Chemical Engineers in Action
INNOVATION

CHEMICAL ENGINEERS AND MATERIALS SCIENCE

The dictionary defines a material as a “substance or substances out of which a thing is or may be constructed.” Using this definition, it is not hard to understand why materials science and engineering is one of the broadest and most active areas in chemical engineering research and development. By identifying, analyzing, manipulating, and then exploiting the various properties of different materials, chemical engineers and other technical professionals are able to

- discover and create an ever-expanding array of base materials that display the desired characteristics and behaviors needed by various finished products,
- design and engineer the systems needed to produce these base materials so that they have predictable, repeatable properties in commercial-scale quantities, and
- devise complex engineered systems to cost-effectively fabricate useful and revolutionary products from various materials for use in our everyday lives.

By applying chemical engineering principles, such useful properties as electrical, thermal and magnetic properties, load-bearing capabilities, the ability to remain flexible or rigid under certain operating conditions, to withstand common failure (such as creep or brittle failure), and to resist damage by erosion or corrosion can create the things we need in modern life. Materials are often classified in terms of the so-called materials triad—polymers, ceramics, and metals—for their distinct properties.

Polymers

Chemical engineering principles and technologies have been essential to the evolution of polymer processing. Polymers (or plastics) consist of long, chainlike molecules produced when individual chemical compounds called monomers are linked together through a process called polymerization. From these base polymer resins a diverse array of value-added plastics, such as polyethylene, polypropylene, polystyrene, polycarbonate, nylon, and polyvinyl chloride, can be produced. Polymers are used widely in modern life to produce countless items for consumer, industrial, medical, and other applications. In 2006, U.S. production of polymer resins reached 113 billion pounds, according to the American Chemistry Council (www.americanchemistry.com).

The properties of plastics can be manipulated and controlled by modifying their chemical makeup and processing variables the material experiences. While some plastics can be molded at relatively low temperatures, others can be stretched, twisted, or considerably deformed before they break. Still others are strong enough to function as rigid structural materials sustaining large loads, while some can be fabricated as strong, flexible fibers. Chemical engineers have made such versatility a reality.

Today, most plastics are produced by formulating mixtures of polymer resins with a host of performance-enhancing fillers, chemical additives, and reinforcing agents. The additives give the polymer blend certain desired characteristics such as

- improved physical properties (e.g., tensile and impact strength) and flame retardancy,
- increased conductivity and antistatic, antibacterial, and fungicidal capabilities, and resistance to the damaging effects of exposure to oxygen, ozone, or ultraviolet radiation.

Among other things, polymers are valued for their

- broad resistance to attack or damage when exposed to many chemicals,
- ability to function as thermal and electrical insulators,
- light weight and varying degrees of strength (depending on the actual chemical composition of the polymer, the type and amount of functional additives used to produce it, and the type and degree of processing), and
- ability to be processed in various ways for finished products from children’s toys to complex industrial and medical items that must perform under very demanding operating conditions.

Plastics can be classified as thermoplastic or thermoset polymers. Thermoplastic polymers soften when heated and harden when cooled, and can be easily processed into finished products and reprocessed or recycled for use in second- and third-generation products. Commonly used thermoplastics include polyethylene for milk bottles, disposable polystyrene cups for hot beverages, and polyethylene terephthalate for soft-drink bottles.

By comparison, once an object is fabricated from a thermoset polymer, a covalently bonded network is formed via an irreversible process called crosslinking, which can be driven by heat, light, or the addition of chemicals. The object cannot be melted, reformed, or recycled. Its physical properties become “set.” Products made from thermoset polymers include rubber bands, tires, and epoxy resins used during the manufacture of fiber-reinforced composite materials. Products fabricated from polymers are used widely from clothing, bottles, and carpeting and packaging materials to biomedical implants and instruments, industrial machine components, and automotive parts.

Bio-based plastics. Polymers are produced most often from starting materials derived from hydrocarbon sources, specifically from intermediate chemicals from fossil fuels. Recently, however, chemical engineers have been developing “bio-based” plastics from renewable raw materials, such as corn, soybeans, and various other agricultural and forest crops. These “greener” plastics not only help reduce society’s reliance on fossil fuels, but biodegrade more easily and break down more quickly in a landfill, often producing carbon dioxide, water, and nontoxic biomass than traditional plastics.

