

MF9211 ADVANCED MATERIALS TECHNOLOGY

UNIT.V-NON METALLIC MATERIALS

POLYMERS & COMPOSITES

Materials

Extensive materials experience includes:

- Thermoplastic polymers
 - Hydrocarbon polymers
 - Polyethylene (PE)
 - HDPE
 - LDPE
 - Polypropylene (PP)
 - Atactic
 - Isotactic
 - Polybutadiene
 - Syndiotactic
 - Isotactic
 - Polystyrene (PS)
 - Atactic
 - Isotactic
 - Nonhydrocarbon carbon-chain polymers
 - Polyvinyl chloride (PVC)
 - Polyvinyl fluoride (PVF)
 - Polytetrafluoroethylene (PTFE)
 - Polyacrylonitrile (PAN)
 - Polyvinyl alcohol (PVA)
 - Polymethyl methacrylate (PMMA)
 - Acrylonitrile-butadiene-styrene (ABS)
 - Heterochain thermoplastics
 - Polyethylene oxide (PEO)
 - Polyoxymethylene (acetal) POM
 - Polyamide (PA)
 - Nylon 6
 - Nylon 6/6
 - Polyethylene terephthalate (PET)
 - Polybutylene terephthalate (PBT)
 - Polycarbonate (PC)
 - High temperature thermoplastics
 - Polyether ether ketone (PEEK)
 - Polyphenylene sulphide (PPS)

- Polyamide-imide (PAI)
 - Polyether sulphone (PES)
 - Polyether-imide (PEI)
 - Polysulphone (PSU)
 - Polyimide (thermoplastic) (PI)
- Thermoset polymers
 - Phenolics
 - Filled
 - Epoxies
 - Unreinforced
 - Filled
 - Aminos
 - Urea-formaldehyde (UF)
 - Melamine-formaldehyde (melamine) (MF)
 - Polyurethane (PUR)
 - Unfilled
 - Filled
 - Polyesters
 - Vinyl esters
 - Polyimides
 - Silicones
 - Urethanes
- Elastomers/rubbers
 - Natural rubber
 - Styrene-butadiene rubber
 - Acrylonitrile-butadiene rubber
 - Butyl rubber
 - Polychloroprene
 - Polyisoprene
 - Polysulphide polymer
 - Silicone
 - Polyurethane
- Polymer blends
 - Thermoplastic/thermoplastic
 - Thermoset/thermoplastic
- Composites
 - Short fibre thermoplastics
 - Glass fibre
 - Cellulose fibre
 - Carbon fibre
 - Continuous fibre thermoplastics
 - Glass fibre
 - Carbon fibre
 - Short fibre thermosets
 - Glass fibre
 - Cellulose fibre

- Carbon fibre
 - Aramid fibre
 - Ceramic fibres and whiskers
 - Continuous fibre thermosets
 - Glass fibre
 - Cellulose fibre
 - Carbon fibre
 - Aramid fibre
 - Honeycomb materials
 - Ceramics matrix composites
- Highly filled polymers
 - Friction materials
 - Bearings
 - Gaskets
- Fillers
 - Inorganic
 - Organic
 - Reinforcing
 - Plasticisers
 - Lubricants
 - Impact modifiers
 - Stabilizers
 - Low cost fillers
 - Flame retardants
- Fibres
 - Glass fibre
 - Cellulose fibre
 - Carbon fibre
 - Aramid fibre
 - Ceramic fibres and whiskers

Processes

Comprehensive process knowledge includes:

- Compression moulding
- Laminating
- Injection moulding
- Blow moulding
- Extrusion
- Pultrusion

Applications

Application experience includes:

- Automotive
 - brakes
 - clutches
 - body panels
 - motorsport
- Industrial
 - bearings
 - cable
- Aerospace
 - structures
 - fittings
- Railway
 - brakes
- Domestic products
 - electrical
- Sports and leisure
 - tennis rackets
 - golf clubs
 - bicycle wheels and frames
 - fishing line
 - skate boards
- Packaging
- Medical
 - orthodontics
 - prosthetics

Failure Mechanisms

- Additive dispersion and migration
- Polymer structure
 - Blends and single phase
- Polymer identification
- Impurity identification
- Filler identification
- Mechanical failure investigation
- Fibre/polymer bonding
- Polymer wear and transfer films

Manufacturing with polymers

2. Polymer structures

Thermosoftening polymers generally have a 'long chain' molecular structure (Figure 1) formed by the 'addition polymerisation' process which can be strengthened by cross-linking. Cross linking is achieved with the addition of another chemical to the polymer structure eg. using sulphur to vulcanise rubber.

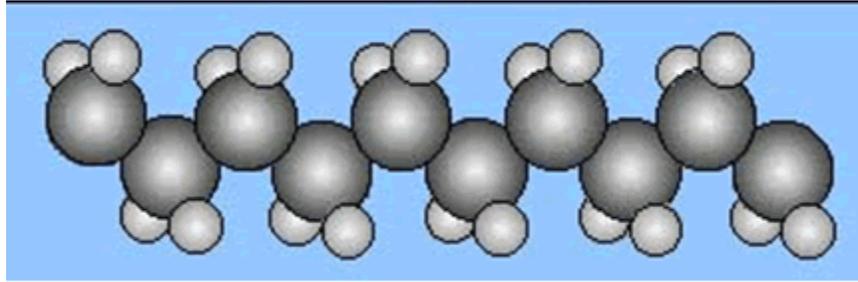


Figure 1. Part of the long chain molecular structure of Polyethylene, a simple combination of one Carbon atom with two Hydrogen atoms.

Thermosetting polymers have a network structure and are formed by the 'condensation polymerisation' process (Figure 2) which produces water as a by-product of the chemical reaction occurring during setting.

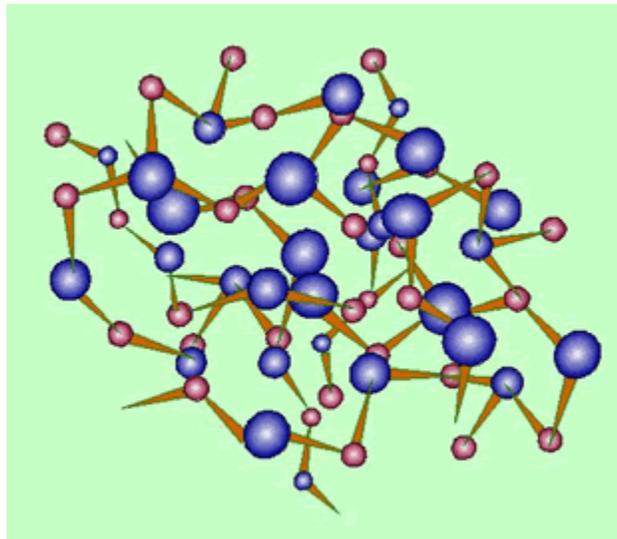


Figure 2. Part of the network structure of phenol formaldehyde (Bakelite).

These structures are extremely important as they determine the method by which components will be manufactured from the polymer.

3. Properties of Polymers

In terms of properties the thermosoftening group of polymers tend to be flexible to some degree, show reasonable impact resistance and are usually able to be re-heated and re-shaped, assuming the 'new' shape upon cooling. From an environmental point of view, these properties make thermosoftening polymers ideal for recycling.

In comparison, thermosetting polymers are rigid, often brittle and cannot be re-heated for the purpose of re-shaping. They tend to degrade or burn when heated significantly.

4. Manufacturing methods

Some of the most common industrial manufacturing processes for polymers include:

Compression moulding

Transfer moulding

Rotational moulding

Injection moulding

Blow moulding

Vacuum forming (Thermo Pressure Forming)

Extrusion

Pultrusion

Fabrication

Compression moulding is the process by which thermosetting polymers are usually formed (Figure 3).

The compression moulding process involves placing the polymer 'dough' into the die cavity. This 'dough' is carefully measured to avoid waste and minimise the amount of 'flashing' (fine, thin webs attached to the moulding) around the finished article.

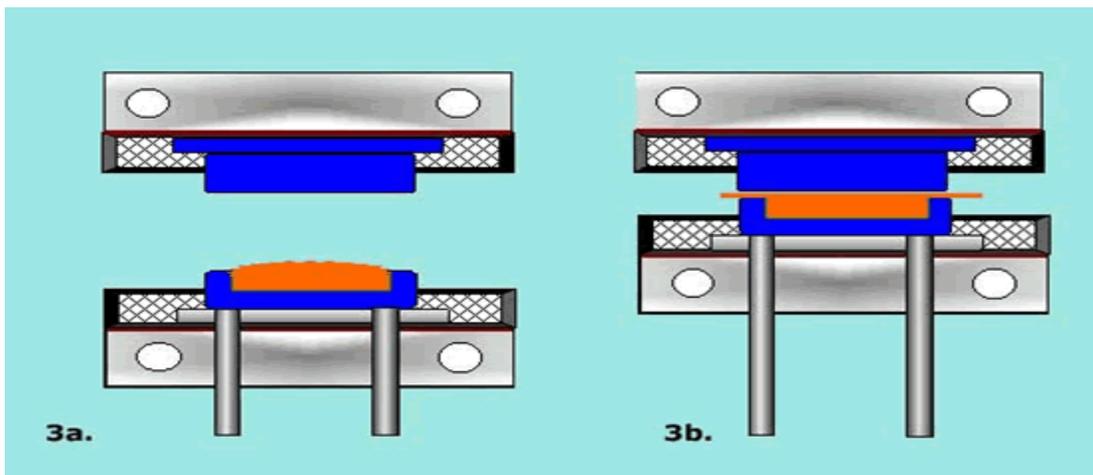


Figure 3a. With the dies apart, the prepared polymer 'dough' is placed into the cavity. Figure 3b. With the die closed, the article is formed and the small amount of flashing on each side will be removed later.

When the die is closed, heat and pressure is maintained until the condensation polymerisation process is completed.

The hot compression moulding process is used to form components from phenolic, urea and melamine thermosetting polymers, as well as alkyd resins.

Transfer moulding is different to compression moulding because the plastic is not fed directly into the die cavity. Instead it is fed into a chamber outside the die. Here it is preheated before a piston forces it through a system of runners and gates that allow it into the die cavity. When the polymer is cured through heat and pressure it is ejected from the mould. The advantage of this process is that the runner system allows the simultaneous production of many small, intricate parts and there is no 'flashing' around the finished article.

Rotational moulding is a unique process for manufacturing thermosoftening polymers as it produces hollow items eg. Lawnmower grass-catchers, balls and some types of children's toys. A split mould is filled with exactly the right quantity of polymer which is then tumbled in the mould once it is bolted together. The die is rotated in a heated chamber until the polymer is completely melted. The die is removed from the chamber and continues to rotate until the polymer is set. The die halves are separated and the article removed.

Injection moulding: In this process thermosoftening polymer powder, or granules, are placed into a feed hopper connected to a heating chamber. When the fluid state is attained, due to the heat, a piston or 'screw type' mechanism forces the plastic through a nozzle and into the die. These are often water-cooled to hasten setting such that when the plastic becomes solid again the die is opened and the component is ejected. Any flashing is then removed.

Modern technology and sophisticated metal machining and finishing techniques means that large objects with fine tolerances are easily produced. The images below (Figures. 4, 5, 6, & 7) show a 60 litre 'tub' and the two-part die which produced it to a high degree of dimensional accuracy. Note the highly polished surfaces of the die.



Figure 4. This complete die weighs in excess of 1.5 tonnes. Note the 4 alignment pins and the ejector pins.



Figure 5. Due to the weight of the die, it must be lifted with a crane and placed into the injection machine. Eyebolts for this purpose are attached to the sides.

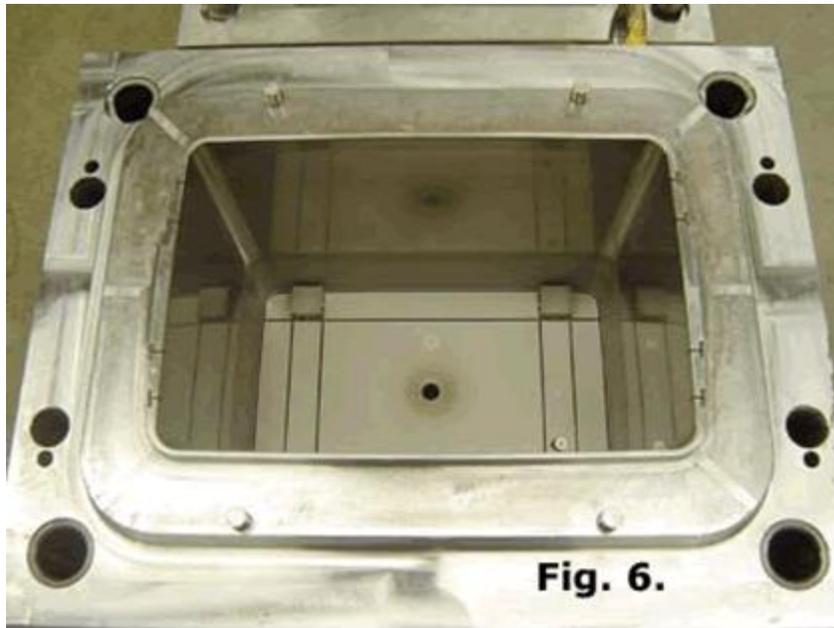
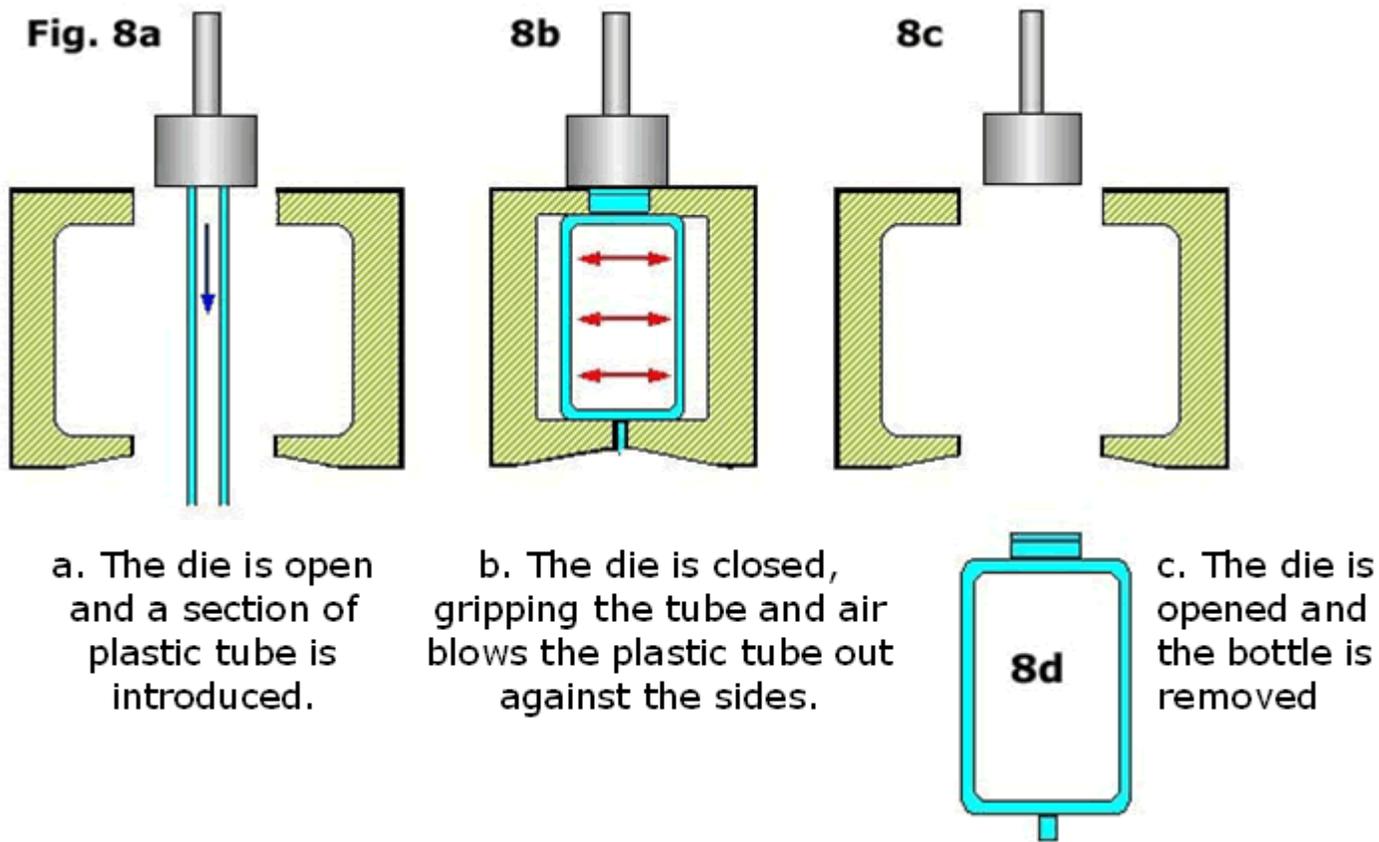


Figure 6. Note the highly polished surfaces of the mould and the polymer inlet hole in the bottom centre of the mould.



