Chapter 1

Executive Summary

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INTRODUCTION

During the past 25 years, unprecedented progress has been made in the development of new structural materials. These materials, which include advanced ceramics, polymers, metals, and hybrid materials derived from these, called composites, open up new engineering possibilities for the designer. Their superior properties, such as the high temperature strength of ceramics or the high stiffness and light weight of composites, offer the opportunity for more compact designs, greater fuel efficiency, and longer service life in a wide variety of products, from sports equipment to high performance aircraft. In addition, these materials can lead to entirely new military and commercial applications that would not be feasible with conventional materials. A graphic example is the construction of the composite airplane Voyager, which flew nonstop around the world in December 1986.

In the next 25 years, 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 systems–e.g., aircraft and automobiles—i n which they are incorporated. Given this multiplier effect, it is likely that the application of advanced structural materials will have a dramatic impact on gross national product, balance of trade, and employment in the United States. All of the industrialized countries have recognized these opportunities and are competing actively for shares of the large commercial and military markets at stake.

As indicated in table 1-1, Congress has long been concerned with materials issues, dating back to the Strategic War Materials Act of 1939. Through the 1950s, legislation continued to focus on ensuring access to reliable supplies of strategic materials in time of national emergency. The 1970s saw legislative interest broaden to include the economic and environmental implications of the entire materials cycle, from mining to disposal.

Table 1-1 .—U.S. Materials and Minerals Legislation

Strategic War Materials Act–1939
53 Stat. 811
Established the National Defense Stockpile, intended to accumulate a 5-year supply of critical materials for use in wartime or national emergency.

Strategic and Critical Materials Stockpiling Act—1946
60 Stat. 596
Authorized appropriation of money to acquire metals, oils, rubber, fibers, and other materials needed in wart i me.

Defense Production Act— 1950
64 Stat. 798
Authorized the President to allocate materials and facilities for defense production, to make and guarantee loans to expand defense production, and to enter into long-term supply contracts for scarce materials.

Resource Recovery Act— 1970
Public Law 91-512
.Established the National Commission on Materials Policy to develop a national materials policy, including supply, use, recovery, and disposal of materials.

Mining and Minerals Policy Act– 1970
Public Law 91-631
Encouraged the Secretary of the Interior to promote involvement of private enterprise in economic development, mining disposal, and reclamation of materials.

Strategic and Critical Stockpiling Revision Act—1979
Public Law 96-41
Changed stockpile supply period to 3 years, limited to national defense needs only; established a stockpile transaction fund.

National Materials Policy, Research and Development Act– 1980
Public Law 96-479
Directed the President to assess material demand, supplies, and needs for the economy and national security; and to submit a program plan to implement the findings of the assessment.

National Critical Materials Act— 1984
Public Law 98-373
Established the National Critical Materials Council in the Executive Office of the President; the Council was authorized to oversee the development of policies relating to both critical and advanced materials; and to develop a program for implementing these policies.

SOURCE Office of Technology Assessment, 1988

In 1984, these concerns were extended to encompass advanced materials with the National Critical Materials Act (Public Law 98-373, Title II). In this Act, Congress established the National Critical Materials Council in the Executive Office of the President and charged it with the responsibility of overseeing the formulation of policies relating to both "critical" and "advanced" materials. The intent was to establish a policy focus above the agency level to set responsibilities for developing materials policies, and to coordinate the materials R&D programs of the relevant agencies.

With the passage of the National Critical Materials Act, Congress formally recognized that a domestic advanced materials manufacturing base will be critical for both U.S. industrial competitiveness and a strong national defense, and that progress in achieving this objective will be strongly influenced by Federal policies. Congressional interest in advanced materials technologies has centered on several key issues:

1. What are the major potential opportunities for advanced structural materials, and what factors will affect the time required to realize these opportunities?
2. What will be the impact of advanced materials on manufacturing industries in the United States?
3. What is the competitive position of the United States in these technologies, and what trends are likely to affect this position?
4. How can the federally funded advanced materials R&D in universities and Federal laboratories be used more effectively to boost the competitiveness of U.S. firms?
5. What are the implications of the large military role in advanced materials development for the commercial sector?
6. What policy options does the Federal Government have to accelerate the commercialization of advanced materials technologies?

These questions comprise the framework of this assessment.

NEW STRUCTURAL MATERIALS

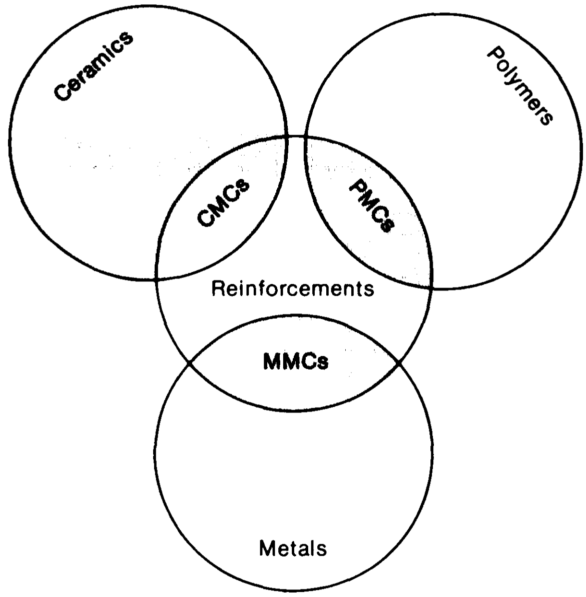
New structural materials can be classified as ceramics, polymers, or metals, as shown in figure 1-1. Two or more of these materials can be combined together to form a composite that has properties superior to those of its constituents. Composites generally consist of fibrous or particulate reinforcements held together by a common matrix, as illustrated in figure 1-2. Continuous fiber reinforcement enhances the structural properties of the composite far more than particles do. However, fiber-reinforced composites are also more expensive and difficult to fabricate.

Composites are classified according to their matrix phase. Thus, there are ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Materials within these categories are often called "advanced" if they exhibit properties, such as high temperature strength or high stiffness per unit weight, that are significantly better than those of more conventional structural materials, such as steel and aluminum. This assessment focuses on advanced structural ceramics (including CMCs), PMCs, and MMCs. New metal alloys and unreinforced engineering plastics, which may also legitimately be considered advanced materials, are not covered.

Figure 1-3 compares the maximum use temperatures of the three primary categories of structural materials. Organic materials such as polymers generally melt or char above 600° F (3160 C); the most refractory metals lose their useful strength above 1900° F (10380 C); ceramics, however, can retain their strength above 30000 F (1649° C) and can potentially be useful up to 5000° F (2760° C). In applications such as heat engines and heat exchangers, in which efficiency increases with operating temperature, ceramics offer potential energy savings and cost savings through simpler designs than would be possible with metals.

Figure 1-4 compares the "specific" strength and stiffness (strength and stiffness per unit weight) of some advanced materials with those of conventional metals. The specific stiffness of aluminum can be increased by a factor of 3 by mixing the metal with 50 percent by volume silicon car-

Figure 1-1.—The Family of Structural Materials



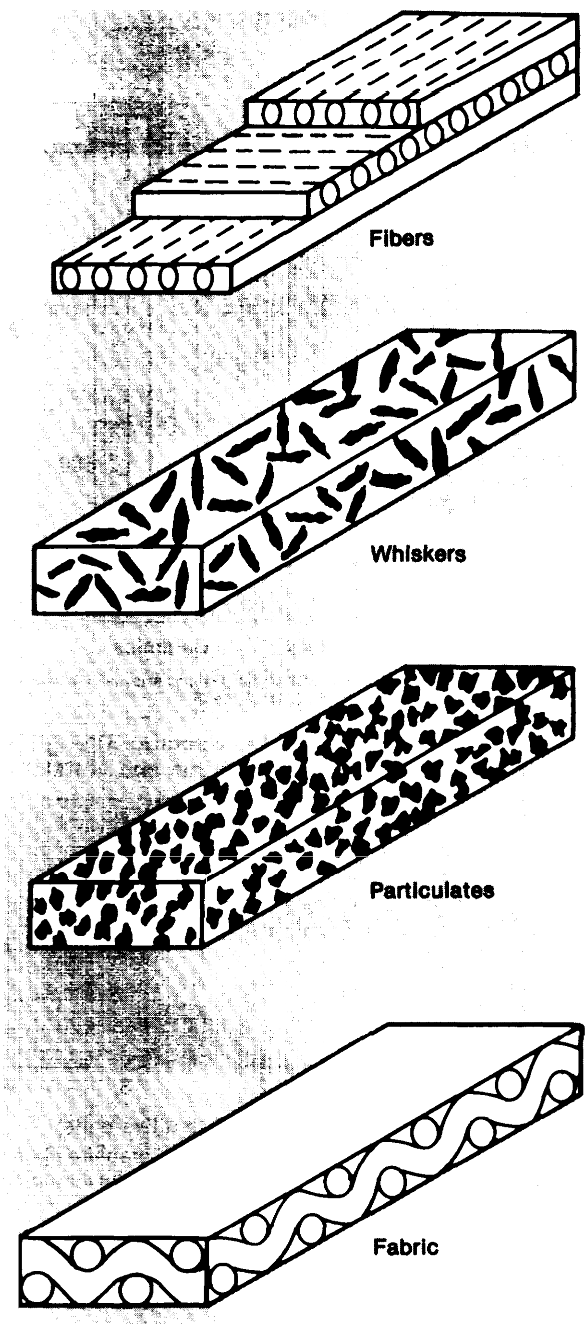
Includes ceramics, polymers, and metals. Reinforcements added to these materials produce ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Materials in the shaded regions are discussed in this assessment.

SOURCE: Office of Technology Assessment, 1968.

bide fibers to form an MMC. Even more impressive are PMCs such as graphite fiber-reinforced epoxy (graphite/epoxy), which may have specific strengths and stiffnesses up to 4 times those of steel and titanium (measured along the direction of fiber reinforcement). Such properties make it possible to build composite structures having the same strength and stiffness as metal structures but with up to 50 percent less weight, a major advantage in aircraft and space applications.

