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Modern Ceramics in Engineering

Instructor: Maryam Golabchi, Ph.D.

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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Introduction

In today's world, ceramics play a critical part in every aspect of our lives; they are much more effective than before and we are dependent on them.
Ceramics have evolved with us. They are the first tools that Homosapiens created and used more than 100,000 years ago. The first tools mostly took the form of natural ceramics, such as flint and stones.

Thousands of years ago, humans discovered how to mold clay, dry it in the sun and heat it in a fire to form pots, dishes, utensils, bricks, etc. The word "ceramic" comes from the Greek word "keramos," meaning "pottery" or "burned earth," and is related to an older Sanskrit word that means "to burn." When clay is heated at high temperatures, an irreversible chemical reaction begins to take place that makes it water resistant and much less vulnerable to environmental interactions than many metals and alloys.

The development of pottery was a significant milestone in human history that tremendously improved wellbeing. The watertight, heat-resistant containers enabled people to boil and steam meat and vegetables, allowing them to explore new sources of food. Cooked food could be eaten by toothless children and the elderly, which was followed by a population explosion.

Archeological exploration indicated that pottery was independently developed in North Africa approximately 12,000 years ago and in South America about 9,000 years ago. Later, pottery was used by various cultures around the world and improved over the time. The invention of the potter's wheel in Mesopotamia around 7,000 years ago revolutionized pottery production and established the very first cities in history.

Figure 1. Ancient pattern tile.

The Chinese built the Great Wall of China using fired or air-dried bricks, and centuries later they refined the clay-making process to create fine china porcelain. Egyptians melted a mixture of silica sand, lime and soda to make glasses and to use as coating or glaze in making jewelries and art pieces. About 2,000 years ago, Romans started mass producing of glassware. During the industrial revolution, ceramics were vastly used as molds, insulations and liners for metallurgical furnaces.

In the twentieth century, high-tech ceramics evolved very rapidly and efficiently. Ceramics with superior mechanical, chemical, electrical, optical, and magnetic properties were designed and have found application in every industry.

The most important applications of ceramics can be categorized in five major groups:

1. Ceramics in households
2. Ceramics in transportation
3. Ceramics in industry
4. Ceramics in electronics
5. Ceramics in medical treatment

This article will provide an overview of these five categories. For more information see "Modern Ceramic Engineering, Properties, Processing and Use in Design", 3rd edition, by D. W. Richerson.

1. Ceramics in Households

Since 24,000 BC, humans have been producing earthenware by mixing clay and water, molding it into a shape, and then drying and firing it. The traditional ceramics cover a wide variety of materials and applications including bricks, refractories, cements, plasters, tiles, sanitary sets, dinnerware, etc.

Figure 2. Hand painted glazed ceramic vase.

Magnetic ceramics and glasses have recently generated many applications in modern households.

Figure 3. Electrical motor of an AC unite, including magnetic ceramics.

1.1. Magnetic Ceramic

Magnetic ceramics are part of all of the power accessories in a home. They are essential components of the motors of many appliances and entertainment devices. Some other applications include household magnets and electrical ignition systems. Table 1 indicates some of these varied uses.

Table 1. Applications of Magnetic Ceramics in Modern Households.

Section	Device / Part
Appliances	Bread maker Food processor Mixer Meat grinder Juice extractor Microwave motor Electric knives
Entertainment	Television Computes Laptops Sound system DVD player Tape recorder
Others	Touch tone phones Electrical toothbrush Hair dryer

1.2. Glass

Glasses are ceramic materials made of non-crystalline silica that have been manufactured from 4,500 years ago to present day. They have a wide range of applications such as drinking glass, cooking ware, storage container, decoration, art, jewelry, glaze, mirror, eyeglass, telescope, microscope, integrated optic, and more.

Modern glasses are designed in order to improve thermal insulation, data transportation, energy saving in form of efficient light source, and reinforcement as described below.

Figure 4. Thermal shock-resistant drinking glass.

1.2.1. Thermal Insulation

Fiberglass insulation is made of thin glass fibers and have a wool-like texture. The combination of glass filaments and air-filled space is an excellent barrier to the thermal flow.

This type of insulation was developed in the 1930s. It has been estimated that more than 25 quadrillion (25,000,000,000,000,000) Btu of heat energy has been conserved in single-family dwellings since 1940, assuming that only half of all homes have fiberglass insulation.

