Chapter 5

Factors Affecting the Use of Advanced Materials

CONTENTS

Tables

Chapter 5

Factors Affecting the Use of Advanced Materials

FINDINGS

Because of the intimate relationship between advanced materials and structures produced from them, the design and manufacture of these new materials must be treated as an integrated process. These materials make it possible to form parts and systems in larger, more combined operations than are possible with traditional metals technology. one operation can form both the part and the material, thereby eliminating costly assembly operations. The need for such an integrated, or unified, approach will affect all aspects of manufacturing.

costs

Although the high per-pound cost is currently a barrier to the increased use of advanced structural materials, low cost could become a selling point for these materials in the future if systems costs are considered. Advanced structural materials offer the opportunity to consolidate parts and reduce manufacturing and assembly costs. In general, use of advanced materials will only be cost-effective if the manufacturer can offset higher raw materials costs with savings in assembly and maintenance costs.

Multidisciplinary Approach

The integrated nature of advanced materials manufacturing will require close cooperation between research scientists, designers and production engineers. Effective commercialization will require teams that bring together expertise from many professional disciplines.

Education and Training

Cooperation and blending across different disciplines in industry will require interdepartmental educational opportunities for students in universities. At the same time there is a need for skilled engineers who have strong backgrounds in these advanced materials. Retraining will be required for engineers already in the work force, and training in manufacturing with these materials will be needed for production workers.

Standards

Several types of standards will facilitate integrated design with advanced materials: quality control standards applied at each stage of the manufacturing process, product specification standards, and standardized test methods for materials qualification. Numerous groups in the United States are working on domestic materials standards, although progress has been slow. There is also a large domestic effort on the part of the Japanese. Several international organizations are also attempting to develop international standards for advanced materials.

Automation

Those forms of automation that aid the integration of design and manufacturing will be of great use in speeding up the acceptance of the new materials. These might include design databases, automated processing equipment and sensors for process information feedback. Automation can help reduce material and process cost, ensure part quality, and eliminate the long manufacturing times inherent in some processes.

Technical challenges for the automation of advanced materials production are generally similar to those for traditional metals production; however, such problems as the lack of design data and strict quality control requirements may be more serious for advanced composite or ceramic part production. Automation will proceed slowly, given the newness of the materials and the time needed to develop experience with, and confidence in, their use.

INTRODUCTION

The future of advanced materials involves more than purely technical changes. Other factors that will affect the development and commercialization of these materials are: an integrated approach to design and manufacturing, a systems approach to cost, interdisciplinary research and production, education and training, standards development, and automation of design and manufacturing processes.

Because advanced ceramics and composites are tailored to suit their applications, these materials cannot be considered apart from the structures made from them. Both material and structure are manufactured together in an integrated fabrication process. This is fundamentally different from the sequential manufacturing processes associated with conventional materials. With metals, the materials and processes are determined by the specifications; with advanced materials, the materials and manufacturing processes are designed with the aid of the specifications.

The principle of integration will have a strong influence on the future use of advanced materials. This development will depend on more unified approaches to problem solving, requiring a broader view on a wide range of issues. An integrated approach will be imperative, not just in finding solutions to technical challenges, but also in dealing with various institutional and economic issues.

INTEGRATED DESIGN

When designing a structure to be made of metal, the design team specifies the metal to be used and has a rough idea of its final properties. This team then can simply hand the design over to the production team. The production team, in separate operations and without further contact with the designers, treats the metal to achieve the microstructure and mechanical properties that the designers envisioned, shapes the structure in a rough fashion, and finishes it to have the precise shape desired.

With advanced composites and ceramics, these steps are collapsed into a single processing step; thus a design team working with these materials cannot be separated from the manufacturers of the part. Design of the material, structure, and manufacturing process is called integrated design.

Integrated design requires a large amount of data. Some of the kinds of materials property information a designer might want are shown in table 5-1. Mechanical properties of ceramic and composite structures, as well as of the constituent materials, will be needed for a wide variety of materials. Processing parameter data and cost data will also be important in material and process choice.

Table 5-1.—Polymer Matrix Composite Design Parameters

1. Tensile strength x,y
2. Tensile stiffnesses x,y
3. Elongation at break x,y
4. Flexural strength
5. Flexural stiffnesses
6. Compressive strength x,y
7. Compressive stiffnesses x,y
8. Shear strength (short beam shear test and/or off-axis tensile test)
9. Shear stiffnesses x,y
10. Interlaminar strength (G_c)
11. Impact strength
12. Compression strength after impact
13. Coefficient of thermal expansion x,y
14. Hydroscopic expansion (moisture coefficient x,y)
15. Poisson's ratios x,y
16. Fiber volume content
17. Void content
18. Density

x,y: In two directions, parallel and perpendicular to the long direction of the reinforcement fiber.

