Ceramics

101 Material Report

Material ConneXion®
A SANDOW Company

What you need to know

While historically, ceramics have been associated with pottery and tiles, recent scientific advances have brought about a new generation of ceramics for high demand applications like engines and surgical implants.

In this report, Material ConneXion will break down everything you need to know about ceramics: what they are, how they are made, and how they can be manipulated to achieve the properties necessary for your products.

01
What is a Ceramic?

Ceramic materials are inorganic, non-metallic, often crystalline oxides, nitrides or carbides. Some elements, such as carbon or silicon, are sometimes classed as ceramics. Ceramic materials are brittle, hard, strong in compression yet weak in shearing and tension, and typically can withstand high temperatures.

02
Traditional vs Advanced

Traditional ceramics, formed from naturally occurring materials, are the types of ceramics we are most familiar with. We often encounter traditional ceramics in pottery, tiles, dinnerware, sanitaryware, and bricks; however, they are also often used to create furnaces or as abrasives. Advanced ceramics are set apart by highly tunable properties such as magnetic capabilities, high electrical conductivity, or biocompatibility. These advanced properties are achievable by specially preparing, and often synthetically producing, highly pure raw materials.

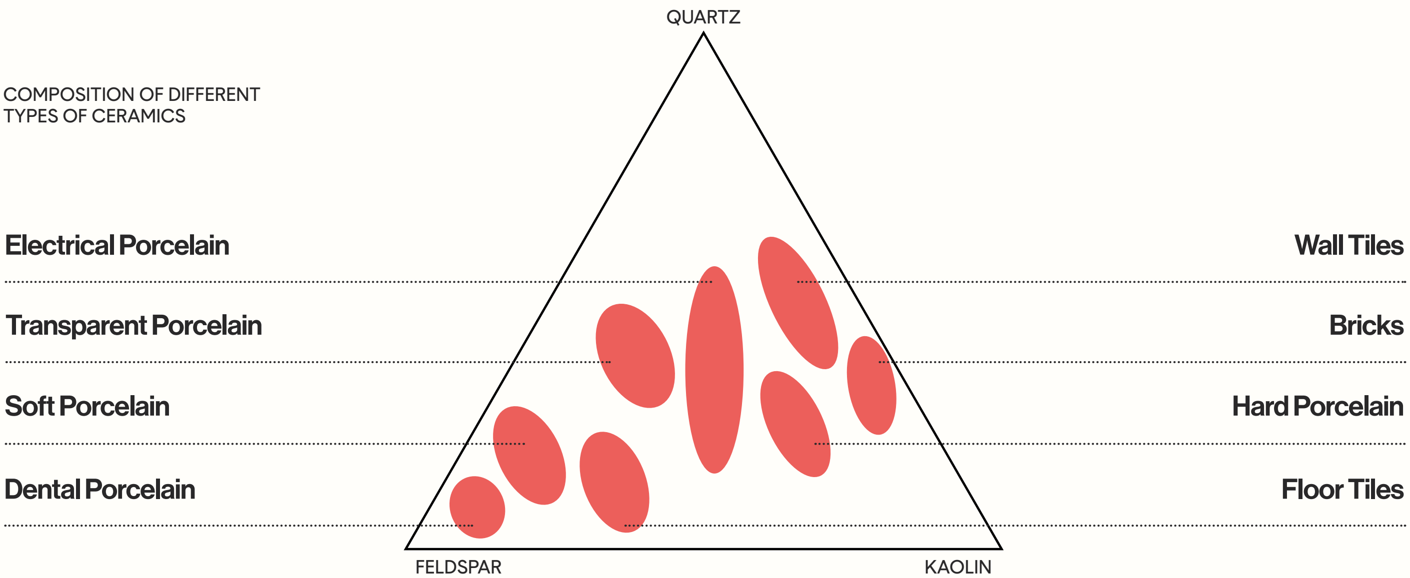
03
Properties

In general, ceramics are bad conductors of electricity and heat, have high melting points, and display strong chemical and corrosion resistance. While ceramics are normally very brittle, they typically have very high compressive strength (pressing forces). There are many notable exceptions to these properties, especially within advanced ceramics, which allows them to be used in unexpected applications. The final section of this report will guide you through ceramic properties and explain what factors can be controlled to adjust them.

