UNIT V APPLICATIONS AND USES

Selection of Materials for Biomedical Applications, Medical Products, Materials in Electronic Packaging, Advanced Materials in Sports Equipment, Materials Selection for Wear Resistance, Advanced Materials in Telecommunications, Using Composites Manufacture and Assembly with Plastics, fiber and Diamond Films.

Advanced Materials in Sports Equipment

Advanced materials with mechanical and physical behavior characteristics well in excess of those exhibited by conventional high-volume materials such as steels and aluminum alloys have contributed significantly to the increased performance of transportation systems in aerospace, automobiles, and rolling stock.

CHARACTERISTICS OF MATERIALS OF IMPORTANCE IN SPORTS EQUIPMENT DESIGN

The optimum design of sports equipment requires the application of a number of disciplines not only for the enhanced performance already mentioned but also to make the equipment as ‘‘user friendly’’ as possible from the standpoint of the avoidance of injuries. Clearly sports equipment design encompasses materials science, mechanical engineering, and physics; however, it also necessitates a knowledge of anatomy, physiology, and biomechanics. Biomechanics can be simply defined as the science of how the body reacts to internal and external forces. It is thus an attempt to apply the basic laws of physics and mechanics to the joints, ligaments, and tissues of the body as they are subjected to loading.

In designing sports equipment, various characteristics of materials must be considered

- Strength
- Density
- Ductility
- Fatigue resistance
- Toughness

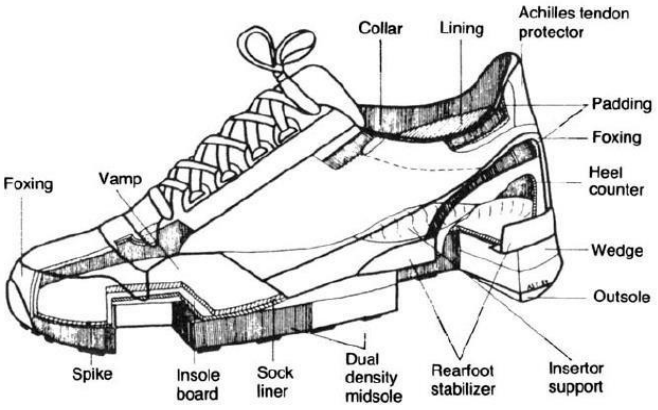
- Modulus (damping)
- Cost

THE IMPACT OF ADVANCED MATERIALS ON SPORTS PERFORMANCE

To illustrate how advanced materials have impacted sports performance a number of sporting events will be considered in which a contribution to the improved performance can be attributed to the materials used to construct equipment.

Running

Shoes have provided substantial improvements in the running events. The human feet are very complex biomechanical structures that are highly prone to stress and injury. Thus, a running shoe needs to be complex and consists of a variety of different materials (Fig. 4),6 which are selected according to their resilience, strength, elasticity (stretch ability), compression, durability, and wear resistance. About 80% of runners hit the ground on the center heel, roll onto the midfoot, and finally push off with the ball of the foot.2 The midsole is key in providing cushioning during impact with the ground. Usually, it is made from a plastic foam that in some concepts includes ‘‘air pockets’’ (Air Max) filled with pressurized gas. However, these cushioning effects break down with use (even after only 100 km of running) with reduced cushioning efficiency.



Parts of a running shoe.

Pole Vaulting

The 1896 Olympics saw a height of 3.30 m achieved with a bamboo pole in the pole-vault event. The bamboo pole, which has more spring and is much lighter for the same stiffness than the hickory pole, was introduced in 1904 by an Olympiad from my hometown of Moscow, Idaho, A. J. Gilbert (Dan O'Brian is the second Olympian from our town of 18,000). Initially this change in materials provided an advantage of about 200 mm in height. Improvements in coaching and technique allowed a gradual increase in height over the years. By the late 1950s, however, the gains were starting to level off and lighter weight aluminum poles were used for a short time.

Cricket

As with tennis rackets, the manufacturers of cricket bats have been concerned with the size of the sweet spot and the reduction of flexural vibrations.Three significant modes of flexural vibrations detract from the ideal rigid-body performance, and whereas distributing the weight of the blade to the edges (perimeter weighting) does not increase modal frequencies significantly, it may increase the width of the sweet spot.

Baseball/Softball

Aluminum baseball bats are banned in the U.S. major leagues because they would make current baseball stadiums obsolete. There would be too many home runs. However, both new aluminum bat concepts such as the ultralight, with a double-walled barrel construction, and titanium bats are revolutionizing softball. These bats have bigger sweet spots and lead to greater velocity off the bat. However, the Softball Association is concerned with an increase in injuries to infielders who cannot react quickly enough to this higher velocity.

Hockey Equipment

The hockey stick has changed dramatically over the years, transitioning from wooden handles and paddles to hybrids of wood and fiberglass composites, and recently to include aluminum and carbon or graphite composite shafts. The latter concept giving improved performance and player comfort.

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Advanced Materials in Telecommunications

The communications revolution of the previous decade is based on transfer of information. Initially, most of the information transferred between people was via voice communication, that is, over the telephone network. Today, due to the birth of the Internet, the transfer of data now exceeds the network capacity demanded by voice communication even though the number of cellular phones is increasing dramatically and the cost per minute of long distance is decreasing.

Cable

The original telephone network was initially assembled for use with telegraphs. Since then with the expansion of nearly a phone in every home, the telephone network links the world. This initial copper cable network was based on twisted wire pairs and coaxial cable.

Optical

Optical fiber possesses nearly infinite bandwidth, or so it seems. Currently, all Internet traffic can be carried on a single optical fiber. The only reason this is still true is due to slow modems using conventional phone networks, which are limited to below 56K (56,000 bits / s) data transfer rates, in addition to the limited number of people connected to the Internet at one time.

Packaging

A package can have many different functions: providing protection, distributing power and signal, and dissipating heat.9 The ability of a package to perform these functions is dependent on the device as well as the materials properties and design of the package. For example, devices with robust passivation and protective layers may require a less robust package. Integrated circuits and devices relevant to telecommunications contain layers of conducting, insulating, and passivating layers, each with different criteria regarding protection from the environment. The telecommunications industry continues to grow, and its growth is enabled by the ability to package its devices. Plastic packaging will play a major role in its future. Oftentimes, however, packaging is a secondary consideration in the development of silicon-based devices. Consequently, packaging has received far less attention than warranted, given its crucial role in reliability, performance, and cost. The tide is shifting as device fabrication continues to explore ways to reduce cost and improve performance.

Ceramic Packages. Ceramic packages are laminate sheets of ceramic powder made from a slurry of ceramic powder and a liquid binding mixture of polymers and solvents. Sheets are cut into the appropriate size and via holes are punched. These via holes are filed with metal powder and conducting traces of metal powder are printed on the surface to form circuit patterns. These sheets (as many as 30) are aligned and laminated.