Figure 7. The finished storage 'tub'. The lid is produced in another mould.

Blow moulding: Thermoplastic polymer articles, such as soft drink bottles made from PET (polyethyleneteraphthalate), are formed by blow moulding. A hot, thin extruded tube (Figure 8a) of the polymer is gripped in a die as an internal blast of air forces it out against the sides of the mould (Figure 8b). It is held in the die until it cools and is then released (Figure 8c). The polymer assumes the shape of the die (Figure 8d).



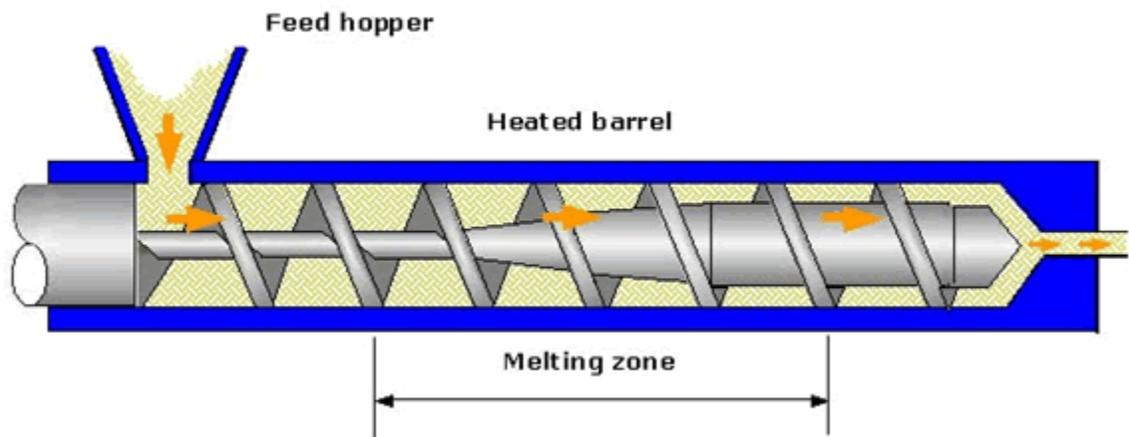
With the die closed and the tube pinched, the air pressure, which has blown the bottle to shape, is maintained until the plastic is cooled to room temperature.

Vacuum forming relies upon air pressure to form a shape. A heated sheet of polymer is clamped above a mould and the air in the mould is evacuated leaving a partial vacuum. The air pressure above the mould forces the plastic sheet down into the mould to form the shape which is removed when cooled. This process is often used for transparent canopies and covers over lit signs such as those seen in service stations or fast food outlets.

For a very comprehensive coverage of the vacuum forming process with many sequenced sectional diagrams, investigate this site presented by smi; SPECIALITY MANUFACTURING

Extrusion (Figure 9) involves the use of powder or granules, mixed with dyes as required, which are placed into a feed hopper connected to a heating chamber.

When the fluid state is attained due to the heat, a piston or 'screw type' mechanism forces the plastic through a nozzle and into the mould or die. The dies are often water-cooled to hasten setting such that when the plastic becomes solid again the die is opened and the component is ejected. Any flashing is then removed.



Pultrusion is similar to extrusion except that thermosetting polymers are used and the composition of the composite polymer requires a greater force to move it through the die. For this reason, a pulling force is incorporated into the forming process to overcome resistance during manufacture of the article.

Fabrication processes may also be used to manufacture complex polymer components. This is due to the ability of some polymers to be 'bent' and 'welded'.

Polymer Structure

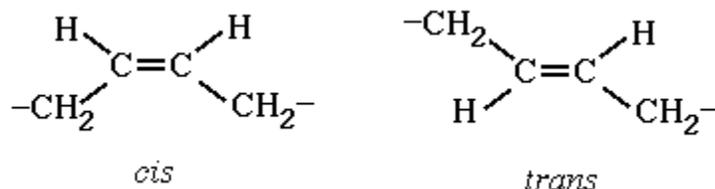
Although the fundamental property of bulk polymers is the degree of polymerization, the physical structure of the chain is also an important factor that determines the macroscopic properties.

The terms **configuration** and **conformation** are used to describe the geometric structure of a polymer and are often confused. *Configuration* refers to the order that is determined by chemical bonds. The configuration of a polymer cannot be altered unless chemical bonds are broken and

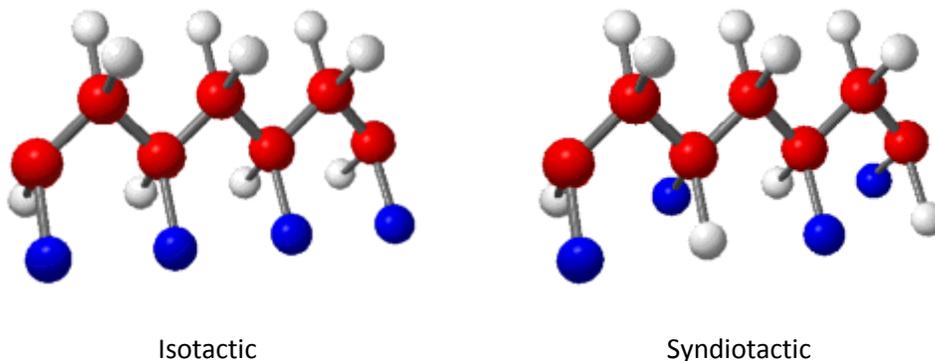
reformed. *Conformation* refers to order that arises from the rotation of molecules about the single bonds. These two structures are studied below.

Configuration

The two types of polymer configurations are *cis* and *trans*. These structures can not be changed by physical means (e.g. rotation). The *cis* configuration arises when substituent groups are on the same side of a carbon-carbon double bond. *Trans* refers to the substituents on opposite sides of the double bond.



Stereoregularity is the term used to describe the configuration of polymer chains. Three distinct structures can be obtained. *Isotactic* is an arrangement where all substituents are on the same side of the polymer chain. A *syndiotactic* polymer chain is composed of alternating groups and *atactic* is a random combination of the groups. The following diagram shows two of the three *stereoisomers* of polymer chain.



Conformation

If two atoms are joined by a single bond then rotation about that bond is possible since, unlike a double bond, it does not require breaking the bond.

The ability of an atom to rotate this way relative to the atoms which it joins is known as an adjustment of the *torsional* angle. If the two atoms have other atoms or groups attached to them then configurations which vary in torsional angle are known as *conformations*. Since different conformations represent varying distances between the atoms or groups rotating about the bond, and these distances determine the amount and type of interaction between adjacent atoms or

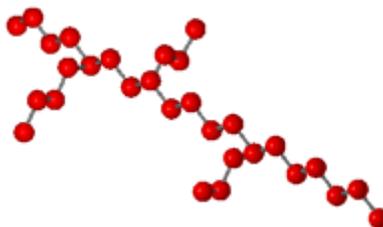
groups, different conformation may represent different potential energies of the molecule. There several possible generalized conformations: Anti (Trans), Eclipsed (Cis), and Gauche (+ or -). The following animation illustrates the differences between them.

Conformation Lattice Simulation

Like the polymer growth simulation, the conformation lattice simulation takes a statistical approach to the study of polymers. Probabilities of the different conformations are assigned which produces a polymer chain with many possible shapes. Click the icon to enter the virtual laboratory.

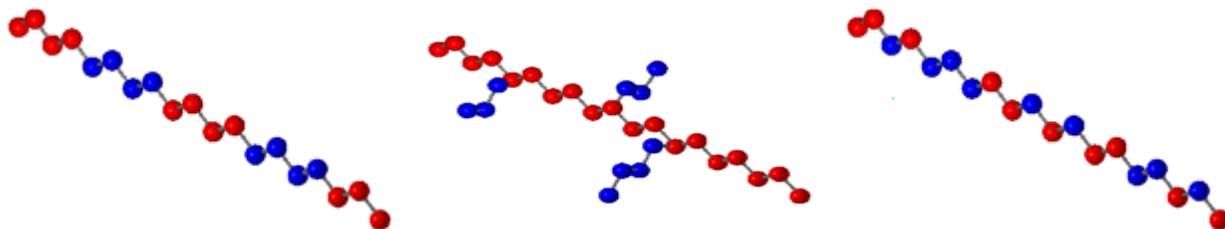
Other Chain Structures

The geometric arrangement of the bonds is not the only way the structure of a polymer can vary. A *branched polymer* is formed when there are "side chains" attached to a main chain. A simple example of a branched polymer is shown in the following diagram.

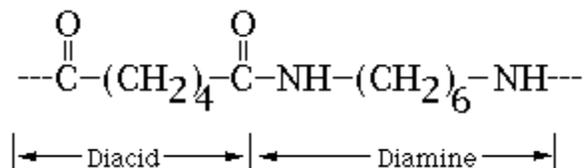


There are, however, many ways a branched polymer can be arranged. One of these types is called "*star-branching*". Star branching results when a polymerization starts with a single monomer and has branches radially outward from this point. Polymers with a high degree of branching are called *dendrimers*. Often in these molecules, branches themselves have branches. This tends to give the molecule an overall spherical shape in three dimensions.

A separate kind of chain structure arises when more than one type of monomer is involved in the synthesis reaction. These polymers that incorporate more than one kind of monomer into their chain are called *copolymers*. There are three important types of copolymers. A *random copolymer* contains a random arrangement of the multiple monomers. A *block copolymer* contains blocks of monomers of the same type. Finally, a *graft copolymer* contains a main chain polymer consisting of one type of monomer with branches made up of other monomers. The following diagram displays the different types of copolymers.



An example of a common copolymer is Nylon. Nylon is an alternating copolymer with 2 monomers, a 6 carbon diacid and a 6 carbon diamine. The following picture shows one monomer of the diacid combined with one monomer of the diamine:



Cross-Linking

In addition to the bonds which hold monomers together in a polymer chain, many polymers form bonds between neighboring chains. These bonds can be formed directly between the neighboring chains, or two chains may bond to a third common molecule. Though not as strong or rigid as the bonds within the chain, these *cross-links* have an important effect on the polymer. Polymers with a high enough degree of cross-linking have "memory." When the polymer is stretched, the cross-links prevent the individual chains from sliding past each other. The chains may straighten out, but once the stress is removed they return to their original position and the object returns to its original shape.

One example of cross-linking is *vulcanization*. In vulcanization, a series of cross-links are introduced into an *elastomer* to give it strength. This technique is commonly used to strengthen rubber.

Classes of Polymers

Polymer science is a broad field that includes many types of materials which incorporate long chain structure of many repeat units as discussed above. The two major polymer classes are described here.

Elastomers, or rubbery materials, have a loose cross-linked structure. This type of chain structure causes elastomers to possess memory. Typically, about 1 in 100 molecules are cross-linked on average. When the average number of cross-links rises to about 1 in 30 the material becomes more rigid and brittle. Natural and synthetic rubbers are both common examples of elastomers. *Plastics* are polymers which, under appropriate conditions of temperature and pressure, can be molded or shaped (such as blowing to form a film). In contrast to elastomers, plastics have a greater stiffness and lack reversible elasticity. All plastics are polymers but not all polymers are plastics. Cellulose is an example of a polymeric material which must be substantially modified before processing with the usual methods used for plastics. Some plastics, such as nylon and cellulose acetate, are formed into fibers (which are regarded by some as a separate class of polymers in spite of a considerable overlap with plastics). As we shall see in the section on liquid

crystals, some of the main chain polymer liquid crystals also are the constituents of important fibers. Every day plastics such as polyethylene and poly(vinyl chloride) have replaced traditional materials like paper and copper for a wide variety of applications. The section on [Polymer Applications](#) will go into greater detail about the special properties of the many types of polymers.

Fiber Manufacturing Technology

Synthetic and Cellulosic Fiber Formation Technology

Most synthetic and cellulosic manufactured fibers are created by “extrusion” — forcing a thick, viscous liquid (about the consistency of cold honey) through the tiny holes of a device called a spinneret to form continuous filaments of semi-solid polymer.

In their initial state, the fiber-forming polymers are solids and therefore must be first converted into a fluid state for extrusion. This is usually achieved by melting, if the polymers are thermoplastic synthetics (i.e., they soften and melt when heated), or by dissolving them in a suitable solvent if they are non-thermoplastic cellulose. If they cannot be dissolved or melted directly, they must be chemically treated to form soluble or thermoplastic derivatives. Recent technologies have been developed for some specialty fibers made of polymers that do not melt, dissolve, or form appropriate derivatives. For these materials, the small fluid molecules are mixed and reacted to form the otherwise intractable polymers during the extrusion process.

The Spinneret

The spinnerets used in the production of most manufactured fibers are similar, in principle, to a bathroom shower head. A spinneret may have from one to several hundred holes. The tiny openings are very sensitive to impurities and corrosion. The liquid feeding them must be carefully filtered (not an easy task with very viscous materials) and, in some cases, the spinneret must be made from very expensive, corrosion-resistant metals. Maintenance is also critical, and spinnerets must be removed and cleaned on a regular basis to prevent clogging.

As the filaments emerge from the holes in the spinneret, the liquid polymer is converted first to a rubbery state and then solidified. This process of extrusion and solidification of endless filaments is called spinning, not to be confused with the textile operation of the same name, where short pieces of staple fiber are twisted into yarn. There are four methods of spinning filaments of manufactured fibers: wet, dry, melt, and gel spinning.



Wet Spinning

Wet spinning is the oldest process. It is used for fiber-forming substances that have been dissolved in a solvent. The spinnerets are submerged in a chemical bath and as the filaments emerge they precipitate from solution and solidify.

Because the solution is extruded directly into the precipitating liquid, this process for making fibers is called wet spinning. **Acrylic, rayon, aramid, modacrylic** and **spandex** can be produced by this process.



Dry Spinning

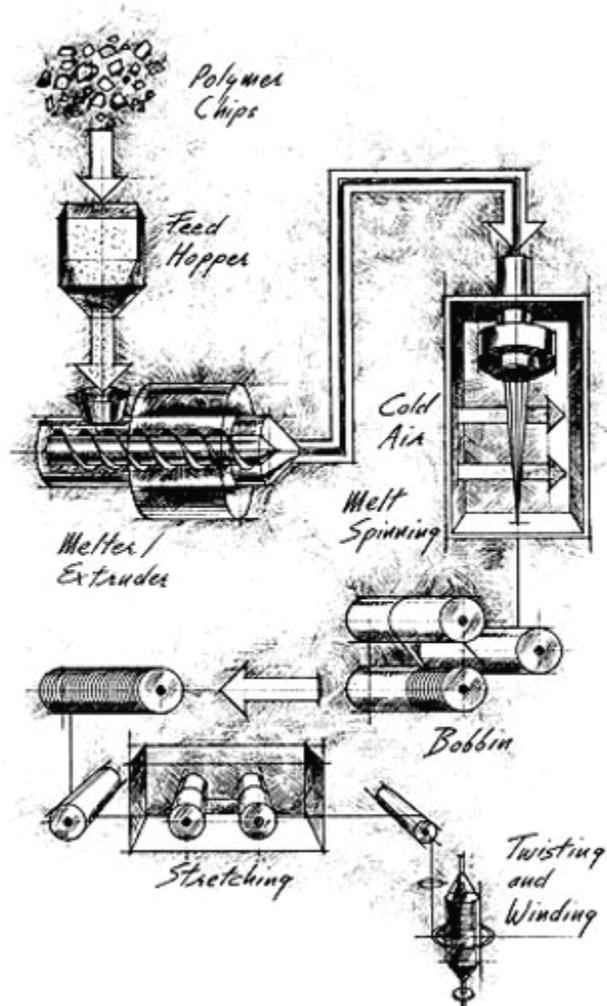
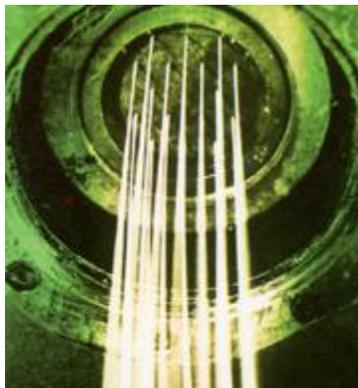
Dry spinning is also used for fiber-forming substances in solution. However, instead of precipitating the polymer by dilution or chemical reaction, solidification is achieved by evaporating the solvent in a stream of air or inert gas.