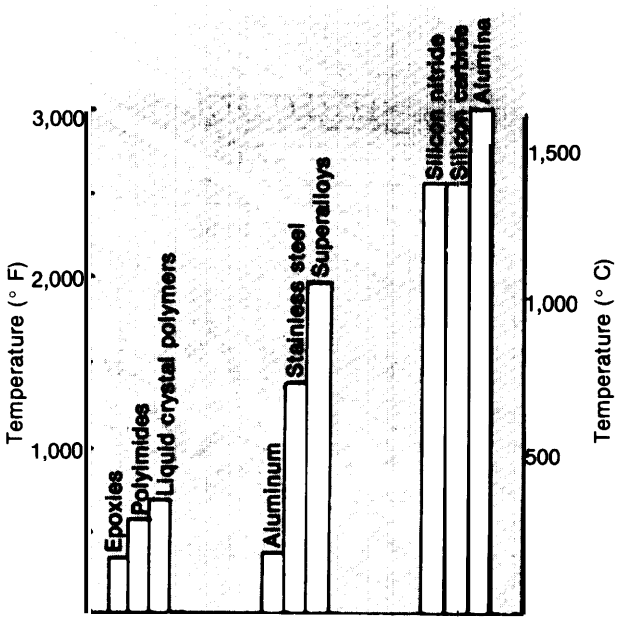
Although the physical and mechanical properties of ceramics and composites are impressive, the true hallmark of these advanced materials is that they are "tailored" materials; that is, they are built up from constituents to have the properties required for a given application. Furthermore, a composite structure can be designed so that it has different properties in different directions or locations. By judicious use of fiber or other reinforcement, strength or stiffness can be enhanced only in those locations where they are most needed. Great efficiencies of design and cost are made possible by this selective placement of the reinforcement.

Figure 1-2.—Composhe Reinforcement Types



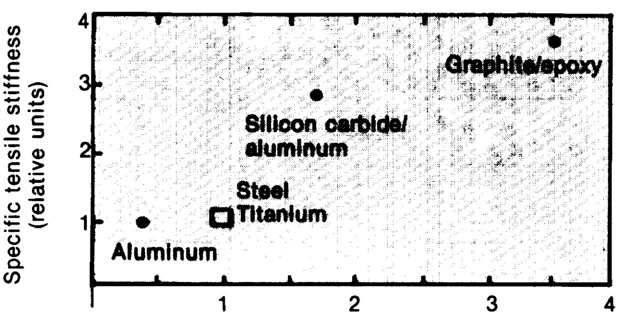
SOURCE: Carl Zweben, General Electric Co.

Figure 1-3.—Maximum Use Temperatures of **Various Structural Materials**



SOURCE: "Guide to Selecting Engineered Materials," a special issue of Advanced *Materials and Processes, vol. 2, No.* 1, 1967.

Figure 1-4.–Comparison of the Specific Strength and Stiffness of Various Composites and Metals[a]



Silicon carbide fiber-reinforced aluminum and graphite fiber-reinforced epoxy composites exhibit many times the strength and stiffness of conventional metals.

[a]Specific properties are ordinary properties divided by density. Properties are measured along the direction of fiber reinforcement.
[b]Steel: AISI 304; Aluminum: 6061-T6; Titanium: Ti-6A1-4V).

SOURCE: Carl Zweben, General Electric Co.

The development of advanced materials has opened a whole new approach to engineering design. In the past, the designer has started with a material and has selected discrete manufacturing processes to transform it into the finished structure. With the new tailored materials, the designer starts with the final performance requirements and literally creates the necessary materials and the structure in an integrated manufacturing process. Thus, with tailored materials, the old concepts of materials, design, and fabrication processes are merged together into the new concepts of integrated design and manufacturing.

These technologies differ greatly in their levels of maturity; e.g., PMCs are by far the most developed, whereas CMCs are still in their infancy. In addition, the applications and market opportunities for these materials vary widely. For these reasons, the three primary categories of materials treated in this assessment are discussed separately below.

Ceramics

Ceramics encompass all solids that are neither organic nor metallic. Compared with metals, ceramics have superior wear resistance, high temperature strength, and chemical stability; they also generally have lower thermal conductivity, thermal expansion, and lower toughness (i.e., they tend to be brittle). This brittleness causes them to fail catastrophically when applied stress is sufficient to propagate cracks that originate at microscopic flaws in the material. Flaws as small as 20 micrometers (about one one-thousandth of an inch) can reduce the strength of a ceramic component below useful levels.

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. Another 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.

Market Opportunities for Ceramics

Market demand for structural ceramics is not driving their development in most applications at the present time. In 1987, the U.S. market for advanced structural ceramics was estimated at only $171 million, primarily in wear-resistant applications. Projections to the year 2000, though, place the U.S. market between $1 billion and $5 billion annually, spread among many new applications discussed below.

Early estimates that projected a $5 billion U.S. market for ceramics in automotive heat engines (gasoline, diesel, or gas turbine) by the year 2000 now appear to have been too optimistic. More recent estimates indicate that the U.S. ceramic heat engine market in the year 2000 will be less than $1 billion, However, a large number of other commercial applications for ceramics are possible over this time period; examples are given in figure 1-5.

Current Production

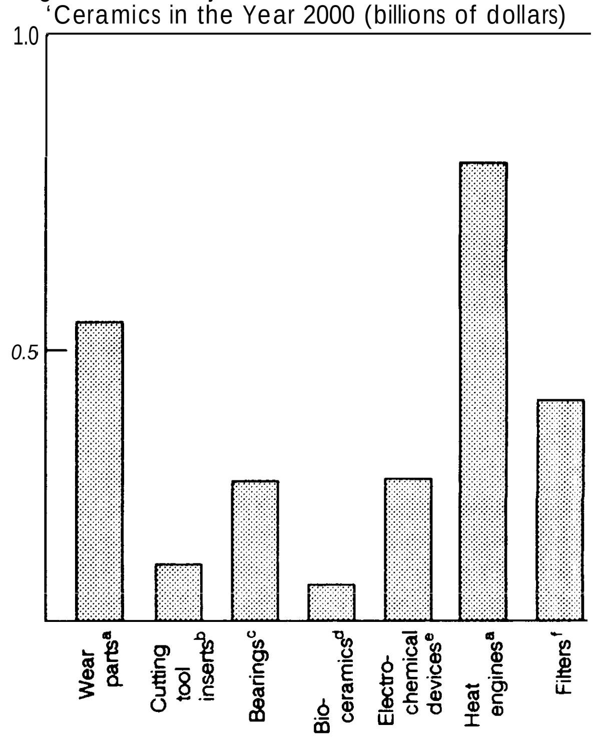
Ceramics such as aluminum oxide, silicon nitride, and silicon carbide are in production for wear parts, cutting tool inserts, bearings, and coatings. The market share for ceramics in these applications is generally less than 5 percent, but substantial growth is expected. The U.S. markets for the ceramic components alone could be over $2 billion by the year 2000. R&D funding is currently being provided by industry and is driven by competition in a known market. Current military applications in the United States include radomes, armor, and infrared windows.

Ceramics are also in limited production (in Japan) in discrete engine components such as turbochargers, glow plugs, rocker arms, and precombustion chambers, as well as a number of consumer products.

Near-Term Production

Near-term production (the next 10 to 15 years) is expected in advanced bearings, bioceramics (ceramics used inside the body), construction applications, heat exchangers, electrochemical devices, discrete components in automobile engines, and military applications, Large markets are at stake. The technical feasibility has been demonstrated, but scale-up, cost reduction, and design optimization are required before U.S. industry will invest large sums in the needed research. In the meantime, government funding will be required to supplement industry R&D in order to

Figure 1-5.—Projected U.S. Markets for Structural 'Ceramics in the Year 2000 (billions of dollars)



SOURCES: [a] U S Department of Commerce, "A Competitive Assessment of the U S Advanced Ceramics Industry" (Washington, DC, U S Government Printing Office, March 1964)

[b] E.P. Rothman, J. Clark, and H.K. Bowen, Ceramic Cutting Tools: A Production Cost Model and an Analysts of Potential Demand," Advanced Ceramic Materials, American Ceramics Society, Vol 1, No 4, October, 1986, pp. 325-331

[c] High Technology, March 1986, p. 14

[d] Business Communications Co, Inc, as reported in Ceramic Industry, Jan 1988, p 10

[e] 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 1965

[f] Assumes a doubling from 1986 Paul Hurley, 'New Filters Can Clean Up in New Markets," High Technology, August 1987

achieve a production capability competitive with foreign sources.

Far-Term Production

Far-term applications (beyond 15 years) of ceramics will require solution of major technical and economic problems. These include an advanced automotive turbine engine, an 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 far-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.

Polymer Matrix Composites

PMCs consist of high strength short or continuous fibers which are held together by a common organic matrix. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the fiber reinforcement.

PMCs are often divided into two categories: reinforced plastics and so-called "advanced composites." The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no clear-cut line separating the two. Plastics reinforced with relatively low-stiffness glass fibers are inexpensive, and 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 are used primarily in the aerospace industry, have superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers (e.g., high stiffness glass, graphite, aramid, or other organic fibers). In this assessment, only market opportunities for advanced composites are considered.

Chief among the advantages of PMCs is their light weight coupled with high stiffness and strength along the direction of reinforcement. Other desirable properties include superior resistance to corrosion and fatigue. One generic limitation of PMCs is temperature. An upper limit for service temperatures with present composites is about 600° F (316 o C). With additional development, however, temperatures near 800° F (427° C) may be achieved.

Market Opportunities for Polymer Matrix Composites

About 85 percent of PMCs used today are glass fiber-reinforced polyester resins. Currently, less than 2 percent of PMCs are advanced composites such as those used in aircraft and aerospace applications. However, U.S. production of advanced PMCs is 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 projected to grow by as much as 22 percent annually in the next few years.

Current Production

Aerospace applications of polymer composites account for about 50 percent of current PMC sales in the United States. Sporting goods, such as golf clubs and tennis rackets, account for 25 percent. The PMC sporting goods market is considered mature, however, with projected annual growth rates of only 3 percent. Automobiles and industrial equipment round out the current list of major uses of advanced composites, with a 25 percent share.