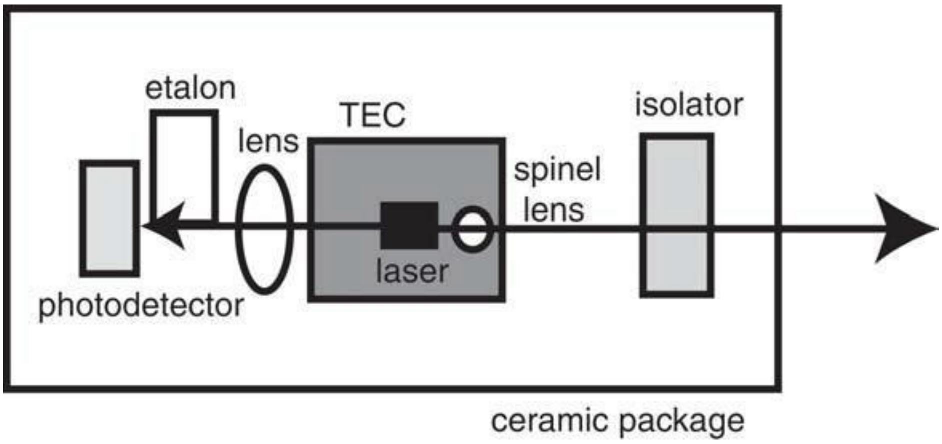
Refractory Glass Packages. A lower cost alternative to ceramic is refractory glass. Although glass has less complexity than laminate ceramic sheets, it is a reliable and hermetic option.

2.2 Solid-State Semiconductor Lasers

Advances in material properties have led to ubiquitous deployment of solid-state lasers in CD players, barcode scanners, and optical communications. Specifically, lasers with output centered around 1.3 or 1.55 _m have been prepared using molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD) to deposit thin films solid solutions, hereafter referred to as InGaAsP.19 The wavelength of the laser light can be selected by choosing a desired lattice constant and then locating the proper composition

Photodetectors

Two main types of photodetectors are used in telecommunications: pin (*p*intrinsic- *n*) and APD (avalance photodiodes).23 APDs are a high-performance ultrafast photodetector that provide gain for weak signals. APD devices are expensive; therefore, if use of pin photodiodes is possible, it is the preferred choice. In addition, APD detectors require large biases on the order of 50 V, whereas pin devices usually are biased about 5 V. Again as in solid-state semiconductor lasers, the materials are chosen based on bandgap and ultimately on quantum efficiency.



Optical Fiber

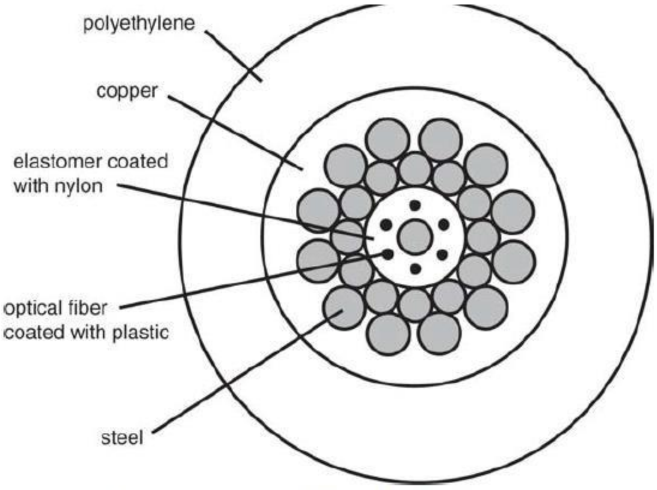
The principle of guiding light within a medium is not new. In 1854, John Tyndall demonstrated that a stream of water could guide light.25 In his experiment, a light shines through a stream of water jetting out from the side of a tank of water would and bends along the stream's path. The stream of water successfully guides light until the turbulence of the stream's surface made the beam more diffuse. The water guides the light by internally reflecting it. That is, the light at the water/ air boundary is reflected back into the water. Internal reflection occurs only when going from a material of high refractive index (water) to a material of lower refractive index (air). Today we have more sophisticated means of guiding light, one of which is through the use of optical fibers. Optical fibers are narrow strands of glass, polymers, or a composite of both. One of the early identified challenges of guiding light through a single medium, such as glass, is that light leaks whenever the medium contacts materials other than air, that is, material with a refractive index greater than air. The solution to this problem was addressed by making a fiber ‘‘sandwich,’’ placing an outer cladding layer around the fiber core. In this manner, light travels along the fiber core confined by the lower refractive outer layer. This arrangement not only confines the light but also prevents leaks should the fiber touch materials that are more highly refractive.

Plastic Fiber

For short distances (maximum 100 m) an all-plastic multimode step-index alternative may be used.Although they have significant signal losses, they are tough and durable and thus do not require special handling. High refractive differences between core and cladding make this an attractive alternative for short haul applications, but costs are still high. Core and clad combination of a polystyrene (index 1.6) core and methyl methacrylate (index 1.49) cladding have been demonstrated.31

Fiber-Optic Cables

Special cable designs are required because of the mechanical properties of glass. These designs are greatly dependent on how the cable will be used. For example, cable may be pulled underground, submerged underwater, or installed outdoors. Generally, a fiber is coated with buffer material and placed loosely in a polyethylene tube. The tube is surrounded by aramid yarn to provide strength and encapsulation.



Cross section of optical fiber cable for undersea deployment.

Electro-Optical Materials

The area of optoelectronics is demonstrating exploding growth. In the past few decades, optical communication used fiber as the transmission medium but relied on electronics for amplification, signal processing, and switching. The conversion of information from optical to electronic to optical represents a bottleneck in the optical network.

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Diamond Films

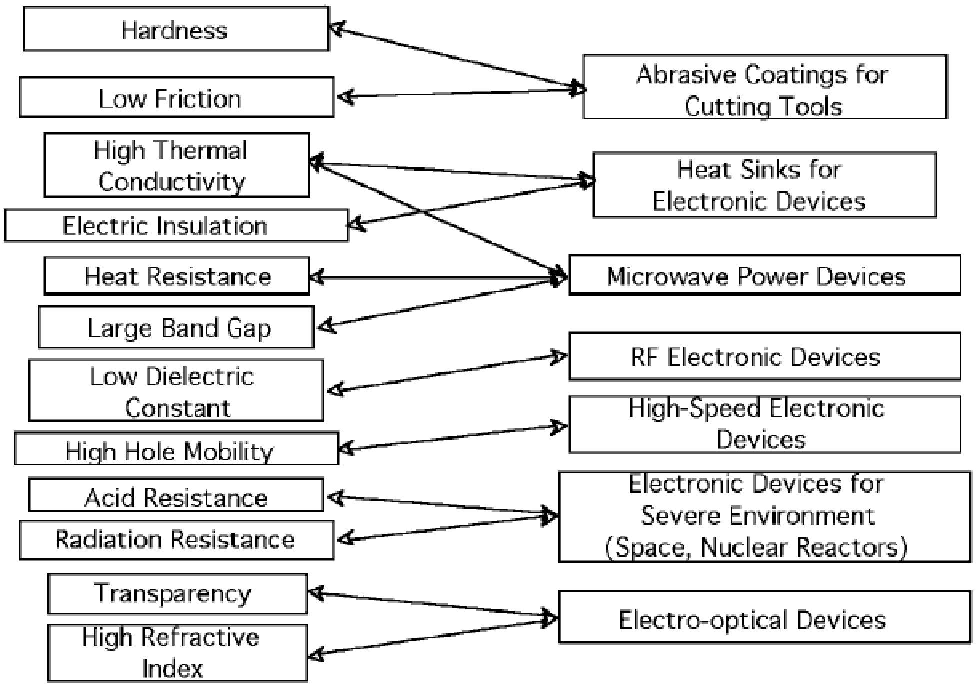
The formation of diamond by artificial means has been an on-going effort for much of the last 150 years. Hannay, Moissan, and Parsons all attempted to make diamond artificially during the nineteenth century. Their claims have been repeatedly examined and usually dismissed. Many of the early attempts at diamond growth did not and still do not fall within the confines of scientific dogma with regard to high-pressure and temperature diamond synthesis; however, some of those early efforts are remarkably similar to those used today to make diamond at low pressures. A review of these early efforts can be found in the book by Davies (1984). Figure 1 presents a rough timetable to show the activity involved in diamond synthesis by chemical vapor deposition (CVD). One early effort at diamond synthesis by Willard J. Hershey

