unit price were small. However, the current engine designs are considered by automotive companies to be mature, reliable, and cost-effective. Very few incentives for change exist. Cost reduction remains a significant incentive, but this is extremely difficult to satisfy for a new material, whose introduction may require redesign of adjacent parts, retooling, and modification of the production line.

Another incentive is to develop new technology which may be applicable to advanced designs. This consists of both generic and directed R&D with the primary objective of maintaining a competitive position. Ceramics within this category which have potential for production include exhaust port liners, cam followers, and turbocharger components. To date, U.S. firms have not introduced these products, although R&D programs continue. Ceramic turbocharger rotors, glow plugs, precombustion chambers, and rocker arm wear pads are currently in limited production in Japan.

The United States is well behind Japan in procuring the advanced production equipment to

“Ibid.

[45] Katz, op. cit., 1985.

[46] Kenney and Bowen, Op. cit., 1983.

“U.S. Department of Commerce, op. cit., March 1984.

“Charles River Associates report prepared for the National Bureau of Standards, ‘Technological and Economic Assessment of Advanced Ceramic Materials, Vol. 2: A Case Study of Ceramics in Heat Engine Applications, ” NBS-GCR *84-4760-2,* August 1984,

[49] Richerson, op. cit., December 1985.

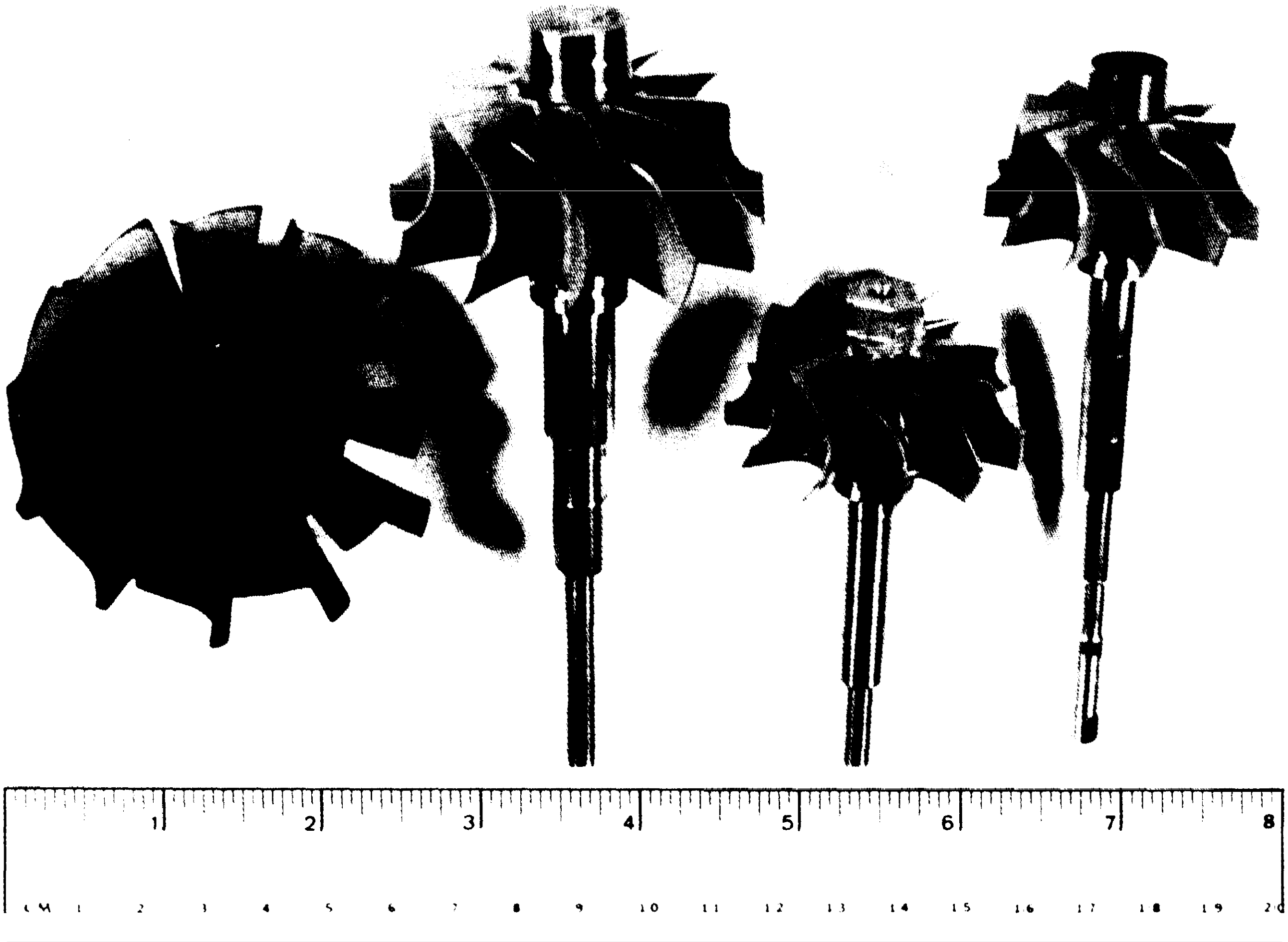


Photo credit The Garrett Corp

Ceramic turbocharger turbine rotors

produce ceramic turbocharger rotors. U.S. automotive companies do not appear to have the same level of confidence as the Japanese that a ceramic turbocharger market will develop. This is an institutional barrier based on perceived risk. In spite of this, U.S. industry is still funding considerable R&D on ceramic turbocharger rotors. One study has estimated that if a ceramic rotor price of $15 can be reached, and if performance and reliability are acceptable, a worldwide market of $60 million could be generated for ceramic turbocharger rotors by the year 2000.[50]

[50] Elaine P. Rothman, "Advanced Structural Ceramics: Technical Economic Process Modeling of Production and a Demand Analysis for Cutting Tools and Turbochargers," Materials Systems Laboratory, Massachusetts Institute of Technology, August 1985.

The ceramic turbocharger has a significance far beyond its contribution to the performance of the engine. It is regarded as a forerunner technology to far more ambitious ceramic engines, such as the advanced gas turbine. Design, fabrication, and testing methods developed for the turbocharger are expected to serve as a pattern for subsequent ceramic engine technology efforts.

Diesel Engines.—There are several levels at which ceramics could be incorporated in diesel engines, as shown in table 9. The first level involves a baseline diesel containing a ceramic turbocharger and discrete ceramic components. The second level adds a ceramic cylinder and piston, and eliminates the cooling system. The ceramic used at this level would provide high-temperature

Table 9.—Future Diesel Engine Technology Development Scenario

Technology level	Engine configuration	Potential ceramic components	Potential payoffs
1	State-of-the-art engine, turbocharged	Turbocharger Valve train components Prechamber, glow plugs	Improved performance Reduced cost? Early manufacturing experience
2	Uncooled, non-adiabatic (no water or air cooling) (no turbo-compounding)	Turbocharger Valve train components Piston, cap Cylinders, liners	Reduced weight - efficiency gain Gives option to improve aero-dynamics - efficiency gain Reduced maintenance Reduced engine systems cost? Flexibility of engine placement
3	Adiabatic turbo-compound	Turbocharger Turbo-compound wheel Valve train components Piston, cap Cylinders, liners Exhaust train insulation	Very significant reduction in specific fuel consumption Improved aerodynamics Reduced maintenance
	Minimum friction technology (could be combined with 1, 2 or 3)	Air bearings High-temperature rings High-temperature bearings Nongalling wear surfaces Low friction liquid, lubricant-free bearings	Lower specific fuel consumption

SOURCE R Nathan Katz," Applications of High Performance Ceramics in Heat Engine Design, " *Material Science and Engineering 71227.249, 1985*

strength, rather than thermal insulation. The third level would utilize ceramics for thermal insulation in the hot section as well as in the exhaust train. Turbocompounding would be used to recycle energy from the hot exhaust gases to the drive train. The fourth level would use advanced minimum friction technology to improve the performance of the engine. Appropriate aspects of this could be utilized at levels one, two, or three,

The four levels listed above place different demands on the ceramic materials. Levels one and two require a low-cost, high-strength material, but without insulating properties; sintered silicon nitride or silicon carbide would be possibilities here. It has been suggested that level two represents the best compromise for light duty ceramic diesels such as those in automobiles.[51] Level three would require an insulating ceramic, probably zirconia or a zirconia-based composite. This is the level where the most significant improvements in fuel efficiency would be realized. The current zirconia and alumina-zirconia transformation toughened ceramics are not reliable at the high stress of the piston cap and do not have a low enough coefficient of friction to withstand the sliding contact stress of the rings against the cylinder liner. These materials do seem to have adequate properties, however, for other components such as the head plate, valve seats, and valve guides.[52]

Emission requirements will likely affect the size of the diesel market for passenger cars and trucks. Diesel engines generally produce a high level of particulate emissions. The higher operating temperatures of the adiabatic diesel could reduce emissions or allow emission control devices to operate more efficiently. The market for ceramics could also be affected in another way: a major candidate for diesel emission control is a ceramic particle trap. However, such a trap is likely to be expensive, and could raise the price of the automobile to an unacceptable level.

Ceramic coatings may be an alternative to monolithic ceramics in diesel applications. Zirconia coatings can be plasma-sprayed onto metal cylinders to provide thermal insulation. In a joint program between the United States Army Tank Automotive Command and Cummins Engine Co., the combustion zone of a commercial Cummins NH diesel engine was coated with a zirconia-based ceramic and installed in a 5 ton Army truck, minus the cooling system. The engine accumu-

[51] Katz, op. cit., *1985*.

[52] Richerson, op. cit., December 1985.

lated over 15,000 km of *successful* road testing.[53] The current state-of-the-art thickness of zirconia coatings is 30 to 50 thousandths of an inch, It is estimated that thicknesses of 125 thousandths will be required to provide thermal insulation comparable to monolithic zirconia,[54] The coating is not as impermeable nor as resistant to thermal shock as the monolithic zirconia. However, the coated metal part has higher strength and toughness than the all-ceramic part.

In the past, confusion has arisen because identical configurations of ceramic and metal engines have not been compared. It is important to separate out the configuration options, such as turbocharging, turbocompounding, heat recovery, cooling, etc., from the material options in order to isolate the benefits of the use of ceramics. Failure to do this has led to overestimation of the benefits of ceramics. For example, a recent study of a ceramic diesel design funded by DOE indicates that "a practical zirconia-coated configuration with a cooled metal liner, intercooled, with combined turbocompounding and Rankine cycle exhaust heat recovery, provides a 26 percent increase in thermal efficiency over a metallic, cooled, turbocharged, intercooled, baseline engine. "[55] The bulk of the performance improvement was attributed to the turbocompounding and the Rankine cycle exhaust heat recovery, Only 5.1 percent was attributed to the improved thermal insulation.

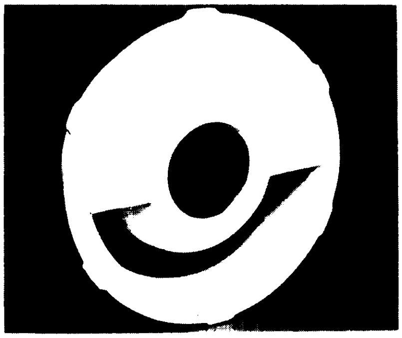
A recent study by Charles River Associates predicts that the uncooled ceramic diesel engine system will be the first to be commercialized.[56] It projects that the initial introduction will be in the late 1980s to early 1990s, and could account for 5 percent of new engines manufactured in 1995, This projection is more optimistic than the above discussion would imply. Zirconia materials do not yet exist which can be used for level three technology, where the greatest fuel efficiencies are expected. It remains to be seen whether the elimination of the cooling system will provide sufficient incentives to U.S. automakers to commercialize level two ceramic technology. However, Japan in particular has very active programs both in material and diesel engine development. The Japanese company Isuzu has reported greater than 300 miles of road testing and is projecting 1990 production. "

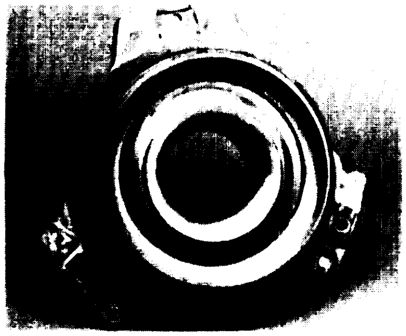
Automotive Gas Turbines.—The major incentive for the use of ceramics in turbines is the possibility of operating the engine at turbine inlet temperatures up to about **2,500°** F (1,3710 C), compared with superalloy designs, which are limited to about 1,900° F (1,038° C) without cooling. This temperature difference translates into an increased thermal efficiency from around 40 percent to nearly 50 percent. 'g Power increases of 40 percent and fuel savings of around 10 percent have been demonstrated in research engines containing ceramic components .59 Other potential advantages include reduced engine size and weight, *re*duced exhaust emissions, and the capability to burn alternative fuels, such as powdered coal.

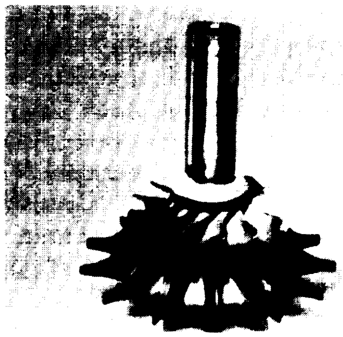
Structural ceramics are an "enabling technology" for the automotive gas turbine; i.e., without the use of ceramics, an automotive turbine cannot be designed and manufactured that can compete in cost or performance with current gasoline and diesel engines. Extensive design, materials, and engine efforts have been made over the past 15 years in the United States, Europe, and Japan. These efforts have resulted in significant progress in design methods for brittle materials, the properties of silicon nitride and silicon carbide materials, fabrication technology for larger and more complex ceramic components, NDE and proof testing, and engine assembly and testing.

Ceramic components have been operated in prototype turbine engines in Germany, Sweden, Japan, and the United States. The tests in the United States have been highly instrumented development engines in test cells. [60] Current pro-

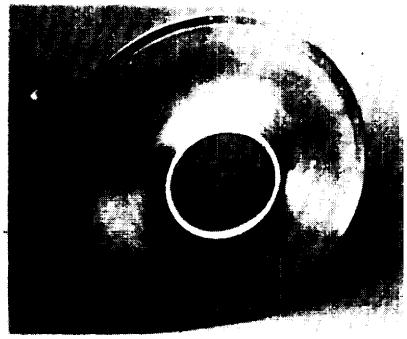
[53]Katz, op. cit., 1985.
[54]Bill Mandler Cummins Engine Co. , personal communication, August 1986. '
[55]T More] et al., "Ana]ysis of Low Heat Rejection Engine Concepts, " Proceedings of the 23rd Automotive Technology Development Contractors Coordination Meeting, to be published by the Society of Automotive Engineers in *1986.*
"Charles Rivers Associates, op. cit., August 1984.
[57]Richerson, op. cit., December 1985.
[58]John Mason, Garrett Corp., presentation at the Society of Automotive Engineers International Congress and Exposition, February 1986.
[59]David W. Richerson and K.M. Johansen, "Ceramic Gas Turbine Engine Demonstration Program, " Final Report, DARPA Navy contract N00024-76-C-5352, May 1982.
[60]D.W. Richerson, "Evolution in the U.S. of Ceramic Technology for Turbine Engines, " *American Ceramics Society Bulletin 64(2):*282-286, *1985.*

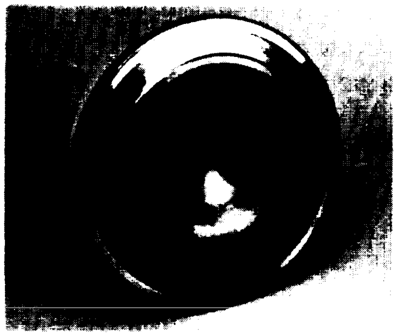

1. Flow Separator Housing


2. Turbine Shroud


3. Turbine Rotor


4. Inner Diffuser HSG

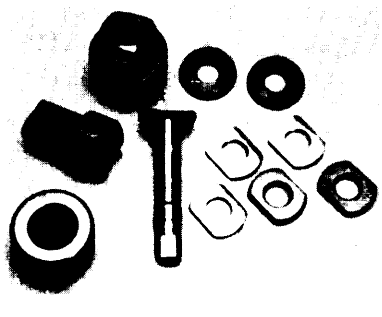

5. Outer Diffuser HSG

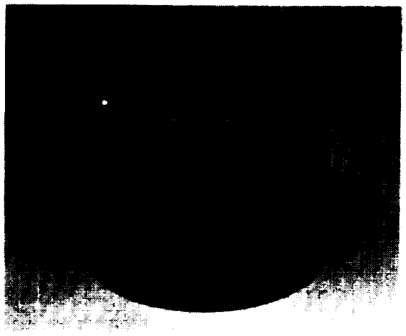

6. Turbine Backshroud


7. Stator Vane Segments


8. Turbine Transition Liner


9. Combustor Baffle


10. Bolts


11. Regenerator Shield

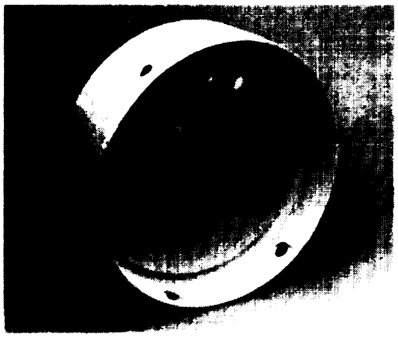

12. Alumina-Silica Insulation

Photo credit The Garrett Corp

Prototype ceramic gas turbine engine components grams have achieved over 100 hours of operation at temperatures above 2,0000 F (1,0930 C). [61] These achievements, while impressive, are still far from the performance required of a practical gas turbine engine, which will involve continuous operation above 2,5000 F (1,3710 C). The limiting component in these engines appears to be the rotor, which must spin at about 100,000 rpm at these temperatures. The best rotors available today are Japanese. 'z The target automotive gas turbine engine is designed to provide about 100 horsepower with fuel efficiencies of about 43 mpg for a 3,000 lb. automobile. [63]

The automotive gas turbine would be a more revolutionary application of ceramics than the diesel. The diesel engine is a familiar technology and incorporation of ceramics can occur in stages, consistent with an evolutionary design. The gas turbine, on the other hand, represents a completely new design requiring completely new tooling and equipment for manufacture. Because of the remaining technical barriers to ceramic gas turbines and the fact that they represent a complete departure from current designs, it is unlikely that a ceramic gas turbine passenger car could be produced commercially before 2010. [64] In view of this long development time, it appears possible that this propulsion system could be overtaken by other technologies, including the ceramic diesel. One factor which would favor the turbine engine would be dramatically increased fuel costs. In the case that traditional fuels became scarce or expensive, the turbine's capability to burn alternative fuels could make it the power plant of choice in the future.