NOTE: These design parameters are a few of the large number of design parameters which give rise to the plethora of variables which must be controlled during manufacturing.

SOURCE: Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites," contractor report for OTA, December 1985.

There is currently a great deal of effort underway by many different groups to determine what might comprise a materials design database for PMCs. (Ceramic and metal matrix composite

[MMC] technologies are less evolved and may not be ready at this time for database development.) Ideally this data should be available for a wide range of fibers and matrices. A comparison of the costs of different materials would also be a desirable feature of such a materials database.

To direct the manufacture of a part, or to be able to design a part with forethought on how it could be manufactured, processing variables databases would also be necessary. These databases would include variables such as curing times of resins and heat treatment curves for obtaining various microstructure, and, most notably, processing costs. A processing database would be of greatest benefit in deriving properties of a composite or ceramic ***structure*** as a whole. Having this knowledge could allow custom tailoring of parts, and may trim costs through reducing tendencies to overdesign and through shortening design time.

Several attempts are being made to establish databases for advanced materials. The National Bureau of Standards is currently attempting to develop a protocol for an electronic database for ceramic materials. In the private sector, one effort underway to create a centralized database is the National Materials Properties Data Network, which plans to provide its subscribers with the capability to search electronically a large number of data sources that have been evaluated by experts.[1]

SYSTEMS APPROACH TO COSTS

It is often stated that the three biggest barriers to the increased use of advanced materials are cost, cost, and cost. In a narrow sense, this observation is correct. If advanced materials are considered on a dollar-per-pound basis as replacements for steel or aluminum in existing designs, they cannot compete. This has often been the perception of potential user industries, which tend to be oriented toward metals processing. However, per-pound costs and part-for-part replacement costs are rarely valid bases for comparison between conventional and advanced materials.

A more fruitful approach is to analyze the overall systems costs of a shift from conventional materials to advanced materials, including integrated design, fabrication, installation, and lifecycle costs.[2] On a systems cost basis, the advanced materials can compete economically in a broad range of applications. Moreover, the high per-pound cost is largely a result of the immaturity of the available fabrication technologies and the low production volumes. Large decreases in materials costs can be expected as the technologies mature. For instance, the cost of a pound of standard high-strength carbon fiber used to be $300 but is now less than $20, and new processes based on synthesis from petroleum pitch promise to reduce the cost even further[3] If high-strength carbon fibers costing only $3 to $5 per pound were to become available, major new opportunities would open up for composites in automotive, construction, and corrosion-resistant applications.

Advanced ceramics and composites should really be considered structures rather than materials. Viewed in this light, the importance of a design process capable of producing highly integrated and multifunctional structures becomes clear. Polymer matrix composites (PMCs) provide a good example. In fact, the greatest potential economic advantage of using such materials, beyond their superior performance, is the reduction in the manufacturing cost achieved by reducing the number of parts and operations required in fabrication. For example, a typical automobile body has about 250 to 350 structural parts. Using an integrated composite design, this total could

---

[1] Materials and Processing Report, Renee Ford, Ed., MIT Press, Cambridge, MA, February, 1987.

[2] "How Should Management Assess Today's Advanced Manufacturing Options," *Industry* Week, May 26, 1986, pp. 45-88.

[3] *Iron Age,* June 20, 1986, p. J6.

be reduced to between 2 and 10 parts, with major savings in tooling and manufacturing costs.[4]

Fuel Costs

Fuel costs also represent an important factor that can affect the competitiveness of advanced ceramics and composites compared with conventional structural materials. The cost of the energy required to manufacture ceramic and composite components is only a negligible fraction of overall production costs. However, the high potential for energy savings when the component is in service is a major reason for using advanced ceramics and composites.[5]

penetration of ceramics into such applications as heat exchangers, industrial furnaces, industrial cogeneration, fluidized bed combusters, and gas turbine engines depends on energy costs. Ceramic heat exchanger systems have potential for greater than 60 percent fuel savings.[6] Ceramics used in advanced turbines could result in 30 to 60 percent fuel savings.[7]

Weight reduction, through intensive use of PMCs in automobiles, may be translated into improved fuel economy and performance, and thereby lower vehicle operating cost. The trend toward fuel-efficient automobiles after the oil crisis of 1973-74 resulted in a substantial decrease in the average weight of an automobile, some 25 percent of it due to the introduction of lightweight materials such as high-strength steel, plastics, and aluminum.[8] Increases in fuel prices would encourage some further interest in advanced composites for automotive applications. (For further discussion of the impact of energy costs on use of composites in automobiles, see chs. 6 and 7.)