The filaments do not come in contact with a precipitating liquid, eliminating the need for drying and easing solvent

recovery. This process may be used for the production of **acetate, triacetate, acrylic, modacrylic, PBI, spandex,** and **vinyon.**

Melt Spinning

In melt spinning, the fiber-forming substance is melted for extrusion through the spinneret and then directly solidified by cooling. **Nylon, olefin, polyester, saran** and **sulfar** are produced in this manner.



Melt Spinning Polymer from Chip

Melt spun fibers can be extruded from the spinneret in different cross-sectional shapes (round, trilobal, pentagonal, octagonal, and others). Trilobal-shaped fibers reflect more light and give an attractive sparkle to textiles.

Pentagonal-shaped and hollow fibers, when used in carpet, show less soil and dirt. Octagonal-shaped fibers offer glitter-free effects. Hollow fibers trap air, creating insulation and provide loft characteristics equal to, or better than, down.

Gel Spinning

Gel spinning is a special process used to obtain high strength or other special fiber properties. The polymer is not in a true liquid state during extrusion. Not completely separated, as they would be in a true solution, the polymer chains are bound together at various points in liquid crystal form. This produces strong inter-chain forces in the resulting filaments that can significantly increase the tensile strength of the fibers. In addition, the liquid crystals are aligned along the fiber axis by the shear forces during extrusion. The filaments emerge with an unusually high degree of orientation relative to each other, further enhancing strength. The process can also be described as dry-wet spinning, since the filaments first pass through air and then are cooled further in a liquid bath. Some high-strength polyethylene and aramid fibers are produced by gel spinning.

Stretching and Orientation

While extruded fibers are solidifying, or in some cases even after they have hardened, the filaments may be drawn to impart strength. Drawing pulls the molecular chains together and orients them along the fiber axis, creating a considerably stronger yarn.

FOAM MANUFACTURING

Polystyrene Foam

- Polystyrene foam, often known as Styrofoam, is made from petroleum by-products called styrenes. The process of turning styrenes into foam is known as polymerization. First the styrene is infused with hydrocarbon gas, which causes the molecules to expand. The hydrocarbon-infused styrene is then heated to further expand each molecule, then placed in a mold. The mold is heated with steam to cause the styrene to take the shape of the mold once it is released. This process is used to produce packing foam and building insulation. The resulting foam material is often known as expanded polystyrene (EPS) and is commonly called "beadboard."

Polyurethane Foam

- Polyurethane foam is manufactured from man-made particles called polymers. The polymers are joined by urethanes, or carbamates, and stored as a liquid in large vats. The vats are continuously agitated to keep the solution mixed and ready for production. To produce polyurethane foam, the liquid is heated and pumped into a series of pipes, where it is sprayed out onto sheets of heavy paper. Once it has been sprayed, it is infused with carbon dioxide gas, which causes it to rise like bread dough. Additional sheets of paper are added to form the foam into the desired shape, and it is then cooled and cut to the desired length. Polyurethane foam is often found in mattresses and other furnishings, and rigid units are used in flower arrangements.

Polyethylene Foam

- Polyethylene foam is an extruded product made from a thermoplastic compound called ethene. The liquid ethene is heated and drawn through a series of molds or dies to create the desired shape. Large sheets of ethene are called "buns," and may be placed into molds and heated to form a variety of products. Soft polyethylene foam is used as padding in shoes and carpeting, while rigid versions are often used in sculpture or insulation.
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Adhesive manufacturing

An **adhesive**, also known as **glue**, is a material, typically **liquid** or semi-liquid, that **adheres** or bonds items together. Adhesives come from either natural or **synthetic** sources. The types of materials that can be bonded are vast but adhesives are especially useful for bonding thin materials. Adhesives **cure** (harden) by either evaporating a solvent or by chemical reactions that occur between two or more constituents.

Adhesives are also very useful for joining thin or dissimilar materials, minimizing weight, and providing a vibration-damping joint. A disadvantage of most adhesives is that most do not form an instantaneous joint, unlike many other joining processes, because the adhesive needs time to cure.

Economic importance

In the course of time and during their development, adhesives have gained a stable position in an increasing number of production processes. There is hardly any product in our surroundings that does not contain at least one adhesive – be it the label on a beverage bottle, protective coatings on automobiles or profiles on window frames. Market researchers forecast a **turnover** of almost US\$50 billion for the global adhesives market in 2019. Especially the dynamic economic development in **emerging countries** such as China, India, Russia or Brazil will cause a rising demand for adhesives in the future.

Types

Adhesives are typically organized by the method of adhesion. These are then organized into reactive and non-reactive adhesives, which refers to if the adhesive **chemically reacts** to harden. Alternatively they can be organized by whether the raw stock is of natural, or synthetic origin, or by their starting **physical phase**.

Non-reactive adhesives

Drying adhesives

There are two types of adhesives that harden by drying: *solvent based adhesives* and *polymer dispersion adhesives*, also known as *emulsion adhesives*. Solvent based adhesives are a mixture of ingredients (typically **polymers**) dissolved in a **solvent**. White glue, contact adhesives and **rubber cements** are members of the *drying adhesive* family. As the solvent evaporates, the adhesive hardens. Depending on the chemical composition of the adhesive, they will adhere to different materials to greater or lesser degrees.

Polymer dispersion adhesives are milky-white dispersions often based on **polyvinyl acetate** (PVAc). They are used extensively in the woodworking and packaging industries; also used with fabrics and fabric-based components, and in engineered products such as loudspeaker cones.

Pressure sensitive adhesives

Pressure sensitive adhesives (PSA) form a bond by the application of light pressure to marry the adhesive with the adherend. They are designed with a balance between flow and resistance to flow. The bond forms because the adhesive is soft enough to flow (i.e. "wet") to the adherend. The bond has strength because the adhesive is hard enough to resist flow when stress is applied to the bond. Once the adhesive and the adherend are in close proximity, molecular interactions, such as **van der Waals forces**, become involved in the bond, contributing significantly to its ultimate strength.

PSAs are designed for either permanent or removable applications. Examples of permanent applications include safety labels for power equipment, foil tape for HVAC duct work, automotive interior trim assembly, and sound/vibration damping films. Some high performance permanent PSAs exhibit high adhesion values and can support kilograms of weight per square

centimeter of contact area, even at elevated temperature. Permanent PSAs may be initially removable (for example to recover mislabeled goods) and build adhesion to a permanent bond after several hours or days.

Removable adhesives are designed to form a temporary bond, and ideally can be removed after months or years without leaving residue on the adherend. Removable adhesives are used in applications such as surface protection films, masking tapes, bookmark and note papers, price marking labels, promotional graphics materials, and for skin contact (wound care dressings, EKG electrodes, athletic tape, analgesic and transdermal drug patches, etc.). Some removable adhesives are designed to repeatedly stick and unstick. They have low adhesion and generally can not support much weight.

Pressure sensitive adhesives are manufactured with either a liquid carrier or in 100% solid form. Articles are made from liquid PSAs by coating the adhesive and drying off the solvent or water carrier. They may be further heated to initiate a [cross-linking](#) reaction and increase [molecular weight](#). 100% solid PSAs may be low viscosity polymers that are coated and then reacted with radiation to increase molecular weight and form the adhesive; or they may be high viscosity materials that are heated to reduce viscosity enough to allow coating, and then cooled to their final form. Major raw material for PSA's are [acrylate](#) based polymers.

Contact adhesives

Contact adhesives are used in strong bonds with high shear-resistance like [laminates](#), such as bonding [Formica](#) to a wooden counter, and in [footwear](#), as in attaching outsoles to uppers.

[Natural rubber](#) and [polychloroprene](#) (Neoprene) are commonly used contact adhesives. Both of these elastomers undergo [strain crystallization](#). In the construction industry a specialised proprietary adhesive known as Liquid Nails (or liquid nails as the generic), is used. This also copes with tasks such as sealing [artificial turf](#).

Contact adhesives must be applied to both surfaces and allowed some time to dry before the two surfaces are pushed together. Some contact adhesives require as long as 24 hours to dry before the surfaces are to be held together. Once the surfaces are pushed together, the bond forms very quickly. It is usually not necessary to apply pressure for a long time, so there is less need for [clamps](#).

Hot adhesives

Hot adhesives, also known as *hot melt adhesives*, are [thermoplastics](#) applied in molten form (in the 65-180 °C range) which solidify on cooling to form strong bonds between a wide range of materials. [Ethylene-vinyl acetate](#) based hot-melts are particularly popular for crafts because of their ease of use and the wide range of common materials they can join. A glue gun (shown at right) is one method of applying hot adhesives. The glue gun melts the solid adhesive then allows the liquid to pass through its barrel onto the material, where it solidifies.

Thermoplastic glue may have been invented around 1940 by [Procter & Gamble](#) as a solution to water-based adhesives commonly used in packaging at that time failing in humid climates, causing packages to open.

Reactive adhesives

Multi-part adhesives

Multi-component adhesives harden by mixing two or more components which chemically react. This reaction causes polymers to cross-link into acrylics, urethanes, and epoxies.

There are several commercial combinations of multi-component adhesives in use in industry. Some of these combinations are:

- Polyester resin – polyurethane resin
- Polyols – polyurethane resin
- Acrylic polymers – polyurethane resins

The individual components of a multi-component adhesive are not adhesive by nature. The individual components react with each other after being mixed and show full adhesion only on curing. The multi-component resins can be either solvent-based or solvent-less. The solvents present in the adhesives are a medium for the polyester or the polyurethane resin. The solvent is dried during the curing process.

One-part adhesives

One-part adhesives harden via a chemical reaction with an external energy source, such as [radiation](#), [heat](#), and [moisture](#).

Ultraviolet (UV) light curing adhesives, also known as *light curing materials* (LCM), have become popular within the manufacturing sector due to their rapid curing time and strong bond strength. Light curing adhesives can cure in as little as a second and many formulations can bond dissimilar substrates (materials) and withstand harsh temperatures. These qualities make UV curing adhesives essential to the manufacturing of items in many industrial markets such as electronics, telecommunications, medical, aerospace, glass, and optical. Unlike traditional adhesives, UV light curing adhesives not only bond materials together but they can also be used to seal and coat products. They are generally acrylic based.

Heat curing adhesives consist of a pre-made mixture of two or more components. When heat is applied the components react and cross-link. This type of adhesive includes epoxies, urethanes, and [polyimides](#).

Moisture curing adhesives cure when they react with moisture present on the substrate surface or in the air. This type of adhesive includes cyanoacrylates and urethanes.

Natural adhesives

Natural adhesives are made from organic sources such as vegetable matter, [starch](#) ([dextrin](#)), natural resins or from animals e.g. casein or [animal glue](#). They are often referred to as [bioadhesives](#). One example is a simple paste made by cooking flour in water. Animal glues are traditionally used in bookbinding, wood joining, and many other areas but now are largely replaced by synthetic glues. Casein is mainly used to adhere glass bottle labels. Starch based adhesives are used in [corrugated board](#) production and [paper sack](#) production, paper tube winding, and wall paper adhesives. [Masonite](#), a wood hardboard, was bonded using natural [lignin](#), (although most modern [MDF](#) particle boards use synthetic thermosetting resins). Another form of natural adhesive is blood [albumen](#) (made from protein component of blood), which is used in the [plywood](#) industry. [Animal glue](#) remains the preferred glue of the [luthier](#). Casein based glues are made by [precipitating](#) casein from [milk protein](#) using the [acetic acid](#) from [vinegar](#). This forms [curds](#), which are neutralized with a [base](#), such as [sodium bicarbonate](#) (baking soda), to cause them to unclump and become a thicker plastic-like substance.

Synthetic adhesives

Synthetic adhesives are based on [elastomers](#), [thermoplastics](#), [emulsions](#), and [thermosets](#). Examples of thermosetting adhesives are: [epoxy](#), [polyurethane](#), [cyanoacrylate](#) and [acrylic](#) polymers. See also [post-it notes](#). The first commercially produced synthetic adhesive was [Karlsons klister](#) in the 1920s.

Application

Applicators of different adhesives are designed according to the adhesive being used and the size of the area to which the adhesive will be applied. The adhesive is applied to either one or both of the materials being bonded. The pieces are aligned and pressure is added to aid in adhesion and rid the bond of air bubbles.

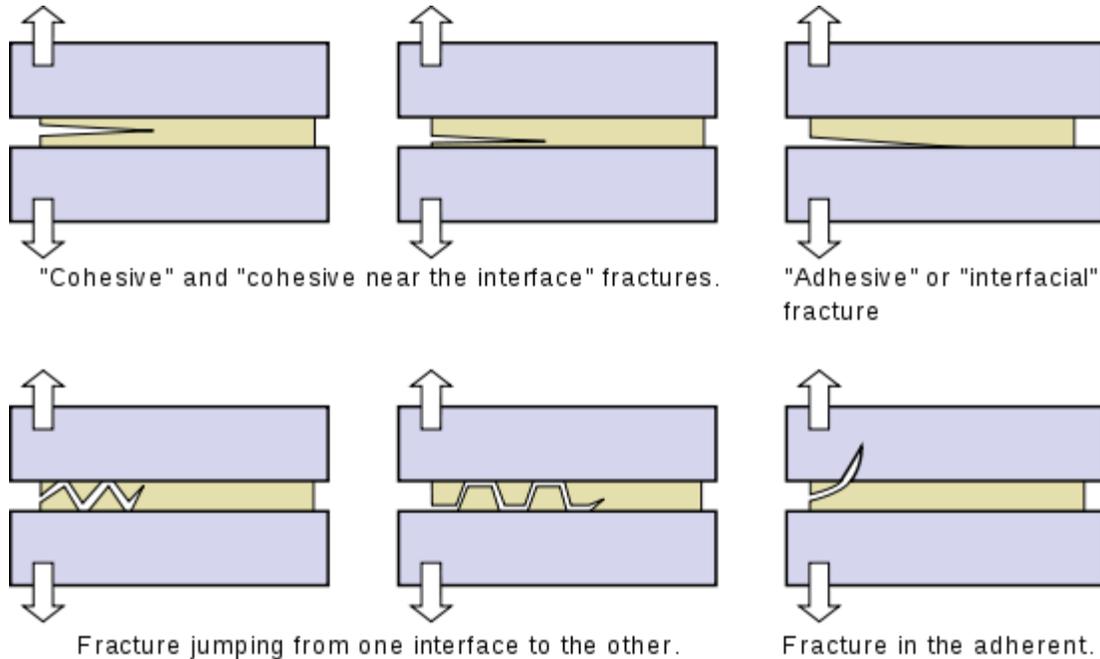
Common ways of applying an adhesive include brushes, rollers, using films or pellets, spray guns and applicator guns (e.g., [caulk gun](#)). All of these can be done manually or can be automated into a machine.

Mechanisms of adhesion

Adhesion, the attachment between adhesive and substrate may occur either by mechanical means, in which the adhesive works its way into small pores of the substrate, or by one of several chemical mechanisms. The strength of adhesion depends on many factors, including the means by which it occurs.

In some cases, an actual [chemical bond](#) occurs between adhesive and substrate. In others, electrostatic forces, as in static electricity, hold the substances together. A third mechanism involves the [van der Waals forces](#) that develop between molecules. A fourth means involves the moisture-aided diffusion of the glue into the substrate, followed by hardening.

Failure of the adhesive joint



There are several factors that could contribute to the failure of two adhered surfaces. Sunlight and heat may weaken the adhesive. Solvents can deteriorate or dissolve adhesive. Physical stresses may also cause the separation of surfaces. When subjected to loading, debonding may occur at different locations in the adhesive joint. The major fracture types are the following:

Cohesive fracture

Cohesive fracture is obtained if a crack propagates in the bulk polymer which constitutes the adhesive. In this case the surfaces of both adherents after debonding will be covered by fractured adhesive. The crack may propagate in the center of the layer or near an interface. For this last case, the cohesive fracture can be said to be "cohesive near the interface".

Interfacial fracture

The fracture is *adhesive* or *interfacial* when debonding occurs between the adhesive and the adherent. In most cases, the occurrence of interfacial fracture for a given adhesive goes along with a smaller fracture toughness. The interfacial character of a fracture surface is usually to identify the precise location of the crack path in the interphase.