In summary, the outlook for ceramic heat engines for automobiles appears to be highly uncertain. The performance advantages of ceramic engines are more apparent in the larger, more heavily loaded engines in trucks or tanks than they are in automobiles. Ceramic gas turbines and adiabatic diesel designs do not scale down in size as efficiently as reciprocating gasoline engines. [65] Thus, if the trend toward smaller automobiles continues, reciprocating gasoline engines are likely to be favored over advanced ceramic designs.

The prevailing approach of U.S. automakers is to wait and see if an clear market niche for ceramics develops before investing heavily in the technology. This is likely to mean that previous forecasts of the U.S. ceramics heat engine market, which cluster in the $1 to $5 billion range by the year 2000, are too optimistic. On the other hand, the Japanese approach, in which ceramics are steadily being incorporated in engines on a more experimental basis, reflects greater faith in the future of the technology. If a substantial automotive market for ceramics does develop, heat engine applications for ceramics would be one of the most highly leveraged in terms of economic benefits and jobs.[66] [67]

Military

Production of ceramics for military applications is projected to expand substantially during the next 25 years. [68] Near-term growth is expected for armor, radomes and infrared windows, bearings for missiles, and rocket nozzles (carbon-carbon composites and ceramic-coated carbon-carbon composites). New applications are likely to be laser mirrors, gun barrel liners, rail gun components, and turbine and diesel engine components. Ceramics and ceramic composites in many cases offer an "enabling" capacity which will allow applications or performance that could not otherwise be achieved. Some of the resulting technology will be suitable for commercial spinoff if acceptable levels of fabrication cost and quality control cost can be attained.

Diesels.—In military diesels, ceramics provide much the same benefits as in commercial diesels. Of particular interest to the military is the elimination of the cooling system to achieve smaller packaging volume and greater reliability, Con-

"Mason, op. cit., January 1986.

"Richard Helms, General Motors Corp., presentation at the Society of Automotive Engineers International Congress and Exposition, Detroit, MI, February 1986.

"Katz, op. cit., 1985.

[64]Richerson, op. cit., December 1985,

[65]U.S. Congress, Office of Technology Assessment, *Increased Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports*, OTA-E-185 (Washington, DC: U.S. Government Printing Office, September 1982), p. 145.

"Johnson, Teotia, and Hill, op. cit., 1983.

[67]Charles River Associates, op. cit., August 1984.

[68]Richerson, op. cit., December 1985.

siderable progress has been made through the use of ceramic coatings, Monolithic ceramics have also been tried, but have only been successful in a few components, and require further development. A military diesel with minimum cooling achieved primarily with ceramic coatings could be produced within 5 years. Engines containing more extensive ceramic components are not likely to appear before 1995 to 2000. 69

Turbines.—Turbine engines are in widespread use in the military for aircraft propulsion, auxiliary power units, and other applications. They are being considered for propulsion of tanks, transports, and other military vehicles. Ceramics have the potential to enable advanced turbines to achieve a large increase in performance: as much as ***40*** percent more power, and 30 to 60 percent fuel savings.[70] In addition, they offer lower weight, longer range, decreased critical cross section, and decreased detectability.

Design and material technologies are available in the United States to produce high-performance, ceramic-based turbine engines for short life applications such as missiles and drones. Furthermore, it appears that these engines have potential for lower cost than current superalloy-based short life engines.[71] Longer life engines will require considerable development to demonstrate adequate reliability. This development must address both design and materials in an iterative fashion. While the use of ceramic thermal barrier coatings in metal turbines is well underway, new turbines designed specifically for ceramics are not likely to be available before the year *2000.*

Future Trends in Ceramics

Ceramic Matrix Composites

Dramatic improvements in the fracture properties of ceramics have been obtained by reinforcing with continuous, high-strength fibers. Optimum microstructure result in composites that do not fail catastrophically, and therefore have mechanical properties that are very different from those of monolithic ceramics, as shown in figure 5. The most developed composites to date are silicon carbide fiber-reinforced glass/ceramic matrices.

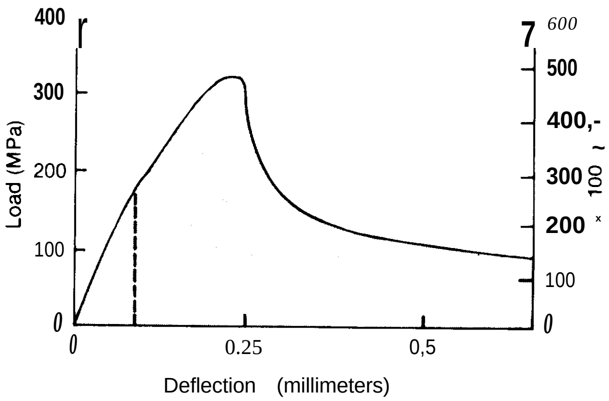
Recent analysis suggests that fibers resist the opening of a matrix crack by frictional forces at the matrix-fiber interface .72 One of the important results is that the strength of the composite becomes independent of preexisting flaw size. This means that strength becomes a well-defined property of the material, rather than a statistical distribution of values based on the flaw populations,

Ceramic matrix composites present an opportunity to design composites for specific engineering applications. This will require a detailed understanding of the micromechanics of failure and explicit quantitative relations between mechanical properties and microstructural characteristics. The most important breakthrough in ceramic composites will come with the development of new high-temperature fibers that can be processed with a wider range of matrix materials. New chemical methods to form fibers and matrices together could yield even more revolutionary advances.

[69]Ibid.
[70]Ibid.
[71]Ibid.

[72]D. B. Marshall and A.G. Evans, "The Mechanics of Matrix Cracking in Brittle-Matrix Fiber Composites, " *Acta Metal].* 33(11): *2013-2014, 1985.*

Figure 5.— Load-Deflection Curve for a SiC/Glass-Ceramic Composite



Dotted line indicates deflection at which a single crack has passed completely through the matrix, but remains bridged by intact fibers,

SOURCE: D.B. Marshall and A.G. Evans, "The Mechanics of Matrix Cracking in Brittle-Matrix Fiber Composites," *Acta Metall.* 33(1 1):2013-2021, 1985

Chemical Processing of Ceramics

In the future, chemical approaches to the fabrication of ceramics will probably be preferred to the traditional methods of grinding and pressing of powders. Chemical methods, such as sol-gel processing,[73] are already used extensively in the production of electronic ceramics, and will become increasingly important in structural ceramics as well. These techniques afford greater control over the purity of the ceramic and over its microstructure. It has been estimated that by the year *2010, 50* percent of structural ceramics will be processed chemically.[74]

Ceramics Factory of the Future

Because of the extreme reliability and reproducibility problems of ceramics, production processes in the future must be highly automated, Processing equipment will be microprocessor controlled, including automatic load/unload devices and numerically controlled grinding and finishing machines.

Computer-process control of critical steps combined with nondestructive, in-line test methods such as acoustic flaw detection and radiography will form the heart of the manufacturing operation. In the near term, off-line proof testing of critical components will be required.

Quality assurance will be integrated into the process and will range from incoming raw materials inspection to automated dimensional inspection techniques such as computer controlled coordinate measuring machines of either a contact or noncontact (optical) configuration. Great emphasis will be placed on the characteristics of the starting powders, and use of clean rooms will be the rule in the initial forming steps.

Perhaps the most important processing goal in the future will be forming to net shape. This will reduce the costs of ceramics by eliminating costly grinding steps, and by making more efficient use of the material. Moreover, it will increase the reliability and yields, by eliminating flaws which are introduced in the finishing operations.

Biotechnology

Structural ceramics could have a significant interaction with the developing field of biotechnology in the future. Ceramics could be used extensively in fermenters, and are likely to be important in a broad range of product separation technologies.

Fermenters.—Most current fermenters are made of 316 grade stainless steel.[75] Steel fermenters suffer from several disadvantages, including contamination of the cultures with metal ions, corrosion caused by cell metabolizes or reagents, and leaks around gaskets and seals during sterilization and temperature cycling. Glass-lined steel bowls are sometimes used, especially for cell cultures, which are more sensitive to contamination than bacterial cultures. However, the thermal expansion mismatch between the glass lining and the metal causes problems during steam sterilization. Ceramics offer a solution to these problems, because of their chemical stability and low thermal expansion. Ceramics could be used in the bowl and agitator as well as in the peripheral plumbing joints and agitator shaft seal to prevent leaking.

Separation Technology.—Separation and purification of the products of cell and bacterial cultures is a key aspect of biotechnology. In general, the separation techniques are based less on filtration than on active interactions between a solid phase and the liquid mixture, as in chromatography. For example, biologically produced insulin is now being purified with a chiromato-graphic process based on a modified silica material,[76] Silica or alumina particles can also be used as a solid support for attaching monoclinal antibodies, which bind to specific proteins and effect a separation by affinity chromatography.[77] The strength and hardness of the ceramics are key to the avoidance of deformation of the ceramic particles under conditions of high throughput.[78] In

“See for example: David W. Johnson, Jr., “Sol-Gel Processing of Ceramics and Glass,” *American Ceramic Society Bulletin* 64(12):1597-1602, *1985.*

‘*R. Nathan Katz, in presentation at the Society of Automotive Engineers International Congress and Exposition, Detroit, MI, February 1986.

“Richard F. Geoghegan, E.I. du Pent de Nemours & Co., Inc., personal communication, August 1986.

“Joseph J. Kirkland, E.I. du Pent de Nemours & Co., Inc., personal communication, August 1986.

“George Whitesides, Department of Chemistry, Harvard University, personal communication, August 1986.

“Ibid.

the future, the most efficient processes could be hybrids based on both filtration and chromatography.[79] As these processes are scaled up to production units, a large increase in the demand for specially modified silica and alumina column packing materials can be anticipated.

Energy Production

Power Turbines.—The performance requirements for power turbines are much greater than those for automotive gas turbines.[80] Power turbines must have a lifetime of 100,000 hours, compared with about 3,000 hours for the auto turbine. In addition, the consequences of power turbine failure are much greater. In light of these facts, a recent report has concluded that power turbines will be commercialized after automotive gas turbines.[81] While some of the processing technology developed for the auto turbine may be applicable to power turbines, the scale-up from a rotor having a 6 inch diameter to one having a much larger diameter may require completely new fabrication techniques. The larger ceramic structures may also require different NDE techniques to ensure reliability. Thus, use of monolithic ceramics in the critical hot section components of power turbines is not anticipated in the next *25* years. However, ceramics may find applications in less critical structures, such as combustor linings, and ceramic coatings could be used to augment the high-temperature resistance of cooled superalloy rotor blades .82

“Michelle Betrido, Celanese Research Corp., personal communication, August 1986.

80 Johnson and Rowcliffe, op. cit., January 1986.

‘*Ibid.

Research and Development Priorities for Ceramics

In 1986, the U.S. Government spent about $60 million on structural ceramics research and development (table 10). R&D expenditures in private industry may be roughly comparable .83 The Departments of Energy and Defense spent the largest fractions, at *47* percent and 36 percent, respectively. Funding for fiscal year 1987 is expected to decrease by over 20 percent, with 50 percent reductions in the DARPA program and in the DOE vehicle propulsion program. The following hierarchy of R&D priorities is based on the opportunities identified above. These are then correlated with the actual spending on structural ceramics R&D in fiscal year 1985.

[82]Ibid.

“Charles River Associates, op. cit., August 1984, p. 38.

Table 10.—Structural Ceramic Technology: Federal Government Funded R&D (in millions of dollars)

	FY 1983	FY 1984	FY 1985	FY 1986	Estimated FY 1987
Department of Energy:					
Conservation and renewable energy:					
Vehicle propulsion	11.4	12.7	11.9	10.0	5.2
Advanced materials	3.2	5.1	6.0	8.7	6.5
Industrial programs	1.0	2.3	1.7	1.5	0.8
Energy utilization research	0.5	1.5	1.8	1.8	1.0
Fossil energy:					
Advanced research and technology development	1,0	1.1	1.5	1.2	0.9
Energy research:					
Basic energy science	3.0	4.4	4.6	4.5	4.5
NASA:					
Lewis Research Center	3.0	2.5	5.4	4.5[a]	4.6[a]
National Science Foundation	2.9	3.3	3.6	3.6	3.7
National Bureau of Standards				2.2	3.0
Department of Defense:					
Defense ARPA	7.7	8.2	9.4	10.0	5.0
U.S. Air Force	3.0	3.4	4.7	4.7	5.0
U.S. Army	4.7	6.0	2.5	4.4[b]	4.7[b]
U.S. Navy	1.2	1.3	1.4	2.3	2.3
Total	42.6	51.8	54.5	59.4	47.2

[a]Includes $1.6 for Manpower Salaries.
[b]Includes $4.0 for TACOM Diesel.

SOURCE: Robert B. Schulz, Department of Energy

Very Important

Processing Science.—There is a great need for generic research to support the development of practical manufacturing technologies within industry. The agenda for such research is long, but includes such topics as:

- development of near-net-shape processes;
- development of pure, reproducible powders, whiskers, and fibers which can be formed and densified with a minimum of intermediate steps; role of solution chemistry in powder preparation and control of interface properties in composites;
- development of practical in-process inspection devices to identify problems at the earliest possible stage in the process;
- iterative development of new equipment such as hot isostatic presses (HIP) and multistage processes such as sinter-HIP, with emphasis on scaling up to commercially viable size; and
- understanding the relationships between coating process variables and final properties and performance of ceramic coatings.

Environmental Behavior.—Many of the applications for ceramics mentioned above require long-term performance in severe environments. In order to develop higher temperature, corrosion resistant materials, it is necessary to understand the long-term behavior of candidate ceramic materials in the anticipated environments.

- For heat engine applications, the general requirement is to understand the mechanical and chemical behavior of advanced ceramics such as silicon nitride, silicon carbide, zirconia, and composites based on these materials in environments of 1,0000 to 1,4000 C (1,8320 to 2,5520 F) in air, carbon monoxide, or carbon dioxide.
- In ceramic wear parts, it will be necessary to understand the relationship between wear, erosion, and toughness in the presence of lubricating fluids and gases. Generally, wear parts include hard materials like tungsten carbide, titanium boride, and materials which have good lubrication characteristics, like silicon nitride.
- Since heat exchangers generally fail as a result of long-term corrosion at high temperatures, it is important to understand the chemical processes of corrosion in environments like salts of sodium, potassium, magnesium, calcium, vanadium, and mixed metals. In addition to existing materials (e.g. silicon carbide, cordierite, and zirconium silicate), newer materials, including silicon nitride and composites, should be investigated. Corrosion-resistant ceramic coatings may become important here.
- Considering the large size of the potential markets in bioceramics, it will be critical to understand the long-term effects of body fluids on chemical structure and mechanical properties. In view of the many years which ceramic implants must serve without failure, the interaction between slow crack growth and the body environment should be investigated.
- The long-term environmental stability of advanced chemically bonded ceramics will be crucial to their effectiveness in construction and other applications. The deterioration of the properties of some advanced cements in the presence of moisture remains a problem, and the chemical degradation of the fiber interface in reinforced cements and concretes have limited the structural uses of these materials.

Reliability. -No factor is more important to the success of ceramics in all of the applications discussed than reliability. Since the performance specifications and environment of each application are different, it will be necessary to establish the most appropriate and cost-effective nondestructive testing methods for each one.

In order to facilitate design, models need to be developed for predicting the service lifetime of ceramic parts containing various kinds of flaws. Such models must depend heavily on information derived from the categories of environmental behavior of ceramics and composite failure mechanisms discussed above. Beyond a dependence on intrinsic flaws in the material, however, lifetime also depends on the location and nature of the flaw relative to the structure itself. It is not sufficient to characterize the behavior of a coupon of the material from which a structure is made; either the structure itself must be tested, or additional models must be available to predict the effects of a particular flaw on a particular structure.