PROPERTIES OF CVD DIAMOND

CVD diamond may be used in thin-film form for mechanically hard infrared transmission coatings, machine tooling, electronic devices and substrates, and coatings for bearings. Thick diamond films may also be used in machine tooling but also as free-standing optical and infrared windows, electronic substrates, and bearings. CVD diamond may be made in powder form that can be used as the starting material for diamond ceramics and diamond filled composites, monosized abrasives, and as feedstock for high-pressure diamond crystal synthesis (Spear, 1989). Diamond is the hardest naturally occurring material (Field, 1991). The great hardness of diamond makes it appropriate to consider diamond as a low-wear material. If it is very difficult to break a bond then the chances of breaking bonds (wear) will be low. Several other materials have higher bond strengths than does diamond, but those strengths are anisotropic. The hardest material that is known is a synthetically prepared type of diamond. Analysis of elastic constant data for 13C diamond has shown that its bond strength is greater than that of ordinary natural diamond or commonly made CVD diamond. The reason for this is the slightly shorter bond length that results from having an extra neutron in the carbon atom's nucleus. Actual hardness measurements have not been made on the material to date, but the strength should scale with the elastic constants (Ramdas et al., 1993). Additionally, diamond has a low coefficient of friction (0.01) in the presence of air or hydrogen (Field, 1991). This makes the material as slippery as Teflon but far more wear resistant. The slippery nature of the hydrogen-saturated surface would reduce both frictional horsepower losses and decrease surface erosion when used in wear applications

DIAMOND FILM DEPOSITION

Diamond films cannot be deposited on all materials and surfaces. Substrates that present problems to diamond deposition are the ferrous materials including iron, nickel, cobalt, in addition to copper, zinc, tin, and the precious metals. Diamond will grow on a substrate successfully at high temperature only if the material has a low solubility for carbon and forms a carbide. There is nearly always an interface that keeps diamond separated from its deposition substrate, and there is typically no direct diamond-to-metal contact



MODIFYING CVD DIAMOND

The physical properties of CVD diamond can be modified and controlled by altering deposition parameters, using additives, changing substrate selection, and varying the seeding and nucleation method. For example, a carbon-rich environment will produce a diamond film with both a larger conductivity than natural diamond and one with a greater degree of compliance showed that the electrical conductivity and the quality of their Raman spectra of boron-doped diamond films were found to increase and improve with increased diborane concentration in the deposition environment. Bernholc et al. (1988, 1992) predicted that with boron as a dopant ‘‘the reduced self-diffusion activation energy should lead to better quality material.’’ Phelps (1990) suggested that features observed in the Raman spectra of diamond films are the result of defects in the diamond structure, and boron doping of the material appears to substantially affect its Raman spectra. Defects in boron-doped CVD diamond have been shown many times to scale with the amount of boron doping in the material. A TEM study by Wang et al. (1992) showed cross-sectional views of several doped diamond at various dopant levels, and it is clear that the number of dislocations in the diamond structure show a marked decrease. The oxidation resistance of boron-doped CVD diamond is shown to increase with boron content by the temperature measured at the onset of oxidation (Loparev et al., 1984).

DIAMOND FILM ADHESION

Adhesion of CVD diamond films to working substrates is one of the most important aspects of diamond wear coating technology. Diamond has the particular disadvantage that little is known about how to best attach a diamond film to a substrate surface. Good adhesion must be considered at the system design level in order to realize superior state-of-the-art bearings. Adequate adhesion between the diamond film and the substrate must be present in order to use the remarkable mechanical properties of diamond. There are many reasons why a diamond film would not be adherent. Identifying these reasons can lend direction to solving the adhesion problem.

	Thick Films	Thin Films
Advantages	Longer wearing Bulk properties Reduce buckling	High intrinsic strength Lower residual stress Short deposition time
Disadvantages	Long deposition time High residual stress Film roughness	Film punch-through Short wear life Buckling

Decision box showing relationship between thick and thin coatings.

There are several means by which an adherent diamond film may be produced on a substrate surface.

1. Deposit the diamond wear film on top of a strong carbide-forming substrate. This results in a strong diamond-to-carbide chemical bond and help hold the film onto the substrate.

2. Deposit the diamond film on an intermediate layer that is a strong carbide former deposited on top of the substrate. This results in a strong diamondto- carbide chemical bond and a strong carbide-to-substrate chemical bond.

3. Electroplate diamond anchors onto the substrate surface . This allows the adhesion of the diamond film to a substrate that has no chemical compatibility with the diamond such as steel or INCO 718.

4. Braze a free diamond film onto a prepared substrate. The brazing material is usually a low-temperature alloy that can be a copper–silver or other easily flowing alloy that contains powder of a carbide former such as titanium or zirconium. The carbide former makes a good chemical bond with the diamond surface and in turn bonds to the braze material also.

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Materials in Electronic Packaging

GENERAL

The process of materials selection for an electronic packaging application involves a variety of considerations, and the end result is often a material chosen for reasons not immediately evident at the beginning of the process. This seeming paradox stems from the nature of the work faced by the electronic packaging engineer. That is, the span of problems faced by the electronic packaging engineer is multidisciplinary and involves finding a balance between function, performance, manufacturability, reliability, and cost.

Approach

The selection of a material from a set of materials includes the following steps:

1. Define the dominant considerations for the design application under consideration.
2. Define any overriding considerations that narrow the field of choice.
3. Review typical applications regarding materials selection.
4. Compile a list of the most likely set of candidate materials.
5. Compare the properties of the selected material(s) and select one or more materials that appear to offer the most likely solution.
6. Test each selected material physically and against the original design criteria to verify suitability.

Electrical Conductivity

A material may be required to conduct electrical currents. This includes metals and some nonmetallic elements such as adhesives, greases, and other compounds loaded with graphite or metal powder. If electrical conductivity is important, then the resistivity of the material must be considered because electrical resistance creates voltage drop and heat generation, either of which may be a desirable or an undesirable consequence. In screening for electrical conductors, a maximum electrical resistance requirement must be defined, thus materials with equal or lower electrical resistivity become candidates for selection. *Electrical resistivity* is temperature sensitive; thus it is necessary to make sure that the material electrical resistivity is satisfactory over the temperature range of interest.

3.2 Thermal Conductivity

All materials conduct heat; however, among materials there is a wide range of thermal conductivity. Good conductors of heat include metals, and poor conductors of heat such as ceramic and plastic foam materials are considered to be thermal insulators. The cooling of electronic components and the protection of electronic components from excessive temperatures is managed by employing mounting devices, heat sinks, and thermal insulators using materials of the appropriate thermal conductivity.

3.3 Thermal Emissivity

The thermal emissivity of a material is a measure of the efficiency by which a material will radiate or receive infrared energy. The thermal emissivity is a surface characteristic of a material and to some extent a function of material color. Thus a highly polished light-colored material will have a low thermal emissivity and dark-colored, high surface roughness materials will exhibit a higher thermal emissivity. When an electronic component is mounted near a high-temperature emitter, the heat absorbed by the component may be reduced by using material and finish with a low thermal emissivity to protect the component.