In aircraft, one of the major benefits of using PMCs is lower lifecycle costs derived from better fuel efficiency, lower maintenance costs and longer service life. This has already been demonstrated by the fact that there was a significant increase in the use of PMCs in aircraft when oil prices were greater than $30 per barrel.[9] It is also evident however, that lifecycle costs and capital, materials, and labor costs (notably the high labor costs of hand lay-up) are design trade-offs which determine the choice of materials. When oil prices drop as low as $12 per barrel (as they did in the fall of 1986), the relatively high cost of composite materials makes them unattractive to the aircraft manufacturer.[10]

There are predictions that low oil prices will continue through the year 2000, and that jet fuel prices will not even increase as quickly as crude oil prices.[11] This does not necessarily mean that gains made in use of composites in aircraft will be reversed. Rather, the persistent low energy costs are likely to reduce the incentives to increase the use of composites in structures now made of aluminum.

EDUCATION AND TRAINING

The expanding opportunities for advanced ceramics and composites will require more scientists and engineers with broad backgrounds in these fields. At present, only a few U.S. universities offer comprehensive curricula in ceramic or composite materials. There is also a shortage of properly trained faculty members to teach the courses. However, considerable progress is being made in the number of students graduating with degrees in advanced materials fields. In the

---

[4] P. Beardmore et al., Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries—Case Study: Composite Automobile Structure," contractor report for OTA, March 1987.

[5] David W. Richerson, "Design, Processing, Development and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

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

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

[8] Steven R. Izatt, "Impacts of New Structural Materials on Basic Metals Industries," contractor report for OTA, April 1987.

[9] A.S. Brown, "Pace of Structural Materials Slows for Commercial Transports," *Aerospace America,* American Institute of Aeronautics and Astronautics, June 1987, pp. 18-21, 28.

[10] Ibid.

[11] P.D. Holtberg, T.J. Woods, and A. B. Ashby, "Baseline Projection Data Book," Gas Research Institute, Washington, DC, 1986.

1984-85 academic year, a total of 77 M.S. degrees, and 34 Ph.D.s were awarded in ceramics in the United States. One year later the totals were 139 and 78, respectively. About 40 percent of the Ph.D.s were foreign students. No estimates were available on how many of the foreign students subsequently returned to their home countries.[12]

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 now providing greater educational and job opportunities for students, and this trend is expected to continue.

There is a great need for continuing education and training opportunities in industry for designers and engineers 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. Continuing education is especially important in relatively low-technology industries such as construction, which purchase, rather than produce, the materials they use. Some universities and professional societies are now offering seminars and short courses to fill this gap; such educational resources should be publicized and made more widely available,

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

MULTIDISCIPLINARY APPROACH

Commercialization of advanced materials requires a team effort. In producing a typical ceramic component, the team could consist of one or more professionals from each of several technical disciplines, as illustrated in table 5-2. Disciplines that overlap materials science and engineering are: solid state physics; chemistry; mechanical, electrical, and industrial engineering; civil and biomedical engineering; mathematics; and aerospace, automotive, and chemical engineering. Materials research lends itself naturally to collaborative institutional arrangements in which the rigid disciplinary boundaries between different fields are relaxed.

Table 5.2.—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

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

Similarly, interjector cooperation in materials research could speed the development of advanced materials. New mechanisms for collaborative work among university, industry, and government laboratory scientists and engineers are having a salutary effect on the pace of advanced materials development and utilization’, (The role of government/university/industry collaborative R&D is explored in greater detail in ch. 10.)

---

[12] Business Communications Co., Inc., “Strategies of Advanced Materials Suppliers and Users, ” contractor report for OTA, Jan. 28, 1987.

STANDARDS

There are many problems inherent in setting standards in rapidly moving technologies.[13] Standards development is a consensus process that can take years to complete, and it is likely to be all the slower in this case because of the complex and unfamiliar behavior of advanced ceramics and composites. As these technologies mature, though, such difficulties will generally become more tractable.