Interphase in Composites.—The interphase between ceramic fiber and matrix is crucial to the static strength, toughness, and long-term stability of the composite. Very little is known about the relationship between the properties of the interphase and these overall composite properties. The capability to modify the surface chemistry of ceramic fibers and whiskers to provide optimum compatibility between reinforcement and matrix could yield remarkable improvements in ceramic performance and reliability,

Important

Joining of Ceramics. -In most applications, ceramics are not used alone; rather, ceramic components are part of larger assemblies. Therefore, the ceramic must be joined to more conventional materials in the assembly to function properly. Broad research in joining of ceramics to metals, glasses, and other ceramics could have a decisive impact on a future use of monolithic ceramics, coatings, and composites. The key to joining is an understanding of the surface properties of the two materials and of the interface between them. In general, the interface is a critical point of weakness in discrete ceramic components such as those in heat engines, in ceramic coatings on metal substrates, and in ceramic fibers in composites. Principal needs in this area are in the strengthening and toughening of joints, an understanding of their high-temperature chemistry, and improved resistance to corrosion in the environments of interest. As with solution methods in powder preparation, chemistry will make a crucial contribution to this field.

Tribology of Ceramics.—Tribology, the study of friction, wear, and lubrication of contiguous surfaces in relative motion, is a field of key importance to ceramic wear parts and heat engine components. Lubrication is a particularly serious problem in ceramic engines because of their high operating temperatures. Ordinary engine oils cannot be used above about 3500 F (177° C). For operating temperatures of ***500°*** to ***7000*** F ***(2600*** to ***371° C),*** synthetic liquids such as polyol esters are available, but are extremely expensive and require further development. In a low-heat rejection (“adiabatic”) ceramic engine, cylinder liner temperatures may reach 1,000° to 1,700° F (5380 to 927° C), depending on the insulating effectiveness of major engine components. For this elevated temperature regime, synthetic lubricants cannot be used effectively. One approach is to use solid lubricants which would become liquid at elevated temperatures; however, no such lubricants exist for use in the environments envisioned (high temperature, corrosive gases). Moreover, the distribution of solid lubricant around the engine is a persistent problem .84

A second approach involves modifications of the surface of the component to produce “self-Lubrication. ” The lubricant can be introduced through ion implantation directly into the surface (to a depth of several micrometers) of the component; it then diffuses to the surface to reduce friction. Some metal or boron oxides show promise as lubricants. Another alternative is to use surface coatings of extremely hard ceramics such as the carbides and nitrides of zirconium, titanium, or hafnium, without any lubrication. At present, these techniques all lead to sliding friction coefficients which are roughly four times higher than those achieved at low temperatures with engine oils.[85] Further research is needed to improve this situation.

Failure Mechanisms in Composites.—Ceramic matrix composites offer the best solution to the problem of the brittleness of ceramics. However, this field is still in its infancy, and research is characterized by a very empirical approach to mixing, forming, densification, and characterization of fiber-powder combinations. Fundamental understanding of the failure mechanisms in composites would provide guidance for development of new, tougher ceramics. This would include an investigation of: multiple toughening techniques, such as transformation toughening and whisker reinforcement; the role of interphase properties

[84] Manfred Kaminsky, Surface Treatment Science International, personal communication, August 1986.

[85] Ibid.

in fracture; and failure mechanisms in continuous fiber composites.

Standardization and Testing.—Standardized tests and methods of reporting test data are fundamental to the use of any engineering material; however, a consensus on even these basic principles has eluded the ceramics community. It is not surprising that in a new field like structural ceramics, which is constantly inventing new materials and processes, there should be a lag in the development of standards and test methods. Standardization of materials must inevitably follow the formation of a consensus that certain materials are worth pursuing. While there is a danger in prematurely narrowing the possibilities, there may also be a danger in not developing the materials we already have. This is particularly true of the relatively well-studied materials: silicon nitride, silicon carbide, and zirconia.

In the case of ceramic composites, the specification of standard tests is more difficult, because the relationship between the micromechanics of the fibers and matrix and the macroscopic composite behavior is not well understood. In continuously reinforced composites, for example, which display progressive rather than catastrophic failure behavior, the stress at which the composite "fails" is ambiguous.

There is a growing interest, both nationally and internationally, in the development of standards for ceramics.[86] Areas which could benefit from standards include: statistical process control, nondestructive testing, analytical procedures, mechanical properties, performance characteristics in various environments, design procedures and terminology.[87] Standards are essential for the generation of design data, and for reliability specifications for ceramic materials sold domestically or abroad,

Desirable

Chemically Bonded Ceramics.–Chemically bonded ceramics offer great promise for low-cost, net shape fabrication of structures in such applications as wear parts and construction. Recent improvements in the tensile strength of CBCs suggest that the limits of this key engineering property are far from being realized, Further research is required in flaw size reduction, long-term stability in various environments, and the properties of the interphase in fiber-reinforced cements and concretes.

Table 11 shows that the actual structural ceramics R&D spending in fiscal 1985 for all government agencies corresponds roughly with the priority categories recommended above, although specific projects differ. Processing research accounted for the lion's share, with 76 percent. No separate estimate was available of research on the interphase in composites; no doubt a portion of this work was included under composite fabrication, listed in table 11 as a subcategory of processing. Also, no separate figure was obtained for

Table 11.—Breakout of the Fiscal Year 1985 Structural Ceramic Budget According to the R&D Priorities Cited in the Text

Research area	FY 1985 budget percentage
Processing:	
Powder synthesis	4
Monolithic fabrication	32
Composite fabrication	32
Component design and testing	4
Coatings	4
Machining	<1
Subtotal	76
Environmental behavior	4
Reliability:	
Modeling	2
Time dependent behavior	1
Nondestructive evaluation	3
Microstructure evaluation	4
Subtotal	10
Interphase in composites	no separate figure
Tribology	2
Joining	3
Fracture	5
Standards	<1
Total	100 %

SOURCE S J Dapkunas, Department of Energy

[86] Concerned organizations include the American Ceramic Society, the U. S. Advanced Ceramic Association (USACA), the American Society for Testing and Materials (ASTM), the Versailles Project on Advanced Materials and Standards (VAMAS), and the National Bureau of Standards,

[87] Proposal developed by S. J. Schneider, as described in the Ceramic Technology Newsletter, Oak Ridge National Laboratory}', No, 10, Februrary-April 1986.

Federal expenditures on new cements and concretes. In 1983, however, total U.S. Government and industry funding of cement research was estimated at only $1 million, compared with a portland cement sales volume over $1 billion.[88] Assuming that the current breakdown of Federal ceramics research is similar to that in fiscal 1985, a comparison of table 11 with the priorities above suggest that greater emphasis should be placed on standards development, joining, tribology, and cement-based materials.

[88] National Research council, Transportation Research Board, op. cit., 1984.

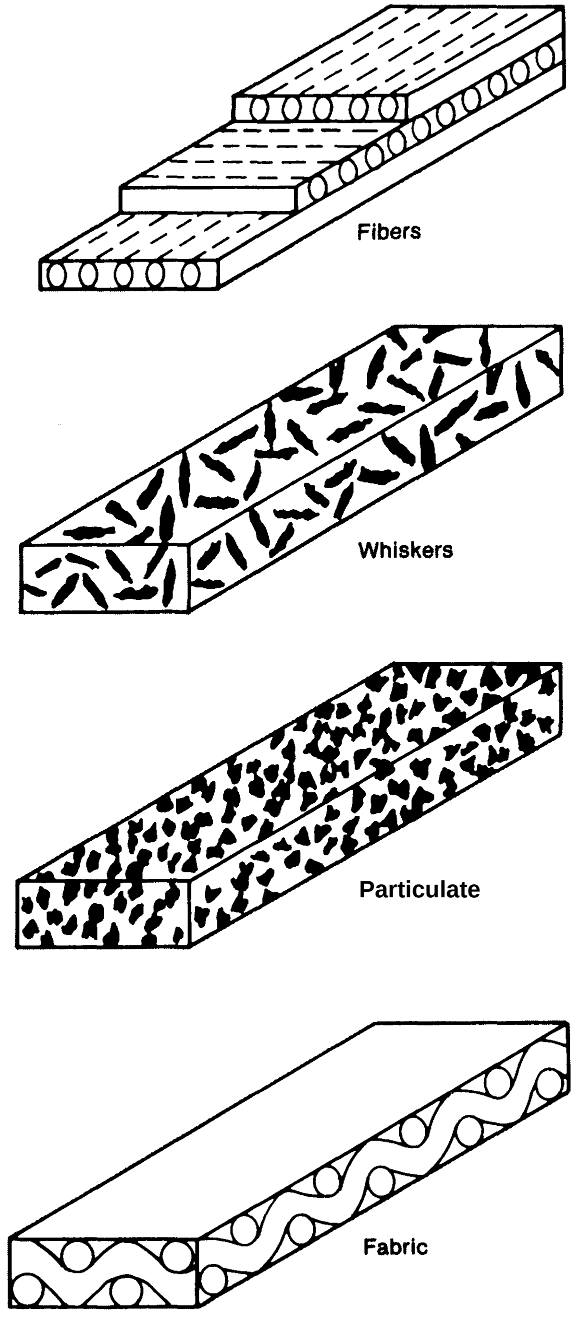
POLYMER MATRIX COMPOSITES

Unlike a ceramic matrix composite, in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a polymer matrix composite (PMC) lends strength and stiffness to the relatively weak matrix. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement. The function of the matrix is to bond the fibers together and to transfer loads between them. As with ceramic matrix composites, the reinforcement may consist of particles, whiskers, fibers, or fabrics, as shown in figure ***6.***

Polymer matrix composites are often divided into two categories: reinforced plastics, and "advanced composites. " The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-strength glass fibers (E-glass); they have been in use for ***30*** to ***40*** years in applications such as boat hulls, corrugated sheet, pipe, automotive panels, and sporting goods. Advanced composites, which have been in use for only about 15 years, primarily in the aerospace industry, consist of fiber and matrix combinations which yield superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers, such as high-strength glass (S-glass), graphite, aramid, or other organic fibers. In this report, market opportunities for both reinforced plastics and advanced composites are considered.

The properties of the composite depend *on* the matrix, the reinforcement, and the boundary layer between the two, called the "interphase." Consequently, there are many variables to consider when designing a composite. These include the type of matrix, the type of reinforcement, their relative proportions, the geometry of the reinforcement, and the nature of the interphase. Each of these variables must be carefully controlled in order to produce a structural material optimized for the conditions under which it is to be used.

Figure 6.—Composite Reinforcement Types



SOURCE: Carl Zweben, General Electric Co

The use of continuous fiber reinforcement confers a directional character ("anisotropy") to the properties of composites. PMCs are strongest when stressed parallel *(O o)* to the direction of the fibers (longitudinal direction), and weakest when stressed perpendicular *(90°)* to the fibers (transverse direction). In practice, most structures are subjected to complex loads, necessitating the use of fibers oriented in several directions (e. g., 0°, + / *–45°, 900).* However, PMCs are most efficiently used in applications which can take advantage of the inherent anisotropy of the materials, as shown in figure 7, which compares the strength and stiffness of composites with various metals.

When discontinuous fibers or particles are used for reinforcement, the properties tend to be more isotropic, since the reinforcement direction is not as well defined. Such composites lack the outstanding strength of continuous fiber PMCs, but they can be produced more cheaply, using the technologies developed for unreinforced plastics, such as extrusion, injection molding, and compression molding. Sheet molding compound (SMC, figure 7) is such a material, which is widely used in the automotive industry.

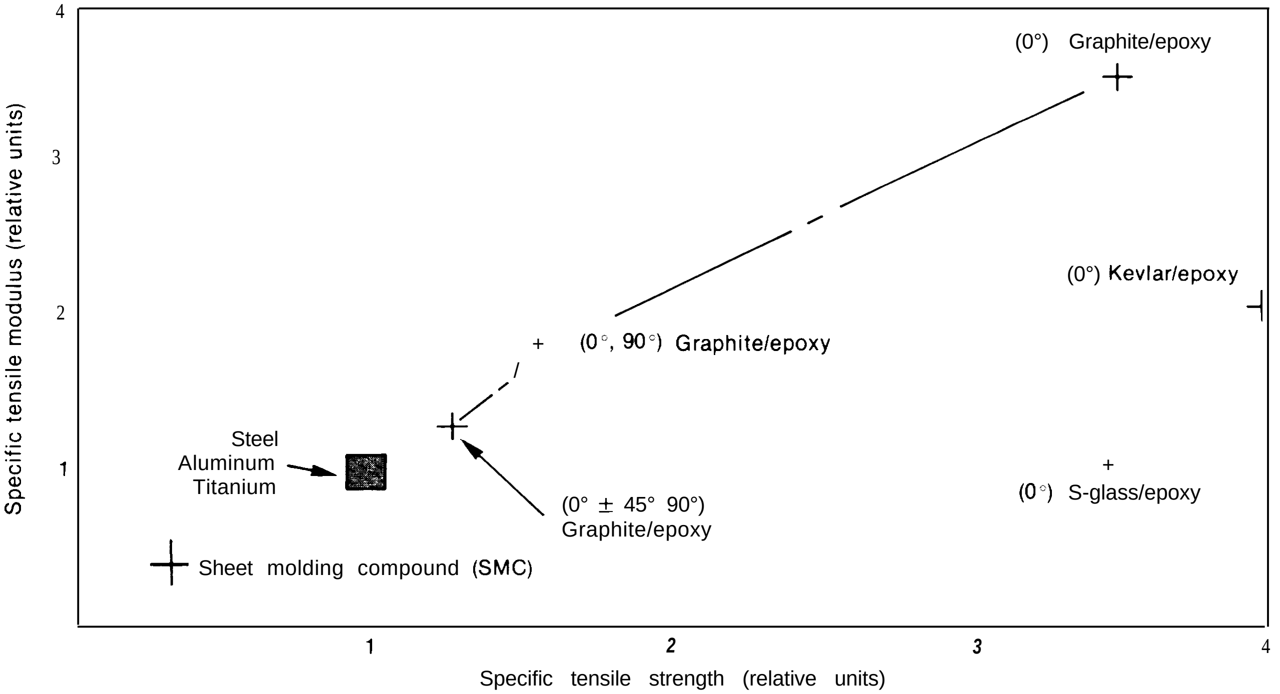
The Polymer Composites Industry

The reinforced plastics/composites industry today encompasses a very broad range of materials, products, and manufacturing processes. About **85** percent of the material used is glass fiber-reinforced polyester resin (often called fiber-reinforced plastic, or FRP).[1] FRP is fabricated by a number of processes to produce a great variety of products, some of which are noted above.

Less than 2 percent of the material used in the reinforced plastics/composites industry goes into

[1]Reginald B. Stoops, R.B. Stoops & Associates, Newport, RI, "Manufacturing Requirements of Polymer Matrix Composites, " contractor report prepared for the Office of Technology Assessment, December 1985.

Figure 7.–Comparison of the Specific Strength and Stiffness of Various Composites and Metals (Steel: AISI 4340; Aluminum: 7075-T6; Titanium: Ti-6A1-4V) Specific Properties are Ordinary Properties Divided by Density. Angles Refer to the Directions of Fiber Reinforcement



SOURCE Carl Zweben, General Electric Co

"advanced composites" for use in "high-tech" applications such as aircraft and aerospace.[2] In 1984, the world produced some 22 million pounds of advanced composite materials, mostly in the United States. The total value of fabricated parts was about $1.3 billion split among four major consuming industries: aerospace ***(60*** percent), sports equipment (20° percent), and industrial and automotive (15 percent).'

It has been estimated that advanced polymer composites will grow at the relatively high rate of about 15 percent per year in the next few years, with the fastest growing sector being the aerospace industry at 22 percent. By ***1995,*** consumption is forecast to be 110 million pounds with a value in ***1985*** dollars of about $6.5 billion. By the year 2000, consumption is estimated to be 200 million pounds valued at about $12 billion.[4]

If we divide these numbers to get a rough idea of the cost per pound of advanced composite material, we find a value of about $60/pound. This compares with a value of about $1/pound for steel or $1 .50/pound for FRP. If these forecasts are correct, it is clear that over this period advanced composites will be used primarily in high value-added applications which can support this level of material costs. However, we shall see that use of composites can lead to cost savings in manufacturing and service. Thus, the per-pound cost is rarely a useful standard for comparing advanced composites with traditional materials.

'Ibid, These are primarily epoxy matrices reinforced with carbon fibers.

[3]According to the market research firm, Strategic Analysis (Reading, PA) as reported in *High Technology,* May 1986, p. 72. Advanced composites were defined as those reinforced with S-glass or superior fibers.

"'Industry News, " *SAMPE Journal,* July August 1985, p. 89.

Composite Constituents

Matrix

The matrix determines the resistance of the composite to most of the degradative processes which eventually cause failure of the structure, including impact damage, delamination, water absorption, chemical attack, and high-temperature creep. Thus, the matrix is typically the "weak link" in the composite structure.

The matrix phase of commercial composites can be classified as either "thermoset" or "thermoplastic. " The general characteristics of each matrix type are shown in figure ***8;*** however, recently developed matrix resins have begun to change this picture, as noted below.