1.2.2. Data Transportation

Fiberglass was used only as a thermal insulator until it was found that a tremendous quantity of information could be transmitted by light through glass fibers. They are much more efficient than ordinary metallic wires in data transportation. Two optical fibers thinner than a human hair (about 0.1 kilogram) can carry more than 600,000 telephone calls at once – the same function as 2,500 kilograms of copper wire.

1.2.3. Efficient Light Source

Fluorescent lights are much more efficient than incandescent lights. For many years, fluorescent lights were only available in a long slender form for overhead lighting. In order to be fit into a fixture designed for an incandescent bulb, a variety of circular and spiral shapes have been engineered and now are a very common light source for homes.

Figure 5. Spiral shaped fluorescent light bulb.

The most common street lights are high-pressure sodium vapor lamps. These are the lights that are mounted on long poles and give off a yellowish hue. They were invented in the 1960s and have been widely used since then due to their efficiency. An incandescent bulb produces only 15 lumens per watt and lasts 1,000 hours, while a high-pressure sodium vapor lamp emits about 10 times more light and lasts almost 25 times longer.

Another efficient light source is electroluminescent lamps. This includes the light in watches, cellular phones and the dash panel of cars. These are all examples of the application of ceramics in lighting.

Figure 6. Electroluminescent light is known as cool light.

1.2.4. Reinforcement

Glasses are used to reinforce polymers by providing great strength and stiffness, and the resulting product can have mechanical properties that exceed that of either material alone. These reinforced composites have applications in a multitude of areas. Pipes and roof shingles are some examples of how they are

used in construction. They also appear in nearly every sport in the form of skateboards, surfboards, fishing poles, shafts for golf clubs, hockey sticks, skis, tennis racquets, racquetball racquets, boat hulls, kayaks and paddles.
In order to control longitudinal and torsional stiffness of some racquets or sticks, different ceramic fibers with desired elastic modulus have been used as reinforcement materials.

Figure 7. Light reinforced composite designed for racquet.

2. Ceramics in Transportation

The transportation system has changed the face of the earth, and the modern style of living is completely dependent upon it. While automobiles are the most important part of ground transportation systems, aircrafts dominate the air space around our planet.

2.1. Automobile

Ceramics are important elements of all engines and energy production recovery systems in general. They are also integrated into every motor and control system in conventional vehicles. Special wear-resistant ceramics are designed for high-performance brake systems. There are also ceramic components in car engines such as actuators, spark plug insulators, turbocharger rotors and oxygen sensors. Multilayer ceramic actuators for high-pressure fuel injectors in diesel engines have improved ignition operation, reduced engine noise and decreased pollution emission. Spark plug insulators are effective electrical insulators able to withstand thermal shocks and chemically corrosive environments. Turbocharger rotors and oxygen sensors improve fuel consumption of internal combustion engines. In order to reduce the pollution for cars and trucks, diesel particle filter devices (DPFs) have been developed based on the porous ceramic structures.

Figure 8. Spark plug insulator of a bush trimmer engine.

A conventional internal combustion engine in a car has approximately 40% thermal efficiency, whereas a turbo compound diesel engine equipped with heat-insulating ceramic components (combustion chamber, exhaust manifold) and additional exhaust-gas energy recovery systems is estimated to achieve a thermal efficiency upwards of 65%.

Magnetic ceramics are one important category of ceramics that are mostly used in motor parts, control systems and entertainment sections, which are more specifically indicated in Table 2.

Table 2. Applications of Magnetic Ceramics in Modern Automobiles.

Section	**Device / Part**
Motors	Starter motor Fuel pump motor Windshield wiper motor Windows lift motor Seat positioning motor Sun roof motor Defogger fan motor Cooling fan motor Heating and air conducting motor Antenna lift motor
Control Systems	Speedometer Cruise control Gauges Automatic temperature control Pollution control
Entertainment	CD drive Speaker DVD player

Glasses are essential parts of a vehicle. They have been used for windows, lamplights and mirrors. In order to improve the strength of window panes, a coating of low thermal expansion glass was applied over the high thermal expansion glass. During the cooling process, the high thermal expansion glass layer shrinks more quickly and pulls the low thermal expansion glass layer into a compressive stress state. Therefore, to break the glass by a tensile force, the compressive stress has to be overcome whereas the compressive stress of glasses or ceramics is very high.

Figure 9. Headlight bulb of a conventional vehicle.

