Avoiding Failures in Advanced Structural Materials

T.W. Eagar, Co-Director Leaders for Manufacturing Program
POSCO Professor of Materials Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract: The dramatic growth of materials science and engineering over the past two decades has made it possible to engineer new materials with specialized properties in a very short period of time. We have changed our philosophy from "designing with materials" to "designing of materials." Indeed, we conceive many new products and systems before the necessary materials are available; we assume that the materials properties which are required can be developed. It is correct that often materials can be designed to meet these applications, but frequently we find that the cost of these specialized materials is excessive. In addition, as materials become ever more specialized, the market volume decreases which further increases the costs. As new designs require the operation of the materials closer to their limits, the failure rates increase. While the growth of materials science and engineering has brought, and will continue to bring, major advances in our standard of living, it is essential that we use sound judgment in selecting the new technologies which are most promising. Reliable use of advanced structural materials will require improvements in every facet of design, production and use of the product.

Key Words: Advanced structural materials; materials design; product design; failure rates; product failures; properties comparison; advanced materials.

Introduction: Currently, there is intense worldwide interest in advanced materials and processing. The Office of Technology Assessment has selected advanced materials, technology, bio-technology, and information technology as the keys to future industries with a growth in the materials market of $100-billion projected over the next decade. The development of these materials has been linked to our national competitiveness and our future standard of living (ref. 1).

Many research findings extol the benefits of newly developed polymers, inter-metallics, ceramics, and composites, with predictions that these new materials will change our lives significantly in the years to come. Many companies have reduced their research efforts in traditional materials and have diversified into these advanced materials. Others, constrained by an increasingly competitive international trade climate, have greatly reduced or eliminated their research and development activities altogether. Some have predicted a continual erosion of the market for traditional materials in favor of advanced materials. The rationality of this prediction is examined in this article.

Advanced materials have exciting properties but their commercialization often is stalled due to several pitfalls including biased presentation of materials properties, failure to consider the implications of materials substitution, and ignoring production-scale processing considerations. All of the factors that influence the substitution of a new material for a traditional one must be examined carefully to derive an accurate prediction of the potential of the new materials. For example, in the commercial-aircraft industry, where the consequences of a system failure can be very serious, there is considerable reluctance to incorporate advanced materials without extensive testing and prototyping. In other industries, such as those governed by industrial codes that have
been built up through years of experience, adoption of a new material can move at a
glacial pace. Also, it is important to realize that in most applications, a traditional
material can perform as well as an advanced material--often at a lower overall cost.
An examination of the methods used to assess a new material’s performance during
product development illustrates why some new materials are commercially successful
while others are not.

The purported potential of an advanced material can be misleading for many reasons.
Some benefits are related to the exuberance of the materials scientist in extolling his/her
accomplishments, while others are related to failure to consider the many dimensions
involved in substituting one material for another, including fair property comparisons
and whether pilot-scale materials can be manufactured and fabricated cost effectively on
a production basis. The real potential of an advanced material is often not apparent due
to the incomplete assessment of its capabilities. The pitfalls involve:

- Discussion of property improvements only on a relative (rather than absolute)
scale
- Use of inappropriate or carefully chosen adjectives that bias the merits of the
  material
- Discussion of the material one-dimensionally
- Comparison of the properties of a new material with the current (as opposed to
  potential) properties of a traditional material
- Ignoring market volume
- Ignoring processing considerations

Discussion of property improvements on a relative rather than absolute scale occurs
when the materials scientist attempts to place the new development in its most favorable
light. The reported improvements in the toughness of quartz glass illustrates this point.
A recent research report claimed an increase of 100% in the fracture toughness of quartz
glass. At first glance, the improvement appears to be a remarkable advance; however,
closer evaluation of the report reveals that the improved glass now has a fracture
toughness equivalent to one-half of that of gray cast iron. Thus, the new material
hardly is a candidate for use in critical structural applications. Consideration of the
absolute value of the toughness was disregarded in favor of the dramatic relative gain in
performance.

Both strength and toughness are important properties in structural applications because
high strength permits more economical use of the material, while toughness provides
resistance to fracture. Metals are extensively used as structural materials because they
have exceptional combinations of strength and toughness. By comparison, although
glass and other ceramics have exceptional strength, they are also very brittle. This is
why ceramics are used only in applications where loads are primarily compressive.
Dramatic increases have been made in the relative toughness of ceramics, but on an
absolute scale, there still is a very long way to go before they are considered for use in
structural applications.