Thermosets. -Thermosetting resins include polyesters, vinylesters, epoxies, bismaleimides, and polyamides. Thermosetting polyesters are commonly used in FRPs, and epoxies make up most of the current market for advanced composite resins. Initially, the viscosity of these resins is low; however, these matrix materials undergo chemical reactions which crosslink the polymer chains, and thus connect the entire matrix together in a three-dimensional network. This process is called "curing. " Thermoses, because of their three-dimensional crosslinked structure, tend to have high dimensional stability, high temperature resistance, and good resistance to solvents. Recently, considerable progress has been made in improving the toughness of thermosets.[5]

'Norman J. Johnston, "Synthesis and Toughness Properties of Resins and Composites, " CP 2321, National Aeronautics and Space Administration, 1984.

Figure 8.—Comparison of General Characteristics of Thermoset and Thermoplastic Matrices

Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughened thermoset	↑			↑	
Lightly crosslinked thermoplastic		1	t		1
Thermoplastic	High	Low	Low	Low	High

SOURCE Darrel R Tenney NASA Langley Research Center

Thermoplastics.—Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyetherimide, polyamide imide, polyphenylene sulfide, polyether ether ketone (PEEK), and liquid crystal polymers. They consist of long, discrete molecules which melt to a viscous liquid at the processing temperature, typically **5000** to **700°** F **(260°** to 3710 C), and, after forming, are cooled to an amorphous, semicrystalline, or crystalline solid. The degree of crystallinity has a strong effect on the final matrix properties. Unlike the curing process of therrnosetting resins, the processing of thermoplastics is reversible, and, by simply reheating to the process temperature, the resin can be formed into another shape if desired. Thermoplastics, while generally inferior to thermosets in high-temperature strength and chemical stability, are more resistant to cracking and impact damage. However, it should be noted that recently developed high-performance thermoplastics such as PEEK, which have a semicrystalline microstructure, exhibit excellent high-temperature strength and solvent resistance.

Thermoplastics offer great promise for the future from a manufacturing point of view, since it is easier and faster to heat and cool a material than it is to cure it. This makes thermoplastic matrices attractive to high-volume industries such as the automotive industry. Currently, thermoplastics are used primarily with discontinuous fiber reinforcements such as chopped glass or carbon/graphite. However, there is great potential for high-performance thermoplastics reinforced with continuous fibers. For example, thermoplastics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft.

Reinforcement

The continuous reinforcing fibers of advanced composites are responsible for their high strength and stiffness. The most important fibers in current use are glass, graphite, and aramid (other organic fibers, such as oriented polyethylene, are also becoming important). Advanced composites contain about **60** percent of reinforcing fiber by volume. The strength and stiffness of some continuous fiber composites are compared with those of sheet molding compound and various metals in figure 7. For example, unidirectional, high strength graphite/epoxy has over three times the specific strength and stiffness of common metal alloys.

Of the continuous fibers, glass has a relatively low stiffness; however, its tensile strength is competitive with the other fibers and its cost is dramatically lower. This combination of properties is likely to keep glass fibers the most widely used reinforcement for high-volume commercial composite applications. Only when stiffness or weight are at a premium will aramid and graphite fibers be used.

Interphase

The interphase of composites is the region where loads are transmitted between the reinforcement and the matrix. The extent of interaction between the reinforcement and the matrix is a design variable, and may vary from strong chemical bonding to weak frictional forces. This can often be controlled by using an appropriate coating on the reinforcing fibers. Generally, a strong interracial bond makes the composite more rigid, but brittle; a weak bond decreases stiffness, but enhances toughness. If the interracial bond is not at least as strong as the matrix, fracture and delamination will occur at the interphase under certain loading conditions. Frequently, the most desirable coupling is intermediate between the strong and weak limits. The bond is also critical to the long-term stability of the composite, playing a key role in fatigue properties, environmental behavior, and resistance to hot-wet conditions.

Properties of Polymer Composites

Composites are designed materials. This is really the fact that underlies their usefulness. Given the spectrum of matrix and reinforcement materials available, the composite properties can be optimized for a specific application. A composite can be designed to have zero coefficient of thermal expansion. It can be reinforced with combinations of fiber materials (hybrid composites) and geometries in order to optimize performance and minimize cost. The inherent anisotropy of the material means that the composite can have different properties in different directions. The design opportunities of PMC materials are just beginning to be realized.

Design, Processing, and Testing of Polymer Matrix Composites

Composites Design

Because of their larger number of components and anisotropic properties, polymer composites are inherently more complex than metals. In fact, composites are more accurately characterized as customized structures rather than materials. While the engineering properties of the homogeneous resins and fibers can be determined, the properties of the composite depend on the composition, fiber geometry, and the nature of the interphase. The categories of mechanical and physical properties used to characterize composites are carried over from the long engineering experience with metals. In many cases, however, properties which are meaningful in metals are not meaningful in composites. "Toughness" is such a property. In metals, where the dynamics of crack propagation and failure are relatively well understood, toughness can be defined relatively easily. In a composite, however, toughness is a complicated function of the matrix, fiber, and interphase, as well as the reinforcement geometry. The shear and compression properties of composites are also poorly defined.

In spite of many years of discussion about standardized test methods for measuring engineering properties, the composites community has not been able to reach a consensus on what it is that the existing tests actually measure. The Army's Materials Technology Laboratory (Watertown, Massachusetts) is currently developing MIL-17, a handbook on advanced composites which will begin to address the questions of how data on composites can be obtained and reported. At present, each company qualifies its material for each separate aerospace or defense application according to its own individual tests and procedures. Data on material properties are often developed under government contract (costing $100,000 to $200,000 and taking about 1 year), and companies are reluctant to share the results. Even when data are reported in the literature, the type of test used and the statistical reliability of the results are not reported with the data. While the lack of standards probably does not inhibit the expert designer of composite aerospace structures, standards could encourage the use of composites in industries such as construction, where designers have no familiarity with the materials.

Computer-Aided Design.—Inasmuch as composites are tailored to meet the design requirements of a particular structure, designers must rely on computer models to analyze and predict the behavior of composite structures using a database containing the properties of the resins, fibers, and unidirectional composites. Such models presuppose a scientific understanding of the underlying physical, chemical, and mechanical processes within the composite at a microscopic level, and the relations between these and the macroscopic properties. In general, this understanding does not exist; the most critical needs in this area are discussed below in the section on research and development priorities.

A number of models exist today to address the needs of composites designers. Elastic behavior modeling is fairly advanced, with programs available to analyze stress distributions and elastic deformation in complex three-dimensional shapes. Several models exist to predict failure in composite structures where the characteristics of the critical flaws are known. These are based on Linear Elastic Fracture Mechanics (LEFM), a body of theory developed to predict fracture in metals. Extension of LEFM to composites is controversial today, because the failure modes of composites are more complex than metals. Very little work has been done in modeling the long-term behavior of composites; for example, in the areas of fatigue, creep, and environmental degradation. Part of the reason for this is the lack of data on which to test and validate models.

In spite of the lack of modeling capability, experience to date has shown that designers and manufacturers can produce reliable composite structures. This is no doubt due to two factors. First, in the face of uncertainty, designers tend to "overdesign"; that is, to be too conservative in their use of material, to avoid any possibility of material failure. Second, composite structures have been extensively tested before use, ensuring that any potential problems show up during the tests. Thus, the composite materials themselves have been proven, in the sense that structures can be fabricated which are reliable and meet all design criteria. However, both overdesign and empirical testing are costly and drive up the prices of composites. The principal benefit of enhanced modeling capability will be to help to make composites more cost competitive.

Manufacturing of Polymer Composite Structures

Given the many different fibers and matrices from which composites can be made, the subject of PMC manufacturing is an extremely broad one. However, more than any other single area, low cost manufacturing technologies are required before composites can be utilized more widely. The basic steps include: impregnation of the fiber with the resin; forming of the structure; curing (thermoset matrices) or thermal processing (thermoplastic matrices); and finishing. Depending on the process, these steps may occur separately or simultaneously. For example, the starting material for many composites is a "prepreg"; i.e., a fiber tape or cloth which has been preimpregnated with resin and partially cured. Therrnoset prepregs may be stored in the freezer for up to 12 months prior to use. Some of the more important fabrication processes for composites are listed in table 12.

Nondestructive Evaluation (NDE) of Polymer Matrix Composites

In general, polymer composites do not have as great a tendency to brittle fracture as do ceramics. This means that the critical flaw size in large PMC structures may be of the order of centimeters, while in ceramics it is some tens of micrometers. PMC structures are increasingly used in life-critical structures such as aircraft wings and fuselages.

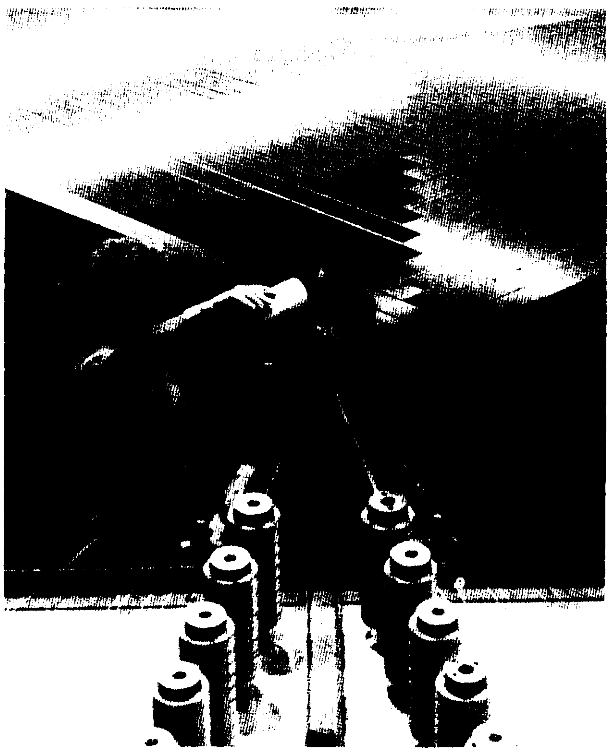


Photo credit: Hercules, Inc.

Filament winding of a rocket motor case.

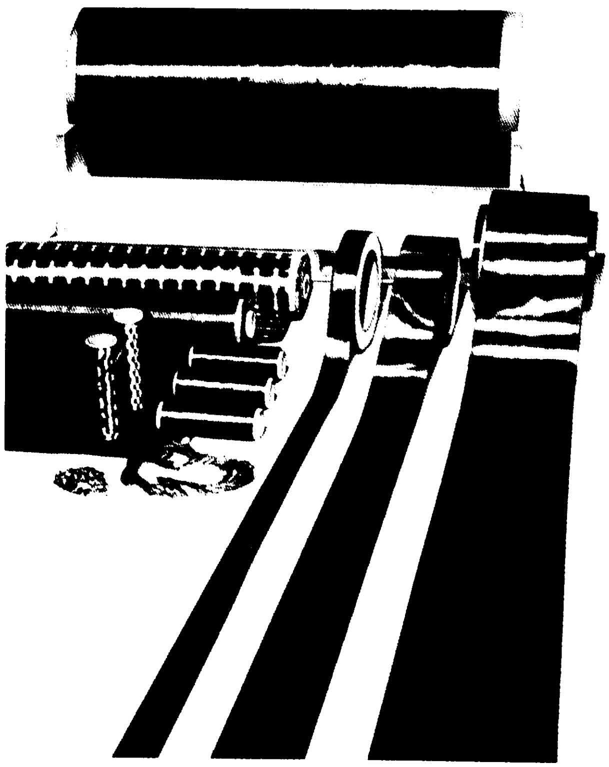


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Table 12.— Production Techniques for Polymer Composites

Technique	Characteristics	Examples
Sheet molding	Fast, flexible, 1 -2" fiber	SMC automotive body panels
Injection molding	Fast, high volume very short fibers, thermoplastics	Gears, fan blades
Resin transfer molding	Fast, complex parts, good control of fiber orientation	Automotive structural panels
Prepreg tape layup	Slow, laborious, reliable, expensive (speed improved by automation)	Aerospace structures
Pultrusion	Continuous, constant cross-section parts	l-beams, columns
Filament windlng	Moderate speed, complex geometries, hollow parts	Aircraft fuselage, pipes, drive shafts
Thermal forming (future)	Reinforced thermoplastic matrices, fast, easy repair, joining	All of above

SOURCE Off Ice of Technology Assessment

This places a special burden on NDE, both in the factory and in the field.

Although NDE is now used primarily for the detection of defects in finished structures, in the future it will be used increasingly for monitoring the status of composites at intermediate steps in the production process. Progress in this field will require development of sophisticated sensors and feedback control systems.

Requirements for NDE of composites differ somewhat from those of ceramics. While the flaw sizes to be detected are not as small, the area of structure to be investigated is frequently much larger, up to hundreds of square feet. Thus, techniques are required which can rapidly scan large areas for flaws or damage. While there are numerous NDE techniques which may be useful in the laboratory for testing of small specimens for research purposes, relatively few are appropriate to production or field-level inspection. Several of the more important NDE techniques which are relevant to production, end product, and field level inspection are listed in table 13. Excellent progress has been made in production-level techniques such as ultrasonics, and manufacturers are confident that large composite surface areas can be inspected reliably and economically for such flaws as bulk delaminations.

The inspection and repair of composite structures (e.g., aircraft components) at the depot and field levels will require a substantial training program for inspectors unfamiliar with composites. All procedures must be standardized and straightforward, since in general composite experts will not be available. In the future, as inspection processes become fully computerized, this will be an excellent application for expert systems which can guide the operator through the process and alert him to any detected anomalies.

Table 13.—NDE Techniques Appropriate for Production, Finished Product, Depot, and Field-Level Inspections of Polymer Matrix Composite Structures

N DE technique	Flaw type	Sensitivity	Complex shapes	Development for commercialization
Production:				
Visual (remote) ... ... , . .	Fiber orientation Foreign material	good	good	none
Ultrasonic ., ...	Porosity, viscosity during cure	good	poor	extensive
Dielectrometry	Degree of cure	good	good	some
End product:				
Visual	surface	good	good	none
Ultrasonic	bulk	good	poor	some
Radiographic	bulk	fair	excel lent	none
Acoustic emission ., ...	bulk	fair	good	extensive
Depot level:				
Ultrasonic ., ...	bulk delamination	good	poor	some
Field level:				
Ultrasonic	bulk delamination	fair	Door	extensive

SOURCE Joseph A. Moyzis, et al , "Nondestructive Testing of Polymer Matrix Composites," a contractor report prepared for OTA, December 1985

Health and Safety

There are a number of unique health and safety issues associated with the manufacture of composite materials. The health hazards stem from the fact that chemically active materials are used and workers handling them may breathe harmful fumes or come in contact with irritating chemicals. The chemical of greatest concern is the styrene monomer used in polyester resins. The problem is most severe when the resin is sprayed, and the monomer evaporates into the air. Inhalation of styrene monomer can cause headaches, dizziness, or sore throat; some people become sensitized to the vapors and can no longer work in a reinforced plastics plant.

The Occupational Safety and Health Administration has specified that styrene monomer concentrations in a plant should not exceed 100 parts per million.[6] In a plant where spray systems are used, extensive air handling equipment, spray booths, and air masks are required to maintain these standards. Where polyester resins are used for compression molding, resin transfer molding, or other enclosed mold systems, the problem can be dealt with by simple exhaust systems.

A new safety hazard was introduced with the advent of carbon fibers, which tend to float around a plant where they are used and, because they are electrical conductors, can get into unprotected electrical devices to cause short circuits. The fiber concentration in the air can be controlled by a negative pressure exhaust system in the area where they are used, but all electrical devices in the area should be sealed (explosion proof).

Recycling and Disposal of Composites

Most polymer composite materials in use today have thermosetting matrices, and after they have been cured, have no apparent scrap value. Although attempts have been made to grind them up and use them as fillers, this has not proven to be economically practical. The reuse of uncured FRP composites offers little economic incentive. Most scrap is simply discarded. One of the potential advantages of composites with thermoplastic matrices is that the scrap can be recycled.

[6] *World of Composites,* quarterly publication of the SPI Reinforced Plastics/Composites Institute, winter 1986.

Cured composites present no particular problem with disposal; they are chemically inert and can be used for land fill. Burning them can generate toxic smoke, and so is generally avoided.

The principal problem of disposal arises with uncured composites. Wet lay-ups, prepregs, SMC, etc., are still chemically active and pose both health and safety problems. If used in landfill, the active chemicals can leach out and cause contamination of the soil or water. A more serious problem is that the catalyzed resins may go on to cure and generate an exotherm that causes spontaneous combustion or self-ignition. The safe way to dispose of uncured composite material is to first bake it until it is cured and then dispose of it.

Applications of Polymer Matrix Composites

Polymer matrix composites are a more mature technology than structural ceramics. With the experience gained in military applications such as fighter aircraft and rocket motor casings beginning in the 1970s, composites now have a solid record of exceptional performance and reliability, They are rapidly becoming the baseline structural material of the defense aerospace industry.

