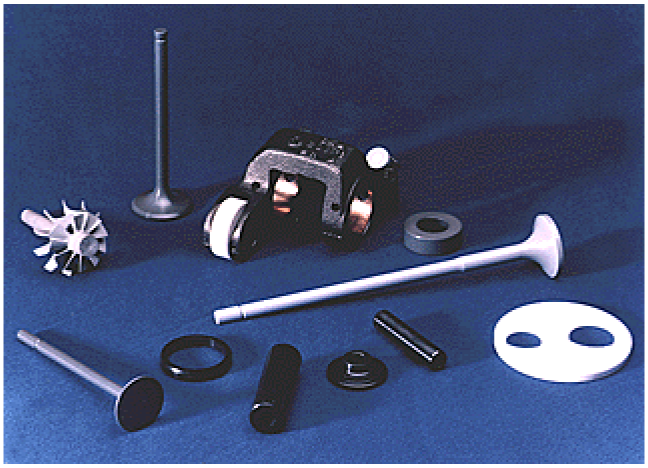
Ceramics

Introduction to Ceramics



Ceramics are inorganic non-metallic materials. Metal oxides (Al2O3, FeO, etc.) are common examples of ceramics, but other compounds such as carbides and nitrides are also included. Porcelain, glass, bricks and refractory materials are some examples of traditional ceramics. In the last 30 years, advances in material science have transformed formerly brittle ceramics into materials tough enough to withstand engine environments. Ceramics are used in a variety of applications including window glass, implantable teeth, brick, ceramic bones, nuclear fuel, tennis racquets, solid-state electronic devices, engine components, cutting tools, valves, bearings, and chemical-processing equipment.

The properties for which ceramics are most often selected include:

- High-temperature resistance (High melting temperatures.)
- High electrical resistivity (Although some ceramics are superconductors.)
- Broad range of thermal conductivity (Some ceramics are excellent insulators)
- High hardness (Many ceramics are brittle.)
- Good chemical and corrosion resistance.
- Low cost of raw materials and fabrication for some ceramics.
- Good appearance control through surface treatments, colorization, etc.

Ceramics are generally more brittle than metals and can have similar stiffness (modulus of elasticity) and similar strength, particularly in compression. But in a tensile test they are likely to fail at a much lower applied stress. This is because the surfaces of ceramics nearly always contain minute cracks ("Griffith cracks"), which magnify the applied stress.

Since ceramics often have very high wear-resistance and hardness, most ceramic parts are formed as near net shape as possible. Ceramics are most often produced by compacting powders into a body which is then sintered at high temperatures. During sintering the body shrinks, the grains bond together and a solid material is produced. Other ceramic forming processes include: Dry Pressing, Isostatic Pressing, Roll Compaction, Continuous Tape Casting, Slip Casting, Extrusion, Injection Molding, Pre-Sinter Machining, Hot-Pressing, Hot Isostatic Pressing, Grinding, Lapping and Polishing.

Ceramics are generally separated into the following categories.

1. **Metallic Oxides**
2. **Glass Ceramics**
3. **Nitrides and Carbides**
4. **Glass**
5. **Carbon and Graphite**
6. **Porcelain**
7. **Ceramic Fibers**

Metallic Oxide

1. Alumina

- Abundant and easily fabricated.
- Good strength and hardness.
- Wear and Temperature Resistant.
- Good electrical insulators.
- Low dielectric loss

2. Beryllium Oxides

- Exceptionally high thermal conductivities (for ceramics) at low to moderate temperatures.

3. Zirconia

- Extreme inertness to most metals.
- Good toughness and strength.

Glass Ceramics

Glass-Ceramics

- Low, medium or high thermal expansion depending on composition type.
- Good electrical insulators.
- Transparent
- One can be machined with steel tools.

Nitrides and Carbides

1. Silicon Nitrides

- Silicon Nitrides
- Resistant to high temperatures, to thermal stress and shock.
- High strength and oxidation resistant.
- Good electrical insulators.

2. Boron Carbide

- High hardness and low density.
- Best abrasion resistance of any ceramic.
- Low strength at high temperatures.

3. Silicon Carbides

- Low electrical resistivity.
- High strength and resistance to chemical attack, high temperature and thermal stress.

4. Tungsten Carbides

- Used for tool tips.
- Excellent hardness and mechanical strength.
- Good thermal conductivity.
- Good wear and abrasion resistance

Glass

Glasses (Oxide (silica), Silicates, Phosphates, Borosilicates)

- Good resistance to thermal shock.
- Large range of special optical characteristics.
- Transperent.
- Low thermal expansion and high dielectric strength.
- Good chemical resistance

Carbon and Graphite

1. Carbons and Graphites

- Poor strength except when produced as fibre.
- Good electrical and thermal conductivity
- Creep resistant at high temperatures in non-oxidizing conditions.
- Self-lubricating.
- Good refractoriness and thermal shock resistance.
- Low density and chemically inert

2. Carbon/Carbon Composites

- High strength and low coefficient of thermal expansion at temperatures above 2000C.
- Excellent thermal shock resistance.
- Superior toughness, excellent thermal and electrical conductivity
- Resistance to corrosion and abrasion.
- High cost.