Near-Term Production

Advanced PMCs were introduced into the horizontal stabilizer of the F-14 fighter in 1970, and they have since become the baseline materials in high-performance fighter and attack aircraft. The major near-term challenge for composites will be use in large military and commercial transport aircraft. Advanced PMCs currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757, but that fraction could eventually rise to more than 65 percent in new transport designs.

The single largest near-term opportunity for PMCs is in the manufacture of automobiles. Composites currently are in limited production in body panels, drive shafts, and leaf springs. By the late 1990s, composite automobile bodies could be introduced by Detroit in limited production. The principal advantage of a composite body would be the potential for parts consolidation, which could result in lower assembly costs. Composites can also accommodate styling changes with lower retooling costs than would be possible with metals.

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

Far-Term Production

Beyond the turn of the century, PMCs could be used extensively in construction applications such as bridges, buildings, manufactured housing, and marine structures where salt water corrosion is a problem. Realization of this potential will depend on development of cheaper materials, changes in building codes, and of designs that take advantage of compounding benefits of PMCs, such as reduced weight and increased durability. In space, a variety of composites will be used in the proposed National Aerospace Plane, and they are also being considered for the tubular frame of the National Aeronautics and Space Administration's (NASA) space station. Composites of all kinds, including MMCs, PMCs, and CMCs would be a central feature of space-based weapons systems, such as those under consideration for ballistic missile defense.

Metal Matrix Composites

MMCs usually consist of a low-density metal such as aluminum or magnesium reinforced with particulate or fibers of a ceramic material, such as silicon carbide or graphite. Compared with the unreinforced metal, MMCs have significantly greater stiffness and strength, as indicated in figure 1-4; however, these properties are obtained at the cost of lower ductility and toughness.

Market Opportunities for Metal Matrix Composites

At present, metal matrix composites remain primarily materials of military interest in the United States, because only the Department of Defense's (DoD) high-performance specifications have justified the materials' high costs. The future commercial markets for MMCs remain uncertain for two reasons. First, their physical and mechanical properties rarely exceed those of PMCs or CMCs. For example, the melting point of the metal matrix keeps the maximum operating temperature for MMC components to a level significantly below that of ceramics; as new high-temperature PMCs are developed, this squeezes further the temperature window in which MMCs have an advantage. Also, because the density of the metal matrix is higher than that of a polymer matrix, the strength-to-weight ratio of MMCs is generally less than that of PMCs (figure 1-4).

A second source of uncertainty relates to cost. MMCs tend to cluster around two extreme types: one type consists of high-performance composites reinforced with expensive continuous fibers and requiring expensive processing methods; the other consists of relatively low-cost, low-performance composites reinforced with relatively inexpensive particulate and fibers. The cost of the first type is too high for any but military or space applications, whereas the cost/benefit advantages of the second type over metal alloys remain in doubt.

Photo credit United Technologies Research Center

Fracture surface of boron fiber-reinforced aluminum metal matrix composite.

Thus, it is unclear whether MMCs will become the materials of choice for a wide variety of applications or whether they will be confined to specialty niches in which the combinations of properties required cannot be satisfied by other materials. The key factors will be whether the costs of the reinforcements and of the manufacturing processes can be reduced while the properties are improved. Costs could be reduced substantially if net-shape processes currently used with metals, such as casting or powder techniques, can be successfully adapted to MMCs.

Current Production

Current markets for MMCs are primarily in military and aerospace applications. Experimental MMC components have been developed for use in aircraft, jet engines, missiles, and the NASA space shuttle. The first production application of a particulate-reinforced MMC is a set of covers for a missile guidance system.

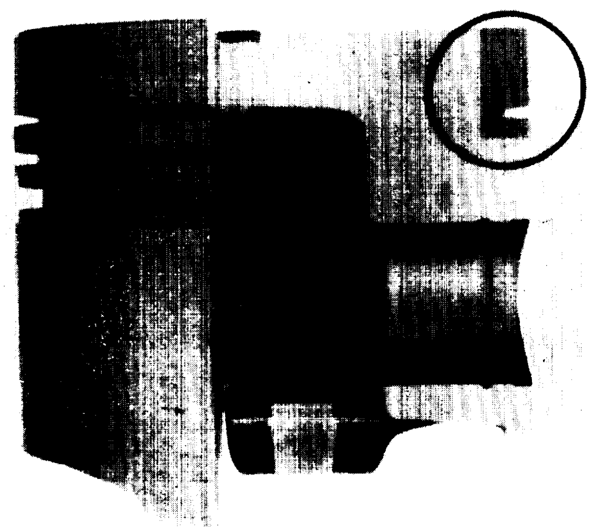


Photo credit: Toyota Motor Corp.

Aluminum diesel engine piston with local fiber reinforcement in ring groove area.

The most significant commercial application of MMCs to date is an aluminum diesel engine piston produced by Toyota that is locally reinforced with ceramic fibers. Toyota produces about 300,000 annually. The ceramic reinforcement provides superior wear resistance in the ring groove area. Although data on the production costs of these pistons are not available, this development is significant because it suggests that MMC components can be reliably mass-produced to be competitive in a very cost-sensitive application.

Future Production

Based on information now in the public domain, the following military and aerospace applications for MMCs appear attractive: high-temperature fighter aircraft engines and structures; the National Aerospace Plane skin and engines; high-temperature missile structures; high-speed mechanical systems, and electronic packaging.

Applications that could become commercial in the next 5 to 15 years include automotive pistons, brake components, connecting rods, and rocker arms; rotating machinery, such as propeller shafts and robot components; computer equipment, prosthetics, electronic packaging, and sporting goods. However, the current level of development effort appears to be insufficient to bring about commercialization of any of these applications in the United States in the next 5 years, with the possible exception of diesel engine pistons,

MMC materials with high specific stiffness and strength could be used in applications in which an important factor is reducing weight. Included in this category are land-based vehicles, aircraft, ships, and high-speed machinery. The relatively high cost of MMCs will probably prevent their extensive use in commercial land-based vehicles and ship structures. However, they may well be used in specific mechanical components such as propeller shafts, bearings, pumps, transmission housings and components, gears, springs, and suspensions.

Research and Development Priorities

In spite of the fact that ceramics, PMCs, and MMCs are at different stages of technological maturity, the R&D challenges for all three categories are remarkably similar. The four most important R&D priorities are given below.

Processing Science

This is the key to understanding how processing variables such as temperature, pressure, and composition influence the desired final properties. The two principal goals of processing science should be to support development of new, low-cost manufacturing methods, and to help bring about better control over reproducibility so that large numbers of components can be manufactured within specification limits.

Structure-Property Relationships

The tailorable properties of advanced materials offer new opportunities for the designer. However, because advanced materials and structures are more complex than metals, the relationships among the internal structure, mechanical properties, and failure mechanisms are less well understood. A better understanding of the effects of an accumulation of dispersed damages on the failure mechanisms of composites is especially desirable.

Behavior in Severe Environments

Many applications may require new materials to withstand high-temperature, corrosive, or erosive environments. These environments may exacerbate existing flaws or introduce new flaws, leading to failure. Progress in this area would facilitate reliable design and life prediction.

Matrix= Reinforcement Interface in Composites

The poorly understood interracial region has a critical influence on composite behavior. Particularly important would be the development of interracial coatings that would permit the use of a single fiber with a variety of matrices.

FACTORS AFFECTING THE USE OF ADVANCED MATERIALS

Broader use of advanced structural materials will require not only solutions to technical problems, but also changes in attitudes among researchers and end users who are accustomed to thinking in concepts more appropriate to conventional materials.

Traditionally, materials are considered to be one (usually inexpensive) input in a long chain of discrete design and manufacturing steps that result in the output of a product. The new tailored materials require a new paradigm. The materials and the end products made from them become indistinguishable, joined by an integrated design and manufacturing process. This necessitates a closer relationship among researchers, designers, and production personnel, as well as new approaches to the concept of materials costs.

Integrated Design and Manufacturing

Advanced ceramics and composites should really be considered as structures rather than as materials. Accordingly, it becomes essential to have a design process capable of producing highly integrated and multifunctional structures. Consider the body structure of an automobile. A metal body currently has between 250 and 350 distinct parts. Using PMCs, this number could be reduced to between 2 and 10.

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 capable of balancing all of the relevant design and manufacturing variables. Such a design process requires an extensive database on matrix and fiber properties, sophisticated software capable of modeling fabrication processes, and three-dimensional analysis of the properties and behavior of the resulting structure. Perhaps the most important element in the development of integrated design algorithms will be an understanding of the relationships among the constituent properties, microstructure, and the macroscopic properties of the structure. The R&D priorities listed above are intended to provide this information.

Automation

The need for integrated design and manufacturing sheds light on the extent to which automation will be able to reduce the costs of advanced materials and structures. Automation can be used for many purposes in advanced materials manufacturing, including design, numerical modeling, materials handling, process controls, assembly, and finishing. Automation technologies that aid in integrating design and manufacturing will be helpful. For example, computer-aided design (CAD) and numerical modeling are likely to help bring the designer and production engineer in closer contact.

Automation in the form of computer control of advanced materials processing equipment is an important evolving technology for solving current manufacturing problems. In ceramics, new processes controlled by microprocessors or computers will be critical in minimizing flaw populations and increasing process yields. In PMCs, the costly process of hand lay-up will be replaced by computer-controlled tape laying machines and filament winding systems. However, large-scale process automation will be effective in reducing costs only if the process is well characterized and the allowable limits for processing variables are well understood. In general, manufacturing processes for advanced materials are still evolving, and attempts to automate them in the near term could be premature.

Multidisciplinary Approach

Advanced materials development lends itself naturally to—and probably will demand—relaxing the rigid disciplinary boundaries among different fields. This is true whether the materials development is performed in government laboratories, universities, or industry. For example, the necessity for integrating design and manufacturing of advanced materials and structures implies closer working relationships among industry professionals involved in manufacturing a product. For a typical ceramic component, an industry team could include one or more professionals from each of the disciplines in table 1-2.