3.4 Thermal Expansion

Measured by a property known as the coefficient of thermal expansion, this material property allows the electronic packaging engineer to predict the linear or volumetric change (expansion or contraction) of a material when the material is exposed to a change in temperature.

3.5 Chemical Inertness

Materials may be exposed to chemicals during the life of a product. This may include fuels and lubricants, cleaning fluids, fluxes, and other chemicals used in industrial processes. Most tables that list material properties also provide limited information regarding chemical resistance. If the material is exposed to conditions not covered by information in the tables, then the designer must contact the provider of the material for additional information. It also may be necessary to experimentally determine and to verify the suitability of a material in the presence of a chemical. It is important to note that chemical reactions are affected by temperature and the presence of other chemicals.

3.6 Corrosion

Most tables of material properties provide information of corrosion resistance; however, this information may not be sufficiently specific to give confidence regarding the intended usage of a material. This may (for metals) include susceptibility to intergranular or stress corrosion cracking in the presence of certain acids or bases. For all materials, and especially nonmetals, corrosion deterioration includes processes similar to those identified regarding the chemical inertness of a material.

3.7 Temperature Range

The operating and storage temperature ranges applicable to the application of a material must be known and the properties of the material reviewed for stability over the range of temperatures. This is important for any material including metals especially when the temperatures are very high or very low. Metals and nonmetals will become brittle and stiff at lower temperatures, and may soften, lose strength, and creep or flow at elevated temperatures. This is especially true with nonmetal materials, where the temperature ranges may be severely limited.

3.8 Strength

A guide to the load-bearing capacity or strength of a material is its tensile strength, which for many metals is a function of process conditioning or heat treating (i.e., is the material annealed, half-hard, or hard?). Strength of non-metals (plastics) varies significantly with temperature and the rate at which a load is applied (impact strength). Weight reduction is achieved in electronics by using smaller quantities of high-strength materials for forming brackets, structures, and fasteners.

3.9 Density

Density is a measure usually taken as the weight of a material for a given unit of volume. This property may be used as a guide to reducing weight in a design. Material density establishes the inertia and resonant frequency of mechanical elements and thus the degree to which they are affected by mechanical vibration and mechanical shock loading. Another indicator of the density of a material is its specific gravity, which is a comparative ratio of the weight of a material compared with the weight of an equivalent volume of water.

3.10 Electromagnetic and Electrostatic Shielding

Electromagnetic shielding is employed to prevent the imposition of electrical waves from the environment (such as radio waves) on circuit elements and thus inducing currents and voltages leading to circuit mal performance and possible component damage. Electrostatic shielding is employed to prevent penetration of high-voltage charges on the surface of an electronic enclosure (such as caused by static discharge) from entering the enclosure and therein causing damage to components or causing circuit performance malfunction. Protection of an equipment from both of these sources of potential equipment performance deterioration involve shielding the equipment such as to prevent radio waves or other electromagnetic noise from entering the enclosure, to shield the equipment to promote the collection of static charges on the surface of the equipment, and to dissipate the unwanted energy by providing a conductive path to drain the energy to an appropriate sink (ground).

3.11 Magnetic Shielding

Magnetic shielding pertains to protecting a circuit from the presence of fluctuating magnetic field energy that may induce currents in wires and metal structural elements and lead to circuit malfunction or failure. A simple Faraday shield such as used for electromagnetic wave or static discharge protection will not suffice for protection from magnetic fields. It is usually necessary to restrict the shielding materials to high-nickel alloy iron. Iron-bearing alloys are magnetic and block penetration of magnetic flux into an equipment, which may induce noise within a circuit or which may cause malfunction of a circuit including erasure of memory from several classes of memory storage devices such as integrated circuits.

3.12 Fatigue Resistance

Fatigue is the loss of physical strength and eventual failure of a material as a result of the material being subjected to repeated loads. Such loads may be the result of thermal expansion stresses that occur during temperature cycles, mechanical loads induced during the operation of the device, shipping and handling stresses, exposure to vibration, and repeated mechanical impact shock loads.

3.13 Hardness

Hardness is taken as the ability of a material to resist denting as caused by a load bearing on the material using a dimensionally standardized probe. There are different scales by which hardness is measured, the most common are the Brinell hardness and the Rockwell hardness number for a given Rockwell scale. Unless otherwise specified the hardness in a chart refers to the intrinsic hardness of the base material. Hard surface materials are used to reduce wear in mechanical latches, sliding surfaces, and electrical contacts. The lubricity of polymers such as nylon and Teflon is used to reduce friction in applications such as drawer slides where a plastic material is used to rub against a hard metal surface.

3.14 Ductility

The ductility of a material refers to the ability of the material to be deformed without breaking. Extreme examples would include tin (very ductile) and glass (brittle and thus not ductile). This is an important property for materials that are to be mechanically formed, are subjected to bending stresses during use, and must withstand impact shock loading without cracking or shattering.

3.15 Wear Resistance

Wear resistance is a property of materials that does not often appear in tables of materials properties. A guide to wear is hardness—the harder and smoother the material the greater it’s resistance to wear. Also consider ductility for the reason that a material may become brittle at low temperatures and exhibit surface fractures and fretting under load. Wear life is also a function of the magnitude of load-induced localized compressive stresses and the methods used to reduce friction such as lubrication. Some nonmetallic materials, such as nylon, are self-lubricating and useful as bearing materials.

3.16 Sublimation

Sublimation is the loss of material when the material is exposed to low pressures (vacuum) and or elevated temperatures. It involves the conversion from solid form immediately to gaseous form apparently without passing through a liquid phase. Sublimation conversion may occur uniformly to the surface of a uniform and pure material, or if the material is a more complex matrix one or more constituent materials may sublimate leaving a residual material possessing poor mechanical or electrical properties.

3.17 Combustibility

Combustibility is the property of a material, under a given set of conditions, to rapidly oxidize or burn, which may range from the ability to burn but not sustain flame when the ignition source is removed, or to burn and sustain flame after the ignition source is removed. Combustion may lead to the generation of noxious gasses and destructive deterioration of the circuit elements in the vicinity of the combustion.

3.18 Creep

Creep is the ongoing deformation (flow) of a material under mechanical load. Failure due to creep is often very slow, and it may occur only during certain conditions (such as a solder-sealed case that is sealed at sea level but operated in an aircraft, or the same case operating at seal level but within which the internal pressure is increased due to heating during normal operation of the equipment). It is good design practice to never place such a soldered joint in sustained mechanical stress for the reason that the solder will creep until the stress is relieved or the joint fails. Thus the design of a mechanical joint where solder is employed (e.g., to achieve an enduring electrical connection or to seal a joint) must have the mechanical load taken by structural members without the solder present. Mechanical joints or seals that utilize adhesives, elastomers, and other nonmetallic materials must be treated in the same way to avoid eventual failure.

3.19 Moisture Absorption

In many instances when a material is selected for use as an insulator, or the material must have dimensional stability in humid environments, the moisture absorption characteristics of the material becomes important. For metals, moisture absorption is not a significant consideration; however, the presence of moisture will hasten galvanic corrosion when different metals are in intimate contact.