Promising early products based on such environment-friendly plastics are available commercially for relatively simple applications, such as composting bags, mulch film, and baby diapers. Chemical engineers continue to improve bio-based plastics with even greater strength and resistance to damage in the face of abrasion or elevated temperatures, which make them suitable for more demanding applications.

Ceramics

Ceramics are composed of inorganic materials, such as aluminum and oxygen (alumina or Al_2O_3), calcium and oxygen (calcium oxide or CaO), aluminum silicates, and silicon and nitrogen (silicon nitride or Si_3N_4). When fired at high temperatures during manufacturing, these constituents produce hard, crystalline finished products and rugged, durable coatings and linings on various industrial and medical components, which can improve the item’s ability to withstand damage from extreme temperatures, erosive conditions, and so forth. Common materials made from ceramics include insulators for electronics; rugged (erosion- and temperature-resistant) engine, machine, and tool components; dinnerware; floor tiles; high-temperature refractory linings for industrial kilns and smokestacks; jet-engine turbine blades; and biomedical implants.

Metals

Metals are hard materials made from various metallic elements found in nature, and valued for their inherent mechanical strength and being good conductors of heat and electricity. Commonly used metals include

- copper in manufacturing semiconductor chips,
- iron-based structural steel in constructing bridges, ships, and machinery,
- stainless steel for industrial process equipment and surgical instruments that must resist corrosion under harsh operating conditions,

- aluminum for food and beverage cans, and
- titanium, aluminum, and magnesium alloys for aircraft and spacecraft applications requiring materials stronger and more lightweight than other metallic options.

So-called normal steel is used widely for low-cost, high-strength applications, in which weight restrictions and corrosion do not pose a problem. Stainless steel and galvanized steel are more costly, so these materials tend to be reserved for applications where resistance to corrosion is important and the manufacturer or end user is willing to pay a premium price.

Specialized nickel-based alloys are often required for use in highly corrosive environments and for applications requiring such nonmagnetic material as turbochargers, pressure vessels, heat exchangers, and other chemical process equipment.

Recently, chemical engineers have been investigating advanced metal alloys (e.g., those based on aluminum, magnesium, and titanium providing greater structural strength at a reduced weight than steel. Engineers must then create or improve the manufacturing processes needed to produce these alloys on a commercial scale. Ongoing work is also aimed at improving the processing requirements, reducing costs, and developing advanced coatings that can help stainless or galvanized steel and nickel-based alloys withstand increasingly harsh operating conditions.

Chemical engineers also pioneer advances in metal matrix composites (MMCs), which use one or more metals (typically such nonferrous metals as aluminum, magnesium, titanium, cobalt, and cobalt-nickel alloys) as the base matrix. They then uniformly disperse reinforcing additives (such as fibers or particulates of carbon, often in the form of graphite, or such ceramics as alumina and silicon carbide) to improve structural strength, wear resistance, or thermal conductivity, as well as to reduce the material’s likelihood to experience friction. As with many other materials science efforts, the final suite of physical properties demonstrated by a particular MMC is dictated by selected matrix metal or alloy and reinforcement materials, volume and shape of the additives, location of the reinforcing additives within the overall matrix, and fabrication method.

Chemical engineering research on materials is focused primarily on determining the “structure-property-processing” relationships that characterize a material. This triad reflects the fact that the properties of a material in an application are often a direct function of both the internal structure of the material and the type and degree of processing used to fabricate the material and finished product. The internal structure is dictated by attributes ranging in scale from the intrinsic atomic or nanoscale structure of its molecules to the supramolecular arrangements and crystalline structure of the material.

Chemical engineer’s evolving role

Most chemical engineers working in material design and engineering are involved with process design research developing various engineering processes needed to synthesize, purify, and manufacture diverse materials. Such efforts result in the fabrication of the desirable base material, not the finished consumer, industrial or medical end products. The goal is to produce the material in commercial quantities whose properties are consistent and predictable from batch to batch or lot to lot in producing finished goods and commercial products.