Traditional Raw Material

Traditional ceramics are comprised of three core components: clay, fluxes (which promote the firing by lowering the melting point of the clay), and fillers. The choice for each component and the amount used will affect properties of the ceramic material, such as shrinking rate, texture, strength and color.

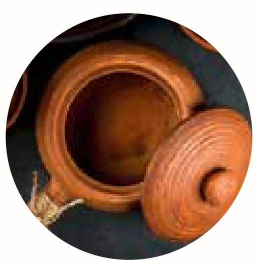
COMPOSITION OF DIFFERENT TYPES OF CERAMICS



Quartz, feldspar and, kaolin are the major constituents in all traditional ceramics. Quartz is the only one of the three that has a simple, recognizable chemistry (SiO_2), and is the basis for almost all glass. Feldspar is the name given to a group of minerals containing alumina ($Al2O_3$) and silica (SiO_2), including aluminum silicates of soda, potassium, or lime. It is the single most abundant mineral group on earth. Kaolin is a clay mineral $Al_2Si_2O_5(OH)_4$, sometimes known as china clay, and is typically white, though the presence of iron oxide can make it pink.

Traditional Ceramic Examples

Porcelain Porcelain, commonly referred to as china, has high kaolin clay content, is fired at high temperatures (1200 °C–1400 °C), and exhibits toughness and low permeability even without glazing.



Earthenware Earthenware is fired at relatively low temperatures (typically less than 1200 °C). It is porous, opaque, and easily scratched. A common example of earthenware is terra cotta, which has a distinct brownish-orange color due to high iron content.

Stoneware Stoneware is formed using stoneware clay and is fired at temperatures similar to porcelain. It is opaque like earthenware but is nonporous.

Advanced, aka 'Technical,' Raw Material

Advanced ceramics can be classified as oxides, non-oxides, or composites based on the chosen raw materials. Just as choosing the clays, fillers, and fluxes allows the user to fine-tune traditional ceramics, the choice of advanced raw materials will give specific properties to the ceramic product.

Oxides

Examples of oxides used in advanced ceramics are aluminum oxides (associated with high strength and hardness, temperature stability, and high wear resistance), magnesium oxides (associated with good electrical insulation and thermal conductivity properties), silicon oxides (known for extremely high thermal shock resistance), and zirconium oxides (highest mechanical strength and resistance to fracture of all advanced ceramics).

Non-Oxides

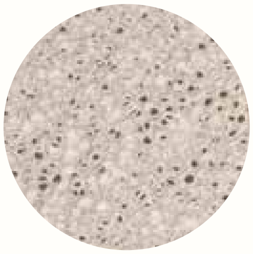
Examples of non-oxide ceramics include aluminum titanates (known for low thermal conductivity and low coefficient of thermal expansion), lead zirconate titanates (associated with piezoelectric properties), aluminum nitride (known for very high thermal conductivity), and cubic boron nitrides (almost as hard as diamond and used in cutting and boring tools).

Composites

Ceramic composites are a category of advanced ceramics that are either reinforced with metals, polymers, or natural materials, or are comprised of both oxides and non-oxides.

Advanced Ceramic Application Examples

The applications of advanced ceramics are seemingly endless. Advanced ceramics have been used as surgical implants, armor for both vehicles and soldiers, and in the nuclear energy industry.