2.2. Aerospace

The aerospace industry is trying to satisfy human ambitions not only for exploration but also transportation, and ceramics have played very important roles in that industry. Many aircrafts and space shuttles are required to have parts that encompass strength, high temperature stability and corrosion resistance; specifications that only ceramics could fully cover. Some examples of these parts include:

- Jet turbine blades
- Rocket nozzle liners
- Thruster liners
- Igniter and after burner components
- Thermal protection for airplanes and space shuttles

The bottom, nose and leading edge of the wings of shuttles are exposed to extreme temperatures reaching more than 1,500^{o}C. A high thermal-shock resistance carbon-carbon composite, covered with a glassy layer to prevent oxidation, was selected for the nose cap and the leading edge of the wings. Carbon fibers are used extensively in fabrication of lightweight structures and materials for aircrafts. It has been estimated that a Boeing 757 aircraft contains about 3,300 pounds of weight-saving carbon-epoxy composite.

3. Ceramics in Industry

Ceramics have superior mechanical and chemical properties. They are among the hardest and the most erosion-resistant materials. Table 3 indicates the hardness of some ceramics. They are also among the chemically inertest and the most corrosion-resistant materials. Due to these special characteristics, ceramics have been an important part of the process of energy production and material manufacturing that will be discussed more in the following sections.

Table 3. Hardness of Some Ceramics.

Material	Hardness (kg/mm^2)
Single crystal diamond	7000-9500
Boron carbide	3200
Titanium carbide	2800
Silicon carbide	2300-2900
Aluminum oxide	2000
Tungsten carbide	1500
Zirconium oxide	1100-1300
Silicon dioxide	550-750
Borosilicate glass	530

3.1. Energy Industry

The most transferable form of energy is electrical energy. Therefore, electrical energy production is the most common process of energy production in the way that the word “power” mostly refers to electrical power. In this section, we first examine the role of ceramics in electrical energy production by gas turbine engines as the most common power generators. Then, ceramic involvement in mechanical energy production processes in internal combustion engines will be reviewed. Finally, we will explore ceramics in green energy production by fuel cells and laser machines.

3.1.1 Gas Turbine Engine

Heat engines convert the chemical energy of fuels to heat energy and then to mechanical energy just like very early steam engines. In the gas turbine engine, there is another cycle of converting mechanical energy to electrical energy. The higher the temperature and pressure of inlet gas, the more efficient the engine will be. Most of the metals cannot tolerate the elevated temperature and corrosive environment of gas turbines or jet engines. Therefore turbine parts and blades need to be covered by ceramics with high levels of hardness, oxidant resistance and thermal shock resistance, while having very low heat conductivity and thermal expansions similar to steel. Gas turbine engines with ceramic coated parts are not only more efficient but also have enhanced life time and require smaller associated cooling systems.

Zirconia-based ceramics are used as a coating for combustion chambers, transition sections, nozzles and rotor blades in gas turbines for power generators and aircrafts. A thin layer of this ceramic composite, less than 300 μm, can maintain a temperature gradient of 70°C from the hot gas to the metallic substrate under stationary conditions.

In addition to coating, sealing is another important application of ceramics in jet engines. The main rotor bearing seal of a jet engine must seal the oil lubricating system from 800,000 Pascal hot air at temperatures up to 600°C and a surface speed up to 6,000 meters per minute. Recently, a composite of graphite impregnated with other material to increase its strength and oxidation resistance was developed to be used as the seal element for the main rotor as well as other critical gas turbine engine shaft seals.

Figure 10. The external view of a gas turbine engine.

3.1.2. Internal Combustion Engine

Spark plug insulators, actuators, turbocharger rotors and oxygen sensors are specific parts of an internal combustion engine. Parts of them have to be made of ceramic due to the special thermal and chemical resistance these materials provide. Turbocharger rotors and oxygen sensors improve fuel consumption and actuators decrease pollution emissions.
Spark plug insulators in cars must function as effective electrical insulators, have high chemical corrosion resistivity, and also withstand increased temperatures and thermal shocks. Whereas ceramic for a turbocharger rotor should have low specific weight and thermal expansion, moderate thermal conductivity and significant toughness and strength.

3.1.3. Fuel cell

Fuel cells are a new source of energy that have a simple concept; air or oxygen is on one side and a fuel such as hydrogen or natural gas is on the other. The dense thin layer of zirconia acts as a solid electrolyte and is impermeable to gases. This layer is doped to have some vacancies that oxygen ions can use as a diffusion path to travel through. Oxygen molecules in the air side of the cell take electrons from the electrode (the external circuit) and convert to oxygen ions, then penetrate through the electrolyte to reach the fuel side of the cell. There, they react with the hydrogen and give up electrons to the external circuit. Fuel cells are green; if the fuel is pure hydrogen, the only emission will be water vapor. The efficiency of this direct conversion of chemical energy to electrical energy is about 60% almost twice that of burning the fuel in a heat engine such as a car engine or a conventional coal-powered generation plant.