Chemical engineers work to modify molecular structures by enhancing or suppressing certain physical characteristics and material properties, particularly to develop a fundamental understanding of the exact relationships between specific modifications and resulting property changes to bring forth sought-after physical traits and performance attributes while suppressing unwanted ones. They are also involved with all aspects of materials-related R&D, materials characterization, and commercial scale-up ranging from molecular and macroscopic investigations to materials synthesis and product design. They also develop sophisticated, cost-effective processing techniques and engineered systems needed to fabricate intricate finished products and to apply complex single- and multilayer surface coatings (e.g., to increase resistance to wear, corrosion, and oxidation damage) for countless consumer, industrial medical and other applications.

Resisting corrosion

One of the most important pursuits in materials science and engineering is to protect costly industrial machinery that must function in aggressive chemical process environments against corrosion. In some cases, corrosion can be reduced or even eliminated by choosing a steel-based alloy with higher levels of chromium, nickel, or molybdenum. In others, specialized or titanium- or zirconium-based alloys may be used.

Costly exotic metal alloys often can be replaced (or the component can be coated or lined) with other lower-cost, inherently corrosion-resistant glass, standard polymers (such as polypropylene, polyvinylidene fluoride, and polytetrafluoroethylene) or more specialized “engineered plastics” that are even better able to resist attack from acids, alkalis, and other aggressive media during use. In more demanding applications, ceramic coatings may be required, since they provide extraordinary resistance to corrosion, abrasion, and elevated temperatures (these coatings sometimes can withstand temperatures up to 3,000˚F).

Analytical devices and advanced modeling techniques

An important aspect of materials science R&D and scale-up has been to develop techniques to characterize and model the physical properties of various materials. The ability to properly analyze materials properties is essential to the creation of new, improved materials. Access to such tools is also critical to the scale-up of producing winning materials, once they have been successfully demonstrated in the laboratory.

The list of analytical techniques available to chemical engineers continues to grow and includes

- scanning electron microscopy,
- acoustic microscopy,
- atomic force microscopy,
- scanning tunneling microscopy,
- X-ray diffraction,
- calirometry,
- neutron diffraction,
- spectrophotometry,
- gas chromatography,
- thermal and infrared imaging, and
- acoustic waveform analysis.

With the information from these analytical devices, as well as advanced modeling and simulation techniques, chemical engineers are better able to effectively test and predict the potential impact of various chemical modifications. Once the effect of the modifications has been determined, engineers can modify and optimize chemical processing techniques to produce materials with the desired physical properties and behaviors under different operating conditions. These tools are also essential to scale up winning strategies demonstrated in the laboratory and to design commercial-scale production facilities. Similarly, such analytical devices are used to identify key relationships between specific microstructures and resulting properties, and to analyze and predict structural defects, internal dislocations, and other common failure modes, such as creep, fatigue, brittle failure, and crack propagation.

Chemical engineering theorists develop and use advanced conceptual theories, mathematical models, and sophisticated software programs that can help model, simulate, and predict the thermodynamic and physical properties of materials. Such modeling techniques often provide high-quality graphical visualization of materials and their structures to help picture what is going on inside the material as it is exposed to simulated changes in chemical composition, operating conditions, and other factors.

Achievements in materials science

Chemical engineers engaged in resolving materials-related problems work in all industrial sectors—chemicals and petrochemicals, building construction, cosmetics and personal care, pharmaceuticals, plastics and composites, glass, microelectronics and semiconductor manufacturing, biomedical devices, and machine design, to name a few. Due to the diversity of material options, the range of desired functionality, and the complexity of the product and processing requirements, the problems they work on can vary considerably from sector to sector.

Semiconductor and electronics manufacturing. As society moved from the Industrial Revolution to the Computer Revolution, ongoing advances in microelectronic and optoelectronic devices have been of critical importance, and chemical engineers have filled a vital role in their development. Computers are pervasive in modern life and provide essential, enabling technology in school-related functions, business dealings, industrial operations, telecommunications applications, automotive applications, and more. Many of today’s young people, who have grown up in the Computer Age, cannot imagine their lives without computers for homework, surfing the Internet for academic or social purposes, or computer games, digital movies, and music on MP3 players.