Porcelain

- Good chemical and thermal resistance.
- High density, strength, resistivity and dielectric strength
- Good thermal shock, wear and hot strength.
- Chemically inert.

Ceramic Fibers

- Oxides spun to fiber and bulked to felt.
- Used for high temperature insulation including former applications of asbestos

Definition

The word ceramic, derives its name from the Greek ***keramos***, meaning "pottery", which in turn is derived from an older Sanskrit root, meaning "to burn". The Greeks used the term to mean "burnt stuff" or "burned earth". Thus the word was used to refer to a product obtained through the action of fire upon earthy materials.

Ceramics make up one of three large classes of solid materials. The other material classes include metals and polymers. The combination of two or more of these materials together to produce a new material whose properties would not be attainable by conventional means is called a composite. Examples of composites include steel reinforced concrete, steel belted tyres, glass or carbon fibre - reinforced plastics (so called fibre-glass resins) used for boats, tennis rackets, skis, and racing bikes.

Ceramics can be defined as inorganic, non-metallic materials that are typically produced using clays and other minerals from the earth or chemically processed powders. Ceramics are typically crystalline in nature and are compounds formed between metallic and non-metallic elements such as aluminium and oxygen (alumina- Al_2O_3), silicon and nitrogen (silicon nitride- Si_3N_4) and silicon and carbon (silicon carbide-SiC). Glass is often considered a subset of ceramics. Glass is somewhat different than ceramics in that it is amorphous, or has no long range crystalline order.

Most people, when they hear the word ceramics, think of art, dinnerware, pottery, tiles, brick and toilets. The above mentioned products are commonly referred to as traditional or silicate-based ceramics. While these traditional products have been, and continue to be, important to society, a new class of ceramics has emerged that most people are unaware of. These advanced or technical ceramics are being used for applications such as space shuttle tile, engine components, artificial bones and teeth, computers and other electronic components, and cutting tools, just to name a few.

History and Impact on Society

Archaeologists have uncovered human-made ceramics that date back to at least 24,000 BC. These ceramics were found in what was formerly Czechoslovakia and were in the form of animal and human figurines, slabs, and balls. These ceramics were made of animal fat and bone mixed with bone ash and a fine clay-like material. After forming, the ceramics were fired at temperatures between 500-800°C in domed and horseshoe shaped kilns partially dug into the ground with loess walls. While it is not clear what these ceramics were used for, it is not thought to have been a utilitarian one.

The first use of functional pottery vessels is thought to be in 9,000 BC. These vessels were most likely used to hold and store grain and other foods. Ancient glass manufacture is thought to be closely related to pottery making, which flourished in Upper Egypt about 8,000 BC. While firing pottery, the presence of calcium oxide (CaO) containing sand combined with soda and the overheating of the pottery kiln may have resulted in a coloured glaze on the ceramic pot. It is thought that it was not until 1,500 BC that glass was produced independently of ceramics and fashioned into separate items.

Since these ancient times, the technology and applications of ceramics (including glass) has steadily increased. We often take for granted the major role that ceramics have played in the progress of humankind. Lets us look at a few examples of the importance of ceramics in our lives.

Modern iron and steel and non-ferrous metal production would not be possible without the use of sophisticated refractory materials that are used to line high temperature furnaces, troughs and ladles. Metals make automobiles, machinery, planes, buildings, and thousands of other useful things possible. Refractory ceramics are enabling materials for other industries as well. The chemical, petroleum, energy conversion, glass and other ceramic industries all rely on refractory materials.

Much of the construction industry depends on the use of ceramic materials. This includes brick, cement, tile, and glass. Cement is used to make concrete which in turn is used for roadways, dams, buildings, and bridges. Uses of glass in the construction industry include various types of windows, glass block, and fibres for use in insulation, ceiling panels and roofing tiles. Brick is used for homes and commercial buildings because of its strength, durability, and beauty. Brick is the only building product that will not burn, melt, dent, peel, warp, rot, rust or be eaten by termites. Tile is used in applications such as flooring, walls, countertops, and fireplaces. Tile is also a very durable and hygienic construction product that adds beauty to any application.