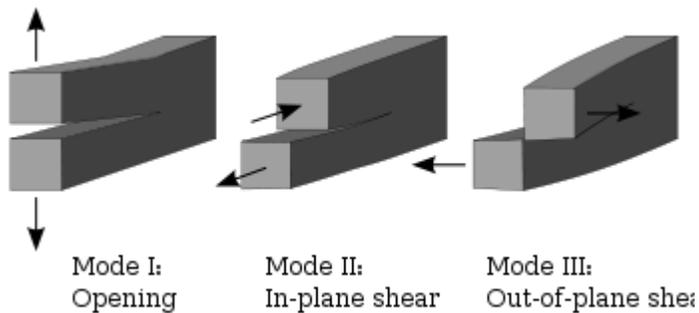
Other types of fracture

Other types of fracture include:

- The *mixed* type, which occurs if the crack propagates at some spots in a cohesive and in others in an interfacial manner. Mixed fracture surfaces can be characterised by a certain percentage of adhesive and cohesive areas.

- The *alternating crack path* type which occurs if the cracks jump from one interface to the other. This type of fracture appears in the presence of tensile pre-stresses in the adhesive layer.
- Fracture can also occur in the adherent if the adhesive is tougher than the adherent. In this case, the adhesive remains intact and is still bonded to one substrate and remnants of the other. For example, when one removes a price label, the adhesive usually remains on the label and the surface. This is cohesive failure. If, however, a layer of paper remains stuck to the surface, the adhesive has not failed. Another example is when someone tries to pull apart [Oreo](#) cookies and all the filling remains on one side; this is an adhesive failure, rather than a cohesive failure.

Design of adhesive joints



As a general design rule, the material properties of the object need to be greater than the forces anticipated during its use. (i.e. geometry, loads, etc.). The engineering work will consist of having a good model to evaluate the function. For most adhesive joints, this can be achieved using [fracture mechanics](#). Concepts such as the [stress concentration](#) factor and the [strain energy release rate](#) can be used to predict failure. In such models, the behavior of the adhesive layer itself is neglected and only the adherents are considered.

Failure will also very much depend on the opening *mode* of the joint.

- *Mode I* is an opening or tensile mode where the loadings are normal to the crack.
- *Mode II* is a sliding or in-plane shear mode where the crack surfaces slide over one another in direction perpendicular to the leading edge of the crack. This is typically the mode for which the adhesive exhibits the highest resistance to fracture.
- *Mode III* is a tearing or antiplane shear mode.

As the loads are usually fixed, an acceptable design will result from combination of a material selection procedure and geometry modifications, if possible. In adhesively bonded structures, the global geometry and loads are fixed by structural considerations and the design procedure focuses on the material properties of the adhesive and on local changes on the geometry.

Increasing the joint resistance is usually obtained by designing its geometry so that:

- The bonded zone is large
- It is mainly loaded in mode II
- Stable crack propagation will follow the appearance of a local failure.

Alumina (Al₂O₃) - Properties and Applications by Precision Ceramics

Topics Covered

Characteristics of Alumina and Aluminium Oxide

Properties of Aluminium Oxide

Corrosion Resistance of Aluminium Oxide

Applications of Aluminium Oxide

Alumina Bead as Electrical Insulators

Characteristics of Alumina and Aluminium Oxide

Alumina is the more common name of **Aluminium Oxide** (Al₂O₃) and is a hard wearing material used for many applications. Once fired and sintered, it can only be machined using diamond-grinding methods.

Aluminium oxide is an **electrical insulator** but has a relatively high thermal conductivity (40 W/m K). In its most commonly occurring crystalline form, called corundum or **α-aluminium oxide**, its hardness makes it suitable for use as an abrasive and as a component in cutting tools.

Properties of Aluminium Oxide

Aluminium oxide is responsible for metallic aluminium's resistance to weathering. Metallic **aluminium** is very reactive with atmospheric oxygen, and a thin passivation layer of **alumina** quickly forms on any exposed **aluminium** surface. This layer protects the metal from further oxidation. The thickness and properties of this oxide layer can be enhanced using a process called anodising.

Corrosion Resistance of Aluminium Oxide

A number of alloys, such as **aluminium** bronzes, exploit this property by including a proportion of **aluminium** in the alloy to enhance corrosion resistance. The **alumina** generated by anodising is typically amorphous, but discharge assisted oxidation processes such as plasma electrolytic oxidation result in a significant proportion of crystalline **alumina** in the coating, enhancing its hardness.

Applications of Aluminium Oxide

Alumina's combination of hardness, high temperature operation and good electrical insulation makes it useful for a wide range of applications. **Alumina** is the most commonly used type of

ceramic and is available in purities up to 99.9%. Typical applications include electrical insulators; seal faces; valve seats.



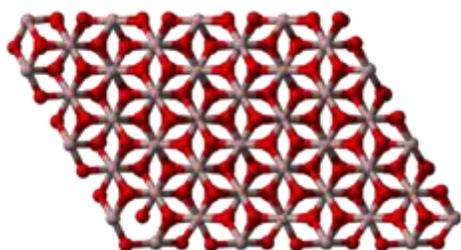
Alumina Bead as Electrical Insulators

For many years [fish spine beads](#) have been used as a practical method of insulating wires with the beads interlocking together to provide continuous [electrical insulation](#). Traditionally, the [beads](#) have been manufactured from a porcelain which although excellent for electrical purposes has not been mechanically strong or dense enough to be used in vacuum chambers or similar scientific instruments.

[Precision Ceramics](#) has now launched a range of standard [fish spine beads](#), all manufactured from high purity [alumina](#) and therefore vacuum compatible and fully dense.

Aluminium oxide

Aluminium oxide





Properties

Molecular formula	Al_2O_3
Molar mass	$101.96 \text{ g mol}^{-1}$
Appearance	white solid
Odor	odorless
Density	$3.95\text{--}4.1 \text{ g/cm}^3$
Melting point	$2,072 \text{ }^\circ\text{C}$ ($3,762 \text{ }^\circ\text{F}$; $2,345 \text{ K}$) ^[2]
Boiling point	$2,977 \text{ }^\circ\text{C}$ ($5,391 \text{ }^\circ\text{F}$; $3,250 \text{ K}$) ^[3]
Solubility in water	insoluble
Solubility	insoluble in diethyl ether practically insoluble in ethanol
Thermal conductivity	$30 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ^[1]
Refractive index (n_D)	$n_\omega=1.768\text{--}1.772$ $n_\epsilon=1.760\text{--}1.763$ Birefringence 0.008

Structure

Crystal structure	Trigonal, hR30 , space group = R3c , No. 167
Coordination geometry	octahedral

Thermochemistry

Std enthalpy of formation $\Delta_f H_{298}^\circ$ -1675.7 kJ·mol⁻¹[4]

Standard molar entropy S_{298}° 50.92 J·mol⁻¹·K⁻¹[4]

Hazards

MSDS [External MSDS](#)

EU classification Not listed.



NFPA 704 0

1

0

Flash point non-flammable

Related compounds

Other anions [aluminium hydroxide](#)

Other cations [boron trioxide](#)
[gallium oxide](#)
[indium oxide](#)
[thallium oxide](#)

Supplementary data page

Structure and properties [n, \$\epsilon_r\$, etc.](#)

Thermodynamic data [Phase behaviour](#)
[Solid, liquid, gas](#)

Spectral data [UV, IR, NMR, MS](#)

Aluminium oxide is a [chemical compound](#) of [aluminium](#) and [oxygen](#) with the [chemical formula](#) Al_2O_3 . It is the most commonly occurring of several [aluminium oxides](#), and specifically identified as **aluminium(III) oxide**. It is commonly called **alumina**, and may also be called **aloxide**, **aloxite**, or **alundum** depending on particular forms or applications. It commonly occurs in its crystalline [polymorphic phase](#) $\alpha\text{-Al}_2\text{O}_3$, in which it comprises the [mineral corundum](#), varieties of which form the precious gems [ruby](#) and [sapphire](#). Al_2O_3 is significant in its use to produce [aluminium](#) metal, as an abrasive owing to its hardness, and as a [refractory](#) material owing to its high melting point

Natural occurrence

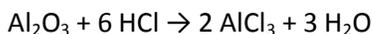
[Corundum](#) is the most common naturally occurring [crystalline](#) form of aluminium oxide. [Rubies](#) and [sapphires](#) are gem-quality forms of corundum, which owe their characteristic colors to trace impurities. Rubies are given their characteristic deep red color and their [laser](#) qualities by traces of [chromium](#). Sapphires come in different colors given by various other impurities, such as iron and titanium.

Properties

Al_2O_3 is an electrical [insulator](#) but has a relatively high [thermal conductivity](#) ($30 \text{ Wm}^{-1}\text{K}^{-1}$ ^[1]) for a ceramic material. In its most commonly occurring crystalline form, called [corundum](#) or α -aluminium oxide, its hardness makes it suitable for use as an [abrasive](#) and as a component in [cutting tools](#).

Aluminium oxide is responsible for the resistance of metallic aluminium to [weathering](#). Metallic aluminium is very reactive with atmospheric [oxygen](#), and a thin [passivation layer](#) of aluminium oxide (4 nm thickness) forms on any exposed aluminium surface.^[6] This layer protects the metal from further oxidation. The thickness and properties of this oxide layer can be enhanced using a process called [anodising](#). A number of [alloys](#), such as [aluminium bronzes](#), exploit this property by including a proportion of aluminium in the alloy to enhance corrosion resistance. The aluminium oxide generated by anodising is typically [amorphous](#), but discharge assisted oxidation processes such as [plasma electrolytic oxidation](#) result in a significant proportion of crystalline aluminium oxide in the coating, enhancing its [hardness](#).

Aluminium oxide is completely insoluble in water. However it is an [amphoteric](#) substance, meaning it can react with both acids and bases, such as [hydrochloric acid](#) and [sodium hydroxide](#).



Aluminium oxide was taken off the [United States Environmental Protection Agency's](#) chemicals lists in 1988. Aluminium oxide is on EPA's [Toxics Release Inventory](#) list if it is a fibrous form.

Structure



Corundum from [Brazil](#), size about 2x3 cm.

The most common form of crystalline aluminium oxide is known as [corundum](#). The oxygen ions nearly form a hexagonal close-packed structure with aluminium ions filling two-thirds of the octahedral interstices. Each Al^{3+} center is [octahedral](#). In terms of its [crystallography](#), corundum adopts a [trigonal](#) Bravais lattice with a space group of R-3c (number 167 in the International Tables). The primitive cell contains two formula units of aluminium oxide.

Aluminium oxide also exists in other phases, namely γ -, δ -, η -, θ -, and χ - Al_2O_3 .^[8] Each has a unique crystal structure and properties. Cubic γ - Al_2O_3 has important technical applications. The so-called β - Al_2O_3 proved to be $\text{NaAl}_{11}\text{O}_{17}$.

Production

Aluminium [hydroxide](#) minerals are the main component of [bauxite](#), the principal [ore](#) of [aluminium](#). A mixture of the minerals comprise bauxite ore, including [gibbsite](#) ($\text{Al}(\text{OH})_3$), [boehmite](#) (γ - $\text{AlO}(\text{OH})$), and [diaspore](#) (α - $\text{AlO}(\text{OH})$), along with impurities of [iron oxides](#) and hydroxides, quartz and [clay minerals](#).^[10] Bauxites are found in [laterites](#). Bauxite is purified by the [Bayer process](#):



Except for SiO_2 , the other components of bauxite do not dissolve in base. Upon filtering the basic mixture, Fe_2O_3 is removed. When the Bayer liquor is cooled, $\text{Al}(\text{OH})_3$ precipitates, leaving the silicates in solution. The solid is then [calcined](#) (heated strongly) to give aluminium oxide:



The product aluminium oxide tends to be multi-phase, i.e., consisting of several phases of aluminium oxide rather than solely [corundum](#).^[8] The production process can therefore be optimized to produce a tailored product. The type of phases present affects, for example, the solubility and pore structure of the aluminium oxide product which, in turn, affects the cost of aluminium production and pollution control.

Known as alundum (in fused form) or aloxite^[11] in the [mining](#), [ceramic](#), and [materials science](#) communities, aluminium oxide finds wide use. Annual world production of aluminium oxide is approximately 45 million [tonnes](#), over 90% of which is used in the manufacture of aluminium metal.^[5] The major uses of specialty aluminium oxides are in refractories, ceramics, and polishing and abrasive applications. Large tonnages are also used in the manufacture of [zeolites](#), coating titania pigments, and as a fire retardant/smoke suppressant.

Applications

The great majority of aluminium oxide is consumed for the production of aluminium, usually by the [Hall process](#).

Filler

Being fairly chemically inert and white, aluminium oxide is a favored filler for plastics. Aluminium oxide is a common ingredient in [sunscreen](#) and is sometimes present in cosmetics such as blush, lipstick, and nail polish.

Catalysis

Aluminium oxide catalyses a variety of reactions that are useful industrially. In its largest scale application, aluminium oxide is the catalyst in the [Claus process](#) for converting hydrogen sulfide waste gases into elemental sulfur in refineries. It is also useful for dehydration of [alcohols](#) to alkenes.

Aluminium oxide serves as a [catalyst support](#) for many industrial catalysts, such as those used in [hydrodesulfurization](#) and some [Ziegler-Natta](#) polymerizations.

Purification

Aluminium oxide is widely used to remove water from gas streams. Other major applications are described below.

Abrasive

Aluminium oxide is used for its hardness and strength. It is widely used as an [abrasive](#), including as a much less expensive substitute for [industrial diamond](#). Many types of [sandpaper](#) use aluminium oxide crystals. In addition, its low heat retention and low [specific heat](#) make it widely used in grinding operations, particularly [cutoff](#) tools. As the powdery abrasive mineral aloxite, it is a major component, along with [silica](#), of the [cue tip](#) "chalk" used in [billiards](#). Aluminium oxide powder is used in some [CD/DVD polishing](#) and scratch-repair kits. Its polishing qualities are also behind its use in toothpaste. Aluminium oxide can be grown as a coating on aluminium by [anodising](#) or by [plasma electrolytic oxidation](#) (see the "Properties" above). Both its strength and abrasive characteristics originate from the high [hardness](#) (9 on the [Mohs scale of mineral hardness](#)) of aluminium oxide.

Paint

[Template:Main:Alumina effect pigment](#) Aluminium oxide flakes are used in paint for reflective decorative effects, such as in the automotive or cosmetic industries.

Composite fiber

Aluminium oxide has been used in a few experimental and commercial fiber materials for high-performance applications (e.g., Fiber FP, Nextel 610, Nextel 720).

Other

In lighting, transparent aluminium oxide is used in some [sodium vapor lamps](#). Aluminium oxide is also used in preparation of coating suspensions in [compact fluorescent lamps](#).

In chemistry laboratories, aluminium oxide is a medium for [chromatography](#), available in [basic](#) (pH 9.5), [acidic](#) (pH 4.5 when in water) and neutral formulations.

Health and medical applications include it as a material in [hip replacements](#).^[5]

As well, it is used as a [dosimeter](#) for radiation protection and therapy applications for its [optically stimulated luminescence](#) properties.

Aluminium oxide is an electrical [insulator](#) used as a substrate ([Silicon on sapphire](#)) for [integrated circuits](#) but also as a [tunnel barrier](#) for the fabrication of [superconducting](#) devices such as [single electron transistors](#) and superconducting quantum interference ([SQUID](#)) devices.

Insulation for high-temperature furnaces is often manufactured from aluminium oxide. Sometimes the insulation has varying percentages of silica depending on the temperature rating of the material. The insulation can be made in blanket, board, brick and loose fiber forms for various application requirements.

Small pieces of aluminium oxide are often used as [boiling chips](#) in chemistry.

It is also used to make [spark plug insulators](#).

Using a plasma spray process and mixed with titania, it is coated onto the braking surface of some [aluminium bicycle](#) rims to provide abrasion and wear resistance.^[*citation needed*]

Aluminum Oxide, Al₂O₃ Material Characteristics

Alumina is the most cost effective and widely used material in the family of engineering ceramics. The raw materials from which this high performance technical grade ceramic is made

are readily available and reasonably priced, resulting in good value for the cost in fabricated alumina shapes. With an excellent combination of properties and an attractive price, it is no surprise that fine grain technical grade alumina has a very wide range of applications.

Key Properties

- ✓ Hard, wear-resistant
- ✓ Excellent dielectric properties from DC to GHz frequencies
- ✓ Resists strong acid and alkali attack at elevated temperatures
- ✓ Good thermal conductivity
- ✓ Excellent size and shape capability
- ✓ High strength and stiffness
- ✓ Available in purity ranges from 94%, an easily metallizable composition, to 99.5% for the most demanding high temperature applications.