OVERRIDING CONSIDERATIONS

Overriding considerations may include:

- Customer preference for a given shape, material, or finish
- Ergonometric (human factors) considerations
- Product is part of a family of products that must have identical materials
- Product manufacturing technique limited to available factory machiner
- Industrial design constraints dictated by the application
- Part to be designed must interface with a component or material for which there is no alternate

Service temperature range Shock or vibration

environment Physical abuse in service

Exposure to chemicals Mechanical strength

Exposure to electromagnetic, electrostatic, ionizing, ultraviolet, or infrared radiation

- Corrosive environments
- Availability of the material

TYPICAL APPLICATIONS

An important guide to materials selection is found by considering how materials have been used for like or near-like applications. Electronic packaging applications often fall into one or more of the following applications:

- Equipment attachment
- Equipment racks, frames, and mounting structures
- Equipment and module enclosures
- Temperature control
- Mechanical joints
- Finishes
- Position-sensitive assemblies
- Electrical contacts
- Harsh environment endurance

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Materials Selection for Wear Resistance

The selection of materials and methods for wear applications is an important part of both technological advancement and manufacturing activities. However, materials selection is often viewed as a random process or worse. The individuals charged with designing new parts, developing new processes, or overseeing component trade study projects rarely have had the opportunity or time needed to develop a ‘‘feel’’ for the general materials performance of metals, ceramics, or plastics during a typical undergraduate university education. The good news is that ignorance is curable and its treatment should leave no permanent scars. Methods and approaches to solving materials problems have been developed over time that may help clarify needs and reduce the degree to which materials selection may be considered a ‘‘black art.’’ Materials application, performance, and manufacturability are all key parts in the selection for wear resistance applications, but the general methods are also extensible to other areas of materials selection.

PROPERTIES OF WEAR MATERIALS

A wear material may be used to reduce dimensional changes due to unwanted material removal, reduce frictional losses, to tailor the physical performance of a component, and/or to provide a physically stable working surface. Wear can be divided into several categories such as adhesive and abrasive wear that take place during sliding contact. Surface fatigue and deformation wear are an impact or loading rate phenomenon, and corrosive wear is caused by the interaction of the wear surface with the local environment. These wear mechanisms may act singly or in combination with one another to alter a surface. The proper selection of a material for a wear application will strongly depend on both the type of wear to be countered and on the wear environment. The wear environment can be dry, wet, warm, cold, and so on. Wear taking place in a corrosive marine environment will be more damaging than the marine environment or the wear alone. Wear phenomenon is a factor in applications where it might not be readily apparent. Optical windows that are exposed to the natural elements have a need for wear protection where dust, sand, and ice can impact and roughen soft optical surfaces. Fan and propeller blades in water can experience wear by cavitation erosion in water and bug and dust impact erosion in air.

MATERIALS SELECTION PROCESS

The classic method of selecting a wear material is to use what has always been used in the past for a particular application.The following guidelines can allow for the rapid selection and insertion of an optimal wear system into operational use.

1. Specify the maximum operational limits of the wear materials system for safety and lifetime. Properties that make some wear films excellent for one particular application may be completely unsuitable for other uses.
2. Specify the normal operational parameters and acceptable performance criteria of the wear materials system. Performance criteria would include the number of cycles of use and the physical and chemical exposure environment before, during, and after use. This step provides for the selection of a broad range of materials and technologies that could fit the needs of the application. No preemptive elimination of technology should be attempted at this stage. Some of the materials and technologies may later be found to be mutually exclusive or inappropriate for use at a later point. Preemptive preselection at this point may eliminate ‘‘poor’’ candidates but also serves to too narrowly focus the materials search too early in the process. Early candidate elimination is attractive, but it can eliminate an entire class of potential solutions and can possibly restrict the ultimate wear material selection to a good solution but perhaps not the best solution. The more care that is taken during this crucial step will enable the actual materials selection phase to be much smoother in terms of performance, availability, and price.

3. Establish the degree of mechanical, physical (thermal expansion, dielectric constant, and so on), and chemical compatibility the wear material must have with the system. The real process of wear material selection begins once the preceding steps have been taken.

4. Material availability and cost are closely related factors usually taken into account at the same time. The cost of a particular wear material is almost exclusively controlled by its availability. Availability is directly controlled by prevalence of use (numerous examples exist of high-priced finished parts made from more common materials than their lower cost cousins) with the attendant savings of resulting from high-volume manufacturing. Availability of raw materials and the ability to work, shape, and form those materials can also influence materials cost.

A General Hierarchy in Cost of Manufacture of Wear Materials

Bulk materials of commonplace composition that are easy to work and form

(a) Materials that can be made in final shape with no post processing

(b) Materials that can be made wear resistant after final shaping as by tempering of metal or firing a ceramic Coatings of commonplace composition that may be applied to easily manufactured substrates

(a) Coating applied under ambient conditions such as room temperature and pressure

(b) Coatings formed in nontoxic water baths

(c) Coatings and treatments that require high temperatures and controlled atmospheres

(d) Small batch vacuum-based treatments

Wear materials that are formed *ex situ* and then are attached to a substrate

(a) Gluing

(b) Cementing

(c) Brazing

(d) Diffusion bonding

Bulk materials of uncommon composition that are difficult to work and form such as solid carbides, borides, and silicides

MANUFACTURING PROCESS SELECTION

Process selection is a second-tier consideration in most instances of wear materials selection. The physical properties of wear coatings may vary depending on the deposition method and technique. The standard cost savings from continuous and semi continuous manufacturing methods such as extrusion and rolling versus stamping and milling operations also apply for wear materials. Method of manufacture becomes very important when directional or textural property characteristics of a material need to be considered. Many of the physical, optical, chemical, electrical properties of wear films will be controlled or modified by their degree of deviation from perfection imparted during manufacture.This is a common consideration in the area of composites manufacture. The component materials of a composite structure are only slightly more important than the manner in which they are arranged in space and bound to one another. Workpieces with apparently similar material compositions can have dramatically varied performance characteristics depending on the arrangement in space of their component parts as influenced by their method of manufacture.

APPLICATIONS AND EXAMPLES OF WEAR MATERIALS

Wear materials are generally thought of in terms of metallurgical materials systems. Overall volume of wear materials would certainly demonstrate the importance of metals and metallurgy. There are a variety of other materials that have and are being used in wear applications. While the total volume of these materials combined is small compared to metals, they do represent a significant fraction of wear materials. Ceramics are slowly being phased in as wear materials in expected and unexpected places. Ceramics are now being used in high performance ball bearing applications as well as high-end cutlery.

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Medical Products

Medical device and medication delivery system products are critical sectors in the medical, pharmaceutical, and health-care industries. Many medical devices and solution drug delivery systems are disposed after a single use. These disposable devices and delivery systems are generally produced from polymeric materials. The disposable materials that host solution drugs or biological agents are recognized as parts of drugs and biological agents. New drug applications (NDA) to the Food and Drug Administration (FDA) and to foreign government regulatory agents are required.