Today’s computing systems rely on semiconductor chips, complex microelectronic circuits, and other optoelectronic components. Chemical engineers have developed specialized materials and complex chip-manufacturing processes (such as optical lithography techniques, ion implantation, chemical vapor deposition, and dielectric etching). Consumers increasingly demand faster, smaller and cheaper electronic devices. Revolutionary advances in materials science are essential for progressively smaller semiconductor chips, which offer ever-increasing speed of execution, greater memory capacity, and broader functionality. In producing progressively advanced semiconductor chips and other computer components, chemical engineers use their expertise in

- kinetics and thermodynamics to crystallize silicon wafers (the base materials for most semiconductor chips),
- polymer science to develop patterned photoresist coatings, and
- heat transfer to maintain desired temperatures and manage heat buildup during the chip-making process.

Mass transfer comes into play during the etching of complex semiconductor chip patterns and the plating of electronic microchannels using copper and other conductive metals during chip production.

Telecommunications. Breakthroughs in materials science and engineering have enabled advances in telecommunications and optoelectronics, which have affected modern life in diverse ways ranging from perfectly timed LED-based traffic lights to instantaneous global telecommunications and data transmission via both fiber-optic and satellite networks. Who could imagine life today without the instant audio, video, and e-mail capabilities provided by today's omnipresent cell phones and Blackberry-type devices?

Fiber-optic cables form the backbone of much of today's instantaneous transmission of voice, video and data. Without chemical engineers' development of reliable processes to fabricate fiber-optic cables, the modern "land-line" phone system, the cable television system, and the Internet would not be possible, nor would real-time videoconferencing or electronic commerce. The fiber-optic cables are composed of bundles of long, thin glass fibers narrower than a human hair. Because light travels effectively through these cables via a principle called total internal reflection, it can bend around corners and reach its destination very rapidly. These glass strands transmit light signals over hundreds and thousands of miles, allowing real-time telecommunications and digital data transfer.

Compared with conventional metal (typically copper) wire, optical fibers are less costly and more effective, with greater carrying capacity and less signal degradation, using lower-power transmitters. While the process required to draw glass into small-diameter fibers is straightforward, the thin glass fibers are brittle and fracture easily. To solve this problem, chemical engineers invented a process called modified chemical vapor deposition to coat the drawn glass fibers with a specialized polymer, which not only maintains the required optical properties to guide light and data within the fibers but prevents them from fracturing, even in the face of severe bending. Today, millions of miles of fiber-optic cables form the backbone of the instantaneous, worldwide global data transmission and telecommunications.

Polymer processing. During the last several decades, polymer engineering has matured as a field of academic study and a lucrative worldwide industry. Early efforts to produce polymeric materials had focused on sources in nature, such as tar, shellac, tortoise shells, various animal horns, and tree saps, but in the 1800s these polymers began to be chemically modified to produce such commercially important materials as vulcanized rubber and celluloid. The first synthetic polymer, called Bakelite (made from phenol and formaldehyde), was produced by Leo Baekeland (1863–1944), one of the founding fathers of the chemical engineering profession, and its commercial production began around 1907.

World War II accelerated the pace and scale of synthetic polymer development, as supplies of natural rubber from Southeast Asia became scarcer. At that time, natural rubber was a commodity of vital economic and military importance and critical for automotive, aviation and tank tires, among others. While the public is generally aware of the U.S. Government's top-secret atomic bomb project, the equally important, large-scale Synthetic Rubber Program of 1939-1945 has not been publicized. With U.S. Government sponsorship, a consortium of companies (many of them competitors), and university and government research labs unprecedentedly produced a general-purpose, commercial-scale synthetic rubber, GR-S (Government Rubber-Styrene), to meet the needs of the U.S. and its allies during World War II. This remarkable collaboration resulted in an expansion of U.S. synthetic rubber output from a scant 231 tons per year in 1941 to 70,000 tons per month by 1945, according to the American Chemical Society (www.acs.org). These efforts also stimulated the development of many other synthetic polymers, such as nylon, acrylics, neoprene, and polyethylene, which have over time displaced natural materials, such as latex, wool, and silk, in many applications.

The widespread commercial-scale availability of synthetic rubber fueled a transportation boom in the 1950s, which has been a key defining factor in American culture. Nearly 70% of the rubber used now in manufacturing processes is synthetic, according to the ACS, and the composition is a direct descendant of the general-purpose synthetic GR-S developed during World War II.