Typical Uses

- ✓ Gas laser tubes
- ✓ Wear pads
- ✓ Seal rings
- ✓ High temperature electrical insulators
- ✓ High voltage insulators
- ✓ Furnace liner tubes
- ✓ Thread and wire guides
- ✓ Electronic substrates
- ✓ Ballistic armor
- ✓ Abrasion resistant tube and elbow liners
- ✓ Thermometry sensors

- ✓ Laboratory instrument tubes and sample holders
- ✓ Instrumentation parts for thermal property test machines
- ✓ Grinding media

General Information

Aluminum oxide, commonly referred to as alumina, possesses strong ionic interatomic bonding giving rise to its desirable material characteristics. It can exist in several crystalline phases which all revert to the most stable hexagonal alpha phase at elevated temperatures. This is the phase of particular interest for structural applications and the material available from Accuratus.

Alpha phase alumina is the strongest and stiffest of the oxide ceramics. Its high hardness, excellent dielectric properties, refractoriness and good thermal properties make it the material of choice for a wide range of applications.

High purity alumina is usable in both oxidizing and reducing atmospheres to 1925°C. Weight loss in vacuum ranges from 10^{-7} to 10^{-6} g/cm².sec over a temperature range of 1700° to 2000°C. It resists attack by all gases except wet fluorine and is resistant to all common reagents except hydrofluoric acid and phosphoric acid. Elevated temperature attack occurs in the presence of alkali metal vapors particularly at lower purity levels.

The composition of the ceramic body can be changed to enhance particular desirable material characteristics. An example would be additions of chrome oxide or manganese oxide to improve hardness and change color. Other additions can be made to improve the ease and consistency of metal films fired to the ceramic for subsequent brazed and soldered assembly.

Engineering Properties*

94% Aluminum Oxide			
Mechanical	Units of Measure	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.69	(230.4)
Porosity	% (%)	0	(0)
Color	—	white	—
Flexural Strength	MPa (lb/in ² x10 ³)	330	(47)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	300	(43.5)

Shear Modulus	GPa (lb/in ² x10 ⁶)	124	(18)
Bulk Modulus	GPa (lb/in ² x10 ⁶)	165	(24)
Poisson's Ratio	—	0.21	(0.21)
Compressive Strength	MPa (lb/in ² x10 ³)	2100	(304.5)
Hardness	Kg/mm ²	1175	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	3.5	—
Maximum Use Temperature (no load)	°C (°F)	1700	(3090)
Thermal			
Thermal Conductivity	W/m•°K (BTU•in/ft ² •hr•°F)	18	(125)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	8.1	(4.5)
Specific Heat	J/Kg•°K (Btu/lb•°F)	880	(0.21)
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	16.7	(418)
Dielectric Constant	@ 1 MHz	9.1	(9.1)
Dissipation Factor	@ 1 kHz	0.0007	(0.0007)
Loss Tangent	@ 1 kHz	—	—
Volume Resistivity	ohm•cm	>10 ¹⁴	—

96% Aluminum Oxide			
Mechanical	Units of Measure	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.72	(232.2)
Porosity	% (%)	0	(0)
Color	—	white	—

Flexural Strength	MPa (lb/in ² x10 ³)	345	(50)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	300	(43.5)
Shear Modulus	GPa (lb/in ² x10 ⁶)	124	(18)
Bulk Modulus	GPa (lb/in ² x10 ⁶)	172	(25)
Poisson's Ratio	—	0.21	(0.21)
Compressive Strength	MPa (lb/in ² x10 ³)	2100	(304.5)
Hardness	Kg/mm ²	1100	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	3.5	—
Maximum Use Temperature (no load)	°C (°F)	1700	(3090)
Thermal			
Thermal Conductivity	W/m•°K (BTU•in/ft ² •hr•°F)	25	(174)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	8.2	(4.6)
Specific Heat	J/Kg•°K (Btu/lb•°F)	880	(0.21)
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	14.6	(365)
Dielectric Constant	@ 1 MHz	9.0	(9.0)
Dissipation Factor	@ 1 kHz	0.0011	(0.0011)
Loss Tangent	@ 1 kHz	—	—
Volume Resistivity	ohm•cm	>10 ¹⁴	—

99.5% Aluminum Oxide			
Mechanical	Units of Measure	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.89	(242.8)

Porosity	% (%)	0	(0)
Color	—	ivory	—
Flexural Strength	MPa (lb/in ² x10 ³)	379	(55)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	375	(54.4)
Shear Modulus	GPa (lb/in ² x10 ⁶)	152	(22)
Bulk Modulus	GPa (lb/in ² x10 ⁶)	228	(33)
Poisson's Ratio	—	0.22	(0.22)
Compressive Strength	MPa (lb/in ² x10 ³)	2600	(377)
Hardness	Kg/mm ²	1440	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	4	—
Maximum Use Temperature (no load)	°C (°F)	1750	(3180)
Thermal			
Thermal Conductivity	W/m°K (BTU•in/ft ² •hr•°F)	35	(243)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	8.4	(4.7)
Specific Heat	J/Kg•°K (Btu/lb•°F)	880	(0.21)
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	16.9	(420)
Dielectric Constant	@ 1 MHz	9.8	(9.8)
Dissipation Factor	@ 1 kHz	0.0002	(0.0002)
Loss Tangent	@ 1 kHz	—	—
Volume Resistivity	ohm•cm	>10 ¹⁴	—

CUBIC BORON NITRIDE (CBN)

In 1969 General Electric launched cubic boron nitride – called CBN for short – on to the market under the brand name "BORAZON" as a revolutionary development in the field of superabrasives. Produced in the retort, it achieves a Knoop intrinsic hardness of about $4,700 \text{ N/mm}^2$, i.e. it is more than half as hard again as diamond ($7,000 \text{ N/mm}^2$) and not quite twice as hard as silicon carbide (SiC) at $2,500 - 2,700 \text{ N/mm}^2$. The originally monocrystalline CBN, which chips rather block-like, was joined a few years later by the microcrystalline version with completely different, considerably finer chipping characteristics.



The spectrum of use of CBN starts at relatively soft but tough materials (from about 50 HRC) and extends up to very hard carbide-containing alloys (tool steels, special steels, HSS, etc.). For amorphous and ceramic materials CBN is of less suitability than for working carbides. In a vitrified bond, the wheels can be given different profiles and/or conditioned considerably more easily and economically.

Because of the long service life, conventional grinding wheels are now increasingly being replaced by those of CBN, especially where production series are long or recurring. G ratios of 1,200 to 15,000 can be achieved with CBN wheels, which is 500 to about 5,000 times more than what could be achieved with conventional grinding materials under favourable conditions of use. CBN is used in a 1-layer electroplated form or in a resinoid, brittle bronze or vitrified bond form. In the precision grinding sector, however, the trend is quite clearly in the direction of vitrified bonding.

CBN grinding wheels – with the exception of wheels with an electroplated bond – are produced in various concentrations, depending on the nature of their use. The term concentration means the carat weight per cm^3 of coat volume.

Thermal properties of CBN

CBN has a higher thermic stability than diamond. Oxidation takes place only above about $1,400^\circ\text{C}$. The usual relatively high grinding temperatures do not attack CBN chemically during working of either iron, nickel or cobalt. The excellent machining properties of CBN result in "cool" grinding. The good thermal conductivity of CBN – which is about five times the heat conductivity of copper – additionally assists this effect. When used correctly, the majority of the grinding heat generated is therefore absorbed by the CBN grinding wheel and released to the coolant emulsion and/or the surroundings. As a result, the workpiece heats considerably less compared to working with corundum, since the latter can absorb far less heat.

DIAMOND

General

Category Native Minerals

Formula
(repeating unit) C

Strunz
classification 01.CB.10a

Identification

Formula mass 12.01 g·mol⁻¹

Color Typically yellow, brown or gray to colorless. Less often blue, green, black, translucent white, pink, violet, orange, purple and red.

Crystal habit Octahedral

Crystal system Isometric-Hexoctahedral (Cubic)

Cleavage 111 (perfect in four directions)

Fracture Conchoidal (shell-like)

Mohs scale
hardness 10

Luster Adamantine

Streak Colorless

Diaphaneity Transparent to subtransparent to translucent

Specific gravity 3.52±0.01

Density	3.5–3.53 g/cm ³
Polish luster	Adamantine
Optical properties	Isotropic
Refractive index	2.418 (at 500 nm)
Birefringence	None
Pleochroism	None
Dispersion	0.044
Melting point	Pressure dependent
References	[1][2]

In mineralogy, diamond (from the ancient Greek ἀδάμας – *adámas* "unbreakable") is a metastable allotrope of carbon, where the carbon atoms are arranged in a variation of the face-centered cubic crystal structure called a diamond lattice. Diamond is less stable than graphite, but the conversion rate from diamond to graphite is negligible at ambient conditions. Diamond is renowned as a material with superlative physical qualities, most of which originate from the strong covalent bonding between its atoms. In particular, diamond has the highest hardness and thermal conductivity of any bulk material. Those properties determine the major industrial application of diamond in cutting and polishing tools and the scientific applications in diamond knives and diamond anvil cells.

Diamond has remarkable optical characteristics. Because of its extremely rigid lattice, it can be contaminated by very few types of impurities, such as boron and nitrogen. Combined with wide transparency, this results in the clear, colorless appearance of most natural diamonds. Small amounts of defects or impurities (about one per million of lattice atoms) color diamond blue (boron), yellow (nitrogen), brown (lattice defects), green (radiation exposure), purple, pink, orange or red. Diamond also has relatively high optical dispersion (ability to disperse light of different colors), which results in its characteristic luster. Excellent optical and mechanical properties, notably unparalleled hardness and durability, make diamond the most popular gemstone.

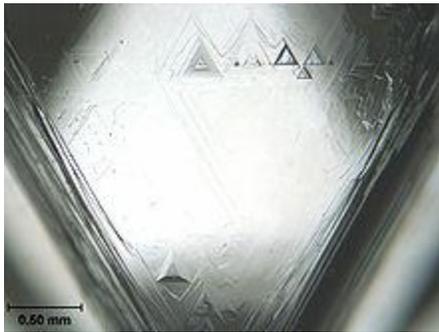
Most natural diamonds are formed at high temperature and pressure at depths of 140 to 190 kilometers (87 to 120 mi) in the Earth's mantle. Carbon-containing minerals provide the carbon source, and the growth occurs over periods from 1 billion to 3.3 billion years (25% to 75% of the age of the Earth). Diamonds are brought close to the Earth's surface through deep volcanic eruptions by a magma, which cools into igneous rocks known as kimberlites and lamproites. Diamonds can also be produced

synthetically in a high-pressure high-temperature process which approximately simulates the conditions in the Earth mantle. An alternative, and completely different growth technique is chemical vapor deposition (CVD). Several non-diamond materials, which include cubic zirconia and silicon carbide and are often called diamond simulants, resemble diamond in appearance and many properties. Special gemological techniques have been developed to distinguish natural and synthetic diamonds and diamond simulants.

Natural history

The formation of natural diamond requires very specific conditions—exposure of carbon-bearing materials to high pressure, ranging approximately between 45 and 60 kilobars (4.5 and 6 GPa), but at a comparatively low temperature range between approximately 900–1300 °C (1652–2372 °F). These conditions are met in two places on Earth; in the lithospheric mantle below relatively stable continental plates, and at the site of a meteorite strike.[10]

Formation in cratons



One face of an uncut octahedral diamond, showing trigons (of positive and negative relief) formed by natural chemical etching

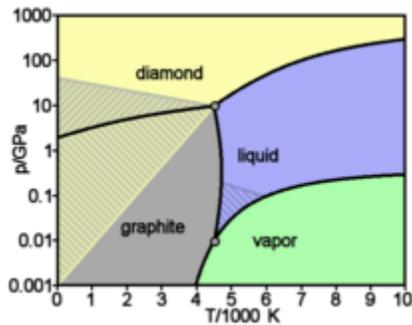
The conditions for diamond formation to happen in the lithospheric mantle occur at considerable depth corresponding to the requirements of temperature and pressure. These depths are estimated between 140 and 190 kilometers (87 and 120 mi) though occasionally diamonds have crystallized at depths about 300 kilometers (190 mi).[11] The rate at which temperature changes with increasing depth into the Earth varies greatly in different parts of the Earth. In particular, under oceanic plates the temperature rises more quickly with depth, beyond the range required for diamond formation at the depth required. The correct combination of temperature and pressure is only found in the thick, ancient, and stable parts of continental plates where regions of lithosphere known as cratons exist. Long residence in the cratonic lithosphere allows diamond crystals to grow larger.[11]

Through studies of carbon isotope ratios (similar to the methodology used in carbon dating, except with the stable isotopes C-12 and C-13), it has been shown that the carbon found in diamonds comes from both inorganic and organic sources. Some diamonds, known as harzburgitic, are formed from inorganic

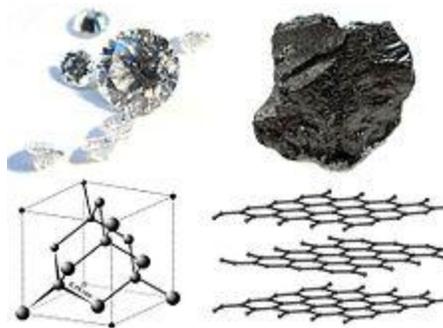
carbon originally found deep in the Earth's mantle. In contrast, eclogitic diamonds contain organic carbon from organic detritus that has been pushed down from the surface of the Earth's crust through subduction (see plate tectonics) before transforming into diamond. These two different source of carbon have measurably different $^{13}\text{C}:^{12}\text{C}$ ratios. Diamonds that have come to the Earth's surface are generally quite old, ranging from under 1 billion to 3.3 billion years old. This is 22% to 73% of the age of the Earth.[11]

Diamonds occur most often as euhedral or rounded octahedra and twinned octahedra known as macles. As diamond's crystal structure has a cubic arrangement of the atoms, they have many facets that belong to a cube, octahedron, rhombicosidodecahedron, tetrakis hexahedron or disdyakis dodecahedron. The crystals can have rounded off and unexpressive edges and can be elongated. Sometimes they are found grown together or form double "twinned" crystals at the surfaces of the octahedron. These different shapes and habits of some diamonds result from differing external circumstances. Diamonds (especially those with rounded crystal faces) are commonly found coated in nyf, an opaque gum-like skin.

Material properties



Theoretically predicted phase diagram of carbon



Diamond and graphite are two allotropes of carbon: pure forms of the same element that differ in structure.

A diamond is a transparent crystal of tetrahedrally bonded carbon atoms in a covalent network lattice (sp³) that crystallizes into the diamond lattice which is a variation of the face centered cubic structure. Diamonds have been adapted for many uses because of the material's exceptional physical characteristics. Most notable are its extreme hardness and thermal conductivity (900–2,320 W·m⁻¹·K⁻¹),[20] as well as wide bandgap and high optical dispersion.[21] Above 1,700 °C (1,973 K / 3,583 °F) in vacuum or oxygen-free atmosphere, diamond converts to graphite; in air, transformation starts at ~700 °C.[22] Diamond's ignition point is 720 - 800 °C in oxygen and 850 - 1,000 °C in air.[23] Naturally occurring diamonds have a density ranging from 3.15–3.53 g/cm³, with pure diamond close to 3.52 g/cm³.^[1] The chemical bonds that hold the carbon atoms in diamonds together are weaker than those in graphite. In diamonds, the bonds form an inflexible three-dimensional lattice, whereas in graphite, the atoms are tightly bonded into sheets, which can slide easily over one another, making the overall structure weaker.

Hardness

Diamond is the hardest known natural material on the Mohs scale of mineral hardness, where hardness is defined as resistance to scratching and is graded between 1 (softest) and 10 (hardest). Diamond has a hardness of 10 (hardest) on this scale.[25] Diamond's hardness has been known since antiquity, and is the source of its name.

Diamond hardness depends on its purity, crystalline perfection and orientation: hardness is higher for flawless, pure crystals oriented to the <111> direction (along the longest diagonal of the cubic diamond lattice).[26] Therefore, whereas it might be possible to scratch some diamonds with other materials, such as boron nitride, the hardest diamonds can only be scratched by other diamonds and nanocrystalline diamond aggregates.

The hardness of diamond contributes to its suitability as a gemstone. Because it can only be scratched by other diamonds, it maintains its polish extremely well. Unlike many other gems, it is well-suited to daily wear because of its resistance to scratching—perhaps contributing to its popularity as the preferred gem in engagement or wedding rings, which are often worn every day.



The extreme hardness of diamond in certain orientations makes it useful in materials science, as in this pyramidal diamond embedded in the working surface of a Vickers hardness tester.

The hardest natural diamonds mostly originate from the Copeton and Bingara fields located in the New England area in New South Wales, Australia. These diamonds are generally small, perfect to semiperfect octahedra, and are used to polish other diamonds. Their hardness is associated with the crystal growth form, which is single-stage crystal growth. Most other diamonds show more evidence of multiple growth stages, which produce inclusions, flaws, and defect planes in the crystal lattice, all of which affect their hardness. It is possible to treat regular diamonds under a combination of high pressure and high temperature to produce diamonds that are harder than the diamonds used in hardness gauges.