Becaues of their high cost, diffusion of advanced composites into the civilian economy is likely to be a "top-down" process, progressing from relatively high value-added applications such as aircraft to automobiles and then to the relatively "low-tech" applications such as construction. On the other hand, there is also a "bottom-up" process at work in which savings in manufacturing costs permit unreinforced engineering plastics and short fiber-reinforced composites to replace metals in applications where high strength and stiffness are not required. Use of sheet molding compound for automobile body panels is one example of this phenomenon.

Markets for Advanced Polymer Matrix Composites

Aerospace.—This sector has been estimated to consume as much as 80 percent of all high-performance PMCs.[7] Growth projections for aero-

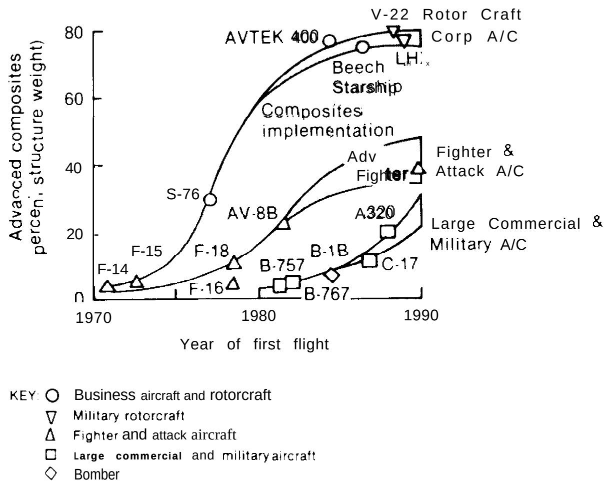
[7] According to the market study conducted by Business Communications Co., "Advanced Composites: An Evaluation of Commercial Prospects, " Stamford, CT, as reported in *World of Composites,* a publication of the Society of Plastics Industries, winter 1986, p. 4.

space usage of composites have ranged from 8.5 percent per year[8] to 22 percent per year.[9] The primary matrix materials in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e. g., Du Pent's "Kevlar 49"), and high-strength glass fibers. However, high-temperature thermoplastics such as PEEK are considered by many to be the matrices of choice for future aerospace applications. Composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for composites is in large military and commercial transport aircraft.

The principal advantages of PMCs in aerospace applications are their superior specific strength and stiffness compared with metals, resulting in weight savings of 10 to **60** percent over metal designs, with **20** to **30** percent being typical.[10] This weight reduction can be used to increase range, payload, maneuverability and speed, or reduce fuel consumption. It has been estimated that a pound of weight saved on a commercial transport aircraft is worth $100 to **$300** over its service life, depending on the price of fuel, among other factors.[11] This high premium for weight saved is unique to this sector, and explains why it leads all others in growth rate. Additional advantages of PMCs are their superior fatigue and corrosion resistance, and vibration damping properties.

Military *Aircraft.—Advanced* composites have become essential to the superior performance of a large number of fighter and attack aircraft (figure 9). Indications are that composites may account for up to 40 percent of the structural weight of the Advanced Technology Fighter (ATF), which is still in the design phase. Because the performance advantages of composites in military aircraft more than compensate for their high cost,

Figure 9.—Composite Aircraft Structure (by **percent)**



SOURCE. Richard N Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structure of High Performance Aircraft, " a presentation to the National Research Council, Aeronautics and Space Engineering Board Naval Postgraduate School, Monterey, CA, Feb 10, 1986

this is likely to be the fastest growing market for advanced composites over the next decade. One estimate, which assumes only existing production plus the ATF, projects a growth from about **0.3** million pounds per year in 1985 to 2 million pounds per year in 1995.[12]

Commercial Aircraft. —If glass fiber reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft.[13] In *current* commercial transport aircraft, such as the Boeing **767,** composites make up about **3** percent of the structural weight, and are used exclusively in the secondary (not flight-critical) structure.[14] However, several companies, including Beech and Avtek, are awaiting FAA approval of "all composite" business aircraft prototypes, which utilize composites in the wings, empennage, and fuselage.[15]

[8] According to the market study conducted by Frost & Sullivan, 'Worldwide High Performance Composites, " New York, as reported in *World of Composites,* a publication of the Society of Plastics Industries, winter 1986, p. *4.*

[9] According to a market study by Charles H. Kline & Co., "Advanced Polymer Composites, " Fairfield, NJ, as reported in *Plastics Engineering,* June 1985, p. 62.

[10] Carl Zweben, "polymer Matrix Composites, " *Frontiers in Materials Technologies,* M.A. Meyers and O.T. Inal (eds.) (The Netherlands: Elsevier Science Publishers, 1985), p. 365.

[11] Bob Hammer, Boeing Commercial Aircraft Co., personal communication, August 1986.

[12] Richard N, Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structures of High Performance Aircraft, " a presentation to the National Research Council, Aeronautics and Space Engineering Board, Naval Postgraduate School, Monterey, CA, Feb. 10, 1986.

[13] Ibid.

[14] Darrel R, Tenney, NASA Langley Research Center, "Advanced Composite Materials: Applications and Technology Needs, " presentation to the Metal Properties Council, Inc., Miami, FL, Dec. 5, 1985.

[15] Hadcock, op. cit. , Feb. 10, 1986.

Photo credit" Hercules, Inc.

A modern lightweight fighter incorporating 64 different components—more than 900 pounds of composite structure per airplane.

Although growth of the business aircraft fleet over the next 5 years is expected to be only around 10 percent, two categories (turboprops and turbojets) are expected to grow significantly. " These aircraft are also the best candidates for composite fuselages. The estimated value (derived from cost and volume estimates) of composite fuselages, assuming all business aircraft manufacturers adopt this technology, is about $100 million a year.[17] These fuselages could account for 1.2 million pounds of graphite/epoxy consumption annually. Large transport or commercial aircraft fuselages will probably not be made from advanced composites until the technology is demonstrated in business aircraft.

By the year **2000,** composites could make up 65 percent of the structural weight of commercial transport aircraft.[18] Estimating a structural weight of 75,000 pounds per aircraft and production of 500 aircraft per year, this application alone should account for 24 million pounds of advanced composite per year. Assuming a starting material value of $60/lb, the market in the year **2000** is valued at about $1.5 billion for the composite material alone. A more conservative estimate, which assumes that no new commercial aircraft will be built by 1995, has placed the U.S. composite commercial airframe production at between 1 and 2 million pounds in that year.[19]

Helicopters.–With the exception of the "all-composite" business aircraft prototypes, which are still awaiting certification, composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of composites are much the same as in aircraft: weight reduction, parts consolidation, and fatigue and corrosion resistance. Over the past 15 years, composites have become the baseline materials for rotors, blades, and tail assemblies. Sikorsky's **S-76** commercial model, which is about **25** percent composite by weight (figure 9), was certified in the late 1970s. Future military helicopters, such as the Army's LHX (with major airframe design teams at Bell/McDonnell Douglas and Boeing/Sikorsky), or the Navy's tilt-rotor V-22 "Osprey" (designed by Bell/Boeing), have specifications which force designers to consider composites, which are likely to comprise up to 80 percent of the structural weight (figure 9). Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while the less stiff glass/epoxy composites will be used in the rotor systems. As with aircraft, there could be a long-term trend away from epoxy resins and toward thermoplastic resins.

Automotive Industry .—The automotive industry is widely viewed as being the industry in which the greatest volume of advanced PMC materials will be used in the future. Because the industry is mature and highly competitive, the principal motivation for introducing composites is cost savings. In contrast to the aircraft industry, there is no clear-cut premium associated with a pound of weight saved. Nevertheless, Detroit continues to be interested in saving weight as it pursues the conflicting goals of larger automobiles and higher fuel efficiency. Automakers are looking to the vehicle skin/frame systems to provide the next big leap in weight reduction. Other potential advantages of composites, such as corrosion resistance, appear to be secondary to the cost issue.

"Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites, " Massachusetts Institute of Technology, a contractor report prepared for the Office of Technology Assessment, December 1985.

[17] Ibid.

[18] Tenney, op. cit. , Dec. 5, 1985.

[19] Hadcock, op. cit., Feb. 10, 1986.

By far the greatest volume of composite material is sheet molding compound (SMC) used in exterior panels.[20] The most visible automotive use of SMC in recent years is the Pontiac Fiero, which has an all composite exterior. The Fiero is constructed with a steel "space frame" superstructure to which the composite body panels are attached. By using different composite exterior panels, automakers can achieve model differentiation for limited production runs (100,000 to **200,000** units) while avoiding the prohibitive tooling costs which would be involved with use of steel. Automobile companies have adopted the space frame concept and will be using PMC materials for exterior panels in the future. In the short run, these will be mostly SMC.

The next major opportunity for composites in automobiles is in structural components.[21] Two structural components currently in service are the composite drive shaft and leaf spring. Some **3,000** drive shafts manufactured by filament winding graphite and E-glass fibers in a polyester resin are used annually in the Ford Econoline van.[22] Also, glass fiber reinforced plastic leaf springs in the Corvette and several other models are in production at the rate of approximately **600,000** per year. Leaf springs are regarded as a very promising application of composites, and are expected to show strong growth, especially in light trucks. Prototype primary body structures have been constructed with weight savings of **20** percent or more.

[20] Materials Modeling Associates, op. cit., December 1985.
[21] P. Beardmore, "Composite Structures for Automobiles," *Composite Structures* 5:163-176, *1986.*

Photo credit *Ford* Motor Co

Compression molded composite rear floor pan prototype for the Ford Escort. Ten steel components were consolidated into a single molding, with 15 percent weight savings.

Advance engineering groups within the Big Three automobile producers are targeting the mid-1990s to launch composite unibody vehicles.[23] Initially, composite unibodies will appear in limited production, in models like the Corvette or Fiero. Annual production should be in the range of **25,000** to 100,000 vehicles. It is likely that a composite unibody would not look like a conventional metal unibody, but would have a shape more consistent with the requirements of the manufacturing process used; resin transfer molding or filament winding would be two candidate Drocesses. However, an estimate of the amount of composite material required can be obtained from the following. A typical mid-size, stamped steel unibody weighs between 500 and **600** pounds. It is expected that the equivalent composite system will weigh **25** to **45** percent less. Based on these assumptions, consumption of composites will amount to about 12,000 tons in the first full year, which represents about 10 percent of current reinforced plastic consumption in the domestic automotive sector. Estimating the value of composite unibodies at $6/lb, the estimated market would be about **$150** million for these components alone.[24]

The automakers are exploring composite unibodies for a variety of reasons. Composite vehicles would enable designers to reduce the number of parts required in assembly; some manufacturers are looking into a one-piece composite structure. By reducing the number of parts, better consistency of parts can be achieved at considerably reduced

[22] Although composite drive shafts are technically successful, Ford will take them out of production in 1987 in favor of a new aluminum design
[23] Materials Modeling Associates, op. cit., December *1985.*
[24] Ibid.

assembly costs. Composites also offer substantial improvements in specific mechanical properties, with the possibility of reducing weight while increasing strength and stiffness. Finally, PMCs offer greatly improved corrosion resistance over steel or galvanized steel, since they do not rust. Observers have estimated that composite automobiles could last **20** or more years, compared to the current average vehicle lifetime of 10 years.[25]

Without question, the major technical barrier to use of PMCs in the automotive industry is the lack of manufacturing technologies capable of matching the high production rates of metal stamping technology. The fact that steel parts can be stamped in seconds while plastics mold in minutes has led to lower production costs for steel. A major reason behind the increased use of plastics in automobiles is that the time of manufacture has fallen, not the cost of the equipment, tools, or materials. The fastest current technologies can process material at the rate of tens of pounds per minute, while true economy will require rates of 100 pounds per minute or more.[26] Thus, there is a gap of roughly an order of magnitude between current and economical rates.

If composites are used extensively in automobile unibodies, there could be large, secondary economic effects. These would involve the automobile producers and suppliers, the service network, and those involved in disposal of automobiles.

Auto producers will have to build new facilities or modify existing physical plant in order to fabricate composite unibodies in-house. Alternatively, they may elect to outsource the molding operations. This would lead to the creation of new specialized composites molding businesses, similar to the custom molders of plastics which now serve Detroit. Production lines would have to be altered to accommodate different processes for joining components together. Segments of the automobile service network would be directly affected by a change to composite unibodies. Body shops would have to change their repair procedures, or switch from repairing to replacing damaged parts. Rust-proofing services might be eliminated altogether.

Finally, an all-composite unibody will greatly reduce the supply of steel scrap and may render the recycling of automobiles unprofitable. Should this occur, disposing of millions of auto hulks per year could become a national problem. In addition, since steel minimills use steel scrap as their starting material, they might be placed in jeopardy.

Reciprocating Equipment.—PMC materials have considerable potential for use in many different kinds of high-speed industrial machinery. Current applications include such components as centrifuge rotors, weaving machinery, hand-held tools, and robot arms. All of these applications take advantage of the low inertial mass, but they also benefit to various extents from the tailorable anisotropic stiffness, superior strength, low thermal expansion, fatigue life, and vibration damping characteristics of composites.

The productivity of robotic work stations and flexible manufacturing cells could be improved if robots could operate at higher speeds with more accurate endpoint positioning, Stiffness is the key mechanical property, since the endpoint accuracy is limited by bending deflections in the beam-shaped robot members. With metal designs, stiffness is obtained at the cost of higher mass, which limits the robot response time. Consequently, the ratio of the weight of the manipulator arm to that of the payload is rarely lower than 10:1.[27] Because of their superior stiffness per unit weight, composites are a promising solution to this problem. At present, only one U.S. company[28] has marketed a robot incorporating composites, although there are several Japanese models and a number of other countries are funding research.

Although the benefits of using composites in reciprocating equipment are clear, initial attempts to penetrate this market have been disappointing. The market is a highly fragmented one, and equipment manufacturers, who tend to be oriented

[25] Ibid.

[26] Charles Segal, President, Omnia, Raleigh, NC, in OTA workshop on "Future Applications of Advanced Composites," Dec. 10, 1985.

[27] B.S. Thompson and C.K. Sung, "The Design of Robots and Intelligent Manipulators Using Modern Composite Materials," *Mechanism & Machine Theory* 20: 471-482, 1985.

[28] Graco Robotics of Lavonia, Michigan manufactures a spray painting robot with a hollow graphite/epoxy arm. However, this arm is being phased out in favor of a new aluminum design.

toward metals, have shown a reluctance to consider the use of a higher cost material (particularly when its use requires new processes and tooling) even when performance advantages are demonstrated. No attempt has been made to quantitatively estimate future markets. Composite penetration is likely to be slow but steady.

Shipping and Storage.—Plastics have long been known to be inert to chemical attack from a wide variety of substances. This has made them useful as containers for many corrosive chemicals. With the addition of fiber reinforcement, the increased strength makes them suitable for large structures such as large diameter pipe, holding tanks, and pressure vessels. One generic limitation of composites for these applications is temperature. As the structures are generally made out of glass fiber reinforced polyester or epoxy, the maximum service temperature is about ***3000*** F ***(1490 C).*** A further potential problem is that the glass fibers are subject to corrosive attack if the matrix cracks and exposes them to water or other chemicals. Assuming fiber cost reductions can be achieved, use of corrosion-resistant graphite or ceramic fiber reinforcement could be a promising solution to this problem in the future.

Pipe. -Glass fiber reinforced plastic (FRP) pipes have major applications in the oil and the chemical process industry. The demand for composite pipe is directly affected by the level of economic activity within these industries. Chemical manufacturing expenditures have been decreasing over the past few years, and low oil prices have brought acquisition of new oil field equipment to a halt. Consequently, the demand for fiberglass-reinforced pipe in these sectors has been declining. 29

Industry sources predict that any growth in the demand for composite pipe will come from the petroleum industry. One high-volume application which has shown strong growth is pipe used in pumping of gasoline. It is expected that fiberglass-reinforced pipe will penetrate 15 to 30 percent of the oil field market in such applications as sucker rods, downhole tubing, and casing, However, growth in these areas is predicated on rising oil prices. The FRP pipe industry is approximately 30 years old. It saw tremendous growth until 1980, but is now leveling off. A maximum of ***5*** percent annual growth is expected .30

Storage Tanks.—FRP has captured about 40 percent of the market for underground tanks for storing fuel and corrosive chemicals and could increase its market share to about 80 percent over the next 5 to 10 years.[31] FRP underground tanks are expected to last at least 30 years, compared with 13 to 15 years for bare steel.

Above-ground tanks for storage of oil, chemicals, and food represent a large potential market for FRP. Above-ground tanks smaller than about 12 feet in diameter or less than 30 feet high are predominantly FRP, but for larger tanks, the difficulty of manufacturing, handling, and shipping with FRP makes steel the more economical material.

Composites could be used widely in the future for portable storage tanks and pressure vessels. The two properties of greatest importance are corrosion resistance and light weight. In Europe today there are currently some 20,000 tanker trucks which use an FRP shell reinforced by a steel frame. In the United States there is one prototype tanker which utilizes a reinforcement combination of chopped glass fiber and glass filament wound layers.[32] The standard tanker design for hauling corrosive chemicals (a business which accounts for about 5 percent of the total shipping market), is stainless steel lined with rubber, epoxy, or glass. These liners must be replaced every 1 to 5 years, at considerable expense. The composite tanker can be produced for approximately the same price as the steel design, and, based on the European experience and the performance record of underground composite tanks, it is expected to last longer, reduce costs, and increase safety. As of September ***1984,*** composite tanker trucks were approved by the Department of Transportation for travel on U.S. roads; however, the difficulty of obtaining insurance continues to be a serious barrier to use of composite tankers .33

Material Modeling Associates, op. cit., December 1985.