Synthetic polymers or plastics began to outpace the use of steel by the mid-1970s, thanks to the inherent performance and cost advantages, as well as the ability to be easily produced in commercial-scale quantities from various hydrocarbon (and in some cases bio-based) feedstocks. Almost every aspect of modern-day life involves polymer including clothing, the paint, wood, insulation, and carpeting, automobile tires and car interior, and packaging. The trade names of many polymers are now used routinely: Styrafoam (a specialized form of polystyrene foam whose closed-cell structure provides buoyancy, and insulating and water-resistant properties); Teflon (a synthetic fluoropolymer, polytetrafluoroethylene, or PTFE, which is prized for its "nonstick" properties); and Kevlar (a light, but very strong, heat- and cut-resistant synthetic fiber that is a member of the Aramid family, long molecular chains produced from polyparaphenylene terephthalamide).

Chemical engineering R&D has been instrumental in helping decipher how the fundamental molecular structures and thermodynamic characteristics of various polymers yield different mechanical and physical properties. Chemical engineers are also responsible for developing viable processes for polymerizing polymers, purifying the reaction products, managing vapor emissions and solid and liquid waste streams, and fabricating finished goods out of them. Using such chemical engineering unit operations as kinetics and reactor design, heat transfer, fluid mechanics, and process control, chemical engineers working in polymer processing help produce various finished goods.

Of particular importance to the polymer processing field have been advances in understanding non-Newtonian fluids (fluids whose viscosity changes with the applied strain rate without a well-defined viscosity; by comparison a Newtonian fluid, like water, continues to flow, regardless of the forces acting on it). R. Byron Bird and his colleagues contributed an important basis for the quantitative treatment of polymer flow and processing. The pioneering work of Donald Paul with the Chemical Engineering Department at the University of Texas at Austin helped advance the practice of polymer blending considerably. Ongoing polymer research aims to develop even more sophisticated products, such as adaptive and responsive materials, conductive materials, recyclable materials, biocompatible materials, nanocomposites, and other high-performance materials.

Biocompatible materials and medical implants. Over the last several decades many chemical engineers have been working at the intersections among chemical engineering, materials science, and medicine. They are also at the forefront of the ongoing biomedical revolution, whose discoveries have helped extend human life, improve disease diagnosis and treatment, ease suffering, and improve the quality of life.

Chemical engineers over the last several decades have been clsoely involved in the discovery and development of biocompatible materials based on specialized metals, polymers, and ceramics. The specialized materials must be suitable for use within the human body (in terms of potential toxicity), tolerated well when circulating in the blood or implanted in the body (to reduce the risk for inflammation or rejection), and able to resist damage or degradation when exposed to the particular conditions likely to be encountered within the human body (such as elevated temperatures, changes in pH, and exposure to moisture).

From the everyday gel cap used to deliver prescription drugs to artificial hips and knees, to vascular meshes, and medical stents, the development of advanced materials has affected virtually all aspects of modern medicine.

Biomedical applications generally fall into two categories: those used inside the human body (*in-vivo* applications) and those used for demanding medical applications outside of the body such as surgical tools, sterile blood bags, polymeric bandages, disposable contact lenses, syringes, sutures, and tubing. Widely used *in-vivo* products include

- strong, yet lightweight, vascular grafts fabricated from specialized polyester woven to ensure suitable vascular integration to repair or reinforce existing veins and arteries,
- strong, yet lightweight, stents fabricated from specialized stainless-steel alloys that facilitate drainage and reinforce weak arterial tissue,
- various spinal, cardiovascular, and ophthalmic devices made from a variety of specialized polymers, ceramics, and metals, and
- rugged, yet flexible, artificial knees and hips fabricated from combinations of biocompatible polymers and surgical titanium to help those with damaged or diseased joints regain flexibility and mobility.

Without pioneering materials breakthroughs and medical inventions, which chemical engineers have helped develop, it would have been difficult for patients to regain comfort, flexibility, and mobility, and to enhance the quality of life and prospect for longevity.

Materials engineering has also been essential to the field of *tissue engineering*, which originated almost 40 years ago in numerous chemical engineering departments and is now at the heart of many biomedical engineering activities. Tissue engineering involves the development and engineering of biological substitutes that can restore, maintain, or improve the function of human tissue (such as bone, cartilage, blood vessels, or, in some cases, whole organs).