Somewhat related to hardness is another mechanical property toughness, which is a material's ability to resist breakage from forceful impact. The toughness of natural diamond has been measured as 7.5–10 MPa·m^{1/2}. [27][28] This value is good compared to other gemstones, but poor compared to most engineering materials. As with any material, the macroscopic geometry of a diamond contributes to its resistance to breakage. Diamond has a cleavage plane and is therefore more fragile in some orientations than others. Diamond cutters use this attribute to cleave some stones, prior to faceting. [29] "Impact toughness" is one of the main indexes to measure the quality of synthetic industrial diamonds.

Electrical conductivity

Other specialized applications also exist or are being developed, including use as semiconductors: some blue diamonds are natural semiconductors, in contrast to most diamonds, which are excellent electrical insulators. [30] The conductivity and blue color originate from boron impurity. Boron substitutes for carbon atoms in the diamond lattice, donating a hole into the valence band.

Substantial conductivity is commonly observed in nominally undoped diamond grown by chemical vapor deposition. This conductivity is associated with hydrogen-related species adsorbed at the surface, and it can be removed by annealing or other surface treatments.

Surface property

Diamonds are lipophilic and hydrophobic, which means the diamonds' surface cannot be wet by water but can be easily wet and stuck by oil. This property can be utilized to extract diamonds using oil when making synthetic diamonds.

Chemical stability

Diamonds are not very reactive. Under room temperature diamonds do not react with any chemical reagents including strong acids and bases. A diamond's surface can only be oxidized a little by just a few oxidants [which?] at high temperature (below 1,000 °C). Therefore, acids and bases can be used to refine synthetic diamonds.

Color



Brown diamonds at the National Museum of Natural History in Washington, D.C.

Diamond has a wide bandgap of 5.5 eV corresponding to the deep ultraviolet wavelength of 225 nanometers. This means pure diamond should transmit visible light and appear as a clear colorless crystal. Colors in diamond originate from lattice defects and impurities. The diamond crystal lattice is exceptionally strong and only atoms of nitrogen, boron and hydrogen can be introduced into diamond during the growth at significant concentrations (up to atomic percents). Transition metals Ni and Co, which are commonly used for growth of synthetic diamond by high-pressure high-temperature techniques, have been detected in diamond as individual atoms; the maximum concentration is 0.01% for Ni[33] and even much less for Co. Virtually any element can be introduced to diamond by ion implantation.

Nitrogen is by far the most common impurity found in gem diamonds and is responsible for the yellow and brown color in diamonds. Boron is responsible for the blue color.[21] Color in diamond has two additional sources: irradiation (usually by alpha particles), that causes the color in green diamonds; and plastic deformation of the diamond crystal lattice. Plastic deformation is the cause of color in some brown[35] and perhaps pink and red diamonds.[36] In order of rarity, yellow diamond is followed by brown, colorless, then by blue, green, black, pink, orange, purple, and red.[29] "Black", or Carbonado, diamonds are not truly black, but rather contain numerous dark inclusions that give the gems their dark appearance. Colored diamonds contain impurities or structural defects that cause the coloration, while pure or nearly pure diamonds are transparent and colorless. Most diamond impurities replace a carbon atom in the crystal lattice, known as a carbon flaw. The most common impurity, nitrogen, causes a slight to intense yellow coloration depending upon the type and concentration of nitrogen present.[29] The Gemological Institute of America (GIA) classifies low saturation yellow and brown diamonds as diamonds in the normal color range, and applies a grading scale from "D" (colorless) to "Z" (light yellow). Diamonds of a different color, such as blue, are called fancy colored diamonds, and fall under a different grading scale.

In 2008, the Wittelsbach Diamond, a 35.56-carat (7.11 g) blue diamond once belonging to the King of Spain, fetched over US\$24 million at a Christie's auction.[37] In May 2009, a 7.03-carat (1.41 g) blue diamond fetched the highest price per carat ever paid for a diamond when it was sold at auction for 10.5 million Swiss francs (6.97 million euro or US\$9.5 million at the time).[38] That record was however

beaten the same year: a 5-carat (1.0 g) vivid pink diamond was sold for \$10.8 million in Hong Kong on December 1, 2009.

Identification

Diamonds can be identified by their high thermal conductivity. Their high refractive index is also indicative, but other materials have similar refractivity. Diamonds cut glass, but this does not positively identify a diamond because other materials, such as quartz, also lie above glass on the Mohs scale and can also cut it. Diamonds can scratch other diamonds, but this can result in damage to one or both stones. Hardness tests are infrequently used in practical gemology because of their potentially destructive nature.[25] The extreme hardness and high value of diamond means that gems are typically polished slowly using painstaking traditional techniques and greater attention to detail than is the case with most other gemstones;[8] these tend to result in extremely flat, highly polished facets with exceptionally sharp facet edges. Diamonds also possess an extremely high refractive index and fairly high dispersion. Taken together, these factors affect the overall appearance of a polished diamond and most diamantaires still rely upon skilled use of a loupe (magnifying glass) to identify diamonds 'by eye'.

Industry



A round brilliant cut diamond set in a ring

Cutting





The Darya-I-Nur Diamond—an example of unusual diamond cut and jewelry arrangement

Mined rough diamonds are converted into gems through a multi-step process called "cutting". Diamonds are extremely hard, but also brittle and can be split up by a single blow. Therefore, diamond cutting is traditionally considered as a delicate procedure requiring skills, scientific knowledge, tools and experience. Its final goal is to produce a faceted jewel where the specific angles between the facets would optimize the diamond luster, that is dispersion of white light, whereas the number and area of facets would determine the weight of the final product. The weight reduction upon cutting is significant and can be of the order of 50%.[61] Several possible shapes are considered, but the final decision is often determined not only by scientific, but also practical considerations. For example the diamond might be intended for display or for wear, in a ring or a necklace, singled or surrounded by other gems of certain color and shape.

The most time-consuming part of the cutting is the preliminary analysis of the rough stone. It needs to address a large number of issues, bears much responsibility, and therefore can last years in case of unique diamonds. The following issues are considered:

The hardness of diamond and its ability to cleave strongly depend on the crystal orientation. Therefore, the crystallographic structure of the diamond to be cut is analyzed using X-ray diffraction to choose the optimal cutting directions.

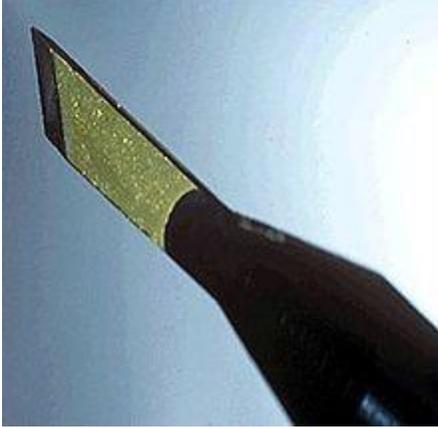
Most diamonds contain visible non-diamond inclusions and crystal flaws. The cutter has to decide which flaws are to be removed by the cutting and which could be kept.

The diamond can be split by a single, well calculated blow of a hammer to a pointed tool, which is quick, but risky. Alternatively, it can be cut with a diamond saw, which is a more reliable but tedious procedure.

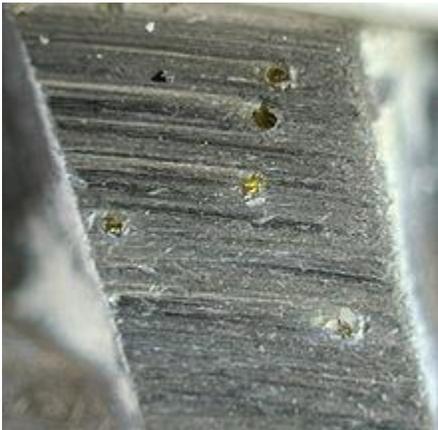
After initial cutting, the diamond is shaped in numerous stages of polishing. Unlike cutting, which is a responsible but quick operation, polishing removes material by gradual erosion and is extremely time consuming. The associated technique is well developed; it is considered as a routine and can be performed by technicians.[64] After polishing, the diamond is reexamined for possible flaws, either remaining or induced by the process. Those flaws are concealed through various diamond enhancement techniques, such as repolishing, crack filling, or clever arrangement of the stone in the jewelry. Remaining non-diamond inclusions are removed through laser drilling and filling of the voids produced.

If buyers are only able to purchase the diamond mounted, so that buyers are unable to fully inspect the product, or if the diamond comes without a full GIA lab grading report, or a written guarantee that it was sourced from a legitimate supplier, these are other indicators of a lower valued diamond.[72]

Industrial-grade diamonds



A scalpel with synthetic diamond blade



Close-up photograph of an angle grinder blade with tiny diamonds shown embedded in the metal

Industrial diamonds are valued mostly for their hardness and thermal conductivity, making many of the gemological characteristics of diamonds, such as the 4 Cs, irrelevant for most applications. This helps explain why 80% of mined diamonds (equal to about 135,000,000 carats (27,000 kg) annually), unsuitable for use as gemstones, are destined for industrial use. In addition to mined diamonds, synthetic diamonds found industrial applications almost immediately after their invention in the 1950s; another 570,000,000 carats (110,000 kg) of synthetic diamond is produced annually for industrial use. Approximately 90% of diamond grinding grit is currently of synthetic origin.

The boundary between gem-quality diamonds and industrial diamonds is poorly defined and partly depends on market conditions (for example, if demand for polished diamonds is high, some suitable stones will be polished into low-quality or small gemstones rather than being sold for industrial use). Within the category of industrial diamonds, there is a sub-category comprising the lowest-quality, mostly opaque stones, which are known as bort.

Industrial use of diamonds has historically been associated with their hardness; this property makes diamond the ideal material for cutting and grinding tools. As the hardest known naturally occurring material, diamond can be used to polish, cut, or wear away any material, including other diamonds. Common industrial adaptations of this ability include diamond-tipped drill bits and saws, and the use of diamond powder as an abrasive. Less expensive industrial-grade diamonds, known as bort, with more flaws and poorer color than gems, are used for such purposes.[75] Diamond is not suitable for machining ferrous alloys at high speeds, as carbon is soluble in iron at the high temperatures created by high-speed machining, leading to greatly increased wear on diamond tools compared to alternatives.

Specialized applications include use in laboratories as containment for high pressure experiments (see diamond anvil cell), high-performance bearings, and limited use in specialized windows.[74] With the continuing advances being made in the production of synthetic diamonds, future applications are becoming feasible. Garnering much excitement is the possible use of diamond as a semiconductor suitable to build microchips, or the use of diamond as a heat sink[77] in electronics.

Mining

Approximately 130,000,000 carats (26,000 kg) of diamonds are mined annually, with a total value of nearly US\$9 billion, and about 100,000 kg (220,000 lb) are synthesized annually.

Roughly 49% of diamonds originate from Central and Southern Africa, although significant sources of the mineral have been discovered in Canada, India, Russia, Brazil, and Australia.[73] They are mined from kimberlite and lamproite volcanic pipes, which can bring diamond crystals, originating from deep within the Earth where high pressures and temperatures enable them to form, to the surface. The mining and distribution of natural diamonds are subjects of frequent controversy such as concerns over the sale of blood diamonds or conflict diamonds by African paramilitary groups.[79] The diamond supply chain is controlled by a limited number of powerful businesses, and is also highly concentrated in a small number of locations around the world.

Only a very small fraction of the diamond ore consists of actual diamonds. The ore is crushed, during which care is required not to destroy larger diamonds, and then sorted by density. Today, diamonds are located in the diamond-rich density fraction with the help of X-ray fluorescence, after which the final sorting steps are done by hand. Before the use of X-rays became commonplace,[61] the separation was done with grease belts; diamonds have a stronger tendency to stick to grease than the other minerals in the ore.





Siberia's Udachnaya diamond mine

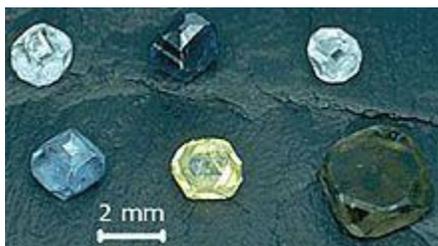
Historically, diamonds were found only in alluvial deposits in Guntur and Krishna district of the Krishna River delta in Southern India.[80] India led the world in diamond production from the time of their discovery in approximately the 9th century BC[4][81] to the mid-18th century AD, but the commercial potential of these sources had been exhausted by the late 18th century and at that time India was eclipsed by Brazil where the first non-Indian diamonds were found in 1725.[4] Currently, one of the most prominent Indian mines is located at Panna.[82]

Diamond extraction from primary deposits (kimberlites and lamproites) started in the 1870s after the discovery of the Diamond Fields in South Africa.[83] Production has increased over time and now an accumulated total of 4,500,000,000 carats (900,000 kg) have been mined since that date.[84] Twenty percent of that amount has been mined in the last five years, and during the last 10 years, nine new mines have started production; four more are waiting to be opened soon. Most of these mines are located in Canada, Zimbabwe, Angola, and one in Russia.[84]

In the U.S., diamonds have been found in Arkansas, Colorado, Wyoming, and Montana.[85][86] In 2004, the discovery of a microscopic diamond in the U.S. led to the January 2008 bulk-sampling of kimberlite pipes in a remote part of Montana.

Today, most commercially viable diamond deposits are in Russia (mostly in Sakha Republic, for example Mir pipe and Udachnaya pipe), Botswana, Australia (Northern and Western Australia) and the Democratic Republic of Congo.[87] In 2005, Russia produced almost one-fifth of the global diamond output, reports the British Geological Survey. Australia boasts the richest diamantiferous pipe, with production from the Argyle diamond mine reaching peak levels of 42 metric tons per year in the 1990s.[85][88] There are also commercial deposits being actively mined in the Northwest Territories of Canada and Brazil.[73] Diamond prospectors continue to search the globe for diamond-bearing kimberlite and lamproite pipes.

Synthetics



Synthetic diamonds of various colors grown by the high-pressure high-temperature technique

Synthetic diamonds are diamonds manufactured in a laboratory, as opposed to diamonds mined from the Earth. The gemological and industrial uses of diamond have created a large demand for rough stones. This demand has been satisfied in large part by synthetic diamonds, which have been manufactured by various processes for more than half a century. However, in recent years it has become possible to produce gem-quality synthetic diamonds of significant size.[11]

The majority of commercially available synthetic diamonds are yellow and are produced by so-called High Pressure High Temperature (HPHT) processes.[93] The yellow color is caused by nitrogen impurities. Other colors may also be reproduced such as blue, green or pink, which are a result of the addition of boron or from irradiation after synthesis.[94]



Colorless gem cut from diamond grown by chemical vapor deposition

Another popular method of growing synthetic diamond is chemical vapor deposition (CVD). The growth occurs under low pressure (below atmospheric pressure). It involves feeding a mixture of gases (typically 1 to 99 methane to hydrogen) into a chamber and splitting them to chemically active radicals in a plasma ignited by microwaves, hot filament, arc discharge, welding torch or laser.[95] This method is mostly used for coatings, but can also produce single crystals several millimeters in size (see picture).[78]

At present, the annual production of gem quality synthetic diamonds is only a few thousand carats, whereas the total production of natural diamonds is around 120,000,000 carats (24,000 kg). Despite this fact, a purchaser is more likely to encounter a synthetic when looking for a fancy-colored diamond because nearly all synthetic diamonds are fancy-colored, while only 0.01% of natural diamonds are.[96]

Simulants





Gem-cut synthetic silicon carbide set in a ring

A diamond simulant is a non-diamond material that is used to simulate the appearance of a diamond, and may be referred to as diamante. Cubic zirconia is the most common. The gemstone Moissanite (silicon carbide) can be treated as a diamond simulant, though more costly to produce than cubic zirconia. Both are produced synthetically

Enhancements

Diamond enhancements are specific treatments performed on natural or synthetic diamonds (usually those already cut and polished into a gem), which are designed to better the gemological characteristics of the stone in one or more ways. These include laser drilling to remove inclusions, application of sealants to fill cracks, treatments to improve a white diamond's color grade, and treatments to give fancy color to a white diamond.[98]

Coatings are increasingly used to give a diamond simulant such as cubic zirconia a more "diamond-like" appearance. One such substance is diamond-like carbon—an amorphous carbonaceous material that has some physical properties similar to those of the diamond. Advertising suggests that such a coating would transfer some of these diamond-like properties to the coated stone, hence enhancing the diamond simulant. Techniques such as Raman spectroscopy should easily identify such a treatment.[99]

Identification

Early diamond identification tests included a scratch test relying on the superior hardness of diamond. This test is destructive, as a diamond can scratch diamond, and is rarely used nowadays. Instead, diamond identification relies on its superior thermal conductivity. Electronic thermal probes are widely used in the gemological centers to separate diamonds from their imitations. These probes consist of a pair of battery-powered thermistors mounted in a fine copper tip. One thermistor functions as a heating device while the other measures the temperature of the copper tip: if the stone being tested is a diamond, it will conduct the tip's thermal energy rapidly enough to produce a measurable temperature drop. This test takes about 2–3 seconds.[100]

Whereas the thermal probe can separate diamonds from most of their simulants, distinguishing between various types of diamond, for example synthetic or natural, irradiated or non-irradiated, etc., requires more advanced, optical techniques. Those techniques are also used for some diamonds simulants, such as silicon carbide, which pass the thermal conductivity test. Optical techniques can distinguish between natural diamonds and synthetic diamonds. They can also identify the vast majority of treated natural diamonds.[101] "Perfect" crystals (at the atomic lattice level) have never been found, so both natural and synthetic diamonds always possess characteristic imperfections, arising from the circumstances of their crystal growth, that allow them to be distinguished from each other.[102]

Laboratories use techniques such as spectroscopy, microscopy and luminescence under shortwave ultraviolet light to determine a diamond's origin.[101] They also use specially made instruments to aid them in the identification process. Two screening instruments are the DiamondSure and the DiamondView, both produced by the DTC and marketed by the GIA.[103]

Several methods for identifying synthetic diamonds can be performed, depending on the method of production and the color of the diamond. CVD diamonds can usually be identified by an orange fluorescence. D-J colored diamonds can be screened through the Swiss Gemmological Institute's[104] Diamond Spotter. Stones in the D-Z color range can be examined through the DiamondSure UV/visible spectrometer, a tool developed by De Beers.[102] Similarly, natural diamonds usually have minor imperfections and flaws, such as inclusions of foreign material, that are not seen in synthetic diamonds.