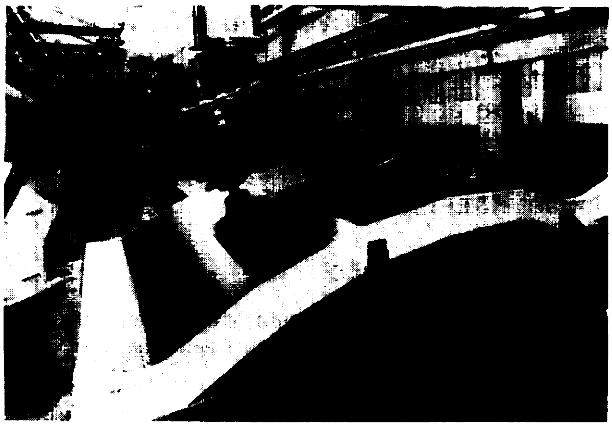


Photo credit: Cincinnati Milacron Co.

Composite tape-laying machine shown applying 3-inch-wide tape to compound-angle "tool" in the manufacture of an aircraft part.

Education and Training

The expanding market opportunities for ceramics and composites will require more scientists and engineers with broad backgrounds in these fields. At present, only a few universities offer comprehensive courses in ceramic or composite materials. There is also a shortage of prop-

Table 1-2.—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 and costs

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

erly trained faculty members to teach such 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 PMCs, for instance, most of the design expertise is concentrated in the aerospace industry. Small businesses, professional societies, universities, and Federal laboratories could all play a role in providing this training. Continuing education regarding the potential of advanced materials is particularly important in relatively low-technology industries such as construction, which must purchase, rather than develop, the materials they use.

Beyond the training of professionals, there is a need for the creation of awareness of advanced materials technologies among corporate executives, planners, technical media personnel, 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 such materials can have a high-tech appeal to the public, even if they are relatively expensive.

Systems Approach to Costs

Without question, the high cost per pound of advanced materials will have to come down before they will be widely used in high-volume, low-cost applications. This high cost is largely attributable to the immaturity of the fabrication technology and to low production volumes, and can be expected to drop significantly in the future. For example, a pound of standard high-strength carbon fiber used to cost $300, but now costs less than $20, and new processes based on synthesis from petroleum pitch promise to reduce the cost even further. However, these advanced materials will always be more expensive than basic metals. Therefore, end users must take advantage of potential savings in fabrication, installation, and life-cycle costs to offset the higher material costs; in other words, a systems approach to costs is required.

As the example of the PMC automobile body cited above demonstrates, savings in tooling, assembly, and maintenance costs could result in lower cost, longer lasting cars in the future. Viewed from this systems perspective, advanced materials may become more cost-effective than conventional materials in many applications.

Energy Costs

The cost of energy used in the manufacture of advanced materials and structures is generally only 1 to 2 percent of the cost of the finished product. However, the energy cost savings obtained over the service life of the product is a major potential advantage of using the new materials. For example, the high temperature capabilities of ceramics can be used to increase the thermal efficiency of heat engines, heat exchangers, and furnace recuperators. Fuel savings also result from reducing the weight of ground vehicles and aircraft through the use of lightweight composites.

The decline of fuel prices in recent years has reduced energy cost savings as a selling point for new products, and has therefore reduced the attractiveness of new materials. For example, in the early 1980s one pound of weight saved in a commercial transport aircraft was worth $300 in fuel savings over the life of the aircraft, but is now worth less than $100. At $300 per pound of weight saved, the higher cost of using composites could be justified; at a premium of only $100 per pound, aluminum or aluminum-lithium alloys are more attractive. Persistently low fuel prices would delay the introduction of advanced materials into such applications.

IMPACTS OF ADVANCED MATERIALS ON MANUFACTURING

The advent of advanced structural materials raises questions concerning their impact on existing manufacturing industries in the United States. This impact can be conceptually divided into two categories: substitution by direct replacement of metal components i n existing products, and use in new products that are made possible by the new materials. Compared with other supply and demand factors affecting basic metals manufacturing, the impact of direct substitution of advanced materials for these metals is likely to be relatively minor. In contrast, more innovative application of the materials to new or redesigned products could have substantial impact on manufacturing industries, including development of more competitive products, and new industries and employment opportunities, as described below.

Substitution

From the viewpoint of the commercial end user considering the introduction of a new material into an existing product, the material must perform at least as well as the existing material, and do so at a lower cost. This cost is generally calculated on the basis of direct substitution of the new material for the old material in a particular component, without redesign or modification of surrounding components. in fact, if substantial redesign is necessary, this is likely to be considered a significant disincentive for the substitution.

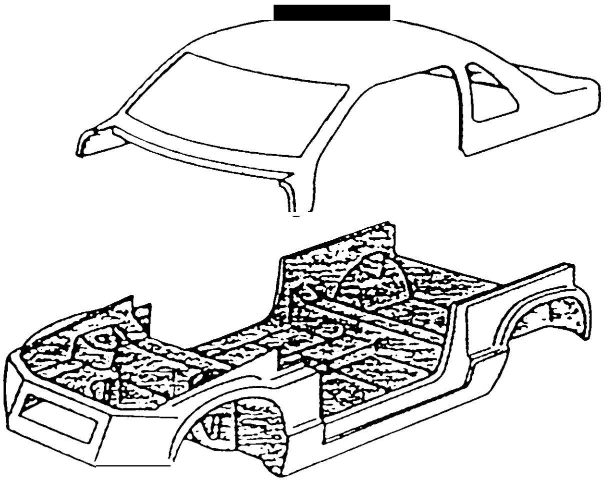
Generally, advanced materials cannot compete with conventional materials on a dollars-per-pound substitution basis. Direct substitution of a ceramic or composite part for a metal part does not exploit the superior properties and design flexibility inherent in advanced materials, key advantages which can offset their higher cost. Yet direct substitution is frequently the only option considered by end users, who are wary of making too many changes at once. This Catch-22 situation is a major barrier to the use of advanced materials in large volume applications. However, commercial end users who wish to exploit the long-term opportunities offered by advanced materials may fail to achieve their goal unless they are willing to employ advanced materials more aggressively in the near term, thereby gaining production experience.

It is sometimes suggested that substitution of advanced materials for steel and aluminum will *soon* become a significant factor affecting the demand for these metals. OTA's analysis indicates that this is highly unlikely. Because of their low cost and manufacturability, these metals are ideally suited for many of the applications in which they are now used, and will not be replaced by advanced materials. Moreover, the threat of substitution has led to the development of new alloys with improved properties, such as high-strength, low-alloy steel and aluminum-lithium. The availability of these and other new alloys will make it even more difficult for new, nonmetallic materials to substitute for metals. As new materials technologies mature and costs come down, significant displacement of metals could occur in four markets: aircraft, automobiles, containers, and construction. However, in those applications where substitution is substantial, by far the greatest volume of steel and aluminum will be displaced by relatively low-performance, low-cost materials, such as unreinforced plastics, sheet molding compounds, and high-strength concrete.

Innovative Designs and New Products

The automotive industry provides an excellent paradigm for understanding the potential impact of using advanced materials in cost-sensitive manufacturing applications. Design teams at the major automakers are currently evaluating the use of PMCs in primary body structures and chassis/suspension systems, as illustrated in figure 1-6. The potential advantages of using PMCs include: weight reduction and resulting fuel economy; improved overall quality and consistency in manufacturing; lower assembly costs due to parts consolidation; improved ride performance; product differentiation at a reduced cost; lower investment costs for plant, facilities, and tooling; improved corrosion resistance; and lower operating costs. These advantages reflect a systems

Figure 1-6.—Typical Body Construction Assembly Using Two Major PMC Moldings



SOURCE P. Beardmore, C F Johnson, and G G Strosberg, Ford Motor Co , "Impact of New Materials on Basic Manufacturing Industries: Case Study Composite Automobile Structure," contractor report for OTA, March 1987

approach to costs, as described above. However, major challenges remain that will require extensive R&D to resolve. These include: lack of high-speed, high-quality, low-cost manufacturing processes; uncertainties regarding performance requirements, particularly crash integrity and long-term durability; lack of adequate technologies for repair and recycling of PMC structures; and uncertain customer acceptance.

There is a growing body of evidence that glass fiber-reinforced composites are capable of meeting the functional requirements of the most highly loaded automotive structures. However, major innovations in fabrication technologies are still required. There are several candidate fabrication methods, including resin transfer molding, compression molding, and filament winding. At this time, none of these methods can satisfy all of the production requirements; however, resin transfer molding seems the most promising.

Large-scale adoption of PMC automotive structures would have a major impact on the fabrication and assembly of automobiles. For instance, metal forming presses would be replaced by a much smaller number of molding units, the current large number of welding machines would be replaced by a limited number of adhesive bonding fixtures, and the assembly sequence would be modified to reflect the tremendous reduction in parts. Factories would be smaller because fewer assembly machines require less floor space.

The overall labor content of producing a PMC automobile body would be reduced as numerous operations would be eliminated. However, it is important to note that body assembly is not a labor-intensive segment of total assembly. Other assembly operations that are more labor-intensive (e.g., trim) would not be significantly affected. Thus, the overall decreases in direct labor due to adoption of PMCs may be relatively small. The kinds of skills required of factory personnel would be somewhat different, and significant retraining would be necessary. However, the overall skill levels required are likely to be similar to those in use today.

Extensive use of PMCs by the automotive industry would cause completely new industries to arise, including a comprehensive network of PMC repair facilities, molding and adhesive bonding equipment suppliers, and a recycling industry based on new technologies. Current steel vehicle recycling techniques will not be applicable to PMCs, and cost-effective recycling technologies for PMCs have yet to be developed. Without the development of new recycling methods, incineration could become the main disposal process for PMC structures. The lack of acceptable recycling and disposal technologies could translate into higher costs for PMC structures relative to metals.

INDUSTRY INVESTMENT CRITERIA FOR ADVANCED MATERIALS

The potential for advanced materials in the manufacturing sector will not be realized unless companies perceive that their criteria for investment in R&D and production will be met. The investment criteria used by advanced materials companies vary depending on whether they are materials suppliers or users; whether the intended markets are military or commercial; and whether the end use emphasizes high materials performance or low cost.

Suppliers of advanced structural materials tend to be technology-driven; they are focused primarily on the superior technical performance of advanced materials and are looking for both military and commercial applications. Suppliers tend to take a long-term view, basing investment decisions on qualitative assessments of the technical potential of advanced materials. On the other hand, users of advanced materials tend to be market-driven; they are focused primarily on short-term market requirements, such as return on investment and time to market.