An important invention that changed the lives of millions of people was the incandescent light bulb. This important invention by Thomas Edison in 1879 would not be possible without the use of glass. Glass’s properties of hardness, transparency, and its ability to withstand high temperatures and hold a vacuum at the same time made the light bulb a reality. The evolution of lighting technology since this time has been characterized by the invention of increasingly brighter and more efficient light sources. By the middle of twentieth century, methods of lighting seemed well established - with filament and fluorescent lamps for interiors, neon lamps for exterior advertising and signs, and sodium discharge lamps for streets. Since this time, light-emitting diode (LED) technology has been developed with applications in watches, instrument panel indicators, telecommunications (optical fibre networks), data storage (CD technology), and document production (laser printers).

The electronic industry would not exist without ceramics. Ceramics can be excellent insulators, semiconductors, superconductors, and magnets. It's hard to imagine not having mobile phones, computers, television, and other consumer electronic products. Ceramic spark plugs, which are electrical insulators, have had a large impact on society. They were first invented in 1860 to ignite fuel for internal combustion engines and are still being used for this purpose today.

Applications include automobiles, boat engines, lawnmowers, and the like. High voltage insulators make it possible to safely carry electricity to houses and businesses.

Fibre optic fibres have provided a technological breakthrough in the area of telecommunications.

Information that was once carried electrically through hundreds of copper wires is now being carried through high-quality transparent silica (glass) fibres. Using this technology has increased the speed and volume of information that can be carried by orders of magnitude over that which is possible using copper cable. The reliability of the transmitted information is also greatly improved with fibre optic fibres. In addition to these benefits, the negative effects of copper mining on the environment are reduced with the use of silica fibres.

Ceramics play an important role in addressing various environmental needs. Ceramics help decrease pollution, capture toxic materials and encapsulate nuclear waste. Today's catalytic converters in vehicles are made of cellular ceramics and help convert noxious hydrocarbons and carbon monoxide gases into non-toxic carbon dioxide and water. Advanced ceramic components are starting to be used in diesel and automotive engines. Ceramics' light weight and high-temperature and wear resistant properties, results in more efficient combustion and significant fuel savings. Ceramics are also used in oil spill containment booms that corral oil so it can be towed away from ships, harbours, or offshore oil drilling rigs before being burned off safely.

Reusable, lightweight ceramic tile make NASA's space shuttle program possible. These thermal barrier tile protect the astronauts and the shuttle's aluminium frame from the extreme temperatures (up to approximately 1600°C) encountered upon re-entry into the earth's atmosphere. While the list of examples could go on and on, I think you can get the picture of how important ceramics has been, and will continue to be to humankind.

Advanced Ceramics

Advanced ceramics, also known as engineering or technical ceramics, refer to materials which exhibit superior mechanical properties, corrosion/oxidation resistance, and thermal, electrical, optical or magnetic properties.

Advanced ceramics are generally broken down into the following segments:

- structural ceramics,
- electrical and electronic ceramics,
- ceramics coatings, and
- chemical processing & environmental ceramics

Structural ceramics include applications such as industrial wear parts, bioceramics, cutting tools, and engine components. Electronic ceramics, which has the largest share of the advanced ceramic market includes capacitors, insulators, substrates, integrated circuits packages, piezoelectrics, magnets and superconductors. Ceramic coatings find application in engine components, cutting tools, and industrial wear parts. The applications under chemical processing and environmental ceramics include filters, membranes, catalysts, and catalyst supports.

The beginning of the advanced ceramics era has been said to have started approximately 50 years ago with the expanding use of chemically prepared powders.

For example, the Bayer process for the production of alumina powders initially grew from spark plug production. While these powders would be considered relatively low grade by today's standards, they were more pure and offered more control over the composition, microstructure, and crystal structure over minerals-based ceramics.

Today, the market for advanced ceramics is large and growing as they continue to replace more traditional materials in many applications while providing the only material solution in other applications. In many cases, ceramics are used with other materials to make up only part of an overall system. This is especially true in the electronics field.

According to The Freedonia Group Inc., the estimated world demand for advanced ceramics for the year 2000 is over $25 billion. This is an annual growth rate of 7.2% from the 1994 market of $16.7 billion. The Business Communications Co. Inc. (BCC) (Norwalk, Conn.) estimated the total value of the U.S. advanced ceramics component market for 1996 to be $6.3 billion. This is expected to increase to $9.2 billion by 2001 with a growth rate of 7.9%. BCC estimates that the electronic segment holds 66% of this market in 1996, with chemical processing & environmental ceramics at 20%, ceramic coatings at 8%, and advanced structural ceramics at 6%.

Ceramic powders are a necessary ingredient for most advanced ceramics. These include oxides, nitrides, carbides, and borides. The U.S. ceramic powder industry consists of approximately 40 producers and suppliers. Over twenty of these are suppliers of oxide powders. The U.S. market for advanced ceramic powders was valued at $648 million in 1994, according to BCC. By 2000, the market is expected to reach almost $1.1 billion. The market for nano-sized ceramic powders (including experimental, developmental, and prototype quantities) was less than $500,000 in 1994.