Diamond cutting

Diamond cutting is the practice of changing a [diamond](#) from a rough stone into a [faceted](#) gem. Cutting diamond requires specialized knowledge, tools, equipment, and techniques because of its extreme difficulty.

The first guild of diamond cutters and polishers (diamantaire) was formed in 1375 in [Nuremberg, Germany](#), and led to the development of various types of '**cut**'. This has two meanings in relation to diamonds. The first is the shape: square, oval, and so on. The second relates to the specific quality of cut within the shape, and the quality and price will vary greatly based on the cut quality. Since diamonds are very hard to cut, special diamond-bladed edges are used to cut them. The first major development in diamond cutting came with the "Point Cut" during the later half of the 14th century: the Point Cut follows the natural shape of an octahedral raw diamond crystal, eliminating some waste in the cutting process.

Cutting process

It is possible only because the [hardness](#) of [diamond](#) varies widely according to the direction in which one is trying to cut or grind.

A simplified [round brilliant cut](#) process includes the following stages:

- Sawing the rough stone.
- Table setting where one facet is created. The table facet is then used to attach the stone into a [dop](#) (a [lapidary](#) tool holding gemstones for cutting or polishing).
- Bruting the girdle.
- Blocking four main pavilion facets.
- Transferring to another dop in order to rotate the stone.
- Blocking four main crown facets.
- Cutting and polishing all pavilion facets.

- Transferring to another dop.
- Cutting and polishing all crown facets.

This is just one, although a fairly common way of creating a round brilliant cut. The actual process also includes many more stages depending on the size and quality of the rough stone. For example, bigger stones are first scanned to get the three-dimensional shape, which is then used to find the optimal usage. The scanning may be repeated after each stage and bruting may be done in several steps, each bringing the girdle closer to the final shape.

Silicon Carbide (SiC)– Synthesis, Properties and Applications {TOPIC 1}

Topics Covered

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[Synthesizing Silicon Carbide](#)
[The Structure of Silicon Carbide](#)
[The Discovery of Silicon Carbide](#)
[Types of Silicon Carbide](#)
[Key Properties of Silicon Carbide](#)
[Major Applications of Silicon Carbide](#)
[Machining of Silicon Carbide](#)
[Insaco](#)

What is Silicon Carbide?

The Chemical Formula of [Silicon Carbide](#), which is also known carborundum, is SiC. It is produced by the carbothermal reduction of silica to form an ultra-hard covalently bonded material. It is extremely rare in nature but can be found in the mineral moissanite, which was first discovered in Arizona in 1893.



Precision machined sintered silicon carbide component produced by Insaco.

Synthesizing Silicon Carbide

Typically, [Silicon Carbide](#) is produced using the Acheson process which involves heating silica sand and carbon to high temperatures in an Acheson graphite resistance furnace. It can be formed as a fine powder or a bonded mass that must be crushed and milled before it can be used as a powder feedstock. Once the Silicon Carbide is in a powder form, the grains of the compound can be bonded together by sintering to form a very useful engineering ceramic, which has a wide range of uses in many manufacturing industries.

The Structure of Silicon Carbide

Many structures or polytypes have been identified for [Silicon Carbide](#). These polytypes have different stacking arrangements for the atoms of silicon and carbon in the compound. One of the simplest structures is the diamond structure, which is known as β -SiC. There are more complex hexagonal or rhombic structures of the compound and these are designated as α -SiC.

The Discovery of Silicon Carbide

Dr. Edward Goodrich Acheson was a scientist who once worked for Thomas Edison. He first synthesized [Silicon Carbide](#) by chance in the process of trying to create artificial diamonds. Diamonds could be, at least in theory, baked in the laboratory and so he decided to attempt to synthesize them using carbon based materials. In his experiment he attached a lead from a dynamo to a plumber's bowl, which was filled with clay and powdered coke.

When the mixture was subjected to the high heating temperature from the dynamo lead, he did not produce any diamonds, but he did notice a few bright specks on the end of the lead. He picked up the lead and drew it over a glass pane and it cut the pane like a diamond. What he had succeeded in developing was, the first man made substance that was hard enough to cut through glass.

He was also trying to dissolve carbon in molten corundum or alumina when he discovered the blue black colored crystals which he thought were a compound of corundum and carbon, hence why he called the material carborundum. This became the popular name for [Silicon Carbide](#) and was also the name of the company that Acheson founded. Although the first use of the compound was as an abrasive, it has since been subsequently developed to be used in electronic applications and many other engineering uses.

Types of Silicon Carbide

For use in commercial engineering applications [Silicon Carbide](#) products are produced in three forms. These are:

- Sintered silicon carbide (SSC)

- Nitride bonded silicon carbide (NBSC) and
- Reaction bonded silicon carbide (RBSC)

Other variations of the compound include clay bonded silicon carbide and SiAlON bonded silicon carbide. There is also chemical vapor deposited silicon carbide called CVD Silicon Carbide, which is an extremely pure form of the compound.

To sinter the [Silicon Carbide](#) its is necessary to add sintering aids which help to form a liquid phase at the sintering temperature which allows the grains of silicon carbide to bond together.

Key Properties of Silicon Carbide

[Silicon Carbide](#) has a refractive index that is greater than that of diamond. It has a high thermal conductivity and it has a low thermal expansion coefficient. This combination of these properties give it outstanding thermal shock resistance, which makes it useful to many industries. It is also a semiconductor and lends itself to a range of uses thanks to its electrical properties. It is also known for its extreme hardness and is very corrosion resistant.

The Table below provides further example data for Sintered Silicon Carbide.

Table 1. Properties of sintered silicon carbide.

Property	Minimum Value (S.I.)	Maximum Value (S.I.)	Units (S.I.)	Minimum Value (Imp.)	Maximum Value (Imp.)	Units (Imp.)
Atomic Volume (average)	0.0062	0.0064	m ³ /kmol	378.347	390.552	in ³ /kmol
Density	3	3.2	Mg/m ³	187.284	199.77	lb/ft ³
Energy Content	150	200	MJ/kg	16250.8	21667.7	kcal/lb
Bulk Modulus	181	189.8	GPa	26.2518	27.5281	10 ⁶ psi
Compressive Strength	3047.4	3359.9	MPa	441.988	487.312	ksi
Ductility	0.00076	0.00084		0.00076	0.00084	NULL
Elastic Limit	304.7	336	MPa	44.193	48.7327	ksi
Endurance Limit	259.17	302.37	MPa	37.5894	43.855	ksi
Fracture Toughness	4.28	4.72	MPa.m ^{1/2}	3.895	4.29542	ksi.in ^{1/2}
Hardness	23800	26250	MPa	3451.9	3807.24	ksi

Loss Coefficient	2e-005	5e-005		2e-005	5e-005	NULL
Modulus of Rupture	365.7	403.2	MPa	53.0403	58.4792	ksi
Poisson's Ratio	0.13	0.15		0.13	0.15	NULL
Shear Modulus	171.15	179.8	GPa	24.8232	26.0778	10 ⁶ psi
Tensile Strength	304.7	336	MPa	44.193	48.7327	ksi
Young's Modulus	390.2	410	GPa	56.5937	59.4654	10 ⁶ psi
Latent Heat of Fusion	930	1050	kJ/kg	399.826	451.416	BTU/lb
Maximum Service Temperature	1738	1808	K	2668.73	2794.73	°F
Melting Point	2424	2522	K	3903.53	4079.93	°F
Minimum Service Temperature	0	0	K	-459.67	-459.67	°F
Specific Heat	663	677	J/kg.K	0.513068	0.523902	BTU/lb.F
Thermal Conductivity	90	110	W/m.K	168.483	205.924	BTU.ft/h.ft ² .F
Thermal Expansion	2.7	2.8	10 ⁻⁶ /K	4.86	5.04	10 ⁻⁶ /°F
Breakdown Potential	5	10	MV/m	127	254	V/mil
Dielectric Constant	7	9		7	9	NULL
Resistivity	1e+009	3.16e+010	10 ⁻⁸ ohm.m	1e+009	3.16e+010	10 ⁻⁸ ohm.m

Major Applications of Silicon Carbide

There are many uses of [Silicon Carbide](#) in different industries. Its physical hardness makes it ideal to be used in abrasive machining processes like grinding, honing, sand blasting and water jet cutting.

The ability of [Silicon Carbide](#) to withstand very high temperatures without breaking or distorting is used in the manufacture of ceramic brake discs for sports cars. It is also used in bulletproof vests as an armor material and as a seal ring material for pump shaft sealing where it frequently

runs at high speed in contact with a similar silicon carbide seal. One of the major advantages in these applications being the high thermal conductivity of Silicon Carbide which is able to dissipate the frictional heat generated at a rubbing interface.

The high surface hardness of the material lead to it being used in many engineering applications where a high degree of sliding, erosive and corrosive wear resistance is required. Typically this can be in components used in pumps or for example as valves in oilfield applications where conventional metal components would display excessive wear rates that would lead to rapid failures.

The unique electrical properties of the compound as a semiconductor make it ideal for manufacturing ultra fast and high voltage light emitting diodes, MOSFETs and thyristors for high power switching.

The material's low thermal expansion coefficient, hardness, rigidity and thermal conductivity make it an ideal mirror material for astronomical telescopes. [Silicon Carbide](#) fibers, known as filaments are used to measure gas temperatures in an optical technique called thin filament pyrometry.

It is also used in heating elements where extremely high temperatures need to be accommodated. It is even used in nuclear power to provide structural supports in high temperature gas cooled reactors.

Machining of Silicon Carbide

In all of the applications outlined above, where a high precision engineering components are required, it is important to recognize the difficulties of machining [Silicon Carbide](#). Despite the high hardness values it displays, it is nevertheless a relatively brittle material and can only be machined using diamond grinding techniques. Consequently, it is beneficial that a skilled and experienced operator conducts the machining operations as incorrect procedures can generate sub-surface damage and micro-cracks that may lead to premature failure once the component is subjected to operating stresses in service.

Silicon Carbide, SiC Material Properties

{TOPIC 2}

Silicon Carbide is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Silicon carbide is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics, and numerous high-performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Structural and wear applications are constantly developing.

Key Silicon Carbide Properties

- ✓ Low density
- ✓ High strength
- ✓ Low thermal expansion
- ✓ High thermal conductivity
- ✓ High hardness
- ✓ High elastic modulus
- ✓ Excellent thermal shock resistance
- ✓ Superior chemical inertness

Silicon Carbide Typical Uses

- ✓ Fixed and moving turbine components
- ✓ Suction box covers
- ✓ Seals, bearings
- ✓ Ball valve parts
- ✓ Hot gas flow liners
- ✓ Heat exchangers
- ✓ Semiconductor process equipment

General Silicon Carbide Information

Silicon carbide is composed of tetrahedra of carbon and silicon atoms with strong bonds in the crystal lattice. This produces a very hard and strong material. Silicon carbide is not attacked by any acids or alkalis or molten salts up to 800°C. In air, SiC forms a protective silicon oxide coating at 1200°C and is able to be used up to 1600°C. The high thermal conductivity coupled with low thermal expansion and high strength give this material exceptional thermal shock resistant qualities. Silicon carbide ceramics with little or no grain boundary impurities maintain their strength to very high temperatures, approaching 1600°C with no strength loss. Chemical purity, resistance to chemical attack at temperature, and strength retention at high temperatures has made this material very popular as wafer tray supports and paddles in semiconductor furnaces. The electrical conduction of the material has led to its use in resistance heating

elements for electric furnaces, and as a key component in thermistors (temperature variable resistors) and in varistors (voltage variable resistors).

Silicon Carbide Engineering Properties*

Silicon Carbide Properties			
Mechanical	SI/Metric (Imperial)	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.1	(193.5)
Porosity	% (%)	0	(0)
Color	—	black	—
Flexural Strength	MPa (lb/in ² x10 ³)	550	(80)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	410	(59.5)
Shear Modulus	GPa (lb/in ² x10 ⁶)	—	—
Bulk Modulus	GPa (lb/in ² x10 ⁶)	—	—
Poisson's Ratio	—	0.14	(0.14)
Compressive Strength	MPa (lb/in ² x10 ³)	3900	(566)
Hardness	Kg/mm ²	2800	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	4.6	—
Maximum Use Temperature (no load)	°C (°F)	1650	(3000)
Thermal			
Thermal Conductivity	W/m•°K (BTU•in/ft ² •hr•°F)	120	(830)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	4.0	(2.2)
Specific Heat	J/Kg•°K (Btu/lb•°F)	750	(0.18)
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	—	semiconductor
Dielectric Constant	—	—	—

Dissipation Factor	—	—	—
Loss Tangent	—	—	—
Volume Resistivity	ohm•cm	10^2 – 10^6	dopant dependent

Sic {TOPIC 3}



Properties

Molecular formula	CSi
Molar mass	40.1 g mol ⁻¹
Appearance	Colorless crystals
Density	3.21 g·cm ⁻³ (all polytypes)[1]
Melting point	2730 °C, 3003 K, 4946 °F (decomposes)
Electron mobility	~900 cm ² /V·s (all polytypes)
Refractive index (n _D)	2.55 (infrared; all polytypes)[2]

Hazards

EU classification Not listed



NFPA 704

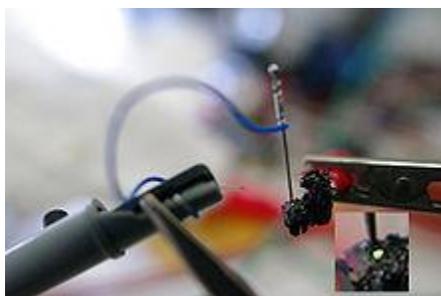
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Silicon carbide (SiC), also known as carborundum /kɑrbəˈrændəm/, is a compound of silicon and carbon with chemical formula SiC. It occurs in nature as the extremely rare mineral moissanite. Silicon carbide powder has been mass-produced since 1893 for use as an abrasive. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics which are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests. Electronic applications of silicon carbide as light emitting diodes (LEDs) and detectors in early radios were first demonstrated around 1907, and today SiC is widely used in high-temperature/high-voltage semiconductor electronics. Large single crystals of silicon carbide can be grown by the Lely method; they can be cut into gems known as synthetic moissanite. Silicon carbide with high surface area can be produced from SiO₂ contained in plant material.