Frequently, advanced materials suppliers and users operate in both military and commercial markets. However, the investment criteria employed in the two cases are very different. Defense contractors are able to take a longer term perspective because they are able to charge much of their capital equipment to the government, and because the defense market for the materials and structures is well-defined. Commercial end users, on the other hand, must bear the full costs of their production investments, and face uncertain returns. Their outlook is therefore necessarily shorter term. This difference in market perspective has hampered the transfer of technology from advanced materials suppliers (who frequently depend on defense contracts to stay in business) to commercial users, and it underlines the importance of well-defined markets as a motivating force for industry investments in advanced materials.

Cost and Performance

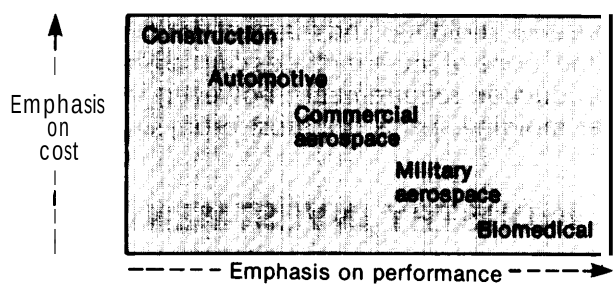
The many applications of advanced structural materials do not all have the same cost and performance requirements. Accordingly, the investment criteria of user companies specializing in different product areas are different. In general, barriers to investment are highest in cost-sensitive areas such as construction and automobiles, wherein expensive new materials must compete with cheap, well-established conventional materials. Barriers are lowest for applications in which a high materials cost is justified by superior performance, such as medical implants and aircraft.

Figure 1-7 provides a schematic view of the relative importance placed on high materials performance versus cost in a spectrum of industrial end uses. in commercial aircraft, automotive, and construction markets, acquisition costs and operating expenses are the major purchase criteria, with progressively less emphasis on high material performance. In military aerospace and biomedical markets, functional capabilities and performance characteristics are the primary purchase criteria.

Because advanced materials may cost as much as 100 times more on a per-pound basis than metals such as steel and aluminum, their first use has generally been in the less cost-sensitive end uses of figure 1-7, particularly in the military. However, because military production runs are typically small, there is little incentive to develop low-cost, mass production manufacturing processes that would make the materials more attractive for commercial applications such as automobiles. The lack of such processes is a major barrier preventing more widespread commercial use of advanced structural materials. This suggests that greater emphasis on military R&D programs to develop low-cost fabrication techniques could facilitate the diffusion of military materials technology into the commercial sector.

The major potential sales value of advanced materials lies in the commercial industries in the middle of figure 1-7; i.e., in aircraft, automobiles, industrial machinery, etc. This is because construction materials are used in high volume but must have a very low cost, and military and biomedical materials can have high allowable costs,

Figure 1-7.—Relative Importance of Cost and Performance In Advanced Materials User Industries



Barriers to the use of advanced materials decrease from upper left to lower right.

SOURCE: Technology Management Associates, "industrial Criteria for Investment Decisions in R&D and Production Facilities," contractor report for OTA, January 1987.

but are used in relatively low volume. However, end users in these "middle" industries do not perceive that use of the new materials will be profitable within the next 5 years, the planning horizon of most companies. Thus, there is virtually no market pull on these technologies in the United States. This suggests that an important policy tool for accelerating the commercialization of advanced materials is to increase incentives for investment by commercial end users.

INTERNATIONAL BUSINESS TRENDS

Advanced structural materials industries have become markedly more international in character in the past several years. In collaboration with industry, governments around the world are investing large sums in multi-year programs to facilitate commercial development. Through acquisitions, joint ventures, and licensing agreements, the firms involved have become increasingly multinational, and are thereby able to obtain access to growing markets and achieve lower production costs. Critical technological advances continue to be made outside the United States; e.g., the carbon fiber technology developed in Great Britain and Japan, and hot isostatic pressing technology developed in Sweden.

This trend toward internationalization of advanced structural materials technologies has many important consequences for government and industry policy makers in the United States. They can no longer assume that the United States will dominate the technologies and the resultant applications. The flow of technology coming into the United States from abroad may soon be just as significant as that flowing out. Moreover, the increasingly multinational character of materials industries suggests that the rate of technology flow among firms and countries is likely to increase. The United States will not be able to rely *on* a superior R&D capability to provide an advantage in developing commercial products. Furthermore, if there is no existing infrastructure in the United States for quickly appropriating the R&D results for economic development, the results will quickly be used elsewhere.

Ceramics

The value of advanced ceramics consumed in the United States, and produced in Japan and Western Europe in 1985 are estimated in table 1-3. (U.S. production data were not available.) In each geographic region, electronic applications, such as capacitors, substrates, and integrated circuit packages, accounted for over 80 percent of the total. Structural applications, including wear parts and cutting tool inserts, accounted for the remainder.

By a margin of nearly 2 to 1, the U.S. ceramics companies interviewed by OTA felt that Japan is the world leader in advanced ceramics R&D. Without question, Japan has been the leader in actually producing advanced ceramic products for both industrial and consumer use. Japanese end users exhibit a commitment to the use of these materials not found in the United States. This commitment is reflected in the fact that although the U.S. and Japanese Governments spend comparable amounts on ceramics R&D (roughly $100 to$125 million in fiscal year 1985, see table 1-4), estimated spending by Japanese industry is about four times that of its government, while in the United States, industry investment in advanced ceramics R&D (estimated at $153 million in fiscal year 1986) is only slightly higher than government spending. Ceramics technology has a high profile in Japan, due in part to production of advanced ceramic consumer goods, such as fish hooks, pliers, scissors, and ballpoint pen tips.

Table I-3.—Estimated Production Value of Advanced Ceramics, 1985 (millions of dollars)

Region	Electronic applications	Structural applications	Total
Japan.	1,920	360	2,280
United States[a]	1,763	112	*1,875*
Western Europe	390	80	470

[a]Consumptlon in 1985, according to Business Communications Co., Inc., Norwalk, CT.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

Table l-4.—Estimated Government Funding in Several Countries for Advanced Ceramics R&D in 1985[a] (millions of dollars)[b]

United States	$125
Japan	100
West Germany	75
France	64
United Kingdom	51
Sweden	7
Italy	6
Finland	5
The Netherlands	4
Belgium	1.5
Other	3

[a]Includes funding for electronic and structural applications.
[b]Inclides government funding for materials, office expenses (e.g. salaries) and facilities in research centers, universities, and private industry.
[c]Includes Denmark, Ireland, Norway, and Switzerland.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

Japanese ceramics companies are far more vertically and horizontally integrated than U.S. corn-panies, a fact that probably enhances their ability to produce higher quality ceramic parts at lower prices. However these companies are still losing money on the structural ceramic parts they produce. This reflects the long-term view of Japanese companies regarding the future of ceramics technologies.

The Japanese market for advanced structural ceramics is likely to develop before the U.S. market. However, given the self-sufficiency of the Japanese ceramics industry, this market is likely to be difficult to penetrate by U.S. suppliers. In contrast, Japanese ceramics firms, which already dominate the world market for electronic ceramics, are strongly positioned to exploit the U.S. structural ceramics market as it develops. One such firm, Kyocera, the largest and most highly integrated ceramics firm in the world, has already established subsidiaries and, recently, an R&D center in the United States.

West Germany, France, and the United Kingdom all have initiated substantial programs in advanced ceramics R&D, as indicated in table 1-4. West German companies have a strong position in powders and finished products, whereas France has developed a strong capability in CMCs. Meanwhile, the European Community (EC) has earmarked about $220 million for R&D on advanced materials (including ceramics) between 1987 and 1991. Overall, industry investment in advanced ceramics in Western Europe is thought to be roughly in the same proportion to government spending as in the United States, i.e., far less than in Japan. Western Europe appears to have all of the necessary ingredients for developing its own structural ceramics industry.

Polymer Matrix Composites

The value of advanced PMC components produced in the United States, Western Europe, and Japan in 1985 was $2.1 billion, divided roughly as follows: the United States, $1.3 billion; Western Europe, $600 million; and Japan, $200 million. As shown in table 1-5, the U.S. and European markets are dominated by aerospace applications. In the United States, PMC development is being driven by military and space programs, whereas in Western Europe development is being keyed more heavily to commercial aircraft use. In contrast, the Japanese market is dominated by sporting goods applications.

On the strength of its military aircraft and aerospace programs, the United States leads the world in advanced PMC technology. Due to the attractiveness of PMCs for new weapons programs, the military fraction of the market is likely to increase in the near term. However, this military technology leadership will not necessarily be translated into a strong domestic commercial industry. Due to the high cost of such military materials and structures, they find relatively little use in commercial applications.

Commercialization of advanced PMCs is an area in which the United States remains vulnerable to competition from abroad. U.S. suppliers

Table 1-5.—Breakdown of Regional Markets for Advanced Composites by End Use

	End use (percentage)[a]		
Region	Aerospace	Industrial[b]	Recreational
United States	50	25	25
Western Europe	56	26	18
Japan	10	35	55

[a]Based on the value of fabricated components.
[b]Includes automotive, medical, construction, and non-aerospace military applications.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

of PMC materials report that foreign commercial end users (particularly those outside the aerospace industry) are more active in experimenting with the new materials than are U.S. commercial end users. For example, Europe is considered to lead the world in composite medical devices. It should be noted, however, that the regulatory environment controlling the use of new materials in the human body is currently less restrictive in Europe than in the United States.

France is by far the dominant force in PMCs in Western Europe, producing more than all other European countries combined, as shown in table 1-6. The United Kingdom, West Germany, and Italy make up the balance. The commercial aircraft manufacturer Airbus Industrie, a consortium of European companies, is the single largest consumer of PMCs. At the European Community level, significant expenditures are being made to facilitate the introduction of PMCs into commercial applications through the BRITE and EURAM programs. In addition, the EUREKA program called Carmat 2000 has proposed to spend $60 million over 4 years to develop PMC automobile structures.