[30] Ibid.

[31] *World of* Composites, o. cit,, winter 1986, P. 8.

[32] Joseph M. Plecnik, et al., "Composite Tanker Trucks Have Made the Grade, " Plastics Engineering 41(3):63-65, March 1985.

[33] Joseph M. Plecnik, Department of Civil Engineering, Long Beach State University, personal communication, August 1986.

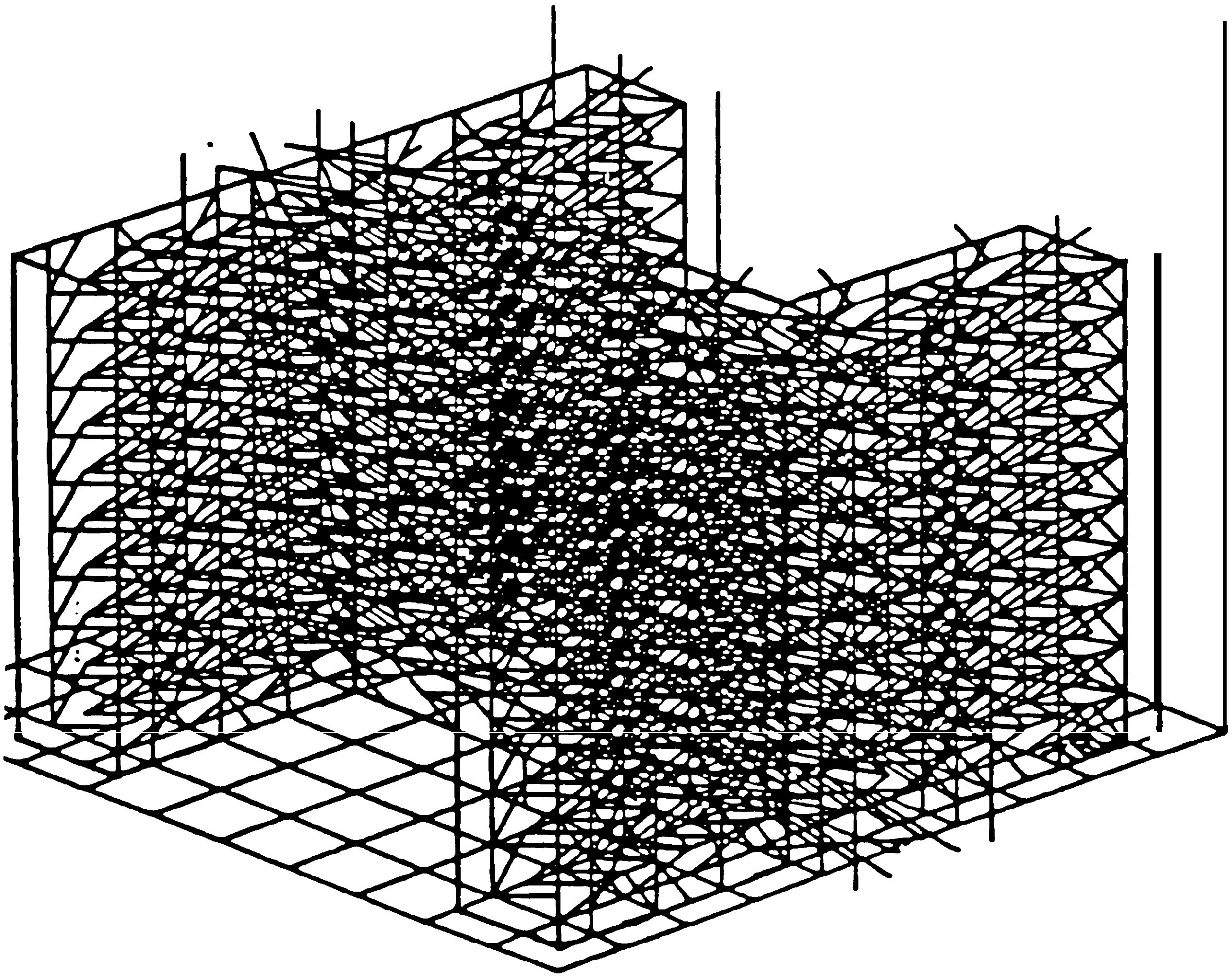


Photo credit: The CUMAGNA Corp.

Computer trace of fiber paths in a three-dimensional braided I-beam. This process yields a composite I-beam which is strong in all directions, but which weighs much less than steel.

Construction.—Construction applications are potentially a very significant opportunity for composites. For example, most highway bridges in the United States are over 35 years old, and most railroad bridges are over 70 years old.[34] Replacing or refurbishing even a small fraction of these with composite materials would involve a substantial volume of fiber and resin. However, significant technical, economic, and institutional barriers exist to the implementation of this technology, such that construction opportunities should be viewed as long term.

A potentially high-volume market for composites is in construction of buildings, bridges, and housing. Additional applications include lamp posts, smokestacks, and highway culverts. Construction equipment, including cranes, booms, and outdoor drive systems, could also benefit from use of composites. Because of the many inexpensive alternative building materials currently being used, cost of the PMC materials will be the key to their use in this sector. The chief advantage of composites would be reduced overall systems costs for erecting the structure, including consolidation of fabrication operations, reduced transportation and construction costs due to

[34] John Scalzi, National Science Foundation, personal communication, August 1986.

lighter weight structures, and reduced maintenance and lifetime costs due to improved corrosion resistance.[35]

Bridges are likely to be the first large scale construction application for polymer composites. The U.S. Department of Transportation is currently evaluating composites for use in bridge decking and stay cables.[36] Fiberglass tendons are also being used in place of steel in prestressed concrete bridge structures. ” Other countries which have active programs in this area include the Peoples' Republic of China, England, West Germany, Israel, and Switzerland. Because the largest load which must be supported by the bridge is its own dead weight, use of light weight composites would allow the bridge to accommodate increased traffic or heavier trucks. Decking materials are likely to be relatively inexpensive vinylester or epoxy resins reinforced with continuous glass fibers. Cables would probably be reinforced with graphite or aramid fibers, because of the high modulus and low creep requirements.

The manufactured housing industry is an especially intriguing potential opportunity for composite materials. In 1984, almost half of all new housing units were partially manufactured; i.e., large components were built in factories, rather than assembled onsite.[38] In the future, factory manufacture of housing promises to reduce housing costs while still maintaining options for distinctive designs. Composite manufacturing techniques such as pultrusion and transfer molding could be used to fabricate wall structures containing structural members and panels in a single step, Components such as I-beams, angles, and channels can also be economically produced by these techniques. In spite of the opportunities, however, Japan and several countries in Europe are far ahead of the United States in composite housing construction technologies.

An important research need affecting the use of composites in construction applications has to

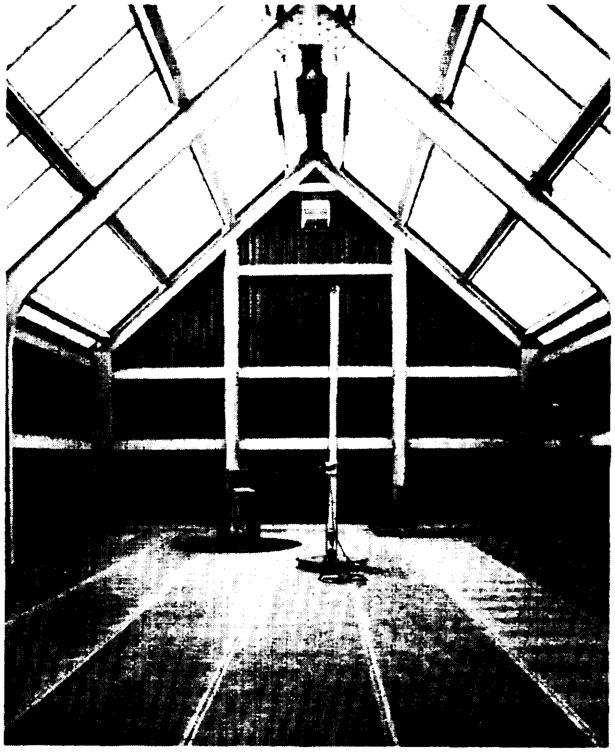


Photo credit: Composite Technology, Inc

Interior of a nonmetallic, nonmagnetic structure built for Apple Computer, Inc., to house a microwave device testing facility. The building components, including fasteners, are entirely made of fiber-reinforced composites.

do with adhesion and joining. The joining of composite materials to other materials for the purpose of load transfer, or to themselves for the purpose of manufacturing components, requires advances in technology beyond present levels. This is a particular obstacle when joining may be done by unskilled labor.

An additional technical barrier is need for development of design techniques for integrated, multifunctional structures. Window frames, which are made by joining together several pieces of wood, can be replaced by molded plastic and composite structures having many fewer pieces, lower assembly costs, and better service performance. The flexibility of the design and manufacture of composite materials could also be used to integrate a window frame into a larger wall section, again reducing the number of parts and the cost of manufacture, This has been done for certain experimental bathroom structures where lavato-

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“Howard Smallowitz, “Reshaping the Future of Plastic Buildings, ” *Civil Engineering,* May *1985,* pp. 38-41.

“According to information provided by Craig A. Ballinger, Federal Highway Administration, August 1986.

“*Engineering News Record,* Aug. 29, 1985, p. 11.

“Thomas E. Nutt-Powell, “The House That Machines Built, ” *Technology Review, Nov. 1985,* p. *31.*

ries, shower rooms, and other structural components have been integrated in a single molding.[39]

The principal barriers to the adoption of new materials technologies in the construction industry in the United States are not so much technological as institutional and economic. Like the highway construction industry discussed above, the housing construction industry is highly fragmented. This makes the rate of R&D investment and adoption of new technology very low. The performance of housing materials is regulated by thousands of different State and local building and fire safety codes, all written with conventional materials in mind. Further, engineers and contractors lack familiarity with the composite materials and processes. Finally, composites must compete with a variety of low-cost housing materials in current use. As a result, composites used in manufactured housing are not likely to be "advanced"; rather, they might consist of wood fibers pressed with inexpensive resins or laminated structures involving FRP skin panels glued to a foam or honeycomb core.

Medical Devices.—PMC materials are currently being developed for medical prostheses and implants. The impact of composites on orthopedic devices is expected to be especially significant. While medical devices are not likely to provide a large volume market for composites, their social and economic value are likely to be high. The total estimated world market for orthopedic devices such as hips, knees, bone plates, and intramedullary nails is currently about 6 million units with a total value of just over $500 million.[40] Estimates of the U.S. market for all biocompatible materials by the year 2000 have been quoted above as up to $3 billion per year.[41] Polymer composites could capture a substantial portion of that, sharing the market with ceramics and metals.

Metallic implant devices of this type, such as the total hip unit which has been used since the early *1960s*, suffer a variety of disadvantages: difficulty in fixation, allergic reactions to various metal ions, poor matching of elastic stiffness, and mechanical (fatigue) failure. Composite materials have the potential to overcome many of these difficulties. Not only can the problem of metal ion release be eliminated, but composite materials can be fabricated with stiffness which is tailored to the stiffness of the bone to which they are attached, so that the bone continues to bear load, and does not resorb (degenerate) due to absence of mechanical loading. This is a persistent problem with metal implants. It is also possible to create implants from biodegradable composite systems which would provide initial stability to a fracture but would gradually resorb over time as the natural tissue repairs itself. Finally, composites can be designed to serve as a scaffold for the invasive growth of bone tissue as an alternative to cement fixation. This leads to a stronger and more durable joint.

Research in composite orthopedic devices is currently being carried out on a relatively small scale in the labs of orthopedic device manufacturers. Further research is required to improve in situ strength and service life, stress analysis, and fabrication and quality control technologies.

In order to overcome the remaining technical barriers, a cooperative effort of an interdisciplinary team is required. At a minimum, the team must include expertise in design, engineering, manufacturing, and orthopedic surgery. Significant strides in this field are being made in Japan, the United Kingdom, France, Germany, Italy, Canada, and Australia, as well as in the United States.[42]

Future Trends in Polymer Matrix Composites

Novel Reinforcement Types

Rigid Rod Molecules.—Composites can be reinforced with individual rigid rod-like molecules or fibers generated from these molecules. One example is poly (phenylbenzobisthiazole), or PBT. Experimental fibers made from this material have specific strength and modulus on a par with the most advanced fibrous reinforcement, exceeding the properties of commercially available metals,

[39] Kenneth L. Reifsnider, Materials Response Group, Virginia Polytechnic Institute, "Engineering Research Needs of Polymer Composites, " a contractor report prepared for the Office of Technology Assessment, December *1985.*
[40] Ibid.
[41] Hench and Wilson, op. cit.

[42] Reifsnider, op. cit., December 1985.

including titanium, by over a factor of 10.[43] A particularly exciting possibility is dissolving the molecular rods in a flexible polymer, and thus creating a composite reinforced by individual molecules. Such a homogeneous composition would mitigate the problem of matching the thermal expansion coefficient between the reinforcement and the matrix, and would virtually eliminate the troublesome interface between them. The future of this technology will depend on solving the problems of effectively dissolving the rods in the "matrix" and on orienting them once dissolved.

Novel Matrices

Because the matrix largely determines the environmental durability and toughness, the greatest improvements in the performance of polymer composites in the future will come from new matrices, rather than new fibers. Perhaps the most significant opportunities lie in the area of molecular design; chemists will be able to design polymer molecules to have the desired flexibility, strength, high-temperature resistance, and adhesive properties .44 Some of the more promising directions are discussed below.

Oriented Molecular Structures. -At present the anisotropic properties of most composites are determined by the directions of fiber orientation. In the future, it may be possible to orient the individual polymer molecules during or after polymerization to produce a "self-reinforced" structure. The oriented polymers will serve the same reinforcing function as fibers do in today's composites. In effect, today's organic fibers (e.g., Du Pent's Kevlar or Allied's Spectra **900),** which consist of oriented polymers and which have among the highest specific stiffness and strength of all fibers, provide a glimpse of the properties which tomorrow's matrices might have.

Recently developed examples of oriented polymer structures are the liquid crystal polymers (LCPs). They consist of rigid aromatic chains modified by thermoplastic polyesters (e.g., poly - ethyleneterephthalate, or PET), or polyaramids, and have a self-reinforcing fibrous character which imparts strength and modulus comparable to those of reinforced thermoplastic molding compounds, such as **30** percent glass reinforced nylons." The fiber orientations of current LCPS are hard to control (current applications include microwave cookware and ovenware, which require high-temperature resistance but not high strength) and this represents a challenge for the future.

High-Temperature Matrices.—The maximum continuous service temperature of organic polymers in an oxidizing atmosphere is probably around **7000** F,[46] although brief exposures to higher temperatures can be tolerated. Currently, the most "refractory" matrices are polyamides, which can be used at temperatures of **600°** F (316° C), although slow degradation occurs." If stable, high-temperature matrices could be developed, they would find application in a variety of engine components and advanced aircraft structures.

Thermotropic Thermosets. -These hybrid matrices are designed to exploit the processing advantages of thermoplastics and the dimensional stability and corrosion resistance of thermoses. The molecules are long, discrete chains which have the latent capacity to form crosslinks. Processing is identical to thermoplastics in that the discrete polymers are formed at high temperatures to the desired shape. Then, however, instead of cooling to produce a solid, the structure is given an extra "kick," with additional heat or ultraviolet light, which initiates crosslinking between the polymer chains. Thus, the finished structure has the dimensional stability characteristic of a thermoset .[48]

[43] Thaddeus Helminiak, "Hi-Tech Polymers From Ordered Molecules, " Chemical *Week,* Apr. 11, 1984.

[44] Charles p, West, Resin Research Laboratories, Inc., Newark, NJ, personal communication, August 1986.

[45] Reginald B, Stoops, R.B. Stoops & Associates, Newport, RI, "Ultimate Properties of Polymer Matrix Materials, " a contractor report prepared for the Office of Technology Assessment, December 1985.

[46] Paul McMahan, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials, " Dec. 10, 1985.

[47] *Aerospace America,* May 1986, p. 22.

[48] John Riggs, Celanese Research Corp. in OTA workshop cited in footnote 46.

The Composites Factory of the Future

It is in the nature of advanced composites that they do not lend themselves to standard processes or manufacturing procedures. The very concept of tailoring a material to each specific application militates against standardization. It is therefore unlikely that we will see completely automated factories in the near future in which manufacturing instructions are fed in at one end and a composite part pops out the other, untouched by human hand.

Computer-Aided Design.—Computer-aided design (CAD) systems currently focus on three-dimensional graphics, and are often coupled with the capability for stress analysis of a structure. However, a comprehensive CAD system which would facilitate the process of choosing suitable materials, reinforcement geometry, and method of fabrication is still far in the future. Such a system would require an extensive database on fiber and resin properties, as well as a processing database which would permit modeling of the manufacturing steps necessary to fabricate the part, including the costs of those operations. The principal advantage of an integrated CAD system would be to clearly define the options and tradeoffs associated with various production strategies.