The use of inappropriate or carefully chosen adjectives to describe advanced materials
can lend an aura of significant practical achievement to a material’s properties when the
development may only have reached the stage of scientific curiosity. Examples of such
terms include: “tough or toughened” structural ceramics; “conductive” polymers,
having a specific electrical conductivity higher than that of copper; and “high-strength”
composites and fibers, having specific strengths greater than that of steel.
Each of these claims could be accurate. However, the important question is: What difference does the statement really make? Advanced ceramics may be tougher than their predecessors, but they hardly can be classified as tough materials, at least not in the sense that a designer or materials engineer understands the word. In the case of conductive polymers, while they are not insulators, the implication that their electrical properties exceed those of copper is misleading. It is true only if specific properties (property/material density) are compared. Although the best conductive polymers have an electrical conductivity that is within an order of magnitude of the conductivity of copper, so does mild steel. Yet, steel wire has never been considered as an alternative material to copper based on steel's electrical properties. Specific conductivity is not the critical measure of performance. If it was, aluminum which has a specific conductivity two times greater than that of copper, should be a viable candidate as a substitute for both copper and conductive polymers (which it is not).

A one-dimensional discussion of materials possibly is the most widespread method of praising new materials. A good illustration involves new high-temperature superconductors (HTSCs). The critical temperature of these ceramic materials was raised more than six-fold over a period of months in early 1987, and there were many claims that our lives would be improved within a few years. Unfortunately, this has not occurred.

A designer of a high-field-strength superconducting magnet must consider at least four materials properties: critical temperature, critical magnetic field, critical current density and tensile strength. With respect to critical temperature, the new superconductors exceed the most optimistic hopes of only a few years ago. HTSCs also perform very well with respect to critical magnetic field. However, HTSCs missed the required level of performance for critical current density by six orders of magnitude initially. More recently, oriented crystals have demonstrated properties close to what is necessary at zero magnetic field. Unfortunately, there is an interaction between the critical current and the applied magnetic field that comes into play as well. Thus, at a useful magnetic field, even these high-current-density superconductors do not have superconductive properties.

Tensile strength has been totally ignored to date. The windings of a high-field-strength magnet experience extremely high tensile hoop stresses; up to 690 MPa (100 x10^3 psi) in some instances. The brittleness of ceramic HTSCs poses an obstacle to their use, at least for the near future.

Another danger in assessing advanced materials is to compare the properties of a new material with the current properties of a traditional material. The danger in using this approach is assuming that the properties of traditional materials will not be improved further, especially when industries are faced with new competition.

The area of soft-magnetic materials illustrates this point. Nearly 20 years ago, a University of Pennsylvania researcher discovered that amorphous Fe-Si-B alloys had only one-tenth the magnetic core losses of crystalline Fe-Si alloys used in electrical transformers. Although the amorphous alloys cost two to three times as much as the traditional alloys, a ten-fold improvement in amorphous-alloy properties looked very promising. Based on the potential benefits of amorphous alloys, a 23-million kg/yr (5 million lb/yr) production facility was commissioned. However, manufacturers of crystalline Fe-Si alloys decided not to give up a $1 billion market easily. Increased R&D of the traditional alloys over the past 20 years resulted in a three-fold improvement in performance properties. While competition is stiff today, the future is
uncertain. Traditional-alloy producers conceivably could recapture the entire market if they could improve the properties of their materials to a level that surpasses that of amorphous alloys. After all, nothing more can be done to improve the structure of amorphous materials.

Ignoring market volume can be disastrous in assessing the commercial potential of advanced materials. For example, estimated world markets (in sales) and annual growth in the year 2000 for advanced ceramics, composites and semiconductors are $5 billion, $15 billion, and $100 billion and 20, 10, and 5%, respectively. While ceramics and composites markets have high growth rates, part of the rapid growth is due to a small initial base. Even at a meager 2% annual growth over the next decade, the increased volume in the already huge steel market will exceed the combined increase in the advanced-ceramics, composites, and semiconductor markets.