In the past few years, the participation of Western European companies in the U.S. PMC market has increased dramatically. This has occurred primarily through their acquisitions of U.S. companies. One result is that they now control 25 percent of resins, 20 percent of carbon fibers, and 50 percent of prepreg (fibers pre-impregnated with polymer resin, the starting point for many fabrication processes) sales in the United States. These acquisitions appear to reflect their desire to participate more directly in the U.S. defense market and to establish a diversified, worldwide business. A secondary benefit for the European companies is likely to be a transfer of U.S. PMC technology to Europe such that in the future, Europe will be less dependent on the United States for this technology.

Table I-6.–Distribution of Advanced PMC Business in Western Europe, 1986

Country	Percent of total
France	55%
United Kingdom	15
West Germany	10
Italy	10
All other	10
Total	100%

SOURCE Strategic Analys!s Inc , "Strategies of Suppliers and Users of Advanced Materials contractor report for OTA, March 1987

Although Japan is the world's largest producer of carbon fiber, a key ingredient in advanced composites, it has been only a minor participant to date in the advanced composites business. One reason for this is that Japan has not developed a domestic aircraft industry, the sector that currently uses the largest quantities of advanced composites. Another reason is that Japanese companies have been limited by licensing agreements from participating directly in the U.S. market.

Few observers of the composites industry expect this situation to continue. Change could come from at least two directions. First, Japanese fiber producers could abrogate existing agreements and sell their product directly in the U.S. market. Second, based on technology gained through their increasing involvement in joint ventures with Boeing, Japan could launch its own commercial aircraft industry.

Metal Matrix Composites

The principal markets for MMC materials in the United States and Western Europe are in the defense and aerospace sectors. Accordingly, over 90 percent of the U.S. funding for MMC R&D between 1979 and 1986 came from DoD. The structures of the U.S. and European MMC industries are similar, with small, undercapitalized firms supplying the formulated MMC materials. Currently, the matrix is supplied by the large aluminum companies, which are considering forward integration into composite materials. There are also in-house efforts at the major aircraft companies to develop new composites and new processing methods. Many analysts feel that the integration of the MMC suppliers into larger concerns having access to more capital and R&D resources will be a critical step in producing reliable, low-cost MMCs that could be used in large-volume commercial applications.

A potential barrier to the commercial use of MMCs in the United States arises from restrictions imposed on the flow of information about MMCs for national security reasons. Because MMCs are classified as a technology of key military importance, exchanges of technical data on MMCs are severely restricted in the United States and exports of data and material are closely controlled.

Unlike the situation in the United States and Western Europe, the companies involved in manufacturing MMCs in Japan are largely the same as those involved in supplying PMCs and ceramics; i.e., the large, integrated materials companies. Another difference is that the Japanese MMC suppliers focus primarily on commercial applications, including electronics, automobiles, and aircraft and aerospace. One noteworthy Japanese development is Toyota's introduction of an MMC diesel engine piston consisting of aluminum locally reinforced with ceramic fibers. This is an important harbinger of the use of MMCs in low-cost, high-volume applications, and it has stirred considerable worldwide interest among potential commercial users of MMCs.

GOVERNMENT/UNIVERSITY/INDUSTRY COLLABORATION AND INDUSTRIAL COMPETITIVENESS

Through the years, the United States has built up a strong materials science base in its universities and Federal laboratories. Many observers believe that U.S. industry, universities, and Federal laboratories need to work together more effectively to translate this research base into competitive commercial products. Collaborative programs offer a number of potential contributions to U.S. industrial competitiveness, including an excellent environment for training students, an opportunity to leverage stakeholder R&D investments, and research results that could lead to new products.

Since the early 1980s, numerous collaborative R&D centers have been initiated. These centers follow a variety of institutional models, including industry consortia, university-based consortia such as the National Science Foundation's Engineering Research Centers, quasi-independent institutes (often funded by State government sources), and Federal laboratory/industry programs.

In advanced materials technologies, most current collaborative programs are based at universities or Federal laboratories. OTA's survey of a sample of these programs suggests that such programs are more successful in training students and leveraging R&D investments than they are in stimulating commercial outcomes.

The collaborative research programs and their industrial participants surveyed by OTA do not rank commercialization as a high priority, and they do not systematically track commercial outcomes. Many of the university-based programs concentrate on publishable research and graduate training. Those programs based at Federal facilities are only now beginning to move away from their primary agency missions toward a broader concern with U.S. industrial competitiveness. Generally, industrial participants value their access to skilled research personnel and graduate students more highly than the actual research results generated by the collaboration. This strongly suggests that such collaborative programs should not be viewed as engines of commercialization and jobs, but rather as a form of infrastructure support, providing industry with access to new ideas and trained personnel.

Industrial participants often have only a modest amount of involvement in the planning and operation of the collaborative programs. For the most part, they approach their relationship with research organizations as being a "window to the future." Furthermore, "collaboration" may be an inaccurate description of many of the programs. In large measure, the programs studied by OTA did not involve intense, bench-level interaction between institutional and industrial scientists; rather, the nature of the collaboration seemed to be mostly symbolic.

There are exceptions to these general observations in some of the newer "hybrid" initiatives, which combine both generic and proprietary research in the same program. Often undertaken in conjunction with State government funding, these hybrid organizations seem to incorporate a greater commitment to commercialization and economic development as their mission.

For the results of collaborative research to be commercialized, there must be a corresponding capacity and incentive on the part of the industrial participants to do so. Fewer than 50 percent of the industrial participants interviewed reported any follow-on work stimulated by the collaborations. Overwhelmingly, OTA's industrial respondents did not feel that changes in institutional arrangements with the research performing centers would facilitate the commercialization process. Rather, they saw the principal barriers as being internal corporate problems: how companies can justify major investments in new manufacturing facilities in light of uncertain markets, how to adopt longer term planning horizons, and how to facilitate better communication between their R&D and manufacturing functions.

Thus, there appears to be a significant gap between the point at which government/university/industry collaborative materials research leaves off and the point at which industry is willing to begin to explore the commercial potential. Policy options that could help bridge this gap are discussed in the policy section below.

MILITARY ROLE IN ADVANCED MATERIALS DEVELOPMENT

Just as universities and Federal laboratories represent unique resources available to U.S. advanced materials companies, the substantial DoD and NASA investments in advanced materials for military and space applications can also contribute to the commercial competitiveness of U.S. firms.

At present, the military establishment is one of the largest customers of advanced materials, especially composites, and its use of these materials is expected to grow rapidly. DoD has committed itself to purchase 80 billion dollars' worth of weapons systems that will incorporate advanced composite components.

Composites have already been used in the Army's Apache and Black Hawk helicopters, Navy aircraft such as the AV-8B, the F-18, and the F-14, and the Air Force's F-1 5 and F-16. PMCs are currently in full-scale development for the Navy's V-22 Osprey, and are under considera-

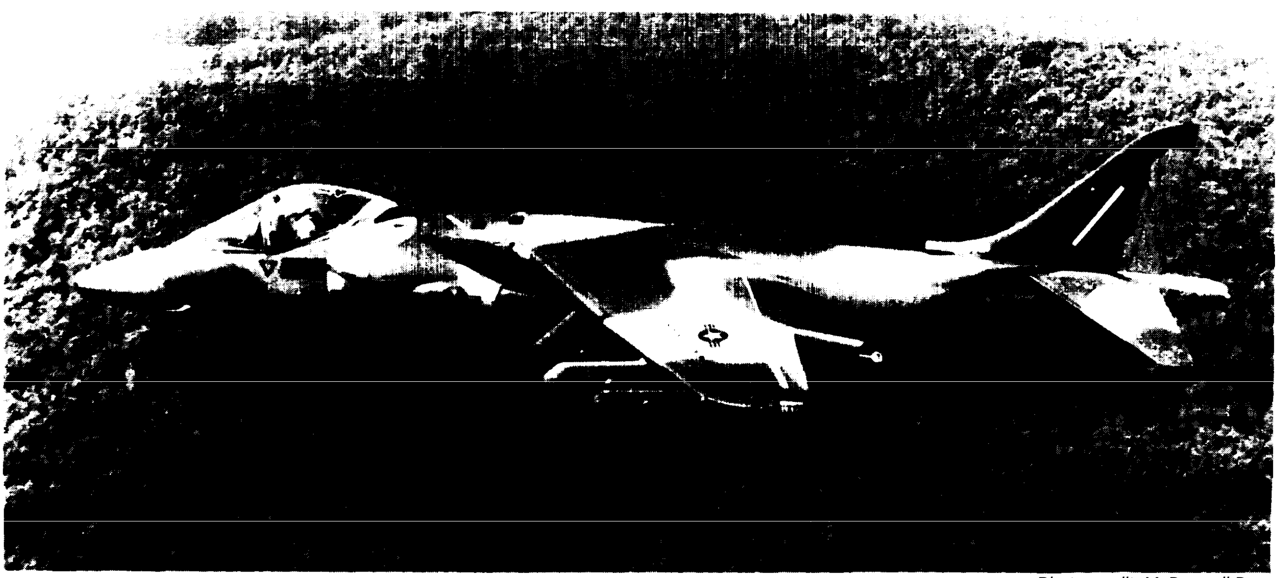


Photo credit: McDonnell Douglas

The Navy AV-8B Aircraft.

tion for several systems including the Army's LHX helicopters and the Air Force's Advanced Tactical Fighter. Ceramics and composites of various kinds will also be enabling technologies in such new programs as the National Aerospace Plane (NASP) and the Strategic Defense Initiative (SDI).

Counting only basic and early applied R&D (budget categories 6.1-6.3A), DoD sponsors about 60 percent ($98 million of a total of $167 million in fiscal year 1987) of Federal advanced structural materials R&D in the United States, as shown in table 1-7. If military development, testing, and evaluation funds (as well as funds for classified programs) were included, this fraction would be much higher. Military research in advanced structural materials has aimed at achieving such goals as higher operating temperatures, higher toughness, lower radar observability, and reduced weight.

Today, it is clear that U.S. leadership in advanced composites technologies of all types stems from the substantial DoD and NASA investments in these materials over the past 25 years. U.S. companies have been able to leverage their resources by using DoD funds for R&D in these technologies. There are some areas of strong overlap between military and commercial sectors. These include basic research in materials synthesis, properties, and behavior, as well as certain applications, such as aircraft, in which the military and commercial performance requirements are similar. DoD has also instituted programs such as the Manufacturing Technologies (ManTech) program to develop low-cost manufacturing methods, a critical need for both military and commercial structures.