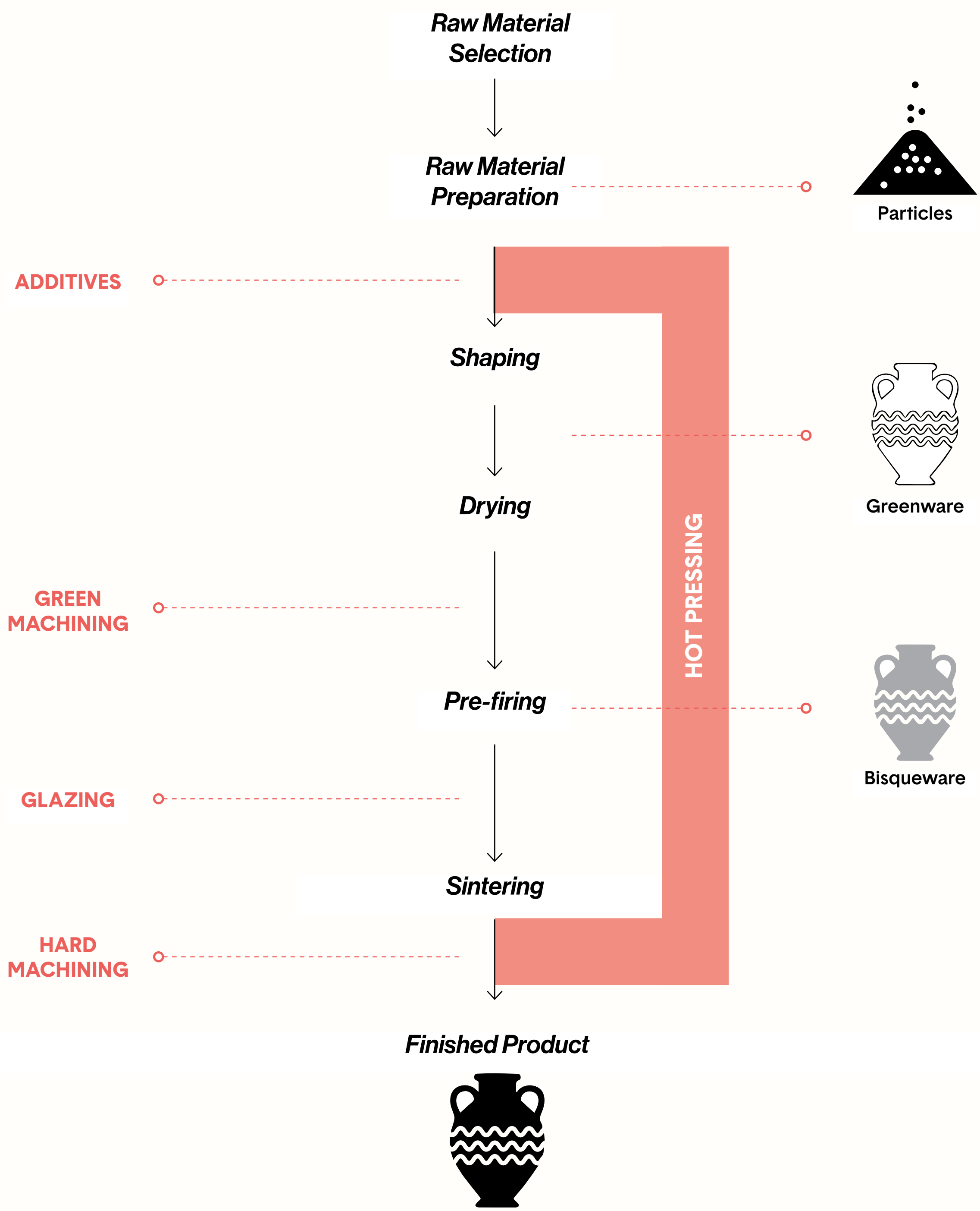
Bioceramics Bioceramics are biocompatible ceramics commonly used for dental and bone implants. Ceramics are advantageous over metals for certain medical applications due to their light weight and high corrosion resistance.

Ceramic Armor Ceramics such as boron carbide can be used for ballistic vests and vehicle armor. High strength and low weight are important for such applications to provide protection and allow a free range of motion.

Nuclear Ceramics Advanced ceramics are often used in the nuclear industry for fuel pellets and nuclear waste containment. Due to the demanding nature of the nuclear industry, high temperature and high corrosion resistance is extremely important for these ceramics.

Ceramic Lifecycle

The way a ceramic product is processed will help to determine which properties the final product will possess. Below is the lifecycle of a typical ceramic product. For certain products, steps may be combined, repeated, or even skipped.



Lifecycle Glossary

Raw Material Selection
The choice of raw material provides different properties such as color, thermal conductivity, or compressive strength; many of these properties can be tuned through other steps in ceramic processing. In general, raw materials for traditional ceramics are cheaper and more readily available than those for advanced ceramics.

Raw Material Preparation
The starting point for any ceramic product is a powder. Raw material preparation helps determine particle size, particle shape, and purity.