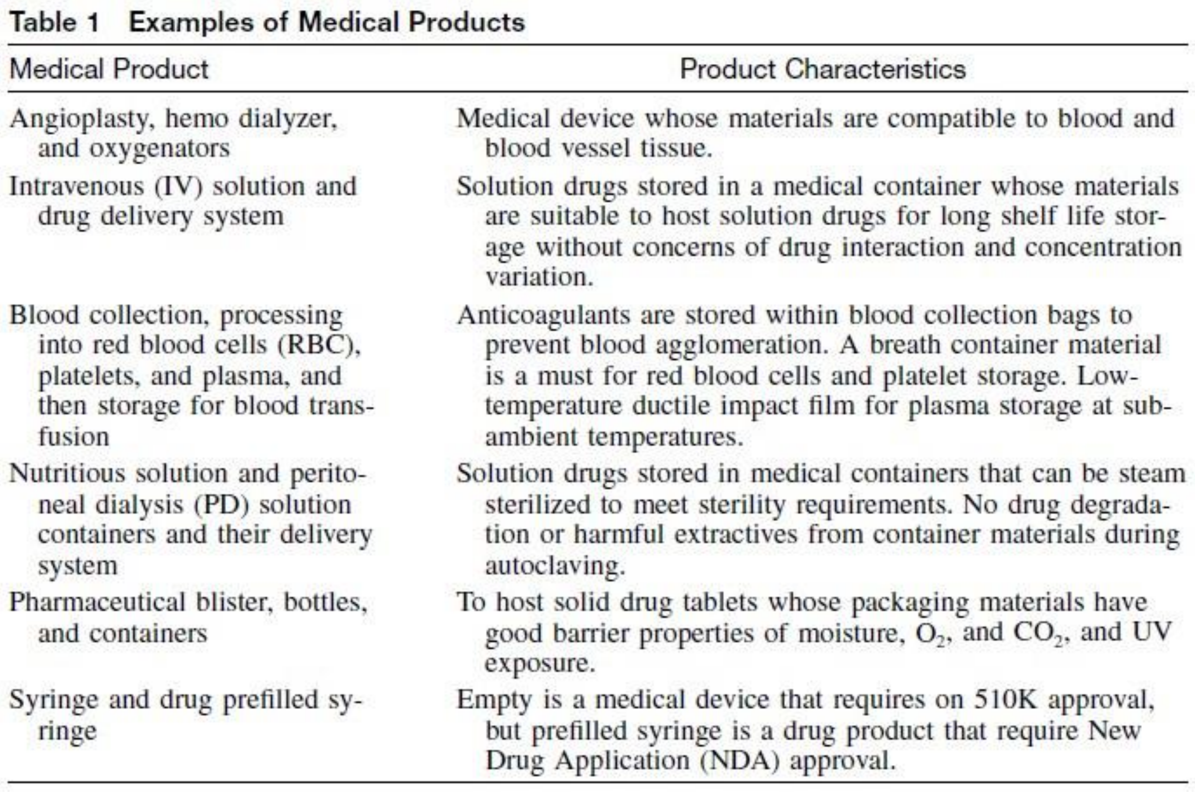

Table 1 Examples of Medical Products

Medical Product	Product Characteristics
Angioplasty, hemo dialyzer, and oxygenators	Medical device whose materials are compatible to blood and blood vessel tissue.
Intravenous (IV) solution and drug delivery system	Solution drugs stored in a medical container whose materials are suitable to host solution drugs for long shelf life storage without concerns of drug interaction and concentration variation.
Blood collection, processing into red blood cells (RBC), platelets, and plasma, and then storage for blood transfusion	Anticoagulants are stored within blood collection bags to prevent blood agglomeration. A breath container material is a must for red blood cells and platelet storage. Low-temperature ductile impact film for plasma storage at subambient temperatures.
Nutritious solution and peritoneal dialysis (PD) solution containers and their delivery system	Solution drugs stored in medical containers that can be steam sterilized to meet sterility requirements. No drug degradation or harmful extractives from container materials during autoclaving.
Pharmaceutical blister, bottles, and containers	To host solid drug tablets whose packaging materials have good barrier properties of moisture, O_2, and CO_2, and UV exposure.
Syringe and drug prefilled syringe	Empty is a medical device that requires on 510K approval, but prefilled syringe is a drug product that require New Drug Application (NDA) approval.

CHALLENGES OF MEDICAL PRODUCTS

Medical product challenges faced today are not only from technical advances but also from business competition. Safety is the highest priority. Product clarity, stability, biocompatibility, and low extractives are highly valued. Many medical and health-care products require a specific level of oxygen (O2), carbon dioxide (CO2), or water vapor transmission rate (WVTR) at room temperature. These products can be either very rigid or very flexible, and for some drug delivery systems and medical devices superior subambient impact is required. Furthermore, the selected medical materials should be compatible to the desired sterilization mode and render no harmful damage to the packed devices, drugs, and disposable systems. In the managed-care environments, the patient care has been gradually switched from doctor care to insurance provider care. The cost is extensively monitored and supervised. Under this great competition, high medical product quality is expected with no further premium increments. Moreover, home care also gradually becomes popular. This requires the medical manufacturers to design ease-of-use medical products for patients with no specific training in the medical field. The medical design and materials selection can play a critical role to fulfill the patient expectation, meet product functions, and achieve business goals.

PRODUCT DEVELOPMENT FUNDAMENTAL FACTORS

3.1 Product Design

Medical product design is focused on safety and efficacy. Product design begins with concept design, design drawing, and stress analysis and ends with the evaluation of the prototype. Different design iterations are created and materials are selected to build prototypes. The prototype is modified after feedback from clinicians, patients, engineers, and manufacturers. The functionality is tested to confirm the desired efficacy

3.2 Selecting Materials

The process of selecting suitable materials for medical products begins with the creation of a precise and accurate definition of the product's material and functional requirements.

Finding the right polymers for medical products requires simultaneous consideration of design, processing, and performance needs

3.3 Newly Commercially Available Polyolefin-Based Materials

Recent progress in metallocene technology, including the ability to produce inexpensive metallocene catalysts, has led to the development of cost-effective metallocene-based polyolefin and cyclo-olefin materials. Metallocene polyolefins have the potential to achieve much better performance than existing PE and PP formulations. Cyclo-olefin materials give a high clarity for medical applications. Because they have properties similar to many specialty polymers and engineering plastics, metallocene polyolefins have the potential to replace PVC and some expensive engineering plastics, particularly for medical products requiring high clarity and impact strength and ductility at low temperatures. As a result, this polyolefin family is showing great potential for use in the medical and healthcare products industries.

3.4 Manufacturing Process

In the medical industry, it often takes great efforts and long cycle time to qualify new polymeric materials and to validate their downstream manufacturing processes before products reach the market. It is well understood that the quality and cost of the medical products depend heavily on the manufacturing processes. From medical manufacturing viewpoints, it is highly desirable to extend the applications of the approved materials to other developing products. This strategy can be achieved by maximizing material properties through an expanding process window to fulfill product performance requirements. Better quality, high throughput rate, less development time, and cost-effective products can be achieved if the manufacturing processes are optimized

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Selection of Materials for Biomedical Applications

Because of its primary role in mechanical support, the stem of a femoral prosthesis can realistically be manufactured from a metal, a ceramic, or a composite material.

Load Support

Because of its primary role in mechanical support, the stem of a femoral prosthesis can realistically be manufactured from a metal, a ceramic, or a composite material. For this discussion, composite materials will not be included, as they have not yet been utilized in commercially available total joint replacements (they are available for bone plate applications).

Strength

The first property to be considered for a load-bearing implant is its mechanical strength. The loading of the femur is dynamic and, while estimated to range up to 8 times body weight, is difficult to determine precisely. Therefore, as the implant will be loaded in essentially the same way as the natural bone, it is reasonable to assume that a material that will provide the same or greater load-bearing capacity as bone will meet the necessary mechanical requirements. Based on the cyclic loading that a material is likely to undergo when implanted in the body, it is reasonable when evaluating selections to compare the endurance limit of the materials under consideration to the experimentally determined strength values for bone.