As a principal supporter of advanced materials R&D, the military has two primary policy goals relating to the technologies. The first is to prevent or slow their diffusion to Eastern bloc countries, and the second is to secure viable domestic sources of supply. In an era of rapid technology diffusion across national borders and the growing multinational character of advanced materials industries, these policy goals are increasingly in conflict with commercial interests. Major issues that will require resolution include export controls, controls on technical information, and government procurement practices.

As commercial markets for these materials continue to grow, effective balancing of military and commercial interests in advanced materials could become a critical factor in U.S. companies' competitiveness in these technologies.

Table 1-7.—U.S. Government **Agency Funding for Advanced Structural Materials in Fiscal Year 1987**
(millions of dollars)

Agency	Ceramics and ceramic matrix composites	Polymer matrix composites	Metal matrix composites	Carbon/carbon composites	Total
Department of Defense[a]	$21.5	$33.8	$29.7	$13.2	$98.2
Department of Energy	36.0	—	—	—	36.0
National Aeronautics and Space Administration	7.0	5.0	5.6	2.1	19.7
National Science Foundation	3.7	3.0	—	—	6.7
National Bureau of Standards	3.0	0.5	1.0	—	4.5
Bureau of Mines	2.0	—	—	—	2.0
Department of Transportation	—	0.2	—	—	0.2
Total	$73.2	$42.5	$36.3	$15.3	$167.3

[a]Includes only budget categories 6.1-6.3A.

SOURCE: OTA survey of agency representatives.

POLICY ISSUES AND OPTIONS

Perhaps the central finding of this assessment is that potential commercial end users of advanced materials, whose investment decisions are determined by expected profits, do not believe that use of advanced materials will be profitable within their planning horizon of 5 years. Thus, there is virtually no market pull on these technologies in the United States. While U.S. commercial end users have placed themselves in a relatively passive, or reactive role with respect to use of advanced materials, their competitors, notably the Japanese, have adopted a more aggressive, "technology push" strategy.

Ultimately, the future competitiveness of U.S. advanced materials industries in worldwide commercial markets depends on the investment decisions made within the industries themselves. These decisions are strongly affected by a variety of Federal policies and regulations.

It is useful to begin the policy discussion by considering what outcomes are likely if current trends continue.

Projections Based on a Continuation of the Status Quo

Because U.S. military markets will expand faster than commercial markets in the near term, the military role in determining the development agenda for advanced materials is likely to broaden. As explained above, military investments in advanced materials can be an asset to U.S. firms; however, they could also tend to direct resources toward development of high-performance, high-cost materials that are inappropriate for commercial applications.

Meanwhile, the reluctance of U.S. commercial end users to commit to advanced materials suggests that foreign firms will have an advantage in exploiting global markets as they develop. Almost certainly, a successful product using an advanced material produced abroad would stimulate a flurry of R&D activity among U.S. companies. However, given the lack of experience in this country with low-cost, high-volume fabrication technologies, it is not obvious that the United States could easily catch up.

The high cost of R&D, scale-up, and production of advanced materials, together with the poor near-term commercial prospects, will drive more and more U.S. companies to pool resources and spread risks through a variety of joint ventures, consortia, and collaborative research centers. Currently, many such collaborative centers are springing up across the United States. These centers will provide an excellent environment for conducting generic research and training of students. However, because of the high risks involved, they will not necessarily lead to more aggressive commercialization of advanced materials by participating companies.

Through acquisitions, joint ventures, and licensing agreements, the advanced materials industries will continue to become more multinational in character. Technology will flow rapidly between firms and across national borders. Critical advances will continue to come from abroad, and the flow of materials technology into this country will become as important as that flowing out. U.S. efforts to regulate these flows for national security reasons will meet increasing resistance from multinational companies intent on achieving the lowest production costs and free access to markets.

These scenarios suggest that there is reason to doubt whether the United States will be a world leader in manufacturing with advanced materials in the 1990s and beyond. The commercialization of these materials is essentially blocked because they do not meet the cost and performance requirements of potential end users. OTA finds that there are four general Federal policy objectives that could help to reduce these barriers:

1. Encourage long-term investment by advanced materials end users;
2. Facilitate government/university/industry collaboration in R&D for low-cost materials fabrication processes;
3. Facilitate more effective commercial exploitation of military R&D investments where possible; and
4. Build a strong advanced materials technology infrastructure.

Policy options for pursuing these objectives range from those with a broad scope, affecting many technologies, to those specifically affecting advanced materials. These options are not mutually exclusive, and most could be adopted without internal contradiction.

Encourage Long-Term Investment by Advanced Materials End Users

Greater investment in advanced materials by potential end users would generate more market pull on these technologies in the United States. The shortfall of long-term investment in advanced materials by potential end user companies is only one example of a more widespread shortfall found in many U.S. industries.

The climate for long-term industry investment is strongly affected by Federal policies and regulations, including tax policy, intellectual property law, tort law, and environmental regulations. Public debate regarding the relationships between these Federal policies and regulations and U.S. industrial competitiveness has given rise to a voluminous literature. Suggested policy changes include: providing tax incentives for long-term capital investments, reducing taxation on personal savings in order to make more investment capital available and thus reduce its cost, and comprehensive tort law reform aimed at making product liability costs proportional to proven negligence.

These policy options have implications far beyond advanced materials technologies, and an analysis of their effects is beyond the scope of this assessment.

Facilitate Government/University/ Industry Collaboration in R&D for Low-Cost Materials Fabrication Processes

More than any other single barrier, the lack of reliable, low-cost fabrication processes inhibits the use of advanced structural materials in commercial applications. Due to the high costs of developing these processes, it is a fruitful area for collaborative research. Three major reservoirs of materials expertise are available to United States companies: 1) universities, 2) Federal laboratories, and 3) small high-technology firms.

Option 1: Establish a limited number of collaborative centers dedicated to advanced materials manufacturing technology.

Creation of a small number of collaborative centers in which manufacturing research and scale-up costs would be shared by government, university, and industry stakeholders, could increase industry incentives to invest in commercialization. These centers need not be new; they could be based at existing centers of excellence.

Option 2: Encourage large companies to work with small advanced materials firms, which have materials fabrication expertise, but lack the capital to explore its commercial potential.

Small advanced materials companies represent a technology resource that could make large materials supplier and user companies more competitive in the future. Whether through acquisitions, joint ventures or other financial arrangements, relationships with small materials companies can provide large companies with access to technologies that have commercial promise, but that are too risky for the large company to develop in-house. Expanding the Small Business Innovation Research (SBIR) program is one option for cultivating this resource.

Facilitate More Effective Commercial Exploitation of Military R&D Investments Where Possible

Military policy will continue to have a major impact on the domestic advanced materials industry. More effective exploitation of the military investment for commercial purposes, while protecting national security concerns, could lead to significant competitive advantages for U.S. firms involved in these technologies.

Export Controls

Early in 1987, the Department of Commerce proposed several changes in the administration of export controls intended to alleviate their impact on U.S. high-technology trade. Among these are proposals to remove technologies that have become available from many foreign sources from the control lists, and to reduce the review period for export license applications. These changes could be helpful, but some further steps should be considered.

Option 1: increase representation by nondefense materials industries in policy planning for export controls.

Currently, advice for making export control policy decisions comes primarily from defense agency personnel and defense contractors. To achieve a better balance between military and commercial concerns, greater non-defense industry participation in this process is desirable. An industry advisory group such as the Materials Technology Advisory Council at the Department of Commerce could provide this perspective.

Option 2: Eliminate or loosen reexport controls.

The United States is currently the only nation that imposes controls on the reexport by other countries of products containing U.S.-made materials or components. Many countries view U.S. reexport controls as unwarranted interference in their political and commercial affairs, and this has led to a process of "de-Americanization" in which foreign companies avoid the use of U. S.-made materials and components. One option would be to eliminate the U.S. reexport restrictions entirely, while encouraging foreign trading partner nations to develop and maintain their own export controls for these products.

Option 3: Streamline and coordinate the various export control lists.

All of the various lists under which technologies are controlled should receive careful review for correctness and current relevance. These lists could also be coordinated more effectively. For example, the Departments of Commerce and State have overlapping legal and regulatory authority to control the export of MMC technology. The present system is extremely confusing to U.S. companies, which have experienced long delays in obtaining approval for export licenses. One option would be to have a single agency regulate both the export of MMC materials and technical data related to them.

Information Controls

Technical information about advanced materials is controlled under a complex regime of laws and regulations administered by the Departments of State, Commerce, and Defense. Currently, dissemination of advanced materials technical information can be controlled by: International Traffic in Arms Regulations (ITAR) of the Department of State; the dual-use technology restrictions of the Department of Commerce; the Defense Authorization Act of 1984; government contract restrictions; and Federal document classification systems. There are so many ways to restrict information that actual implementation of restrictions can appear arbitrary. Under some of these laws, regulations, and clauses, one can file for a license to export, and under others, there is no mechanism to permit export of the information. These controls have led to disruption of scientific meetings and to restriction of some advanced materials conference sessions to "U.S. only" participation.

Option 1: Simplify and clarify the various information restriction mechanisms.

Excessive restrictions on information flow can inhibit technology development and prevent technology transfer between the military and commercial sectors. Relying more on classification and less on the other more tenuous mechanisms of control (such as the Defense Authorization Act or contract clauses), could clarify some of the confusion.

Option 2: Make military materials databases more available to U.S. firms.

The most comprehensive and up-to-date information on advanced materials is now available only to government contractors through the Defense Technical Information Center (DTIC). DTIC contains a significant amount of information that is neither classified nor proprietary, but is still limited to registered users. Such information could be of value to U.S. commercial firms that are not government contractors.

Military Research in Manufacturing Technologies

Although military applications for advanced materials can generally tolerate higher costs for materials and processes than commercial applications, both could benefit greatly from research on low-cost processing methods. The desire to reduce procurement costs led DoD to implement its ManTech program, which includes projects devoted to development of many different materials and manufacturing technologies.