The extensive data requirements of integrated design can be simplified by material standards to reduce the volumes of data that are processed, and by data transfer standards to permit the efficient handling of data. Standards are essential for the generation of design data, and for reliability specifications for advanced materials sold domestically or abroad. Areas that could benefit from the formulation and application of standards include: quality control, product specifications, and, most importantly, materials testing.

The two keys to competitiveness in any area of manufacturing are quality assurance at low cost. Quality control standards applied at each stage of the manufacturing process help to ensure high product quality and low rejection rates. For instance, there is a need for standards applied to ceramic powders and green bodies (unsintered ceramic shapes) to minimize the flaws in the final sintered product. Product specification standards, largely determined by the requirements of the buyer, provide the buyer with assurance that the product will meet his needs.

As a way to accelerate the commercialization of advanced materials, some experts advocate choosing one or two materials in a given category and concentrating on producing uniform, high-quality components from these. In ceramics, for instance, silicon carbide, silicon nitride, and zirconia would be possible candidates, because they have already received a large amount of research funding over the years for heat engine applications. These materials have a broad range of potential uses, but designers cannot compare them or use them without a reliable database on standard compositions having specified properties. While there is a danger in prematurely narrowing the possibilities, these experts say, there is also a danger in not developing the materials already available. Opponents of this view argue that, since large commercial markets are still far in the future, there is no need to settle for present materials and processes. On the contrary, they say, the focus should be on new materials and processes which can “leapfrog” the present state-of-the-art. This classic dilemma is characteristic of any rapidly evolving technology.

Standard Test Methods

The need for standard test methods has long been identified as an important priority. For homogeneous materials such as metals, testing methods are fairly straightforward. In composites, however, the macroscopic mechanical behavior is a complex summation of the behavior of the microconstituents. Consequently, there has been great difficulty in achieving a consensus on what properties are actually being measured in a given test, let alone what test is most appropriate for a given property. Currently there are numerous test methods and private databases in use throughout the industry. This has resulted in considerable property variability in papers and reports. The variability problem is particularly severe for testing of toughness, bending, shear, and compression properties.

Standardized test methods would not only facilitate consistent reporting of materials properties in the research literature, but they could also drastically reduce the costs of the repetitive testing presently necessary to qualify new materials for use in various applications.[14] Due to liability concerns, a new material must be qualified by extensive testing for an individual application before a user company will incorporate it into a system.

---

[13] J. David Roessner, “Technology Policy in the United States: Structures and Limitations,” *Technovation*, *vol. 5, 1987,* p. 237, provides a brief case study of problems in setting standards in the early stages of development of numerically controlled machine tools.

[14] This is discussed for polymer matrix composites in ch. 11.

At present, each defense prime contractor company qualifies its material for each separate defense or aerospace application according to its own individual tests and procedures. Data on material properties are often developed under government contract (costing $100,000 to $10 million and taking up to 2 years), but companies are reluctant to share the results. Even when data are reported in the literature, often the type of test used and the statistical reliability of the results are not reported with the data. Although the lack of standards probably does not inhibit the expert designer of composite aerospace structures, the availability of standards could encourage the use of composites in industries such as construction, where designers have no familiarity with the materials.

U.S. Standardization Efforts

The American Society for the Testing of Materials (ASTM), provides the United States with an excellent and internationally respected mechanism for setting materials standards. ASTM has recently established an Advanced Ceramics Committee (C-28), which is now staffing subcommittees in the fields of properties, performance, design and evaluation, characterization, processing, and terminology. The ASTM Committee on High Modulus Fibers and Their Composites (D-30) and the Committee on Plastics (D-20) are the principal sources of standardized test methods for PMCs. Advanced materials trade associations such as the United States Advanced Ceramics Association (USACA) and the Suppliers of Advanced Composite Materials Association (SACMA) have also been working with ASTM and government agencies to develop standards.

On the users' side, the Aircraft Industries Association has initiated Composite Materials Characterization, Inc. (CMC), a consortium of aerospace companies involved in fabricating composites. CMC is conducting limited materials screening tests on composite materials for its members.[15]

Consistent with its growing interest in composites, the Department of Defense, with the Army as the lead service, has recently initiated a new program for standardization of composites technology (CMPS).[16] CMPS is attempting to promote the integration of diverse standards for composites by gathering standardized test methods (e.g., from ASTM) into Military Handbook 17(MIL-17) and by developing separate test methods where necessary.[17] A Joint Army-Navy-NASA-Air Force (JANNAF) Composite Motor Case Subcommittee is developing standard test methods for filament wound composites used for rocket motor cases.[18]

As part of CMPS, the Army Materials Laboratory in Watertown, MA, has established coordination with a variety of organizations, including ASTM, the Composites Group of the Society of Manufacturing Engineers (COGSME), the Society of Automotive Engineers (SAE), the Society for the Advancement of Material and Process Engineering (SAMPE), American Society for Metals (ASM) International, the Society of Plastics Engineers (SPE), and the Society of the Plastics Industry (SPI).

