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.