Additives
Additives include sintering aids, plasticizers, and binders.

Shaping
There are three main methods of shaping ceramic materials: pressing (including dry pressing, hot pressing, wet pressing, isostatic pressing), plastic forming (including extrusion, injection molding, hand molding), and casting (including slip casting, tape casting). The method choice depends on the product requirements (size, geometry), raw material, and budget.

Drying
Drying is used to carefully remove moisture prior to sintering; however, it often causes shrinkage. Drying time, temperature, pressure, and atmospheric composition influence the final properties of the product.

Green Machining
Green machining involves techniques such as cutting, stamping, and sawing after drying and prior to removing organic additives and sintering. Green machining is used to add complex designs and shapes and to help the product meet dimensional requirements.

Pre-Firing
Additional heating prior to full sintering to carefully burn out remaining plasticizers, binders, and other organic additives. Control of temperature, pressure, atmospheric composition, and time is important for determining final product properties.

Glazes
Glazes are thin, vitreous coatings that can be applied to ceramics to provide attributes such as smoothness, color, increased mechanical strength, and increased chemical inertness. Glazes can be applied through a variety of methods such as dipping, pouring, spraying, and painting.

Sintering
Fine particles are bonded together using heat to increase the strength and density of the ceramics, although this can also cause shrinkage. The temperature, pressure, atmospheric composition, and time help determine final product properties.

Hard Machining
The final, sintered ceramic product may require additional finishing for surface modification and dimensional conformity. These changes can be made through hard machining techniques such as laser cutting, abrasive cutting, grinding, and polishing.

Hot (Isostatic) Pressing
Hot (isostatic) pressing is an example of a processing method that does not fall into the conventional lifecycle because it combines molding and sintering into one process step.

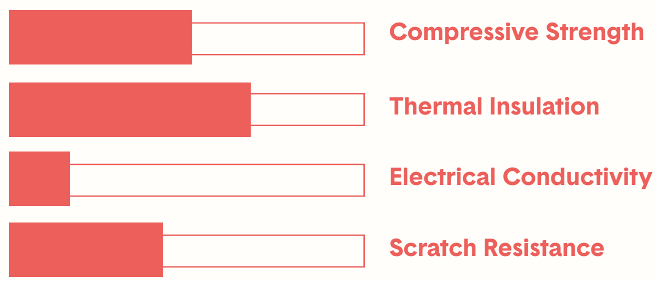
A Property Approach

Traditional and advanced ceramics differ on two accounts, namely raw materials and processing techniques. These factors yield different properties in the finished materials. This section distinguishes the difference between traditional and advanced ceramics. Ceramics have not been compared to other materials such as metals or polymers, but have been graded relative to each other.

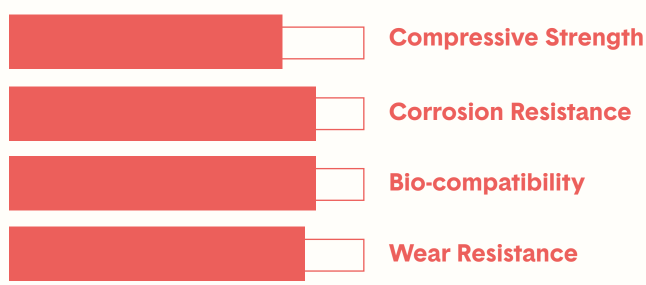
Traditional and advanced ceramic applications

What are the properties that make ceramics perfect for the application?

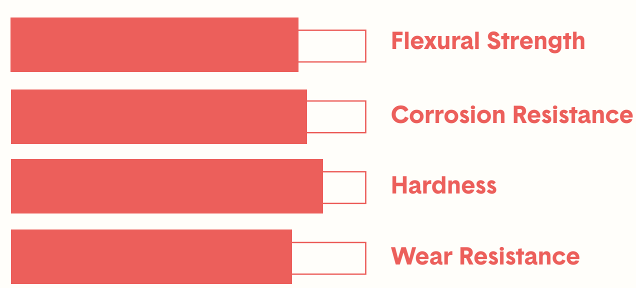
Traditional Ceramic: Coffee Mug
A coffee mug is a traditional ceramic, and has relatively few requirements as compared with the full range of properties available in ceramics. For this application, cost and easy cleaning are the main drivers in selecting a material.