3.1.4. Laser

Light Amplification by the Stimulated Emission of Radiation (LASER) is generally known as a device that generates an intense beam of coherent monochromatic light or other electromagnetic radiation produced by stimulated emission of photons from excited atoms or molecules. The first laser was demonstrated in the 1960s and was a ruby laser based on the phosphorescent behavior of alumina doped with chromium ions.

Since then, lasers have found many applications in communications, guidance system, instrumentation, alignment, drilling, cutting, weapon, powder synthesis, heat treating, medicine, surgery, holography, entertainment, bar code reader, recording and playing compact disc.

Many types of lasers have been developed for different products as they require specific laser characteristics. The lasers often use doped single-crystal ceramics as the laser host such as tungstate, fluoride and garnet compositions doped with chromium, neodymium, europium and other ions. Single crystal ceramics such as ruby, sapphire, garnet and many other laser hosts were manufactured using advanced materials processing technologies for specific laser creation.

3.2. Material Industry

Ceramics are involved in industrial production of diverse material, as no other material can withstand hostile environments such as highly erosive and corrosive atmospheres. Inclusion of ceramics in materials production is divided into five major sections: chemical industry, petrochemical industry, metal manufacturing, glass production and others.

3.2.1. Chemical Industry

Many applications of ceramics are based upon corrosion resistance in high temperature and pressure, and at the same time, resistance to wear. These applications include seals, valves, pump parts, plungers, rotors, bearings, and linings for many parts and vessels, especially for chemical industries, like papermaking. This matter is discussed more comprehensively in the following section.

- *Ball bearing*

Ceramic material for ball bearings must have high strength, hardness and toughness, and also show less elastic or plastic deformation to resist the increased loads to which a bearing is exposed. Some ceramics have higher strength, erosion and corrosion resistance under compression and experience less deformation than a metal. Silicon composites have 60% lower specific gravity than steel, so they consume up to 20% less energy and can be run at up to 80% higher speeds than steel bearings. The use of high-quality ceramic bearings has advanced the rate of grinding, cutting and polishing. Therefore, they have been widely used in the mineral industries.

- *Seal*

Ceramic composites have proven to be a low-cost reliable seal for sand slurry pumps, fuel pumps, torque converters, washing machines, dishwashers, garbage disposals, swimming pools and filter pumps.

- *Valve*

Ceramic valves have been used in many harsh environments, especially when effective sealing is required to prevent leaking.

- *Pump*

Slurry pumps in the mining and mineral processing industries must handle fluids containing large amounts of erosive solid particles. On the other hand, pumps in the chemical and petroleum industries are often subject to corrosive chemicals that can reach temperatures over 300^{o}C. A pump with ceramic parts and lining can last at least 10 times longer than pumps lined with other materials.

3.2.2. Petrochemical Industry

Ceramics are the best options to provide controlled heat and mass transfer in heat exchangers, and also as packing in extraction, absorption or distillation columns in chemical or petroleum industries.

Ceramic seals also play an important role in the extraction of crude oil by salt-water pressure systems. The face seal in the salt-water pump must survive the 17,000,000 Pascal pressure at 300^{o}C and surface speeds of up to 1,500 meters per minute.

The ball-and-seat or check valves have been extensively used in down-hole pumps for deep oil wells. A check valve at the end of a 600-meter deep well must withstand the weight of a column of fluid filling the well, which is about 6,000,000 Pascal. Only a few materials can withstand high mechanical stress; hot, corrosive environments; and the significant erosive rock particles in slurry.

3.2.3. Metals Manufacturing

Today, more than 725 million tons per year of steel and 24 million tons per year of aluminum are produced. Ceramics have been used in many ways for ore exploration, extraction, refining, processing, heat treatment, shape forming, finishing and quality assurance of metals. The ceramic participation in these areas is illustrated in Table 4.

Table 4. Applications of Ceramics in Metal Processing.