International Standardization Efforts

International organizations that are pursuing advanced materials standards include the Versailles Project on Advanced Materials and Standards (VAMAS), and the International Energy Agency (IEA). VAMAS is now formally independent, having begun as an outgrowth of the periodic summit meetings of the heads of government of Canada, France, the United Kingdom, West Germany, Italy, Japan, the United States, and the European Community. Subdivided into 13 technical working areas, VAMAS is attempting to improve the reproducibility of test results among laboratories by round robin testing procedures designed to identify the most important control variables. U.S. liaison with VAMAS is primarily through the National Bureau of Standards (NBS).

---

[15] *Advanced Composites,* July/August 1987, p. 45

[16] U.S. Department of Defense, Standardization program Plan, Composites Technology Program Area (CMPS), Mar. 13, 1987.

[17] A draft of MIL 17 was being evaluated at this Writing.

[18] U.S. Department of Defense, op. cit., footnote 16.

The IEA is developing standards for characterizing ceramic powders and materials. The principal participants are the United States, Sweden, and West Germany. U.S. liaison with the IEA is coordinated through the Department of Energy. Currently, U.S. participation in these international standards-related activities tends to be limited, with funds being set aside from other budgets.

AUTOMATION

The term automation is used here to encompass the wide range of new design and processing technologies for advanced materials. Automation of design and early development work involves standardized materials and processing databases; computer-aided ***design*** (CAD) systems; and computerized ***mathematical/ modeling*** of design and processing of the material. Automation of production processes can involve any combination of the following technologies: ***computerized processing equipment*** that can be used in a stand-alone fashion or in coordination with other technologies; ***robotic,*** instead of human, handling of material; ***sensors*** and process monitoring equipment; ***statistical process control*** for better part quality; ***computer-aided manufacture*** (CAM) and *"expert" systems* software for coordination of design and manufacture.

Computer-Aided Design Systems

CAD systems currently focus on three-dimensional graphics manipulation, and many of them also have the capability for stress analysis of a structure. CAD systems for mechanical drawings currently cannot recognize parts of a drawing as significant features; e.g., the collection of lines that a designer sees as a hole is seen by the CAD system as simply a collection of lines.[19] [20] A comprehensive CAD system that would facilitate the process of choosing suitable materials, reinforcement geometry, and method of fabrication is still far in the future. Such a system would require both materials databases on fiber and resin properties and processing databases that would permit modeling of the manufacturing steps necessary to fabricate the part. The principal advantage of such a system would be to define clearly the options and trade-offs associated with various production strategies, including processing costs.

Computerized Mathematical Modeling

To expand the capabilities of a CAD system, the designer would need accurate models of how the material and the part would behave in the operating environment. Computerized mathematical models will be necessary to describe the relationships among materials properties, material microstructure, environmental conditions, static and dynamic forces, manufacturing variables, and other aspects of design such as life prediction and repairability considerations. Mathematical models may also aid in decreasing the amount of stored data needed. It may also prove possible to develop, during the design of a given component, temporary mathematical models, specific to that component. This would facilitate quick redesign of the component during the design or prototype development phases.[21]

Computerized Processing Equipment

Computer control of all aspects of processing and manufacturing will be an important factor in increasing and maintaining the reliability and reproducibility of parts made of advanced materials. What is required initially is processing equipment similar to today's computer numerically controlled (CNC) machine tools for machining metal. Automated processing equipment is being designed in-house by some aerospace manufacturers and manufacturers of machine tools,

Currently, production equipment (computer controlled or otherwise), designed specifically for advanced materials is at a prototype stage. An example is automated tape-laying machinery for

---

[19] Herb Brody, "CAD Meets CAM, " *High Technology,* May 1987, pp. 12-18.

[20] More sophisticated CAD systems exist for drawing electronic circuits.

[21] Norman Kuchar, General Electric Co., personal communication, Apr. 15, 1987.