Joint Motion

Friction. Frictional forces between the articulating surfaces of a joint have two primary effects: (1) to increase the muscle force required to overcome the internal friction and allow motion to occur and (2) to increase the torque experienced by the implant and/or bone, such as at the location of the femoral neck. Large internal bending moments due to high frictional forces may lead to failure of the implant, and therefore should be avoided.

Wear

Whenever contact surfaces and motion are combined, material wear must be taken into consideration. Wear is the process whereby one object, through motion, removes material from the surface of the contacting object. Generally, the harder material will cause wear to occur on the softer material. Three basic types of wear can occur: abrasive wear, adhesive wear, and third body wear. Abrasive wear exists when a hard material, such as a metal, moves cyclically against a soft material, such as a polymer. Adhesive wear involves the sliding motion of two similar materials, where molecular bonds can be formed at the interface of the structures. In rough materials, the surfaces appear as a series of peaks and valleys. The two articulating surfaces typically come into contact at the peaks of the surface roughness, concentrating the contact load over a much smaller area and increasing the contact stress. As the molecular bonds between the objects are broken through motion, they also break off particles of the underlying material. Third-body wear includes the effect of particles between the articulating surfaces that tend to accelerate wear. The wear rate, or volume of wear particles produced (V), can be approximated for adhesive wear by the equation

$$V = \frac{kF_n x}{3p}$$

Biocompatibility

Once a material is selected for an implant application based on the functional requirements, it must be evaluated in terms of material–body interactions. An implant material will react chemically with the local environment, with the type of reaction dependent on the class of material. Metals are susceptible to corrosion, polymers experience leaching and absorption, while ceramics are generally considered to be chemically inert—unless designed to be bioactive. The effects of chemical degradation may affect both the tissue and the material itself, especially its mechanical properties, and so both aspects must be considered. In addition, degradation products can affect the physiology locally, at a remote location, or systemically.

Corrosion

Metallic materials are susceptible to corrosion, particularly in the ionic fluid environment of the body. To assess the corrosion potential of a metal, it is necessary to examine the half-cell potential of that metal—which will act as an anode when it releases electrons—with respect to the material acting as the cathode. This cathode may be another metal or the ionic environment itself. An electrochemical series lists the half-cell potentials of metals in order from the most noble (or cathodic) to the most anodic. When two materials are in contact with each other directly or through an ionic solution, the metal listed first in the list will act as the cathode while the other will behave as the anode. Practical electrochemical series typically relate half-cell potentials as measured in an application-specific environment and may include alloys. This contrasts with ideal series, which list only pure metals as measured with respect to a hydrogen half cell reaction.

Leaching and Absorption

Polymers placed in a fluid environment can experience two opposite phenomena. In leaching, unreacted monomer molecules, fillers, or small chains of polymers can diffuse from the bulk of the polymer to the surrounding fluid. As in corrosion products, these released molecules may have a negative effect on the local physiology or, if transported through the bloodstream or lymphatic system, on systemic or remote processes. In addition, significant leaching may reduce the density of the polymer and consequently have an adverse effect on the properties of the structure.

All materials, including metals and ceramics, can absorb molecules particularly water—from the surrounding environment. However, this occurs much more readily in the relatively loosely bonded polymers. Absorption in polymers can also result in swelling, due to their low elastic modulus, which may cause geometric changes that interfere with the performance of an implant. The strain that a polymeric object experiences due to swelling may induce cracks and may also reduce the ultimate strength of the object. This latter phenomenon occurs because, due to the new baseline strain in the material, less stress is needed to reach the material's ultimate strain. If the absorbed molecules are small, such as water, they will act as plasticizers and weaken the bonds between the polymer chains, thus reducing the Young modulus of the material. If a polymer is hydrophobic in nature, it is less likely to absorb water. However, absorption of nonpolar molecules such as lipids may still occur.

BLOOD-CONTACTING BIOMATERIALS: VASCULAR PROSTHESES

When blood vessels are damaged through injury or disease, they often must be replaced or bypassed in order to maintain adequate blood flow to and from the regions of the body. Disease-induced damage, such as atherosclerosis and aneurisms, occurs more often in arteries than in veins, due in large part to the higher working pressure of the blood within these vessels. Injury can occur to any blood vessel; however, collateral circulation typically eliminates the need to replace small veins, and the low venous return pressure provides an environment in the larger veins that is much more conducive to traditional surgical repair or auto graft use. As a result, this section will focus on the selection of materials for the development of arterial prostheses.

Biocompatibility

The primary functional need of a blood vessel—transport of blood—can easily be met through general implant design. However, due to the delicate nature of blood cells and the ease at which the clotting cascade can be initiated, biocompatibility issues place substantial limitations on material selection for this application. The natural vessel provides an optimal environment for blood flow, and the mimicking or replacing of its intimal layer is one of the underlying ideas in work to improve biocompatibility in vascular grafts.

There are few, if any, current implants that can be described as perfectly meeting their design goals and constraints so that no further investigation of design or material selection is warranted. As materials continue to be developed, whether specifically for biomedical applications or in some different discipline, the selection of biomaterials for implants will remain a challenge in the design of the optimum implant. The evolution of tissue engineering from a bench-top science to a clinically workable tool for new implant design will also open new doors for the development and use of biomaterials. In all of these cases, however, the same principles apply to the selection of a material for a biomedical application.

The selection process can be summarized in the following way:

1. Determine the functional requirements of the material for the particular application (preferably with an idea of the overall design in hand).
2. Select a group of materials that appear to meet those functional requirements and ensure that all confirming tests are conducted in an environment that simulates human physiology.
3. Determine the biocompatibility of the materials in terms of material degradation, tissue effects, blood compatibility, implant fixation, and long term physiologic consequences.

4. Complete the design and approval process, with mechanisms in place to obtain data on functional or material complications for many years after clinical use is initiated.

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Using Composites

The complex process of conceiving a suitable application for composites and then generating a producible and inspect able design that can be manufactured at a profit. If there are any applicable catch phrases, they would be:

To surpass what is presently available, Imagine what is possible!

- Cooperate within the product team to spread the burden of achieving goals of quality and cost.
- Perfection is not common; define what level of ''bad'' is acceptable.
- Consider failure a learning experience rather than a mistake requiring blame.
- Try to fill a vacuum when there is no one providing your intended product or service. (For example, a recent list of qualified contractors for the restoration of concrete structures with composite patches had no listings for Maine, New Hampshire, and Vermont. Surely there is a need for that service in those states.)

The composites industry is divided by product lines, which determine which particular materials and processes are used in a particular plant. Available combinations of resin and fiber are increased by the choice of fiber form: continuous, chopped, the many types of woven fabrics or braided preforms. Processes range from hand labor to sophisticated computer-controlled mechanical marvels. Although the combinations of materials and processes are numerous, much specialization exists because the technologies are too complex for one person, oreven one company, to master them all. However, the philosophy underlying a successful composite application is always the same

Composites offer a wide range of advantages:

- Rather than having to make assemblies from individually made component parts, an automobile manufacturer can mold an entire assembly, such as a press-molded grill panel, which has tabs for attaching lamps and is shaped to match a car's contour.
- Large structures can be made from composites, such as yachts longer than 100 ft. Using continuous processing and tubular fiberglass cloth, liners for leaking water mains have been produced in lengths up to 1400 ft on site.
- Processes exist to produce either a few prototype parts or a large production run. A 40-ft-diameter orange, featured in the Florida building at the 1964 New York World's Fair, was produced by spraying chopped glass fiber and pigmented resin on an inflated war surplus weather balloon, which served as a mold. Corrugated panels used for patio roofs are produced by a continuous pultrusion process in which dry mat and liquid resin are converted to a stack of panels cut to required lengths by an automated system.
- An exotic application is the development of ablative plastics capable of operating at 3000_F for rocket motors. These materials slowly decompose to form an insulating char that contains the gases that provide the thrust for liftoff. High-temperature metals would have been too heavy and require cooling by the evaporation of excess fuel to prevent melting.