Process	Device / Part
Mining And Ore Exploration	Diamond-drill bit Wear part Vat lining
Refining And Processing	Heat exchanger Molten metal filter Cell liner Oxygen sensor Conveyor
Heat Treatment	Heater Burners Heat exchanger Fixture
Shape Forming	Crucible Mold Nozzle Extrusion die
Finishing	Cutting tool inserts Grinding wheel Bearings Laser
Inspection	Transducer for ultrasonic inspection X-ray radiographic equipment component Dimensional measurement instrument

3.2.4. Glass Production

Molten glass is very chemically active and can dissolve most metals and other materials. The combined effects of temperature, pressure and corrosion are best resisted by ceramics. Some specific ceramic materials can withstand that environment and be used to line huge glass furnaces or tanks.

Ceramic heat exchangers recover the thermal energy of exhaust gases to reduce fuel consumption by preheating the supplied air to furnaces in many industries including the glass production industry.

3.2.5. Others

A modern method of precisely cutting plastics, composites, ceramics and even metals is waterjet cutting. It has been designed based on exposing a surface to high-pressure suspension of hard but fine particles in water. A slurry of micronized ceramic particles mixed with water is blasted under approximately 400,000,000 Pascal pressure through the small bore of a ceramic nozzle.

4. Ceramics in Electronics

Electronic devices have changed the human lifestyle. Television, computers, cell phones and general telecommunication devices are found everywhere throughout the world. Essential components of these products are ceramics with specific magnetic, piezoelectric, dielectric and electrical properties as listed in Table 5.

Table 5. Applications of Ceramics in Electronics.

Type	Device / Part
Semiconductor	IC LED Electric watch
Dielectric	Capacitor LCD
Piezoelectric	Autofocus camera Microphone Speaker
Magnetic	Touch tone telephone High speed tape Disk recording head

Another interesting application is thin film batteries, which have been used in RFID-tags and smart cards.

Figure 11. LCD is made up of several dielectric layers.

There is a stereotypical view that metals are good electrical conductors and ceramics are good electrical insulators. However, some ceramics can be excellent electrical conductors and even superconductors – a material that has zero electrical resistance at sufficiently low temperatures. In the late 1980s, a series of ceramic composites were identified as superconductors at temperatures between 90K and 120K. They are the best option for electrical power transport, communications, experimental motors, special antennas, microwave devices and magnetic shielding.

5. Ceramics in Medical Treatment

Bio-ceramics have been developed very rapidly over the past few decades. Ceramic applications in medical treatment are divided into three categories: diagnosis, therapy and replacement, which are described below:

5.1. Diagnoses

Millions of lives have been saved in the last century using diagnostic devices such as CT scanners, X-ray radiology and ultrasound machines. They are critical parts of bone and tissue diagnostic systems. Ceramics are essential elements of the X-ray beam and the detectors. The quality of the digital image is dependent upon both the quality of the beam and the sensitivity of the detectors.

Ultrasound imaging systems are based on the use of piezoelectric ceramic transducers. The transducer vibrates at a very high frequency as it is moved over the surface of the body, and as the waves penetrate into the body, they are reflected and stimulated to show an image of the tissue on a computer screen.

5.2. Therapy

Modern therapy has been called "a major breakthrough" as it has reduced risk, surgery time and recovery time. Ceramics have enabled many important advances in this field. The endoscope allows major surgery, such as gall bladder removal, to be conducted with several small incisions rather than having to cut the body completely open.

Another example is arthroscopic knee surgery that has relieved pain for thousands of people and helped them to do ordinary and even extraordinary activities such as competing in professional athletics.

Many polyps and tumors can be removed with a tool built into the endoscope consisting of a tiny ceramic rod tipped with a coil of metal and connected to electrical wiring. This system is capable of detecting and burning off a polyp by heating up the high resistance coil.

Other applications in surgery include tools for sawing bones and drilling teeth and also lasers for eye surgery.

5.3. Replacement

Biocompatible structural ceramics with unique mechanical and chemical properties have found applications in orthopedic (hip and knee) and dental implants, as well as in general repair pieces. There are some ceramics that are relatively inert and have a minimal effect on our body defenses or can stimulate bone and tissue growth, therefore allowing them to be used as proper replacements. Now, ceramics are standard materials used for replacements, dentures and restoration techniques.

Summary

In this article, the major applications of ceramics – the most abandoned solid materials on the surface of earth – were briefly described. Readers should come away having gained a better understanding of ceramics and their diverse ways of contributing to our modern lifestyle from an engineering point of view. Hopefully this article will seed innovative engineering ideas in material design and applications as well as production of the new generation of materials.