Advanced Ceramic: Hip Joint
Advanced ceramics can be found in a range of products, from spark plugs to nuclear waste disposal, to hip joint replacements. Ceramics can enhance tissue growth and dissolve in the body. Such materials have high bio-compatibility, high corrosion resistance, and high wear resistance.



Advanced Ceramic: Kitchen Knife
This consumer application for yttria-stabilized zirconia defies the widely-held conception that ceramics are limited in application due to their perceived fragility. The thin, flexible blade possesses both chemical and fracture resistance, without the need to sharpen.



A Property Approach

We have seen how processing and raw materials can induce a variety of properties in ceramics. Primary determinants of such properties are factors such as raw material particle size and purity, processing-induced grain size, porosity, and additives. This section of our property approach to ceramics addresses the array of property types that we can manipulate within ceramics.

Physical

Melting Point From 600 °C to 4000 °C, higher than all polymers. The higher melting point ceramics are well above metals as well.

Density Most ceramics fall within a medium density range between polymers and metals; 2 gcm2–6 gcm2.

Thermal

Conductivity Most ceramics are thermally insulating.

Expansion/Stability Ceramics are very stable with regard to changes in temperature, some having zero expansion.

Electrical

Conductivity Most ceramics are electrically insulating, though some have dielectric properties.

Piezoelectricity Some ceramics such as barium titaniate and lead zirconate titanate are able to generate an electric charge when stressed mechanically.

Optical

Color Much of the color in ceramics is inherent, from white to black, but can also be changed in some with doping.

Transparency The transparency of ceramics is of great value to the aerospace industry. Transparency can be engineered in some ceramics by creating single crystals with high optical transmission.

Luminescence This occurs in some glass and glass ceramic materials when electrically charged.

Mechanical

Compressive Strength This is a hallmark of ceramics and offers a great basis for many applications.

Flexural Strength Very limited, though this can be improved using dopants.

Abrasion/Crack Propagation Most ceramics are highly abrasion resistant, though the brittle failure of ceramics is a limitation to their wider use.

Chemical

Chemical Stability Of all materials, ceramics offer the greatest chemical stability and resistance.

Magnetic

Magnetic Ceramic magnets are a cheaper alternative to metal magnets, and are typically made from strontium carbonate. Ferrite represents more than 75 percent of world magnet consumption (by weight). It is the first choice for most types of DC motors, magnetic separators, magnetic resonance imaging, and automotive sensors.

Non-Magnetic Most ceramics are non-magnetic and, as such, are used as chip capacitors.

A Note on Color

Traditional Ceramics

Traditional ceramics are the color of the minerals from which they are created; translucent white (porcelain), cream and gray (stoneware), and terracotta and brick (terracotta, earthenware). Color is typically added through the use of glazes that create a hard, non-porous surface that has the structure of glass. Pigments are added to the glaze that can withstand the high firing temperatures, and most colors and metallic color effects are possible.

Advanced Ceramics

Due to the purity of the raw materials, there tend to be specific colors for each ceramic type—white for alumina, zirconia, and boron nitride, gray for silicon carbide and silicon nitride. Some degree of coloration is possible through pigmentation or impurities, though this can affect performance and thus tends to be used for decorative applications such as watches and other consumer products. Color can also be achieved by 'alloying' with metals such as copper or titanium, creating materials called 'cermets' (ceramic and metal composites); however, these lose some of the temperature resistance, corrosion, and chemical resistance of pure ceramics.

Transparency

Some advanced ceramics can be manufactured to be transparent to visible light. These include alumina (Al_2O_3), some spinels such as $MgAl_2O_4$, and yttria (Y_2O_3). They are rendered transparent when created as a single crystal, a process that occurs naturally (sapphires and rubies are single crystal alumina) or can be grown slowly from a 'seed' in a crucible at high temperatures. These crystals can then be cut and polished into lenses for high-end optics and aerospace applications, and also used as screens for consumer electronics and point of sale screens.