PMCs. The tape-laying machines now available are modified milling machines similar to those used for metalworking. There is a great deal of interest in developing new programmable automated tape-laying equipment, with computer-aided determination of the tape-laying path.[22]

Another promising technology for automating PMC production is the filament winding machine. Recent development work in flexible filament winding machines indicates that it may be possible to generate complex, noncylindrical parts.[23]

Other processes for producing composite parts that are good candidates for computerized processing are: fast pultrusion processes, impregnation of prepregs, and three-dimensional fabrics and preforms.

Ceramic processing techniques that could benefit from this sort of automation are shaping and densification methods, machining techniques, and particularly techniques for near-net-shape processing, such as hot isostatic pressing and casting techniques.

Microprocessors can monitor and control cycle times and temperatures for such processes as hot isostatic pressing for ceramics and fast-curing spray-up processes for PMCs. Equipment under computer control will eventually be used in part finishing operations and assembly as well as par-t forming.

Robotics and Materials Handling

Robots function as would a human hand and arm in manipulating parts and materials. Robots can also be used to hold and operate tools, such as welding equipment or drills. Processes such as hand lay-up of composites currently require a great deal of human handling of material, but it is not necessarily cost-effective to replace a human with a robot directly in advanced material production. Processes such as filament winding and resin transfer molding are more likely to replace hand lay-up cost-effectively for certain types of composites.[24] For this reason, applications for robots in advanced material production are likely to be limited to the carrying of nondestructive evaluation sensors (see below) and a small amount of part handling. Robots are currently used for assembly operations such as welding. It may be that robots will be used in composite joining operations, such as the application of adhesives.

Sensors and Process Monitoring Equipment

To monitor advanced materials processing on-line (during the process), sensors are needed. This information must be sent to the computer and analyzed, so that errors can be detected and any needed corrections can be made while the part is still being formed. This procedure permits near-instant correction of costly mistakes in processing. This is accomplished through the use of sensors and monitoring equipment that can detect abnormal conditions without interfering with normal processes. Sensors are used not only to detect major processing problems but also for the fine-tuning of quality control.

There are many types of sensors: laser and other visual sensors, vibration-sensing monitors that can operate in many frequency ranges, force and power monitors, acoustic and heat-sensing probes, electrical property probes (e.g., capacitance- or inductance-based) and a host of other types. There are also many types of sensors that can be used for part inspection once a part has been completed; these include such techniques as nondestructive evaluation (using acoustic and other vibrational methods, radiography, holography, thermal wave imaging, and magnetic resonance among other methods) and use of laser-based high-precision dimensional measuring machines.

Statistical Process Control

Quality control, in a general sense, means staying within predetermined tolerances or specifications when manufacturing a batch of parts. Each batch of parts has a statistical distribution of part

---

[22] Roger Seifried, Cincinnati Milacron Co., personal communication, June 1, 1987.

[23] Dick McLane, Boeing Airplane Co., personal Communication, Apr. 29, 1987.

[24] Timothy Gutowski, Massachusetts Institute of Technology, Personal communication, Apr. 15, 1987.

Photo credit: Hercules, Inc.

Filament winding of rocket motor casing for space shuttle.

qualities, all of which must fall within a certain tolerance range. Statistical process control encompasses quality-control practices that ensure that the statistical part quality distribution falls within the tolerance range, and that this distribution is centered within the tolerance range.[25] This procedure ensures not only that part quality of all the parts in the batch is acceptable, but also that the large majority of the parts in the batch are of the most desirable quality.

Statistical process control is mainly mathematical in nature and relies heavily on the sensor technologies described above for information inputs. To apply the information gained from statistical process control techniques most effectively, feedback into the manufacturing system must occur during the process of forming the batch. The information fed back into the process is used to make the minor processing corrections that can significantly increase the reliability of the process, enhance the overall quality of each batch, and reduce the rejection rates of the final parts.

---

[25] Kelth Beauregard, Perception Inc., "Use of Machine Vision To Stay Within Statistical Process Control Limits of Dimensions, " Cutting Tool Materials and Applications Clinic, Detroit, MI, Society of Manufacturing Engineers, Mar. 11-13, 1986.

Computer-Aided Design and Manufacturing

CAD/CAM technology lies further in the future than most of the automation technologies described here. The CAD systems described above could help the designer choose a material and pick the least costly, most sensible process for manufacturing, as well as model the behavior of the part in service. A fully integrated CAD/CAM system would then send instructions to the correct set of machines to process the material. It would also need to include instructions for process variables, raw materials inventory, manufacture or supply of tooling, production time scheduling, and other shop-floor considerations.