Ignoring materials processing may be the most perilous pitfall in predicting the success of advanced materials. For example, while materials science has progressed to the stage where carbon can be converted into diamonds and lead into gold in the laboratory, the diamonds and gold produced are more expensive than what is found in the natural state. None of the new materials that are developed will be useful unless they can be manufactured economically. Unfortunately, development of economical processing is not considered a scholarly activity in much of the scientific community. Many of the brightest scientists refuse to work in this area because of its "low stature." Even worse is that some of these individuals argue that such efforts are unworthy of substantial government or industry support. It is not that we cannot afford research and development on processing and fabrication. Instead, financial resources are directed in other areas. There are indications that this situation is changing, but the change must occur more rapidly if we are to be competitive in a global market.

Challenges in the Use of Advanced Materials: The major question in use of advanced materials is whether these materials can be used cost effectively. Tremendous efforts have been made in improving the processing, structure, properties and performance of new materials, or as the Japanese often call them, "high function materials". Figure 1 shows how these features have changed over time. More elaborate processing produces more complex structures which are tailored to specific applications in which the material is pushed to the limit of performance. We have changed from design with available materials to design of materials for specific applications.

As an example, consider the production of aircraft structures. Fifty years ago, designers selected from available materials consisting of wood, canvas and aluminum. Today, designers dream of the Orient Express, which must endure surface temperatures of 1500°C, in addition to being lightweight, having high strength and resistance to hydrogen degradation. Advanced intermetallics and composite materials must be developed to meet the design rather than the design being tailored to the properties of available materials. Unfortunately, assessment of the reliability of these materials is very difficult and limits the use of these materials in new designs.

A major factor in the reliability of all materials is the quality of the joints in the manufactured product. Joints are ubiquitous in nearly all products. As an example, I often ask my students to think of the largest stand-alone manufactured product that does not contain a joint. For many years, the best response was a cast iron frying pan, but recently one of my faculty colleagues took up the challenge; he thought of an anvil. The point of this exercise is to emphasize that every manufactured product contains
joints and that the quality of the product is directly related to the quality of the joint. Even further, when teaching fracture, another colleague is known to have said, "Something will not fail unless it has been welded!". While this statement appears to be a terrible indictment of welding, there is some truth to it. Welds are often the weakest part of the structure and are generally located at the most highly stressed locations.

The cost of many of these new materials is so high and their properties are so specialized that they will only be used where they are essential. As a result, products will contain more joints and a greater fraction of these will be between dissimilar materials. This will only compound problems of quality and reliability in the final product. The common design rule of eliminating all possible joints is being violated at an increasing rate. Due to a desire to use the minimum amount of these costly, high function materials, the joints are being placed in more aggressive environments. The properties of the joint are pushed to the limit.

In many cases, designers expect the joint to match the properties on either side of the dissimilar joint. If this were an easy task, one would not need to produce a dissimilar materials joint. One could make the entire part from the joint material, if such a materials with maximal values of all properties were available! Some designers assume too much of joining technology. Rather, the solution to the use of many new materials lies in improved design which limit stresses placed on the joints. One challenge for joining engineers is development of new design rules which reduce the risk of failure at the joints. It is no longer possible to select the joint configuration or joining process as an after-thought to the design. Joining technology must become an integral part of the product design.

With increased sophistication in our design techniques, we are able to use materials closer to their limits. Stated more simply, we are reducing the size of our traditional factors of safety. This is fine as long as we fully understand all of the failure modes of the product. Unfortunately, the increasing sophistication of the structure of advanced materials means that they have even more failure modes than traditional materials. For example, the delamination and microbuckling failure modes of composites are much more complex than homogeneous materials. This requires more qualification testing than for traditional materials. The problem is compounded by the fact that the smaller market for high function materials must absorb these higher development and qualification costs. The result is that more and more designers are walking away from many of the specialized advanced materials in favor of the simpler traditional materials. It is likely that this trend back to lower cost, higher reliability traditional materials will continue. The prediction that advanced structural materials will replace most of our traditional materials is false. In the majority of commercial applications, the advanced materials simply do not meet the reliability to performance ratio at an acceptable cost.

We must change the way we manufacture materials. Figure 2 represents the old paradigm of manufacturing. A process contained inputs and outputs. The inputs we inspected prior to use in order to ensure conformance to a standard. After the process was complete, inspectors checked the function of the product and scrapped or repaired any defective parts.