Option: Increase support for advanced materials manufacturing research through the ManTech program.

Development of low-cost manufacturing technologies would not only reduce military procurement costs, but could also hasten the commercial use of advanced materials technologies developed for the military, One mechanism to achieve this would be to augment the ManTech budget for those programs aimed at decreasing production costs and increasing reproducibility and reliability of advanced materials structures.

Procurement Practices

DoD constitutes a special market with unique materials requirements. However, like other customers, DoD seeks the widest variety of materials available at the lowest possible cost. It therefore employs regulatory means to simulate the conditions of commercial markets. This makes the participation by materials suppliers extremely dependent on defense regulations and policies, rather than on conventional economic criteria. Through its policies on dual sourcing, materials qualification, and domestic sourcing of advanced materials, DoD has a profound influence on the cost and availability of a variety of high-performance materials and technologies.

Option: Provide a clear plan for implementing legislation aimed at establishing domestic sources of advanced materials technology.

Uncertainties about how recent domestic sourcing legislation (particularly that relating to procurement of polyacrylonitrile (PAN) -based carbon fibers) will be implemented have caused much concern in the advanced composites community. In order to make intelligent investment decisions, U.S. carbon fiber suppliers will require a clear DoD plan including information on quantities to be purchased and the specific weapons systems involved.

Offsets

Offsets are a foreign policy-related marketing arrangement in which the foreign buyer of aircraft or other high-technology systems receives materials production technology from the U.S. system supplier as part of the sale. This can lead to a production capability abroad that is detrimental to the U.S. advanced materials technology base. Technology offsets are commonly required by foreign governments before bids from U.S. (or other) systems suppliers will be considered. In recent years, little attention has been paid to the effects of offsets.

Option: Initiate a thorough study on the effects of offsets on the competitiveness of U.S. advanced materials industries.

Build a Strong Advanced Materials Technology Infrastructure

For U.S. advanced materials suppliers and users to exploit technological developments rapidly, whether they originate in the United States or abroad, an infrastructure must be built up to reduce barriers to their use. In this context, a technology infrastructure encompasses the availability of basic scientific knowledge, technical data to support design and fabrication, and an adequate supply of trained personnel.

Option 1: Increase R&D funding levels to reduce the costs of advanced materials and improve their performance.

The development of low-cost fabrication processes that are capable of making large numbers of structures with reproducible properties is of primary importance.

Option 2: Develop a comprehensive and up-to-date database of collaborative R&D efforts in advanced materials at the Federal, regional, and State levels, including program goals and funding.

In recent years, a large number of research centers of excellence in advanced materials have sprung up with the aid of government funding at Federal, regional, and State levels. Although there are advantages to such a decentralized approach, the resulting dispersion of talent and resources also could preclude the formation of a "critical mass" necessary to solve the remaining technical and economic problems. Such a database would be an essential first step in bringing greater coordination to these efforts.

Option 3: Gather comprehensive information on current activities in government-funded R&D on advanced structural materials.

One persistent need identified by many industry sources is a central source of information on government projects in advanced materials. In general, this information does exist, but it is rarely in a form that is readily accessible to researchers. An oversight organization such as the National Critical Materials Council could help to gather and disseminate such information.

Option 4: Establish a mechanism for gathering business performance statistics on advanced materials industries.

It is difficult to evaluate the business trends of U.S. advanced materials industries because the statistics are aggregated with those of traditional materials industries. One alternative for correcting this situation would be to create separate Standard Industrial Classification (SIC) codes for advanced ceramics and composites so that statistics on production, imports, and exports can be systematically tracked.

Option 5: Step up person-to-person efforts to gather and disseminate data on international developments in advanced materials.

As several competitor countries around the world approach and exceed U.S. capabilities in advanced materials, it becomes imperative for U.S. companies to have prompt and reliable access to these overseas developments. Rather than engage in massive translation of technical publications, which may compete with private sector efforts, the best Federal approach may be to provide increased funding for U.S. scientists to visit laboratories abroad, encourage them to publish accounts of their experiences, and to disseminate this information to U.S. industry.

Option 6: Increase support for the development of standards for advanced materials.

It is very difficult to set standards in a field such as advanced materials in which technologies are evolving rapidly. However, timely development of standard test methods, production quality control standards, and product specification standards would greatly facilitate the manufacture of high-quality products at a lower cost. Several government and private sector organizations have begun to address this problem, but progress has been slow. Particularly important may be greater Federal support of efforts to establish international standards. If the United States fails to agree on standards or is forced to accept standards developed abroad, this could become a significant competitive disadvantage for U.S. companies.

Option 7: Increase the pool of trained materials scientists and engineers by providing increased funding for multidisciplinary university programs in advanced structural materials, and by providing retraining opportunities for technical personnel in the field.

Advanced materials industry sources contacted by OTA were nearly unanimous in their recommendation that more trained personnel are needed. Because materials science cuts across many traditional academic disciplines, multidisciplinary materials programs for students will be very important. Another important source of manpower will be retraining of designers and manufacturing engineers in the field who are unfamiliar with the new materials. Small businesses, professional societies, universities, and Federal laboratories could all play a role in providing such retraining services.

TWO VIEWS OF ADVANCED MATERIALS POLICIES

Congress and the Reagan Administration have adopted conflicting views of policymaking with respect to advanced materials. The crux of the conflict is whether the Federal Government should establish a high-level plan for advanced materials technology development, or whether goals and priorities should be established in a decentralized fashion by the principal funding agencies according to their various missions.

The United States has long had a decentralized approach to advanced materials policy. To a great extent, the major agencies that engage in materials R&D (DoD, DOE, NASA, and NSF) sponsor projects in the context of their distinct missions.

In the congressional view, the growing technological capabilities of the United States' competitors have underscored the urgency of a nationally coordinated approach to advanced materials R&D. This view is expressed in the National Critical Materials Act of 1984, in which Congress established the National Critical Materials Council (NCMC) in the Executive Office of the President. The NCMC is charged with the responsibility of working with the principal funding agencies and the Office of Management and Budget to define national priorities for materials R&D, and to coordinate the various agency efforts. Advocates of a national materials policy point to the apparent capacity of Japan to identify key technologies for the future and pursue their development by means of a coordinated, government/industry effort. Advanced ceramics have been a high-visibility example.

In the Administration's view, it is not appropriate for the government to engage in advanced materials planning; this is viewed as putting the government in a position of "picking winners"-which, according to current thinking, is best left to the private sector. Because different agencies have different missions and requirements for materials, determination of R&D priorities is best made at the agency level. Administration critics of the national materials policy concept maintain that attempts to make materials policy above the agency level risk the worst aspects of Japanese policies, the overbearing bureaucracy, without achieving the best effect, the commitment and coordination of industry. In their view, the congressionally mandated NCMC is redundant with existing interagency committees.

While the Reagan Administration has resisted the concept of strategic advanced materials planning for commercial competitiveness, it has embraced it with regard to national defense needs. DoD is currently preparing a comprehensive policy initiative aimed at preserving the U.S. defense industrial base. This initiative will target a portfolio of technologies, including machine tools, bearings, castings, semiconductors, and advanced composites, for support. Issues such as technological obsolescence, availability of trained personnel, foreign acquisitions of U.S. companies, international cooperation, and government/university/industry collaboration are being addressed.

A national approach to a materials program has several potential advantages. It can provide a focus for the efforts of individual agencies and collaborative government/industry projects. It can provide a continuity of funding in a given area as fashionable R&D areas change from year to year. Finally, it can provide a rationale for committing large amounts of resources for expensive manufacturing development and demonstration programs. To be successful, such a national program should not be a "top-down" approach, but should be structured with consultation and participation of the university, Federal laboratory, and industry community which will ultimately implement it.

Such a national approach also has disadvantages. It may focus on the wrong materials, and be too inflexible to capitalize on new opportunities that arise. It may tie up resources and manpower in long-term programs that are better invested elsewhere. Finally, because it cannot address the cost and performance requirements of materials in actual commercial markets, it may fail to produce materials or processes that are economically attractive to end users.

The debate surrounding national materials policy has suffered from the lack of a clear definition of what such a policy would entail. Whereas policy goals such as conservation of scarce materials or reliable access to strategic minerals are easily understood in the context of conventional materials, it is much more difficult to define national goals for advanced materials. To succeed in its task, the NCMC will need to establish a more precise definition of these goals, and to develop high-level Administration commitment to the concept of a national materials policy.

Pending the resolution of differences between Congress and the Administration regarding the role of the NCMC, there are three further functions that the NCMC could perform:

- Serve as a point of contact to receive and monitor industry concerns relating to advanced materials

An organization such as the NCMC could provide a forum for interaction between industry and the Federal Government on issues relating to advanced materials, particularly those that transcend the purview of any particular Federal agency. This could promote better mutual understanding of industry and government perspectives on advanced materials development, and could eventually lead to the development of a consensus on promising future directions.

- Serve as an information source and a referral center regarding advanced materials

U.S. advanced materials programs and expertise are widely dispersed throughout various agencies and laboratories. There is currently no definitive source of information that can provide an overview of ongoing efforts. An organization such as the NCMC could gather this information from the relevant agencies, analyze it, and disseminate it.

- Serve as a broker for resolving conflicts between military and commercial agency goals for advanced materials

There are materials issues that transcend individual agencies and that could be resolved by an organization above the agency level. For instance, the export control responsibility for regulating advanced materials and information relating to them is currently spread over the Departments of Commerce, State, and Defense, a situation that is very confusing to industry. An organization such as the NCMC could work with the National Security Council to help simplify and clarify the various agencies' responsibilities.

ADVANCED MATERIALS POLICIES IN A BROADER CONTEXT

Ceramic and composite structural materials clearly represent great potential opportunities for the U.S. economy. However, advanced materials are not unique in their importance to the future competitiveness of U.S. manufacturing industries. Other technologies, including microelectronics, computers, robotics, and biotechnology will also be important. These technologies face similar competitive challenges, and many of the policy objectives and options discussed above could benefit all of them. As such, it may be most appropriate to address the commercialization of advanced materials technologies as part of a broader policy package aimed at achieving greater investment and productivity in the manufacturing sector as a whole.