Expert Systems

Expert systems technology, like the CAD/CAM technology, lies far in the future. An expert system is essentially a type of artificial intelligence and requires an extremely complex program that can make educated guesses when confronted with a lack of hard knowledge. Such a system is an assemblage of interactive software plus databases that offer all of the working knowledge gleaned by experts in a particular field. A designer inexperienced with composites or ceramics might be able to use the system to learn how to design with the unfamiliar material. The benefits of an expert system for materials design are clear. These materials could become more accessible with the advent of such an expert system, and all designers, whatever their level of experience, would have an enhanced base on which to draw.

CONSIDERATIONS FOR IMPLEMENTING AUTOMATION

Full automation implies an integration of all facets of design, development, materials inventory, production, quality assurance, product inventory, and marketing. Clearly such a degree of automation is far in the future for advanced materials and will only occur when the dollar volume of advanced materials products is high enough to warrant the significant capital investment needed for this type of production. Although this degree of technical complexity is not yet available, all of these technologies are individually of continuing interest to advanced materials manufacturers.

It is important to note that this type of complete automation need not occur at once. in fact, for reasons of capital cost alone, it is wise not to implement a high degree of automation quickly. Fortunately, some of these technologies can be verified and put in place well before others are available. It is necessary for each industry or company to decide what benefits of automation are most important and to choose to incorporate those forms of automation that could fill the needs of that company in a timely and cost-effective fashion.

Many industry experts feel that technologies such as advanced ceramics and composites are too new to warrant a large investment in automation. Automation is seen as an inflexible process requiring fixed, well-characterized processing techniques. In the view of these experts, it will be many years before enough experience has been gained with these materials to consider automation cost-effective. It will be useful to consider here what automation technologies offer for composites and ceramics manufacture and what challenges face the automation of advanced material production.

Automation offers three advantages: speed, reliability/reproducibility, and cost, However, these benefits cannot be realized simultaneously; trade-offs are required. A system that offers sophisticated controls and sensors for producing parts to tight specifications may not be a system that has enough speed (or low enough costs) to use in high-volume applications. The capital investment required may not be low enough to make advanced materials attractive enough to use even in high-volume applications. Another trade-off is between flexibility and speed/cost. Robots or materials processing equipment that can perform a wide range of tasks will not be as inexpensive and operationally quick as equipment dedicated to one particular task.

Currently, there are several major roadblocks to automation in the advanced materials field. One is the inability to link machine tools, controllers, and robots made by different manufacturers, or even by the same manufacturer at different points in time. This problem of interfacing nonstandard and dissimilar machines has been under consideration by a number of organizations, most notably the Automated Manufacturing Research Facility (AMRF)[26] at the National Bureau of Standards (NBS) and the Manufacturing Automation Protocol (MAP)[27] system developed by General Motors. Some advanced materials advocates have cited data transfer standards as some of the most important standards needed for increased use of advanced materials.

Another difficulty in automation is the wealth of information needed in electronic form which presents difficulties in data collection and increased probability of errors during data access. To illustrate the formidable problems facing the development of electronic databases of ceramic and composite properties, consider the state of metal machining databases. There are currently thousands of metals and metal alloys, and thousands of types of microstructure that can occur in each metal or alloy. Machining conditions can change with: microstructure of the metal; the type of machining process; the type, size and condition of tool; the depth, length, width, and speeds of cut; and the type and amount of lubricant. Each of these parameters must be selected for each operation that must be performed on a metal part.

In addition, unexpected machining behavior may occur depending on factors that cannot be known in advance, such as the rigidity, age, and brand of machine tool used. Thus, individual corrections must be made after the original parameters are chosen and tested.

There are similarly a large number of variables for the design of a metal part. At present, most of the country's design and production engineers working with metals use handbooks of incomplete tables to make best guesses as to design and process parameters. These data have been derived experimentally in an uncoordinated fashion over a period of decades. The situation for composites databases is even more complicated because of the larger number of component materials and materials interactions that must be taken into account.

Advanced Structural Materials Design

Most of the problems described above are present whether the material is metal, ceramic, or a composite. However automation is a much more problematic undertaking with advanced ceramics or composites than with metals. One major problem is the complexity of design.