The future success of both the traditional advanced ceramic markets and developing non-traditional U.S. markets depends on factors such as increasing the quality and reliability of the finished products, improving the cost/benefit ratio of ceramic components, increasing applied research and development, increased supply of domestic, high-quality raw materials, and overcoming designer and end-user reluctance to use ceramics.

Improvements are occurring however, in areas such as powder processing, shape forming, non-destructive evaluation, machining, standardization and the development of a materials property database. In order to reduce manufacturing expenses, researchers are looking toward innovative, "near-net-shape" forming methods such as gelcasting, freezecasting, injection moulding, and rapid prototyping. These methods will reduce machining cost, which can be as much as 50% of the total manufacturing cost.

Progress will continue in the are of ceramic matrix composites (CMCs). One source sites the CMCs market growing at an annual rate of 14.5% to $400 million in the year 2000. CMCs are attracting increasing attention due to the broader diversity of, and improvements in, the properties they can often provide. The major push for CMCs has been driven by the potential applications in heat engines. CMCs in this application would provide greater fuel efficiency and reduced exhaust emissions.

NASA Lewis Research Centre and the two leading aircraft engine manufacturers, General Electric Aircraft Engines (GE) and Pratt & Whitney (P&W), are developing the technology for an environmentally safe propulsion system for a High Speed Civil Transport (HSCT). This type of supersonic airliner would transport more than 300 passengers in a three-class arrangement over 5,000 nautical miles at Mach 2.4 cruise. Because of its is sheer speed, a trip from Los Angeles to Tokyo, for example, would take just over 4 hours instead of 10 hours on subsonic aeroplanes. CMCs are the current material of choice for the combustor and acoustic liners for the proposed low NOx propulsion system.

What the Future May Hold for Advanced Ceramics

Imagine a car that has a fuel efficiency of 80 mpg, a range of 500 miles, emits no pollutants, and runs on many different fuels such as gasoline, diesel, kerosene, or alcohol. Chrysler Corp. hopes to have a family car with this technology available by 2010, and the cost will be the same as that of a standard petrol-engined car. This type of vehicle is made possible by fuel cell technology. Fuel cells work like batteries, but are better because they won't run down. These fuels cell would not be possible however if not for the use of ceramic materials. Examples of the ceramic materials that might be used include a yttrium oxide stabilized zirconium dioxide (YSZ) electrolyte, a lanthanum manganite cathode, and nickel cermet anode, and lanthanum chromite interconnector.

Another interesting area of research are the so called "smart" ceramics. These ceramic systems provide the necessary life functions of sensing, actuating, control, and intelligence. Some examples of smart systems include: medical systems that treat diabetes with blood sugar sensors and insulin-delivery pumps; water purification systems that sense and remove noxious pollutants; and houses that have electrochromic windows that control the flow of heat and light in response to weather changes and human activity. A major ski manufacturer now offers a "smart" ski that makes use of ceramics piezoelectric properties. When skiing at high speeds, skis tend to vibrate, lessening the contact area between the ski edge and snow surface. This results in reduced stability and control and decreases the skiers speed. The piezoceramic embedded in the ski converts the unwanted vibrations into electrical energy, thus keeping the skis on the snow.

Ceramic, or high-temperature superconductors are now being developed for commercial applications and appear to be a sure bet to enter more commercial markets over the next few years. Electric wires made from these materials carry electricity with little or no resistance losses. In the utility power industry, these wires can be used to produce super efficient coils, magnets, conductors, and machines and power components. The use of high temperature superconductors in these applications could save billions of dollars in energy costs and help the environment at the same time.

Circuits using high-temperature superconducting materials could boost the processing speed of computers, reduce resistance losses in motor controllers, and enhance the ability of magnetic resonance imaging (MRI) scanners and other non-destructive examination devices to sense minute changes in magnetic fields. Even the processes of getting to work and travelling between major cities could be changed by high-temperature superconductors.

Research is being conducted to use this material for magnetic levitation (maglev) trains. These trains would travel efficiently and at high speeds by floating on a frictionless magnetic cushion. Prototype maglev trains already operate in Japan and Germany and researchers are now looking for a new generation of ceramic superconducting magnets for this application.

Another growth area for advanced ceramics is in the medical field. Surgeons are already using bioceramic materials for repair and replacement of human hips, knees, shoulders, elbows, fingers, eyes and wrists. Ceramics are also being used to replace diseased heart valves. Dentists are using ceramics for tooth replacement implants and for brackets for braces. High-temperature superconductors are now finding application in magnetic resonance imaging (MRI) machines.