Newer applications and the reasons for using graphite, now more commonly called carbon, fibers include:

- High-performance race cars (stiffness-to-weight ratio, crash worthiness)
- Rods to stiffen elevated walkways (high modulus)
- Picker sticks to remove drills from oil wells (tensile strength-to-weightratio)

- Reinforcing corroded bridge columns to bring them back to design strength (stiffness)
- Bows for stringed instruments (stiffness)

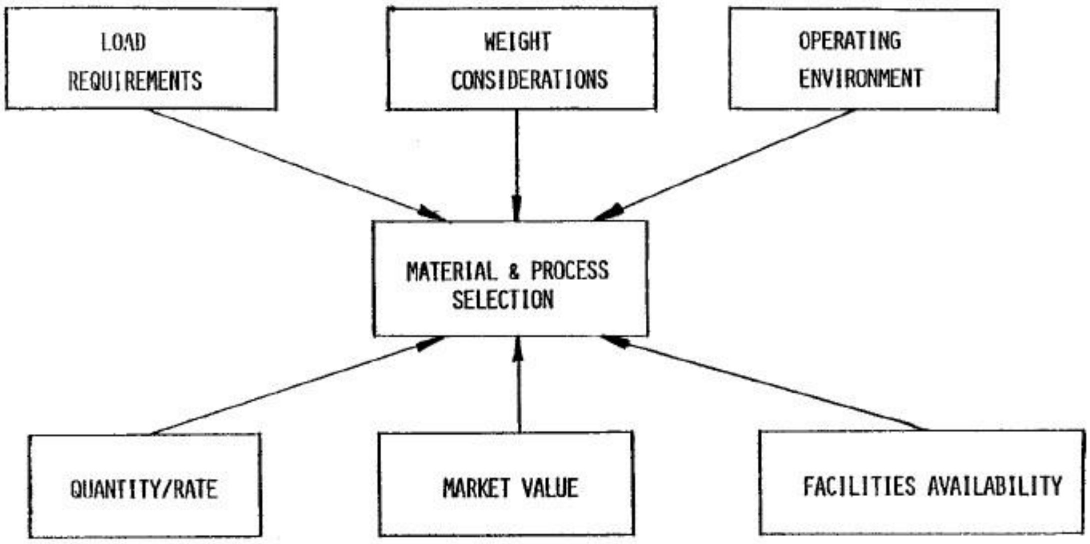
Fiberglass/epoxy can refer to several different types of materials with vastly different properties based on the fiber length and form and the quantity of fibers parallel to the load path. Laminate properties can be varied to match the applied loads by controlling the fiber orientation of tape and fabric plies. Thus, the designer must match the material and process used for his design allowables to that actually used in the product. The required control is obtained by material and process specifications. Composites are not ductile and do not yield before reaching their breaking strength. Failing strains are much lower than those of metals. The design strain for crossplied graphite/epoxy tape panels is 3000 _in. per inch. Thus, the design must eliminate high point loads such as those introduced by forcing mating parts to fit. Load eccentricities must be avoided to prevent internal ply delamination. Also, there is a significant interaction between the lay-up process, which is geared to a certain fiber form, and part shape. Fiber form also impacts the mechanical properties used in the design. For example, a small cylindrical tank is best made by filament winding of continuous glass/carbon fibers because high mechanical properties are combined with low cost. Irregularly shaped water lily ponds used by gardeners are buried in earth so the weight of the water is supported. These items are best produced by spraying a chopped glass fiber/polyester resin mix onto the mold. The low cost process is well suited to irregular shapes, and the ponds do not require high mechanical properties. Lastly, thickness variations of composite parts, typically _5%, may exceed those of metal parts, especially as part thickness increases. Also, each part can have areas that are either above or below nominal thickness. These variations are due to variations in the weight of resin and fiber per unit area in the materials, and resin movement during processing. Sometimes an extra ply is required to carry the load when minimum part thickness is inadequate. Thickness variations complicate assembly by fastening or bonding because composite parts cannot be forced into shape without damage.

As a preview to the major discussion of this chapter, a brief description of the manufacturing operation is desirable. The steps are:

- Clean the mold and apply a release agent to prevent the part from sticking.
- Prepare plies.
- Put the plies on the mold in the specified order (to reduce warpage and obtain optimum mechanical properties).
- Cure the resin by chemical reaction; the resin is transformed from a liquid or paste to a brittle solid.
- Remove the part from the mold.
- Trim, assemble, and paint.

SELECTION OF MATERIAL AND MANUFACTURING CONCEPT

There are four classes of fiber, eight types of matrices, several fiber forms, and eight general manufacturing processes. At first glance, this array of options is bewildering. Often, however, choices are limited. The selection of material and manufacturing process is controlled by design factors such as loading, weight limitations, operating temperature, and perceived value. In addition, customer, government, and industry specifications may apply. Special requirements, such as the increasing use of phenolic materials in trains and aircraft to reduce fire and smoke in case of accident, may apply. Part shape significantly influences process selection. Fiberglass channels for ladders are a perfect application for pultrusion because they have a constant cross section. Skins for wind turbine blades must have a smooth aerodynamic outer surface, and inner surfaces must fit to the substructure within glue line tolerances. The skins are made by resin injection molding in a closed mold to obtain two controlled surfaces. Resin injection tooling/ facilities are less expensive than the alternative of press molding. Parts of complex shape are either vacuum bag or autoclave molded because only one tooled surface is needed for these processes.



Factors affecting the selection of materials and processes.

The manufacturing objective for structurally bonded assemblies is to produce an acceptable unit with a minimum of effort with little rework or scrap. To achieve these aims, the process must provide for:

- Cleaning the mating surfaces to prepare them for bonding
- Good fit up of mating surfaces to glue-line tolerances
- Locating the parts in the proper orientation during adhesive cure
- Using a thin fiberglass/nylon cloth (scrim) to guarantee a continuous bond line
- Obtaining a consistent bond-line thickness within specified limits.

ENVIRONMENTAL CONCERNS

A composite manufacturing plant inherently has many environmental problems simply due to the nature of the materials and processes used. Under prodding by the Environmental Protection Agency (EPA), industrial hygiene has improved significantly since the mid-1980s. Even so, profits from a well-conceived production effort can be lost due to EPA penalties. So environmental concerns must be a part of the materials selection and design effort, as well as a requirement for manufacturing facilities. There are four problem areas: airborne vapors, skin contact with allergens, dust, and disposal of waste.

Many resins contain ingredients with low boiling points. Polyester and vinyl ester contain styrene whose odor permeates even well-ventilated facilities. Phenolic resins have the sweet odor of unreacted phenol and give off formaldehyde. A group of mechanics working on a highly classified project were awarded compensation for medical problems because, reportedly, they were working in an inadequately ventilated area and absorbed some chemicals.