At this stage, design databases, both for materials properties and the processes used in manufacturing parts, are still incomplete for available and familiar metals that have been in use for some decades. With newer materials this is even more of a problem because there is little material experience or history available from any source. Some experts believe that the use of mathematical modeling of manufacturing processes will eventually allow the designer to construct a part-specific database as a new part is being designed. This preliminary database could be updated as the design moved to the prototype and production phases and more knowledge of the material is gained.

One esoteric problem in automating design processes involves engineering knowledge of an intuitive or experiential nature. This human knowledge is difficult to translate into information that can be transferred or used electronically. Examples: The ability to tell the temperature of a molten metal by its color, or to ascertain the

---

[26] "Automated Manufacturing Research Facility," National Bureau of Standards, December 1986.

[27] Catherine A. Behringer, "Steering a Course With MAP," *Manufacturing Engineering,* September 1986, pp. 49-53.

service life left to a cutting tool by the sound it makes during the cut. To translate this kind of know-how into electronic data, extremely accurate, sensitive, durable, and reliable sensors are required. This is particularly important considering the flaw sensitivity of such a material as a ceramic, because a large number of parts can be ruined for a slight margin of error in the sensor. These materials cannot be reworked, and high scrap rates are a major factor contributing to the high cost of ceramic parts.

Advanced Structural Materials Production

Several problems are likely to hamper the development of automated techniques for production of advanced materials that do not arise in the production of parts made from metal. Although new structural materials offer the advantage of combining what would be several metal parts into a single structure, when an error occurs in production, cost-efficiency may be seriously threatened. Advanced materials cost more, the structure cannot be reworked, and the whole composite or ceramic structure is lost where only a single metal part might have been with a metal design. This is another reason why automated production of these advanced materials will require extremely reliable and accurate sensors.

Another problem is the large capital investment involved in automation. Full automation of design through production requires many new and expensive changes at once. Even though one of the main advantages of these new engineered materials is the integration of design and manufacturing, it will not be possible to develop all these technologies at once into a single, unified factory system.

As companies begin to automate, they will use different combinations of automation technologies, depending on the priorities of the user industry. Table 5-3 illustrates how the reasons for automating might differ among manufacturers. In the near term, automation based on the use of robotics to reduce labor costs may not be cost-effective if labor costs are a small pat-t of overall cost, or if part volumes are low.[28] The automobile industry would desire to automate to save materials and manufacturing process costs.

In the aircraft industry, techniques such as automated tape laying to save the labor costs of hand lay-up could be important. Where long design times mean a significant cost, such as in aircraft design, automation is desirable in the form of mathematical modeling, expert systems for designers, and systems for prototype production, such as mold design software. [29] Since the reliability and reproducibility of ceramic parts are of primary importance, automated processing tech-

Table 5-3.—Reasons for Automating, and Appropriate Types of Automation

Reason	Types of automation	Industry example
Save labor costs:	Robotics New processing technologies (i.e., filament winding, tape laying)	Automotive paint spraying, joining
Speed up production:	New processing technologies: High-speed resin transfer molding, automated tape laying	Auto body
Increase part quality:	Process controls, sensor technologies	Ceramic auto engine parts Composite aircraft structures
Shorten design times:	Expert sytems CAD Mathematical modeling Databases	Composite aircraft *structures*

NOTE: Different manufacturing challenges require different types of automation solutions.

SOURCE: Office of Technology Assessment, 1988.

---

[28] S. Krolewski and T. Gutowski, "Effect of the Automation of Advanced Composite Fabrication Process on Part Cost, *SAMPE Quarterly*, October 1986.

[29] Norman Kuchar, General Electric Co., personal Communication, Apr. 15, 1987.

niques and sensor technology would be used to automate the manufacture of ceramics. The plastics industry is turning to robots for several reasons, among them the ability to integrate plastic part manufacturing with "downstream" assembly operations, and flexibility to meet changing production requirements.[30]

The one form of automation nearly all industries require immediately involves better materials processing technologies possessing some degree of automation. This means an increase in the quality of sensors and a higher level of sophistication in equipment for forming advanced materials. As we have seen and will see again in the following chapters, processes such as automated tape laying of **PMCs** and near-net-shape processes for ceramics will need precision forming and monitoring equipment to begin to offer the needed reliability and cost savings.

Automation techniques that foster integrated design through promoting close cooperation between designer and manufacturing engineer should be of highest priority. These would include extensive design databases, automated processing equipment and sensors for process information feedback.

---

[30] Robert V. Wilder, "Processors Take a Second, Harder Look at Robots, " *Modern Plastics,* August 1987, p. 48.