Computer-Aided Manufacturing.—Computer-aided manufacturing (CAM) would alter the processing of composites in several ways. Based on the instructions generated by the CAD system, numerically controlled machine tools would automatically machine molds contoured to the precise outline of the part. CAD instructions would guide automated lay-up of the part, and sensors embedded in the molds or in the materials themselves would make the entire manufacturing process an interactive one in which the computer controller would automatically adjust the processing variables based on real-time information about the state of the structure being fabricated. With the advent of robot-assisted manufacturing, NDE during the production cycle, performed with prcbes manipulated by the robot and analyzed by artificial intelligence, could become the way all high-value composite components are produced. Integration and miniaturization of sensors will lead to improvements in the quality and reliability of the information obtained from a nondestructive test.

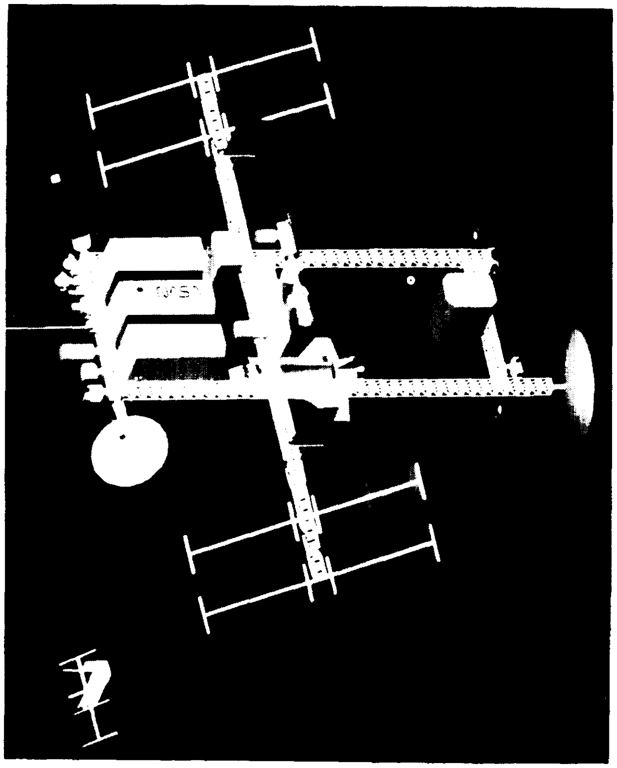
Nondestructive Evaluation.—Experience to date gives no indication that composite structures in service will require more frequent inspection than metal structures. In the future, it will be judged inconvenient to take composite systems out of service merely to inspect them for structural integrity. For such cases it will be necessary to have NDE performed continuously by devices that can sense changes in the mechanical properties which would precede a structural failure. These sensors would be included in the critical components during manufacture, and their signals would be examined regularly by a computer which would integrate the data, using AI, and decide whether to alert a human operator. A candidate NDE test for such a system is acoustic emission, in which the sound emitted by a composite structure under stress can be used to characterize the flaw population. Another possibility would be to include optically or electrically conducting fibers with the structural reinforcement; the degree of transmission of light or electric current by these fibers could be related to fiber breakage in the overall structure.

Thermal Forming.—With the increased use of advanced thermoplastic composites in the future, new thermal forming technologies will become important. The thermoplastic could be applied either as a hot melt or as a prepreg, which is relatively fast and easy to make with thermoplastics. Either method will require the development of new equipment capable of placing the fibers and compacting the structure while maintaining the process temperature.

Space

Space Transportation Systems.—over 10,000 pounds of advanced composites are used on the NASA space shuttle. ” Polymer composites are also being considered in designs for the proposed aerospace plane, although such an aircraft probably will not be available until after the year 2000. The primary limitation on the use of polymer composites in this application is high tempera-

‘* Tenney, op. cit. , Dec. 5, 1985.



Reference configuration for the NASA manned space station. Composites could be used in the tubular struts which make up the frame.

ture. '" Flying at speeds exceeding Mach 7, the lower surfaces and leading edges would experience temperatures of **2,0000** to 3,000 F (1,093 to 1,6490 C) .[51] If PMC materials were available which could retain high strength and stiffness up to 800° F (427° C), they could be used extensively for the cooler skin structure and most of the substructure.

Space Station.—Graphite /epoxy composites and aluminum are both being considered for the tubular struts in the space station reference design. The goal of reducing launch weight favors the use of composites; however, their lower thermal conductivity compared with aluminum could create problems in service. The most serious environmental problem faced by the composite is temperature swings between –250' F (–121" C) and +200" F (+93 °C) caused by periodic exposure to the sun. This thermal cycling produces radial cracks in graphite/epoxy tubes which can reduce the torsional stiffness by as much as **30** percent after only **500** cycles.[52] To reduce the effects of thermal cycling, the composite tubes would be coated with a reflecting, thermally conducting layer to equalize the temperature throughout the tube. The layer would also protect the composite from atomic oxygen, which is a major cause of material degradation in low earth orbit, as well as from solar ultraviolet radiation.

Military .—Composites of all types, including ceramic, polymer, and metal matrix composites, are ideal materials for use in space-based military systems, such as those associated with the Strategic Defense Initiative (SDI). " Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high temperature resistance are all necessary for structures which must maneuver rapidly in space, maintain high dimensional stability, and withstand hostile attack. A program devoted to the development of new materials and structures has recently been established within the SDIO. [54]

Bioproduction

Living cells can synthesize polymeric molecules with long chains and complex chemistries which cannot be economically reproduced in the laboratory. For example, crops and forests are an important source of structural materials and chernical feedstocks. A number of crops such as crambe, rapeseed, and various hardwood trees are now being evaluated for commercial production of lubricants, engineering nylons, and composites. 55 For some materials, such as natural rubber, the United States is totally dependent on foreign sources. Congress has mandated ("Critical Agricultural Materials Act, " Public Law 98-284, 1984) that the Department of Agriculture estab-

[50]Hadcock, op. cit., Feb. 10, 1986.
[51]Ibid.

[52] Tenney, op cit., Dec. 5, 1985

[53]Jerome Persh, ' Materials and Structure,\ Science and Technology Requirement\ for the DOD Strategic Defense Initiative *American Ceramic Society Bulletin* 64(4):555-559 1 985

[54]The effort includes: lightweight structures, thermal and electrical materials, optical materials and processes, tribological materials, and materials durability. Current budgets are about $2 million and are projected to reach $50 million in 1989.

[55]According to information supplied by the USDA's Office of Critical Materials.

lish an Office of Critical Materials to evaluate the potential of industrial crops to replace key imported materials. Several demonstration projects of 2,000 acres or more are planned for 1987.

With the possible exception of wood, it is unlikely that biologically produced materials will compete seriously with polymer matrix composites in the structural applications discussed in this report. Although natural polymers such as cellulose, collagen, or silk can have remarkably high strength, their low stiffness is likely to limit their use in many structures. Nevertheless, their unique chemical and physical properties make them appropriate for certain specialty applications. For example, collagen is a biologically compatible material which is being used to generate artificial skin.[56]

Biotechnology may offer a novel approach to the synthesis of biological polymers in the future. Genetically engineered bacteria and cells have been used to produce proteins related to silk.[57] In the future, production rates could be accelerated by extracting the protein synthetic machinery from the cells and driving the process with an external energy source, such as a laser or electric current.[58] The flexibility inherent in such a scheme would be enormous; by simply altering the genetic instructions, new polymers could be produced.

Research and Development Priorities for Polymer Matrix Composites

Federal R&D spending for polymer matrix composites in fiscal years 1985 and 1986 is shown in table 14; roughly 65 to 70 percent in each year was spent by the Department of Defense. The large drop in Federal expenditures from 1985 to 1986 does not reflect a sharp cut in composites R&D; rather, it can be attributed to the completion of large research programs in 1985 and the transitioning of the technology (particularly for carbon fiber composites) to private industry. Defense applications continue to drive the development of advanced composites, which are used in an estimated $80 billion of weapons systems.[59]

Table 14.—Budgets for Polymer Matrix Composite R&D in Fiscal Years 1985 and 1986 (millions)

Agency	FY 1985	FY 1986
Department of Defense[a] (6.1, 6.2, 6.3A)	55.9	29.2
National Aeronautics Space Agency[b]	23	8.7
National Science Foundation[c]	1-2	1-2
National Bureau of Standards[d]	0.4	0.4
Department of Transportation[e]	—	0.4
Total	80-81	40-41

SOURCES: [a]Jerome Persh, DOD
[b]Michael Greenfield, NASA
[c]Ranga Komanduri, NSF
[d]Leslie Smith, NBS
[e]Craig Ballinger, FHWA

Reliable composite structures can now be designed which satisfy all of the engineering requirements of a given application. However, scientific understanding of composites has lagged behind engineering practice; in order to design more efficiently and cost effectively, and to develop improved materials, it will be necessary to understand and model several important aspects of composites. Based on the opportunities outlined above, some research and development priorities for composites are suggested below.

Very Important

Processing Science.—The primary goal of processing science is to be able to control the fabrication process to assure complete and uniform cure, minimize thermal stresses, control resin content, and assure accurate fiber placement. This requires a model which can predict the influences of key process variables and techniques for monitoring these variables so that pressure and temperature can be adjusted accordingly. Such models would also provide useful guidelines for tool design. At present, modeling is in a very early stage of development.

The existence of low-cost fabrication processes will be critical to the use of new composite systems, such as low-cost, high-performance thermoplastics reinforced with continuous fibers. For

[56] J. Burke, et al., "The Successful Use of Physiologically Acceptable Artificial Skin in the Treatment of Extensive Bum In jury," *Annals of Surgery* 194:413-428, 1982.
[57] Dennis Lang, Syntro Corp., La Jolla, CA, personal communication, August 1986.
[58] Terence Barrett, National Aeronautics and Space Administration, personal communication, August 1986.
[59] Kenneth Foster, Assistant for Materials Policy, Department of Defense, personal communication, August 1986.

example, methods for fabricating shapes with double curvature are needed. Another important problem is the impregnation and wetting of fiber bundles by these relatively viscous plastics. The effect of processing on microstructure requires further study, as does the influence of residual thermal stresses. The latter is a particular concern for resins processed at high temperatures. Finally, as for thermoses, process models are required.

Impact Damage.—The impact damage resistance of a composite structure has a critical effect on its reliability in service. It has been shown that impact damage that is barely visible to the naked eye can cause a reduction in strength of as much as 40 percent.[60] Impact resistance is especially important in primary aircraft structures and other safety-critical components. Tougher thermoplastic matrix materials promise to improve the impact resistance of aircraft structures now made with epoxy matrices.

The complexity of the impact damage process makes modeling very difficult. However, it would be very desirable to be able to relate the extent of damage to the properties of the matrix, fiber, and interphase, along with factors like reinforcement form. This would facilitate the development of more reliable materials and structures. In addition, an understanding of impact damage mechanisms would aid in developing protocols for repair of composite structures, a field which largely relies on empirical methods.

Delamination. -There is a strong body of opinion that delamination is the most critical form of damage in composite structures (particularly those produced from prepregs). As noted above, impact damage barely visible on the surface can cause dramatic reductions in strength through local delamination. Delamination may prove to be a problem of increasing severity in the future, because of the trend toward higher working strains that tend to accentuate this mode of failure.

Analyses to date have concentrated on growth and failure associated with compressive loading. These need to be verified and refined. In addition, the effects of combined loading, resin fracture toughness, reinforcement form, and environment need to be investigated.

Interphase.—The interphase has a critical influence on the composite, since it determines how the reinforcement properties are translated into the composite properties. The characteristics of this little-studied region merit thorough investigation. The objective would be to develop a body of knowledge that would guide the development of fiber surface treatments, matrices, and fiber coatings that will optimize composite mechanical properties and provide resistance to environmental degradation.

Important

Strength.—The excellent strength properties of composites are one of the major reasons for their use. However, as with many properties of composites, their strong heterogeneity makes strength characteristics very complex. This heterogeneity gives rise to failure modes that frequently have no counterpart in homogeneous materials. Even in the simplest composites, unidirectional laminates, the relationships between axial and transverse loading (parallel and perpendicular to the fiber direction) and failure are not well understood. In more complex composites, containing several fiber orientations and various flaw populations, efforts to model strength have been largely empirical. It will be important in the future to have analytical models for the various failure modes of unidirectional composites and laminates that relate strength properties to basic constituent properties.

Fatigue.—Fatigue of composites is an important design consideration. Fatigue resistance is a major advantage which composites enjoy over metals; however, the traditional models for analyzing fatigue in metals do not apply to composites. The risks associated with fatigue failure are likely to increase because of the trend toward use of fibers with higher failure strains, and the desire to use higher design allowable for existing materials. Ideally, it would be desirable to be able to predict composite fatigue behavior based on constituent properties. A more realistic near-term objective is to understand fatigue mechanisms, and how they are related to the properties of fibers, matrix, interphase, loading, and environ-

[60] Carl Zweben, General Electric Co., "Assessment of the Science Base for Composite Materials, " a contractor report prepared for the Office of Technology Assessment, December 1985.

ment of the composite. Important topics which have not received adequate attention are the fatigue properties of the reinforcements and matrix resins, and compression fatigue of unidirectional composites. In view of the increasing interest in thermoplastics, fatigue of these materials also deserves study.

Fracture.—One of the most important modes of failure in metals is crack propagation. Arising at regions of high stress, such as holes, defects, or other discontinuities, cracks tend to grow under cyclic tensile load. When cracks reach a critical size, they propagate in an unstable manner, causing failure of the part in which they are located. This, in turn, may result in failure of the entire structure. In contrast, failure of composites often results from gradual weakening caused by the accumulation of dispersed damages, rather than by propagation of a single crack.

In view of the significant differences in failure modes between metals and composites, use of linear elastic fracture mechanics (LEFM) to describe fracture in these complex materials is controversial. It is open to question whether there are unique values of fracture toughness or critical stress intensity that describe the fracture characteristics of composites. In order to develop reliable design methods and improved materials in the future, it will be necessary to develop a body of fracture analysis which is capable of accounting for the more complex failure mechanisms.

Environmental Effects.—The environments to which composites are subjected can have a significant effect on their properties. Environments that are known to be especially damaging are those of high temperature and moisture under load, ultraviolet radiation, and some corrosive chemicals. The key need in the environmental area is to develop a thorough understanding of degradation mechanisms for fibers, resins, and interphases in the environments of greatest concern. This knowledge will lead to more reliable use of existing materials and provide the information required to develop new, more degradation-resistant ones.

Reinforcement Forms and Hybrid Composites. —There are two main reasons for the interest in new reinforcement forms: improved through-the-thickness properties, and lower cost. A pervasive weakness of composite laminates of all kinds is that the out-of-plane strength and stiffness, being dependent primarily on the matrix, are much inferior to the in-plane properties. This is because in convertional laminates there is no fiber reinforcement in the thickness direction.

New reinforcement forms under development include triaxial fabrics, multilayer fabrics, two-dimensional braids, three-dimensional braids, and various kinds of knits. In addition, laminates have been reinforced in the thickness direction by stitching. From an analytical standpoint, the major drawback to fabrics, braids, and knits is that they introduce fiber curvature, which can cause significant loss of strength, compared to a unidirectional laminate. However, multidirectional reinforcement appears to confer increased fracture toughness on the composite.

Use of several types of fibers to reinforce composites will be driven by the desire to obtain properties that cannot be achieved with a single fiber, and to reduce cost. For example, glass fibers, which are cheap but have a relatively low tensile modulus, can be mixed with more costly, high modulus graphite fibers to achieve a composite which is both stiff and relatively cheap.

With both new reinforcement forms and hybrid reinforcement, there is a great need for analytical methods to identify the configurations required to produce desired properties. Without such tools, it will be necessary to rely on intuition and time-consuming, costly empirical approaches.

Test Methods.—Reliable and standardized test methods are critical to the evaluation of all materials. For homogeneous materials such as metals, such methods are fairly straightforward. In composites, however, the macroscopic mechanical behavior is a complex summation of the behavior of the microconstituents. Consequently, there has been great difficulty in achieving a consensus on what properties are actually being measured in a given test, let alone what test is most appropriate for a given property. There are currently numerous test methods in use throughout the industry, and numerous private databases. This has resulted in considerable property variability appearing in papers and reports. The problem is particularly severe for toughness, bending, shear, and compression properties.

The movement to standardize composites testing began in **1969,** but has stalled in recent years.[61] Standardized methods of testing and reporting results are a prerequisite to the establishment of composite properties databases for design and process modeling. The lack of standards is also a significant barrier to the transfer of test results from one structural application to another.

Desirable

Creep Fracture.—Materials subjected to sustained loading fail at stress levels lower than their static strengths. This is called creep fracture. Topics which require study include tensile and compressive loading of both unidirectional composites and laminates, and the influence of temperature and environment. Since the time-dependent degradation of the matrix and interphase properties are typically greater than those of the fibrous reinforcements, particular attention should be paid to transverse matrix cracking and delamination.

Viscoelastic and Creep Properties.—The occurrence of significant deformation resulting from sustained loading can have an adverse effect on structural performance in some applications, such as reciprocating equipment, bridges, and buildings. Consequently, creep behavior is an important material characteristic. This subject could benefit from development of a database for creep properties of various fibers, matrices, and composites, especially for compressive loading, which has received relatively little attention.