Ceramics Today & in the Future

Ceramics Today

Ceramics today are not limited to the traditional porcelain or cookware that typically come to mind. To meet high-demand applications, advanced ceramics are made with synthesized, highly pure, raw materials. Processing steps for traditional and advanced ceramics not only help determine physical appearance, but they also allow for a variety of properties to be tweaked per application. Most often, changes in properties are induced due to processing and raw material considerations. The ability to carefully tweak factors such as grain size and porosity allows ceramics to meet a wide range of physical, mechanical, thermal, electrical, chemical, optical, and magnetic demands. Because of this versatility, ceramics can find application in almost all industries.

Future Thoughts

The future holds significant promise for advanced ceramics as processing techniques and raw materials are being researched.

Major developments are taking place in fields such as health, electronic device miniaturization, and energy.

In terms of processing, additive manufacturing with ceramics has been gaining some momentum. However, introducing property variations with such processes has been limited.

A lot of work is being done to increase the toughness of ceramics (reducing brittle fracture). This is through process and chemistry control, but also through composite production, such as layering ceramics with plastics (mimicking nacre) and creating metal matrix composites where the hardness of the ceramic is offset by a more malleable metal matrix.

References

Ceramic Processing
2nd Edition
by Mohamed N. Rahaman

Fundamentals of Ceramics
(Series in Materials Science and Engineering)
by Michel Barsoum

Materiology
by Daniel Kula

Learning Guide

Discussion Questions

Which aspect of the report surprised you the most?

What are some characteristics of advanced ceramics?

What are some of the types of traditional ceramics that you interact with in your daily life?

What are some of the limitations of technical ceramics?

How do you achieve color with a traditional ceramic? Are there any limitations in color for these materials?

What are some current or potential applications for advanced ceramics?

Short Answer Questions

What is the difference between an advanced and a traditional ceramic?

What colors are possible with advanced ceramics?

What is sintering?

Can ceramics be machined? If so, how?

What are some advanced ceramic application areas?

Name four advanced ceramic non-oxides.

What are two material types that ceramics can be combined with to create composites?

Learning Guide

Long Form Essays

Ceramics have long been of interest for use in consumer electronics. Explain why they have not been used extensively to date, but where on a phone or other handheld device there may be an opportunity to use them in the future.

Give an overview of the use of ceramics in dentistry. Explain the development of the materials and the reasons for their use. Include dental implants as well as tools.

Team Activity

You are designing a desktop object for sale at the MoMA store.

a. Choose your ceramic

b. Decide which process you would use to create the object

c. Market it based upon the unique properties of that ceramic type

Materials Relevant to this Report

O-Kera®
MC 5603-02

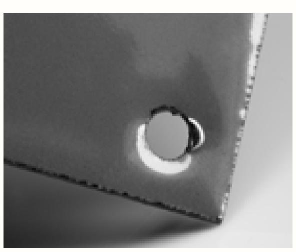
Thin, ceramic sheets have always been problematic in architecture, due to the innate brittleness of this class of material. However, this version uses fibers embedded as a mesh on the material to give toughness. Colorable, decorative, and hard as nails, the sheet offers a variation on the standard wood, metal, or glass surface.

Sinterable Paper
MC 7033-01

Incorporating ceramic powder (!) into paper as a printable sheet, and then firing the material, burns off the paper and leaves a solid, thin, sculptural ceramic part. Fold and shape the unfired material as you would regular paper, then put it in an oven to maintain the ceramic form.

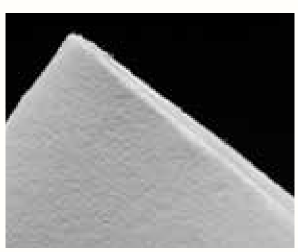
SCProbond™ N
MC 7235-01

Industrially useful ceramic that has excellent heat resistance and, because it is a combination of silicon carbide and silicon nitride, is tougher than most. A workhorse in coal fired power plants and mining.



Evolution™
MC 5438-03

Ceramic 'enamel' coatings used to protect metals that are based on boron silicate chemistry, and act as effective heat and abrasion protectors.



Ceramicpaper Typ 3000
MC 7061-01

Fibrous ceramic 'paper' that is great for heat resistant insulation. Silica and alumina are combined to form a flexible sheet that can withstand up to 1850 °C (3360 °F).