Modern-day tissue engineering would not be possible without the pioneering materials science contributions of such chemical engineers as Robert Langer of the Massachusetts Institute of Technology who has developed numerous biocompatible polymers and constructed ingenious scaffolds to enable tissue growth. The ability to produce appropriate materials(both biocompatible and biodegradable) has been critical to the development of these scaffolds, which provide a locus for human tissue regeneration within the body but are then eventually absorbed by the body over time at a precisely controlled rate.

The availability of appropriate materials has also helped devise more effective *drug delivery* mechanisms. By precise targeting and improved delivery of various therapeutic agents such as insulin, anticancer drugs, growth factors, gene therapy agents, and vaccines the amount of drug that reaches the cancerous or diseased cells is maximized, while sparing healthy cells and thereby minimizing the drug’s potential side effects.

One particularly imaginative type of controlled-release drug delivery system that has received considerable attention in recent years involves the use of tiny, hollow spheres made from specialized polymers. These hollow shells encapsulate powerful, yet toxic, chemotherapy drugs, therapeutic formulations, and contrast agents for use during diagnostic imaging—compounds that are effective but often create unwanted, even toxic, side effects for patients when administered in excessive amounts.

These tiny, drug-filled polymeric shells are designed to be accumulated in the exact desired location within the body (such as a tumor site or within a given organ) once injected into the patient. They then can be made to release their payload of therapeutic or image-contrast agents on demand—either suddenly or in a sustained, time-released fashion—using a variety of imaginative triggering mechanisms. Triggering mechanisms being investigated today include changes in specific environmental conditions (such as changes in temperature, pH, or the presence of certain enzymes) or the use of an outside stimulus such as magnetic, ultrasonic or laser-beam activation.

Many of today's promising drug delivery concepts have been made possible also by breakthroughs in nanotechnology, which enable chemical engineers's ability to reliably produce particles (such as hollow drug carriers) whose remarkably small dimensions are measured in terms of nanometers (1 billion nanometers = 1 meter).

High-performance materials. The 1950s ushered in the Space Age, stimulated in large part by the success of the Russian Sputnik program. Safe, successful space exploration would not have been possible without valuable contributions of chemical engineers who specialized in materials science and engineering working on the many specialized, high-performance materials to withstand the rigors of space travel. For instance, the space shuttle cannot withstand the frictional heating of reentry into Earth's atmosphere without the ceramic tiles and insulating foams used in its construction. Advances in metal alloys, carbon composites, and engineering polymers (which combine light weight with superior structural strength) have been instrumental in designing spacecraft, as well as commercial and military aircraft.

Many of the imaginative materials developed for the space programs and military applications have also found their way into industrial and consumer applications requiring both exceptional strength and light weight, and wherein the materials must withstand high temperature and corrosive or erosive operating conditions.

Nanomaterials and other nanotechnology-related advances

Commercial development and R&D activities related to nanotechnology take advantage of the functional benefits many materials produced in extremely small particle sizes. The term *nanotechnology* pertains to the purposeful creation, manipulation and use of matter, physical structures, and engineered devices with previously unimaginable dimensions. The prefix *nano* (10^{-9}) refers to a billionth of something, and in the case of nanotechnology the basic unit of measurement is a nanometer (nm). (1 nm =1/25,400,000 in.; 1,000 nm = micrometer. The width of an average human hair is 10,000 nm; human DNA molecules are 1.5-nm-wide; and a typical bacterium, say *E. coli*, is a thousand times bigger, measuring between 1,000 and 2,000 nm.)

Today, the use of nanoscaled materials and nanotechnology-related manufacturing techniques is increasing, and many others are being investigated to

- produce composite materials with improved electroconductivity, catalytic activity, hardness, scratch resistance, and self-cleaning capabilities,
- produce consumer products (such as cosmetics and sunscreens) with improved aesthetic appeal and effectiveness,
- improve the performance of compact, ultrasensitive gas sensors and other industrial and medical monitoring devices,
- increase the catalytic activity of industrial catalysts for chemical processing, petroleum refining, and environmental control applications,
- produce improved fuel cells,
- enable more lightweight and longer lasting batteries,
- enable medical advances (such as nanoscaled drug delivery mechanisms),
- produce nanoscaled polymeric membranes whose tiny openings (measured in nanometers) enable complex separations, and
- create specialized polishing slurries that are essential in manufacturing semiconductor chips.

Size-dependent phenomena. As the particle size of any substance decreases, the amount of overall surface area of each particle increases resulting in an inverse relationship between particle size and surface area. Today, specialized techniques developed by chemical engineers allow many common materials—including metals, metal oxides, and different forms of silica, clays, and novel carbon compounds—to be processed so that their individual particles have dimensions measured in terms of several to several hundred nanometers. When produced with these tiny dimensions, the resulting particles have extraordinarily high surface area, a proportionately greater number of atoms on the surface, and increased overall reactivity.

Taken together, these physical attributes allow nanometer-sized particles of common materials to demonstrate a broad range of favorable physical properties (compared with larger-size particles) including improved chemical and abrasion resistance, hardness, tensile strength, and flexural modulus; favorable melting points, magnetic properties, thermal and electrical conductivity, and surface-chemistry effects (enhancing the ability to disperse the powdery particles in a liquid and their reactivity in different situations); higher chemical-conversion rates and catalytic activity; and unusual photonic behavior that changes in the presence of light of varying wavelengths.

Chemical engineers have been intimately involved from the start in efforts both to identify these desirable properties and then to devise engineering strategies and systems to put them to work in the fabrication of end products for various consumer, industrial, medical, and other applications.

Carbon nanotubes are a particular form of nanoscaled material and are being pursued across a number of engineering disciplines for use in diverse applications. Unlike other nanoparticles of common materials, which are just ultrasmall particles of a material, carbon nanotubes are seamless cylinders composed of carbon atoms arranged in a regular hexagonal pattern. These tiny tubes whose diameters are measured in nanometers can be produced as “single-wall” or “multiwall” nanotubes. First discovered by chemistry and chemical engineering researchers at Houston’s Rice University in the early 1990s, research on different aspects of carbon nanotube production and use have been growing.

Carbon nanotubes possess a remarkable suite of material properties with the potential to enable or improve various industrial applications. For instance, carbon nanotubes have a surface area of up to 1,500 mg^2/g and density of 1.22 to 1.40 g/cm^3; exhibit extremely high thermal and chemical stability, with extremely high elasticity (with a modulus of elasticity of 1,000 GPa); can withstand elongation or stretching of up to 10 to 30% before breaking; can function as conductors or semiconductors of electricity and heat depending on their structure; and have enormous tensile strength, which can be greater than 65 GPa (predicted values are as high as 200 GPa) with a tensile strength 100 times that of steel at only one-sixth the weight.

Today, carbon nanotubes are being investigated as key components in a variety of advanced sensors, electronic and optical devices, catalysts, batteries, and fuel cells. They are also being used as a key component in advanced materials that demonstrate greatly enhanced properties and behaviors under novel or extreme operating conditions. For instance, during commercial applications, carbon nanotubes are incorporated into various matrices, including such fluoropolymers as ethylene tetrafluoroethylene and polyvinylidene fluoride, to produce ultra-lightweight composite materials that have exceptional strength and other functional advantages over conventional materials. Such composites are also being used to create advanced thin-film membranes, fibers, and coatings.

Nanotube-enhanced advanced composites are being used in various automotive, electronics and other industrial applications—particularly those that require greater chemical and barrier resistance to chemical or vapor permeation, inherent lubricity, and better resistance to sloughing and control of static electricity.

Polishing slurries for semiconductor chips. One of the earliest commercial uses of nanoparticles has been as a key component in the polishing slurries used during chemical mechanical planarization (CMP). During CMP, nanoscaled particles of abrasive materials—typically oxides of aluminum and zirconium, colloidal or fumed silica, and cerium, with particles between 20 and 300 nanometers in diameter—are formulated into a precision slurry, which is then used to polish semiconductor chips during their manufacture to make the metal and dielectric layers on the silicon semiconductor wafers smooth and essentially defect-free.

Advanced composite materials. In recent years, a variety of advanced composite materials have been developed and commercialized. By adding relatively small amounts of nanoscaled particles of various materials and carbon nanotubes to different polymeric resins, “nanocomposites” demonstrate a range of improved material characteristics such as increased electrical or thermal conductivity, catalytic activity, and flame retardance; greater hardness, scratch resistance, and diffusion-barrier characteristics (such as reduced gas permeability, which is important during food packaging and other critical applications); and self-cleaning capabilities and antimicrobial properties (valuable for such products as automotive windshields, and kitchen and bathroom tiles).

Using nanoscaled fillers, additives, and reinforcement materials has advantages over the traditional approach, which blends conventional macroscaled additives into a polymer base. (Macroscaled particles are still small—often measured microns or micrometers, but are orders of magnitude larger than nanoscaled particles of the same materials.)

When nanoscaled versions of common additives can be used, the desired composite can often be achieved using lower loading levels of additives or fillers (for instance, just 3-5% by weight of nanoscaled additives compared with 20-40% by weight of conventional, micrometer-sized additives). This decrease in additives helps overcome some of the negative consequences that often result during conventional polymer blending and processing. For instance, when higher loading rates of larger-diameter additives are used, the resulting polymer sometimes experiences increased density, increased brittleness, decreased polymer clarity, and loss of transparency (none of which are desirable attributes for a final polymer composite).

Gas sensors and other analytical devices. Various analytical devices have also benefited from a variety of nanotechnology-related advances. For instance, because nanoscaled particles of many different materials possess extraordinary surface area and demonstrate increased reactivity and catalytic properties, such materials are now being used to develop highly sensitive gas sensors and other devices, which can monitor food quality, improve disease detection, and monitor potential chemical, environmental, biological, radiological and nuclear hazards.

Chemical engineers are also investigating the use of nanoscaled particles—with their increased surface area and overall reactivity—to develop highly effective catalysts for chemical process operations, petroleum-refining operations, and pollution control applications.

Improved ceramics. Nanoscaled advances have also led to the development of high-performance ceramics. For instance, by using particles of zirconia (ZrO_2) and alumina (Al_2O_3) that measure 100 nanonmeters or less (rather than 1,000 nanometers, which is more typical of conventional ceramics), the resulting structural ceramics exhibit improved mechanical strength and greater resistance to fracture and chipping. In some cases the ability to reduce particle size also allows the final ceramic materials to be sintered at considerably reduced temperatures.

Such advanced ceramics are increasingly making their way into industrial equipment that is likely to encounter extreme temperatures, harsh operating conditions, and excessive abrasion, such as pump components, cutting tools and extrusion dies, bearings and seals, high-temperature filters and membranes, refractory materials (which are used inside furnaces, industrial stacks, and other high-temperature systems), industrial catalysts, advanced sensors, electronic components, and automotive engine parts.

Personal-care products. Many consumer products, such as sunscreens, cosmetics, and other personal-care products, have become more effective and aesthetically appealing by the use of nanoscaled versions of common additives. Examples include the use of nanoscaled particles of ultraviolet light–blocking titanium dioxide (TiO_2) and zinc oxide (ZnO) to produce sunscreens and cosmetics that are more transparent (unlike opaque white sun-protection products). Meanwhile, nanoparticles of TiO_2 are also being used to improve the ultraviolet light–blocking capabilities of transparent varnishes, textile fibers, and packaging films.

Medical advances. Nanotechnology-based concepts, materials, and systems are also being pursued to improve doctors' ability to diagnose cancer and other diseases earlier and treat them more effectively. For instance, hollow, nanoscaled drug delivery particles are being developed to deliver potent drug treatments more effectively and with fewer side effects and to more precisely target the delivery of contrast-imaging agents in the body to improve the effectiveness of diagnostic testing (for instance, the imaging agents that are routinely used during computerized tomography scanning and magnetic resonance imaging).

Chemical engineers have been instrumental not only in the discovery and characterization of the various performance attributes of nanoscaled materials, but also in developing systems to produce reliable, commercial-scale quantities of nanoscaled particles of materials to enable their use in real-world applications. Among the challenges has been the need to devise technologies and systems allowing nanoscaled particles and carbon nanotubes to be produced with predictable, consistent dimensions, acceptable purity levels, and minimal structural defects (since they can dramatically alter the anticipated behavior of the nanoscaled particles).