In the new paradigm which is evolving, the input materials are received from a pre-qualified supplier; hence, no incoming inspection is necessary. The process is no longer a simple black box. It is the heart of the quality engineer’s job. Rather than inspect the finished product, the quality engineer must sense the process, feed sensed data into a process model, and develop a control methodology which can modify the process.
process to produce acceptable parts see Figure 3. If this sequence of sensing, modeling and controlling is working properly, there is no need for outgoing inspection while scrap and repair are minimized. A process running at this level can be modified to meet not only the explicit requirements of the customer, but can be adapted to meet the latent requirements for which the customer does not yet know there is a desire. In addition, the reduction of waste makes the process environmentally sound. The modern quality engineer measures the process, not the product.

Although quality engineers have always been in the business of measurement, the type of measurements which are needed are changing and it is necessary to make a science of this new work. As Lord Kelvin said:

*I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.*

The quality engineer must put numbers on both the process and the product. Unfortunately, most people tend to measure what they can measure most easily - not what needs to be measured. Traditionally, materials were sold based upon size, thickness, weight, density or the like. These require measurements of length, width, weight and volume. Today, materials are sold based upon structure and properties as well as form and size. These new features require measurements of internal geometry, processing conditions or specific properties. Sensors are not necessarily available for these purposes. It is up to the quality engineer to develop new sensing technologies.

In addition, much of our materials manufacturing in the past was batch processed. Today’s higher productivity requires that continuous flow processing dominates many industries. This requires “measurements on the move” as materials will no longer sit still in order to be inspected. With increasing value added per part, the rate of sensing must increase both spatially and temporally, while maintaining ever tighter environmental restrictions. A potential solution to these challenges lies in microsensor technology, which may make it possible to have many low cost sensors distributed over a wide area.

All of this will require quality engineers to work closely with people in other disciplines such as materials engineers, designers, industrial engineers, physicists, chemists and the like. It will be necessary to have access to the processing equipment in full scale production. This will require new partnerships and new methods of cooperation.

**Learning from our Experience:** The previous sections dealt with challenges in the designing and manufacturing of advanced materials, but improvement in the reliability of advanced materials requires feedback from the users of advanced materials. Traditionally, much of this feedback has been collected as case histories of failure analysis or has evolved in various codes and standards. There are problems with both of these approaches. The case histories are too empirical and have never been collected in an organized database. Development of the codes and standards moves at a glacial pace and will not provide rapid enough feedback in a world which is changing at an accelerating rate. We must develop new methods of improving the dissemination of the knowledge gained by use of these new materials. One impediment which should be addressed, perhaps through legislation, is the reluctance to publicly report the causes of failures due to fear of increased exposure to litigation. There is much knowledge available that is hidden due to fear of having the information used against the producer of the material.
**Conclusion:** Earlier, I noted that one of my colleagues tells his students that something will not fail unless it has been welded. As a welding engineer when I first heard this statement, I was offended, but I quickly changed my attitude to a more positive one -- as long as welds keep failing, I have a job. This can be extrapolated to everyone performing failure analysis of advanced structural materials. With all of the challenges in design, production and use of these materials, we have every reason to expect a long and prosperous career in failure analysis and prevention.

![Diagram](image1.png)

**Figure 1** Advanced materials create more complexity and specificity in every phase of materials science and engineering.

![Diagram](image2.png)

**Figure 2** Traditional paradigm for quality control of a manufacturing process.
NEW PARADIGM

Fitness for:  - Explicit requirements
            - Latent requirements
            - Environment

Figure 3  Evolving paradigm for control of product quality through improved process sensing and control

ADDENDUM

GUIDANCE ON MATERIALS SELECTION FOR DESIGN APPLICATIONS
Metals are widely used in structural applications because they provide a good combination of strength and toughness. By comparison, ceramics have exceptionally high strength, but are very brittle. This is why ceramics are used only in applications where the loads primarily are compressive. The three regions defining elastic and plastic behavior are for 25-mm (1 in.) thick materials. The transition areas shift with both thinner and thicker materials.

In a given application, materials selection generally is based on properties/characteristics that could be of critical or of secondary importance to the part design. The dimensionality of a materials selector’s choices is illustrated by plotting six primary materials-selection factors (strength, toughness, formability, joinability, corrosion resistance, and affordability) along the spokes of a wheel. The values are normalized so the circle represents a specified property level. In the hypothetical situation shown, the metal offers good toughness, formability, joinability, and affordability, but lower strength than ceramic. An intermediate set of properties is obtained by forming a metal-ceramic composite. However, the gain in strength of the composite results in a degradation of the other original metals properties. While composites can provide properties that are unattainable in a homogeneous material, severe penalties are assessed, in terms of the other properties, for the enhanced performance in one dimension.