“Kenneth L. Reifsnider, Virginia Polytechnic Institute, personal communication, August 1986.

GENERAL PREREQUISITES OF THE USE OF ADVANCED STRUCTURAL MATERIALS

Education and Training

The expanding opportunities for ceramics and composites will require more scientists and engineers with broad backgrounds in these fields. At present, only a handful of universities offer comprehensive curricula in ceramic or composite materials. There is also a shortage of properly trained faculty members to teach the courses. The job market for graduates with advanced degrees in ceramic or composite engineering is good, and can be expected to expand in the future. Stronger relationships between industry and university laboratories are providing greater educational and job opportunities for students.

There is a great need for continuing education and training opportunities for designers and engineers in industry who are unfamiliar with the new materials. In the field of polymer composites, for example, most of the design expertise is concentrated in the aerospace industry. Continuing education is especially important in "unsophisticated" industries such as construction, which must purchase, rather than produce, the products they use. Universities and professional societies are offering seminars and short courses to fill this gap; these opportunities should be publicized and made more widely available.

Beyond the training of professionals, there is a need for the creation of awareness of new materials technologies among technical editors, managers, planners, vice presidents, and the general public. In recent years, the number of newspaper and magazine articles about the remarkable properties of ceramics and composites has increased, as has the number of technical journals associated with these materials. The success of composite sports equipment, including skis and tennis rackets, shows that new materials can have a "high-tech" appeal to the public, even if they are relatively expensive.

Multidisciplinary Approach

Progress in materials development often requires a team effort. For example, for a typical ceramic component, the team might consist of one or more specialists from each of the disciplines in table 15. Materials research lends itself naturally to collaborative institutional arrangements in which the rigid disciplinary boundaries between different fields are relaxed. The successes of numerous multidisciplinary materials centers based at universities and national laboratories across the country reflect this fact. A consensus is developing within the materials community that the exploration of new mechanisms for collaborative work between university, industry, and government laboratory scientists and engineers would have a salutary effect on the pace of advanced materials development and utilization. This topic will be examined in greater detail in the final report.

Table 15.—Hypothetical Multidisciplinary Design Team for a Ceramic Component

Specialist	Contribution
Systems engineer	Defines performance
Designer	Develops structural concepts
Stress analyst	Determines stress for local environments and difficult shapes
Metallurgist	Correlates design with metallic properties and environments
Ceramist	Identifies proper composition, reactions, and behavior for design
Characterization analyst.	Utilizes electron microscopy, X-ray, fracture analysis, etc. to characterize material
Ceramic manufacturer	Defines production feasibility

SOURCE J.J Mecholsky, "Engineering Research Needs of Advanced Ceramics and Ceramic Matrix Composites, " contractor report for OTA, December 1985.

Integrated Design

Advanced ceramics and composites should really be considered structures rather than materials. Viewed in this light, the importance of a design process which is capable of producing highly integrated and multifunctional structures becomes clear. Polymer matrix composites provide a good example. Perhaps the greatest single economic advantage of composites, beyond their superior performance, is the potential for reduction in the cost of manufacture achieved by reducing the number of parts and operations required in fabrication. For example, a typical automobile has about ***1500*** structural parts. It has been estimated that, with an integrated composite design, this total could be reduced to a few hundred parts, with major savings in tooling and manufacturing costs.[62] Because composites can be tailored in so many ways to the various requirements of a particular engineering component, the key to optimizing cost and performance is a fully integrated design process which is capable of balancing all of the relevant design and manufacturing variables. Such a design process will require an extensive database on matrix and fiber properties, as well as sophisticated software capable of modeling fabrication processes and three-dimensional analysis of the properties and behavior of the resulting structure. Development of expert systems software for the design of both materials and structures will also be important, particularly for engineers who are new to the field. Perhaps the most important element in the development of integrated design algorithms will be an understanding of the relationships between the constituent properties, microstructure, and the macroscopic properties of the structure. Many of the research and development priorities listed above are intended to provide this information.

The view of ceramics and composites as structures also sheds light on the often-stated need for a "database" for design purposes. The discussion above suggests that the "customized" nature of advanced structural ceramics and composites militates against the very idea of standardized structures with specified properties which could be cataloged in a database. However, depending on the application, a two-tracked approach to standardization and data-collection may be the best overall solution. For design of integrated, multifunctional structures, the best approach may be a database containing the properties of constituents and unidirectional composites, coupled with standardized algorithms for modeling and analysis. Destructive testing of the finished structure would provide data to validate the models. For applications in which standard ceramic or composite components are desired, such as brackets, elbows, or beams, the properties and composition of the structures would be specified and standardized,

[62] Reifsnider, op. cit., December 1985.

Systems Approach to Costs

It is often stated that the three biggest barriers to the increased use of advanced materials are cost, cost, and cost. In a narrow sense, this observation is correct. If advanced materials are considered on a dollar-per-pound basis as replacements for steel or aluminum in existing designs, they cannot compete. This is very often the perspective of potential user industries, who are oriented toward metals processing, and has been the source of great frustration among ceramics and composites suppliers. However, the per-pound cost and part-for-part replacement are rarely valid bases for comparison. This is the reason that the costs of ceramics and composites have not been stressed in this report. A more fruitful approach is an analysis of the overall systems costs of a shift to advanced materials, including integrated design, fabrication, installation, and lifecycle costs.

The high per-pound cost of advanced materials is largely a result of the immaturity of the fabrication technology and the low production volumes. Large decreases in materials costs can be expected as the technologies mature. For example, a pound of standard high strength carbon fiber which used to cost $300 now costs less than $20, and new processes based on synthesis from petroleum pitch promise to reduce the cost even further.[63] If high-strength carbon fibers in the $3

[63] The world's foremost manufacturer of pitch-based carbon fiber, Kureha Chemical Industry Co. of Japan, has developed a new high-strength fiber said to cost one-third as much as polyacrylonitrile (PAN) -based fibers. See *Iron Age,* June 20, 1986, p. J6.

to $5 per pound range became available, major new opportunities would open up for composites in automotive, construction, and corrosion-resistant applications.

Two other economic factors which can affect the competitiveness of ceramics and composites deserve mention: they are energy costs and labor costs. The cost of the energy required to manufacture ceramic and composite components is a negligible fraction of the overall production costs; however, energy savings in service are a major reason for the use of advanced materials in such applications such as heat exchangers, engines, and transportation structures. Persistent low energy costs are likely to reduce the incentives to introduce advanced materials into these applications.

Throughout this report, the vision presented of the materials factory of the future has been one of extensive automation and computer-controlled processing. The reliability and reproducibility requirements of ceramic and composite structures demand a minimum of human intervention. These considerations indicate that the ceramics or composites factory of the future will not be a labor intensive operation. In fact, labor costs, which are currently a large fraction of overall production costs of advanced structures, are a key target for future cost reduction. Thus, rising labor costs could accelerate the utilization of ceramics and composites.

Technical, economic, and institutional factors will all influence the incorporation of ceramics and composites technologies into commercial production. Many of these factors have been discussed in this interim report. However, several key issues are mentioned without discussion. These include: the need for improved cooperation between industry, universities, and government labs; the dramatic changes which new materials will bring to manufacturing; and government policy options which could enhance the international competitiveness of United States advanced materials users and suppliers. The final report will explore these issues in detail.

GLOSSARY

adiabatic: Referring to any process in which there is no gain or loss of heat.

aggregate: Inert filler material such as sand or gravel used with a cementing medium to form concrete or mortar.

alloy: A material having metallic properties and consisting of two or more elements.

anisotropic: Showing different physical or mechanical properties in different directions.

aramid: Lightweight polyaromatic amide fibers having excellent high temperature, flame, and electrical properties. These fibers are used as high-strength reinforcement in composites.

brittle fracture: A break in a brittle material due to the propagation of cracks originating at flaws.

carbon / graphite: These fibers, which are the dominant reinforcement in "advanced" composites, are produced by pyrolysis of an organic precursor, e.g. polyacrylonitrile (PAN), or petroleum pitch, in an inert atmosphere. Depending on the process temperature, fibers having high strength or high elastic modulus may be produced.

cement: A dry powder made from silica, alumina, lime, iron oxide, and magnesia which forms a hardened paste when mixed with water; it may be used in this form as a structural material, or used as a binder with aggregate to form concrete.

ceramic: An inorganic, nonmetallic solid.

chemically bonded ceramics: Used here to distinguish advanced cements and concretes, which are consolidated through chemical reactions at ambient temperatures (generally involving uptake of water) from high-performance ceramics, such as silicon nitride and silicon carbide, which are densified at high temperatures.

chromatographic adsorption: Preferential adsorption of chemical compounds (gases or liquids) according to chemical affinity onto a solid adsorbent material.

composite: Any combination of particles, whiskers, or fibers in a common matrix.

compressive stress: A stress that causes an elastic body to shorten in the direction of the applied force.

concrete: A mixture of aggregate, water, and a binder (usually portland cement) which hardens to stonelike condition when dry.

consolidation of parts: Integration of a number of formerly discrete parts into a single part which encompasses several functions; a key advantage of engineered materials such as ceramics and composites.

continuous fiber: A reinforcing fiber in a composite which has a length comparable to the dimensions of the structure.

creep: A time-dependent strain of a solid, caused by stress.

cross-linking: The formation of chemical bonds between the formerly separate polymer chains.

crystal: A homogeneous solid in which the atoms or molecules are arranged in a regularly repeating pattern.

deflection: Deformation of a material produced without fracturing the material.

deformation, plastic deformation: Any alteration of shape or dimensions of a body caused by stresses, thermal expansion or contraction, chemical or metallurgical transformations, or shrinkage and expansions due to moisture change.

delamination: Separation of a layered structure into its constituent layers.

dielectric: A material which is an electrical insulator or in which an electric field can be sustained with a minimum dissipation in power.

diffusion: The movement of mass, in the form of discrete atoms or molecules, through a medium.

dispersion: Finely divided particles of one material held in suspension in another material.

ductility: The ability of a material to be plastically deformed by elongation without fracture.

E-glass: A borosilicate glass most used for glass fibers in reinforced plastics.

elasticity: The property whereby a solid material deforms under stress but recovers its original configuration when the stress is removed.

engineered materials: Materials whose physical and mechanical properties and function are tailored for a particular application.

extrusion: A process in which a hot or cold semisoft solid material, such as metal or plastic, is forced through the orifice of a die to produce a continuously formed piece in the shape of the desired product.

failure: Collapse, breakage, or bending of a structure or structural element such that it can no longer fulfill its purpose.

fatigue: Failure of a material by cracking resulting from repeated or cyclic stress.

filtration: A process of separating particulate matter from a fluid, by passing the fluid carrier through a medium that will not pass the particulate.

finishing: Final processing operations on a part.

flexure: Any bending deformation of an elastic body in which the points originally lying on any straight line are displaced to form a plane curve,

fracture stress: The minimum stress that will cause fracture, also known as fracture strength,

glass: A state of matter that is amorphous or disordered like a liquid in structure, hence capable of continuous composition variation and lacking a true melting point, but softening gradually with increasing temperature.

glass-ceramic: Solid material, partly crystalline and partly glassy, formed by the controlled crystallization of certain glasses.

grain: One of many crystallite comprising a poly - crystalline material.

green state, greenware: A term for formed ceramic articles in the unfired condition.

hardness: Resistance of a material to indentation, scratching, abrasion, or cutting.

heat treatment: Heating and cooling of a material to obtain desired properties or conditions.

holography: A technique for recording and later reconstructing the amplitude and phase distributions of a wave disturbance.

hot isostatic pressing: A form of ceramic or powder metallurgical forming or compaction process in which the mold is flexible and pressure is applied hydrostatically or pneumatically from all sides,

hot pressing: Forming a metal powder compact or a ceramic shape by applying pressure and heat simultaneously at temperatures high enough for sintering to occur.

impact strength: Ability of a material to resist shock loading,

inclusion: A flaw in a material consisting of a trapped impurity particle.

injection molding: Forming metal, plastic, or ceramic shapes by injecting a measured quantity of the material into shaped molds.

internal stress, residual stress: A stress system within a solid (e. g., thermal stresses resulting from rapid cooling from a high temperature) that is not dependent on external forces.

interphase, interface: The boundary layer between the matrix and a fiber, whisker, or particle in a composite.

lay-up: A process for fabricating composite structures involving placement of sequential layers of matrix-impregnated fibers on a mold surface.

load: The weight that is supported by a structure, or mechanical force that is applied to a body.

matrix: The composite constituent that binds the reinforcement together and transmits loads between reinforcing fibers.

metal: An opaque material with good electrical and thermal conductivities, ductility, and reflectivity; properties are related to the structure in which the positively charged nuclei are bonded through a field of mobile electrons which surrounds them, forming a close-packed structure.

microstructure: The internal structure of a solid viewed on a distance scale on the order of micrometers. The microstructure is controlled by processing, and determines the performance characteristics of the structure.

modulus of elasticity: A parameter characterizing the stiffness of a material, or its resistance to deformation under stress. For example, steel has a relatively high modulus, while Jello has a low modulus.

monolithic: Constructed from a single type of material.

near-net-shape The original formation of a part to a shape which is as close to the desired final shape as possible, requiring as few finishing operations as possible.

nondestructive testing, evaluation: Any testing method which does not involve damaging or destroying the test sample; includes use of X-rays, ultrasonics, magnetic flux, etc.

phase: A region of a material that is physically distinct and is homogeneous in chemical composition.

plasticity: The property of a solid body whereby it undergoes a permanent change in shape or size when subjected to a stress exceeding a particular value, called the yield value.

polymer: Substance made of giant molecules formed by the union of simple molecules (monomers); for example, polymerization of ethylene forms a polyethylene chain.

pore, porosity: Flaw involving unfilled space inside a material which frequently limits the material strength.

prepreg: Fiber reinforcement form (usually tape, fabric, or broadgoods) which has been preimpregnated with a liquid thermosetting resin and cured to a viscous second stage. Thermoplastic prepregs are also available.

proof test: A predetermined test load, greater than the intended service load, to which a specimen is subjected before acceptance for use.

radiography: The technique of producing a photographic image of an opaque specimen by transmitting a beam of X-rays or gamma rays through it onto an adjacent photographic film; the transmitted intensity reflects variations in thickness, density, and chemical composition of the specimen.

radome: A strong, thin shell made from a dielectric material, used to house a radar antenna,

reciprocating (engine or machinery): Having a motion that repeats itself in a cyclic fashion.

refractory: Capable of enduring high-temperature conditions.

S-glass: A magnesia-alumina-silicate glass that provides very high tensile strength fiber reinforcement. Often regarded as the reinforcement fiber dividing "advanced" composites from reinforced plastics.

shearing stress: A stress in which the material on one side of a surface pushes on the material on the other side of the surface with a force which is parallel to the surface.

sintering: Method for the consolidation and densification of metal or ceramic powders by heating without melting.

slip casting, slip, slurry: A forming process in the manufacture of shaped refractories, cermets, and other materials in which slip is poured into porous plaster molds. Slip or slurry is a suspension of ceramic particles in water with a creamy consistency.

strain: Change in length of an object in response to an applied stress, divided by undistorted length.

stress: The force acting across a unit area in a solid material in resisting the separation, compacting, or sliding that tends to be induced by external forces.

structural materials or assembly: Those parts of a system that support most of the loading on the whole system.

substrate: Base surface on which a material adheres, for example a surface to be coated.

systems approach (to cost or to design): Consideration of product design, manufacture, testing, and lifecycle as an indivisible whole; see *comoliclation* of *parts*.

tensile strength, ultimate tensile strength: The maximum stress a material subjected to a stretching load can withstand without breaking.

thermal conductivity: The rate of heat flow under steady conditions through unit area per unit temperature in the direction perpendicular to the area—the ability of a material to conduct heat.

thermoplastic resin: A material containing discrete polymer molecules that will repeatedly soften when heated and harden when cooled; for example, polyethylene, vinyls, nylons, and fluorocarbons.

thermosetting resin: A matrix material initially having low viscosity that hardens due to the formation of chemical bonds between polymer chains. Once cured, the material cannot be melted or remolded without destroying its original characteristics; examples are epoxies, phenolics, and polyamides.

toughness: A parameter measuring the amount of energy required to fracture a material in the presence of flaws.

tribology: The study of the phenomena and mechanisms of friction, lubrication, and wear of surfaces in relative motion.

turbocharger: A centrifugal air compressor driven by the flow of exhaust gases and used to increase induction system pressure in an internal combustion reciprocating engine.

ultrasonic testing: A nondestructive test method that employs high-frequency mechanical vibration energy to detect and locate structural discontinuities or differences and to measure thickness of a variety of materials.

unibody: Integrated structure containing the chassis as well as elements of the body of an automobile.

viscoelasticity: Property of a material that is viscous but which also exhibits certain elastic properties such as the ability to store energy of deformation, and in which the application of a stress gives rise to a strain that approaches its equilibrium value slowly.

wear: Deterioration of a surface due to material removal caused by relative motion between it and another material.

nettability: The ability of any solid surface to be wetted when in contact with a liquid.

whisker: A short, single crystal fiber with a length-to-diameter ratio of 10 or more, often used to improve the fracture toughness of ceramics.

yield strength: The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic.