Materials Science

Course Motivation and Highlights

Materials science (and engineering), MSE, is arguably the most important engineering discipline. Materials have always been important to the advance of civilization: entire eras are named after them. After evolving from the Stone Age through the Bronze and Iron Ages, now in the modern era we have vast numbers of tailored materials to make use of. We are really living in the Materials Age.

The field of Materials Science deals with all classes of materials from a unified viewpoint and with an emphasis on the connections between the underlying structure and the processing, properties, and performance of the material. A materials scientist studies how materials react/behave when subjected to different conditions (such as mechanical loads, temperature and pressure) and understands that all materials can be approached from a common set of principles. Most fields in science and engineering are concerned in some way or other with materials, but only the field of materials science and engineering focuses directly on them.

First, what are materials? That's not difficult. Just look around. Materials are everywhere! The book we are using is made from a variety of materials. The glass in the windows, the aluminium frame, the ceramic dinnerware, the metal silverware and jewelry, automobiles, and everywhere we look we see products made from materials. Most products are made from many different kinds of materials to satisfy the needs of the product.

Work and study in the field of materials science is anchored around an understanding of why materials behave the way they do, and encompasses how materials are made and how new ones can be developed. For example, the way materials are processed is often important. People in the Iron Age discovered this when they learned that soft iron could be heated and then quickly cooled to make a material hard enough to plow the earth; and the same strategy is used today to make high-strength aluminum alloys for jet aircraft. Today we demand more from our materials than mechanical strength, of course--electrical, optical, and magnetic properties, for example, are crucial for many applications. As a result, modern materials science focuses on ceramics, polymers, and semiconductors, as well as on materials, such as metals and glasses, that have a long history of use. In these and other areas of science and technology, materials scientists are indeed key participants.

Materials are classified into number of groups for ease of their characterization as follows:

Metals: Metallic materials that are made of "metallic elements". These elements, when combined, usually have electrons that are non-localized and as a consequence have generic types of properties. Metals usually are good conductors of heat and electricity. Lustrous and beautiful in shades of red, gold, and silver, metals have been coveted for millennia as jewelry and as currency. Very strong, but capable of being formed into complicated shapes, metals have been used for millennia to make tools, weapons, girders, and consumer goods. Metals have been used for more than a century in electrical components from light bulbs to computer chips.

It is no surprise that two of the early eras of human civilization – the Bronze Age and the Iron Age – are named after metals. They were the first materials to be "engineered," meaning that people learned how to modify properties to meet the need at hand, rather than letting the properties of a material determine what could be done with it. Ancient materials scientists learned, for example, how to form a complicated part from a soft, ductile metal, and then, once it was in its final form, to make it hard, strong, and durable.

Modern research in metals is directed toward improving their performance and using them in ways no one could have imagined just a few years ago. For example, the development of "Superalloy" turbine blades has made modern jet transportation possible. These blades operate in environments where temperatures can approach 3,000^{o}F, but blades capable of withstanding even higher temperatures are needed in order to fly farther and faster.

Another important application of metals research is in integrated electronic circuits. In current work, for example, copper is being used to create the tiny wires--less than one-thousandth the diameter of a human hair--that connect different electronic components and are subjected to extremely high electric current densities and mechanical stresses. Continued research will make it possible to keep up the trend toward ever more powerful computers.

Polymers: Plastics (or polymers) are generally organic compounds based upon carbon and hydrogen. They are very large molecular structures. Usually they are of low density and are not stable at high temperatures. We come into everyday contact with polymers more than with any other kind of material. Polymers have an immense range of properties; some have fibers strong enough to stop a bullet and some are soft and stretchable like rubber bands. Familiar products made of polymers include paints and protective coatings, the clothes and shoes we wear, and most of the materials in the electronic devices we use. Even the food we eat is polymeric, since natural polymers make up most of what constitutes animals and plants.

Polymers usually consist of hundreds, perhaps thousands, of covalently bonded units (called monomers) to form string-like macromolecules. These can be used as strings or they can be "stitched" together into a network, as in vulcanized rubber in automobile tires. Size is important: short strings might make up materials with properties like wax, while longer strings might constitute materials such as the ultrahigh-molecular-weight polyethylene, stronger than steel that is used to make bullet-proof vests. Nature has been making complex polymers of this size for millions of years in the form of DNA, and there are remarkable opportunities to pursue in areas of biotechnology.

Because of their immense diversity, we are on the verge of a major expansion in what polymers can do and how we use them. Polymers can conduct electricity and emit light, and be used to produce transistors. They are the basis of the nanotechnology revolution through their use as photoresists. They are used in medical devices and are vital elements in the coming revolution in nano-bio-technology. In the future, polymers can be expected to play a role in almost all technological advances, since we can now control their molecular structure, atom by atom, to form synthetic polymers with uses limited only by our imagination.

Ceramics: Ceramics are generally compounds between metallic and nonmetallic elements and include such compounds as oxides, nitrides, and carbides. Typically they are insulating and resistant to high temperatures and harsh environments. They are inorganic, nonmetallic materials that can be crystalline or amorphous (glassy). Though used since ancient times (the first ceramics were made by firing earthy materials, especially clay, at least as early as 24,000 B.C.), ceramics in forms both familiar and new remain essential materials. Modern ceramics include structural clay products such as bricks, sewer pipes, and tiles; white-wares, refractories; glasses (including fibers for communication – optical fibers); abrasives; and cements.

And then there are so-called advanced ceramics. Among these are structural materials used for engine components and other parts subject to a lot of wear; for cutting tools; and for bio-ceramics such as bone and tooth replacements. Advanced ceramics are also used in capacitors, resistors, insulators, piezo-electrics, magnets, superconductors, and electrolytes. Coatings are used to protect engine components and other parts from fast wear and/or corrosion. Still other advanced ceramics are used for making filters, membranes, catalysts, and--crucial for the automobile industry--catalyst supports.

Many materials scientists are engaged in developing new ceramic materials and improving existing ones. This involves understanding the properties of the materials so as to tailor them for new applications. For example, *doping*--adding chemical elements that are not present in the starting material--can change the electrical conductivity of a ceramic by many orders of magnitude, or change the type of conduction from electronic to ionic. Such conductivity changes are critical for electrochemical sensors and for materials used in clean energy production in solid-oxide fuel cells.

Materials scientists also play a vital role in devising processes for joining ceramics with other materials, including metals and semiconductors, to make new products. Knowledge of properties is needed to overcome difficulties such as mismatches in thermal expansion that can become critical when temperature changes during the manufacture or use of a device. Products made entirely or partly from ceramics are everywhere around us today and promise to be prominent in the technologies of the future.

Electronic and Magnetic Materials: The last forty years of rapid development in microelectronics are sometimes described as the Silicon Age. Without the development of high-purity silicon and silicon-based integrated circuits, there would be no information superhighway as we know it. But if the speed and density of integrated circuits continue to increase rapidly, we will be confronted eventually with a fundamental limit of silicon-based technology; according to some predictions, this could happen as early as the year 2010.

Therefore, new electronic and magnetic materials and new paradigms for devices incorporating these materials have been the subjects of enormous research activity. Only a decade ago, the development of a new type of device for reading magnetic media enabled the rate of growth of magnetic media density to increase dramatically. This new device, called a *magnetoresistive (MR) read-head*, is now commonly found in computer hard drives. It is based on the fact that certain magnetic materials exhibit different electronic properties depending on the direction in which they are magnetized by an external magnetic field.

The first-generation MR heads incorporate magnetic metallic alloys; more recently, IBM developed so-called *giant magnetoresistance (GMR)* materials for MR heads. GMR materials are vastly more sensitive to the magnetic fields from the media than the first-generation metallic alloys are, and therefore can be made much smaller and can detect information in much denser media. Novel complex-oxide materials promise even greater sensitivity and have the potential to read magnetic media of even higher density.

We may imagine that in the future, instead of carrying a laptop, one could pull out a plastic sheet that is both a foldable, portable display and a notebook. Actually, this scenario could become possible not too far in the future, since electronics on plastics (not just on silicon) is already a reality.

Composites: Many of modern technologies require materials with unusual properties, which can’t be met by conventional materials like metals, polymers and ceramics. This led to the development of composite materials. Composites consist of more than one material type. Fiberglass, a combination of glass and a polymer, is an example. Concrete and plywood are other familiar composites. Many new combinations include ceramic fibers in metal or polymer matrix. Wood is best example for natural composite.

Biomaterials: these are employed in components implanted into the human body as substitution to the damaged and diseased body parts. For example, hip joint. Materials used as biomaterials include Stainless steel, Co-28Cr-6Mo, Ti-6Al-4V, ultra high molecular weight polyethelene, high purity dense Al-oxide, etc.

We are constantly reminded that we live in a world that is both dependent on and limited by materials. Everything we see and use is made of materials derived from the earth: cars, airplanes, computers, refrigerators, microwave ovens, TVs, dishes, silverware, athletic equipment of all types, and even biomedical devices such as replacement joints and limbs. All of these require materials specifically tailored for their application. Specific properties are required that result from carefully selecting the materials and from controlling the manufacturing processes used to convert the basic materials into the final engineered product. Further, we now read about exciting new product developments that are possible only through new materials and/or processing.

New technologies developed through engineering and science will continue to make startling changes in our lives in the 21st century, and people in Materials Science and Engineering will continue to be key in these changes and advances. These engineers deal with the science and technology of producing materials that have properties and shapes suitable for practical use. Such activities are found commonly in industries such as aerospace, transportation, electronics, energy conversion, and biomedical systems. Solutions to all these challenges lie in the materials scientist's ability to change the properties and/or behavior of a material for better performance through process-implied structure development. And this is at the heart of what a materials person does!

The future will bring ever increasing challenges and opportunities for new materials and better processing. Materials are evolving faster today than at any time in history. New emerging classes of materials include biomaterials, photonic materials, smart materials, high temperatures materials, etc. New and improved materials are an "underpinning technology" - one which can stimulate innovation and product improvement. Thus the emerging branches of materials science include nanotechnology, bio materials science, etc. It is well understood that many applications are limited by the operating constraints imposed by the properties or behavior of the materials available. Higher quality products result from improved processing and more emphasis will be placed on reclaiming and recycling. For these many reasons, most surveys name the materials field as one of the careers with excellent future opportunities.

The materials field offers unlimited possibilities for innovation and adaptation. While much attention is being focused on developing metals, ceramics, polymers, and composites with improved properties, the ability to actually engineer, or create, materials to meet specific needs is just now being realized. This engineering can be carried out at the atomic level through the millions of possible combinations of elements. Because of the increasing number of exciting materials discoveries, and the impact and influence of materials on an ever-greater number of critical manufacturing and processing industries, the field will play a major role in the competitive global economy. With the developing ability to engineer materials, we have greater potential to make needed improvements and usher in an exciting new phase in the Materials Age.

The purpose of this course is to provide a tool for better understanding of the basics about materials and their structure, different classes of materials, relation between structure and many engineering properties, their performance in different environments, and economical and environmental aspects materials usage in daily life of the world.

The course objectives, thus, include:

1. Classes of materials and their structures
2. Imperfections in materials, limitations of material applications as a consequence
3. Processing of materials
4. Engineering properties of materials
5. Economic and environmental considerations in usage of materials