Discovery and early production



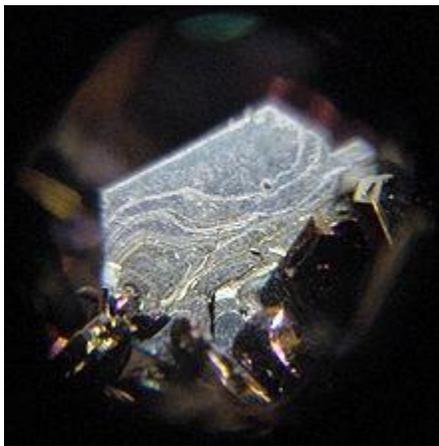
Non-systematic, less-recognized, and often unverified syntheses of silicon carbide were reported early, J. J. Berzelius's reduction of potassium fluorosilicate by potassium (1810); Charles Mansuète Despretz's (1792–1863) passing an electric current through a carbon rod embedded in sand (1849); Robert Sydney Marsden's (1856–1919) dissolution of silica in molten silver in a graphite crucible (1881); Albert Colson's heating of silicon under a stream of ethylene (1882); and Paul Schuetzenberger's heating of a mixture of silicon and silica in a graphite crucible (1881).[3] Nevertheless, wide-scale production is credited to Edward Goodrich Acheson in 1890. Acheson was attempting to prepare artificial diamonds when he heated a mixture of clay (aluminum silicate) and powdered coke (carbon) in an iron bowl. He called the

blue crystals that formed Carborundum, believing it to be a new compound of carbon and aluminum, similar to corundum. In 1893, Henri Moissan discovered the very rare naturally-occurring SiC mineral while examining rock samples found in the Canyon Diablo meteorite in Arizona. The mineral was named moissanite in his honor. Moissan also synthesized SiC by several routes, including: the dissolution of carbon in molten silicon; melting a mixture of calcium carbide and silica; and by reducing silica with carbon in an electric furnace. However, Moissan ascribed the original discovery of SiC to Acheson in 1903.[4]

Acheson patented the method for making silicon carbide powder on February 28, 1893.[5] Acheson also developed the electric batch furnace by which SiC is still made today and formed The Carborundum Company to manufacture bulk SiC, initially for use as an abrasive.[6] In 1900 the company settled with the Electric Smelting and Aluminum Company when a judge's decision gave "priority broadly" to its founders "for reducing ores and other substances by the incandescent method".[7] It is said that Acheson was trying to dissolve carbon in molten corundum (alumina) and discovered the presence of hard, blue-black crystals which he believed to be a compound of carbon and corundum: hence carborundum. It may be that he named the material "carborundum" by analogy to corundum, which is another very hard substance (9 on the Mohs scale).

The first use of SiC was as an abrasive. This was followed by electronic applications. In the beginning of the 20th century, silicon carbide was used as a detector in the first radios,[8] and in 1907 Henry Joseph Round produced the first LED by applying a voltage to a SiC crystal and observing yellow, green and orange emission at the cathode. Those experiments were later repeated by O. V. Losev in the Soviet Union in 1923.[9]

Natural occurrence



Moissanite single crystal (≈ 1 mm in size)

Naturally occurring moissanite is found in only minute quantities in certain types of meteorite and in corundum deposits and kimberlite. Virtually all the silicon carbide sold in the world, including moissanite

jewels, is synthetic. Natural moissanite was first found in 1893 as a small component of the Canyon Diablo meteorite in Arizona by Dr. Ferdinand Henri Moissan, after whom the material was named in 1905.[10] Moissan's discovery of naturally occurring SiC was initially disputed because his sample may have been contaminated by silicon carbide saw blades that were already on the market at that time.[11]

While rare on Earth, silicon carbide is remarkably common in space. It is a common form of stardust found around carbon-rich stars, and examples of this stardust have been found in pristine condition in primitive (unaltered) meteorites. The silicon carbide found in space and in meteorites is almost exclusively the beta-polymorph. Analysis of SiC grains found in the Murchison meteorite, a carbonaceous chondrite meteorite, has revealed anomalous isotopic ratios of carbon and silicon, indicating an origin from outside the solar system; 99% of these SiC grains originate around carbon-rich asymptotic giant branch stars.[12] SiC is commonly found around these stars as deduced from their infrared spectra.[13]

Production

Because of the rarity of natural moissanite, most silicon carbide is synthetic. It is used as an abrasive, and more recently as a semiconductor and diamond simulant of gem quality. The simplest manufacturing process is to combine silica sand and carbon in an Acheson graphite electric resistance furnace at a high temperature, between 1600 and 2500 °C. Fine SiO₂ particles in plant material (e.g. rice husks) can be converted to SiC by heating in the excess carbon from the organic material.[14] The silica fume, which is a byproduct of producing silicon metal and ferrosilicon alloys, also can be converted to SiC by heating with graphite at 1500 °C.[15]



Synthetic SiC crystals ~3 mm in diameter



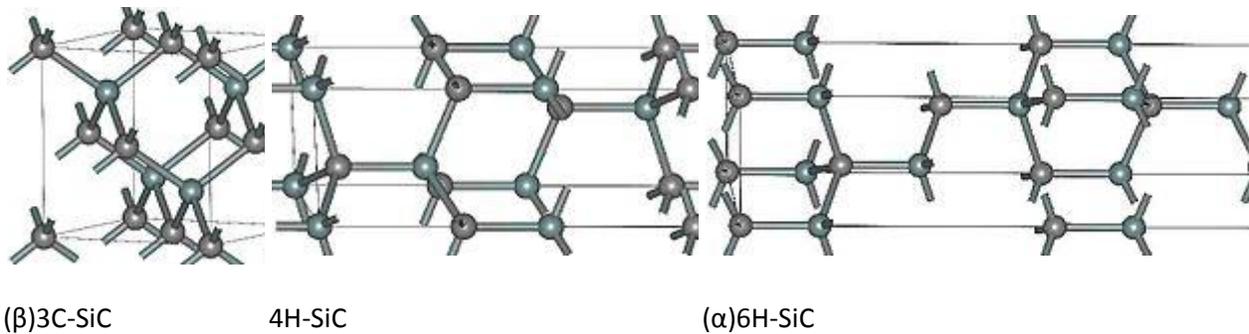
Synthetic SiC Lely crystals

The material formed in the Acheson furnace varies in purity, according to its distance from the graphite resistor heat source. Colorless, pale yellow and green crystals have the highest purity and are found closest to the resistor. The color changes to blue and black at greater distance from the resistor, and these darker crystals are less pure. Nitrogen and aluminium are common impurities, and they affect the electrical conductivity of SiC.[16]

Pure silicon carbide can be made by the so-called Lely process,[17] in which SiC powder is sublimated in argon atmosphere at 2500 °C and redeposited into flake-like single crystals,[18] sized up to 2×2 cm², at a slightly colder substrate. This process yields high-quality single crystals, mostly of 6H-SiC phase (because of high growth temperature). A modified Lely process involving induction heating in graphite crucibles yields even larger single crystals of 4 inches (10 cm) in diameter, having a section 81 times larger compared to the conventional Lely process.[19] Cubic SiC is usually grown by the more expensive process of chemical vapor deposition (CVD).[16][20] Homoepitaxial and heteroepitaxial SiC layers can be grown employing both gas and liquid phase approaches.[21] Pure silicon carbide can also be prepared by the thermal decomposition of a polymer, poly(methylsilane), under an inert atmosphere at low temperatures. Relative to the CVD process, the pyrolysis method is advantageous because the polymer can be formed into various shapes prior to thermalization into the ceramic.[21][22][23][24]

Structure and properties

Structure of major SiC polytypes.



Properties of major SiC polytypes[2][21]			
Polytype	3C (β)	4H	6H (α)
Crystal structure	Zinc blende (cubic)	Hexagonal	Hexagonal
Space group	T2d-F43m	C46v-P63mc	C46v-P63mc

Pearson symbol	cF8	hP8	hP12
Lattice constants (Å)	4.3596	3.0730; 10.053	3.0730; 15.11
Density (g/cm ³)	3.21	3.21	3.21
Bandgap (eV)	2.36	3.23	3.05
Bulk modulus (GPa)	250	220	220
Thermal conductivity (W cm ⁻¹ K ⁻¹) @ 300K (see [28] for temp. dependence)	3.6	3.7	4.9

Silicon carbide exists in about 250 crystalline forms.[25] The polymorphism of SiC is characterized by a large

family of similar crystalline structures called polytypes. They are variations of the same chemical compound that are identical in two dimensions and differ in the third. Thus, they can be viewed as layers stacked in a certain sequence.[26] Alpha silicon carbide (α -SiC) is the most commonly encountered polymorph; it is formed at temperatures greater than 1700 °C and has a hexagonal crystal structure (similar to Wurtzite). The beta modification (β -SiC), with a zinc blende crystal structure (similar to diamond), is formed at temperatures below 1700 °C.[27] Until recently, the beta form has had relatively few commercial uses, although there is now increasing interest in its use as a support for heterogeneous catalysts, owing to its higher surface area compared to the alpha form.

Pure SiC is colorless. The brown to black color of industrial product results from iron impurities. The rainbow-like luster of the crystals is caused by a passivation layer of silicon dioxide that forms on the surface.

The high sublimation temperature of SiC (approximately 2700 °C) makes it useful for bearings and furnace parts. Silicon carbide does not melt at any known pressure. It is also highly inert chemically. There is currently much interest in its use as a semiconductor material in electronics, where its high thermal conductivity, high electric field breakdown strength and high maximum current density make it more promising than silicon for high-powered devices.[29] SiC also has a very low coefficient of thermal expansion ($4.0 \times 10^{-6}/K$) and experiences no phase transitions that would cause discontinuities in thermal expansion.[16]

Electrical conductivity

Silicon carbide is a semiconductor, which can be doped n-type by nitrogen or phosphorus and p-type by aluminium, boron, gallium or beryllium.[2] Metallic conductivity has been achieved by heavy doping with boron, aluminium or nitrogen. Superconductivity has been detected in 3C-SiC:Al, 3C-SiC:B and 6H-SiC:B at the same temperature of 1.5 K.[27][30] A crucial difference is however observed for the magnetic field behavior between aluminium and boron doping: SiC:Al is type-II, same as Si:B. On the

contrary, SiC:B is type-I. In attempt to explain this difference, it was noted that Si sites are more important than carbon sites for superconductivity in SiC. Whereas boron substitutes carbon in SiC, Al substitutes Si sites. Therefore, Al and B "see" different environment that might explain different properties of SiC:Al and SiC:B.[31]

USES

Abrasive and cutting tools



Cutting disks made of SiC

In the arts, silicon carbide is a popular abrasive in modern lapidary due to the durability and low cost of the material. In manufacturing, it is used for its hardness in abrasive machining processes such as grinding, honing, water-jet cutting and sandblasting. Particles of silicon carbide are laminated to paper to create sandpapers and the grip tape on skateboards.

In 1982 an exceptionally strong composite of aluminium oxide and silicon carbide whiskers was discovered. Development of this laboratory-produced composite to a commercial product took only three years. In 1985, the first commercial cutting tools made from this alumina and silicon carbide whisker-reinforced composite were introduced by the Advanced Composite Materials Corporation (ACMC) and Greenleaf Corporation.[33]

[edit] Structural material





Silicon carbide is used for trauma plates of ballistic vests

In the 1980s and 1990s, silicon carbide was studied in several research programs for high-temperature gas turbines in Europe, Japan and the United States. The components were intended to replace nickel superalloy turbine blades or nozzle vanes. However, none of these projects resulted in a production quantity, mainly because of its low impact resistance and its low fracture toughness.

Like other hard ceramics (namely alumina and boron carbide), silicon carbide is used in composite armor (e.g. Chobham armor), and in ceramic plates in bulletproof vests. Dragon Skin, which is produced by Pinnacle Armor, uses disks of silicon carbide.

Silicon carbide is used as a support and shelving material in high temperature kilns such as for firing ceramics, glass fusing, or glass casting. SiC kiln shelves are considerably lighter and more durable than traditional alumina shelves.

Automobile parts



The Porsche Carrera GT's carbon-ceramic (silicon carbide) disc brake

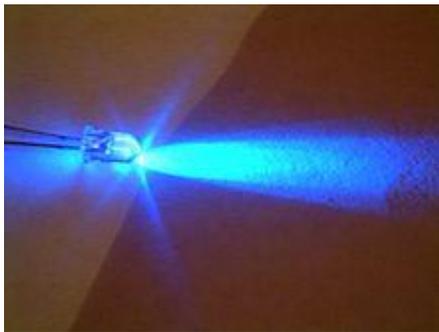
Silicon-infiltrated carbon-carbon composite is used for high performance "ceramic" brake discs, as it is able to withstand extreme temperatures. The silicon reacts with the graphite in the carbon-carbon composite to become carbon-fiber-reinforced silicon carbide (C/SiC). These discs are used on some road-going sports cars, including the Porsche Carrera GT, the Bugatti Veyron, the Chevrolet Corvette ZR1, Bentleys, Ferraris, Lamborghinis, and some specific high performance Audis.[37] Silicon carbide is also used in a sintered form for diesel particulate filters.[38]

Electric systems

The earliest electrical application of SiC was in lightning arresters in electric power systems. These devices must exhibit high resistance until the voltage across them reaches a certain threshold V_T , at which point their resistance must drop to a lower level and maintain this level until the applied voltage drops below V_T .

It was recognized early on that SiC had such a voltage-dependent resistance, and so columns of SiC pellets were connected between high-voltage power lines and the earth. When a lightning strike to the line raises the line voltage sufficiently, the SiC column will conduct, allowing strike current to pass harmlessly to the earth instead of along the power line. Such SiC columns proved to conduct significantly at normal power-line operating voltages and thus had to be placed in series with a spark gap. This spark gap is ionized and rendered conductive when lightning raises the voltage of the power line conductor, thus effectively connecting the SiC column between the power conductor and the earth. Spark gaps used in lightning arresters are unreliable, either failing to strike an arc when needed or failing to turn off afterwards, in the latter case due to material failure or contamination by dust or salt. Usage of SiC columns was originally intended to eliminate the need for the spark gap in a lightning arrester. Gapped SiC lightning arresters were used as lightning-protection tool and sold under GE and Westinghouse brand names, among others. The gapped SiC arrester has been largely displaced by no-gap varistors that use columns of zinc oxide pellets.

Electronic circuit elements



Ultraviolet LED

Power electronic devices

Silicon carbide is a semiconductor in research and early mass-production providing advantages for fast, high-temperature and/or high-voltage devices. First devices available were Schottky diodes, followed by Junction-gate FETs and MOSFETs for high-power switching. Bipolar transistors and thyristors are currently developed.[29] A major problem for SiC commercialization has been the elimination of defects: edge dislocations, screw dislocations (both hollow and closed core), triangular defects and basal plane dislocations.[41] As a result, devices made of SiC crystals initially displayed poor reverse blocking performance though researchers have been tentatively finding solutions to improving the breakdown performance.[42] Apart from crystal quality, problems with the interface of SiC with silicon dioxide have hampered the development of SiC-based power MOSFETs and insulated-gate bipolar transistors. Although the mechanism is still unclear, nitridation has dramatically reduced the defects causing the interface problems.[43] In 2008, the first commercial JFETs rated at 1200 V were introduced to the market, followed in 2011 by the first commercial MOSFETs rated at 1200 V. Beside SiC switches and SiC Schottky diodes (also Schottky barrier diode - SBD) in the popular TO-247 package, companies started

even earlier to implement the bare chips into their power modules. SiC SBD diodes found wide market spread being used in PFC circuits and IGBT power modules.

LEDs

The history of SiC LEDs is quite remarkable: the first LED action was demonstrated in 1907 using SiC and the first commercial LEDs were again based on SiC. Yellow LEDs made from 3C-SiC were manufactured in the Soviet Union in the 1970s,[44] and blue ones (6H-SiC) worldwide in the 1980s.[45] The production was soon stopped because gallium nitride showed 10–100 times brighter emission. This difference in efficiency is due to the unfavorable indirect bandgap of SiC, whereas GaN has a direct bandgap which favors light emission. However, SiC is still one of the important LED components – it is a popular substrate for growing GaN devices, and it also serves as a heat spreader in high-power LEDs.[45]

Astronomy

The low thermal expansion coefficient, high hardness, rigidity and thermal conductivity make silicon carbide a desirable mirror material for astronomical telescopes. The growth technology (chemical vapor deposition) has been scaled up to produce disks of polycrystalline silicon carbide up to 3.5 meters in diameter, and several telescopes (like the Herschel Space Telescope) are already equipped with SiC optics.[46][47]

Thin filament pyrometry





Image of the test flame and glowing SiC fibers. The flame is about 7 cm tall.

Silicon carbide fibers are used to measure gas temperatures in an optical technique called thin filament pyrometry. It involves the placement of a thin filament in a hot gas stream. Radiative emissions from the filament can be correlated with filament temperature. Filaments are SiC fibers with a diameter of 15 micrometers; about one fifth that of a human hair. Because the fibers are so thin, they do little to disturb the flame and their temperature remains close to that of the local gas. Temperatures of about 800–2500 K can be measured.

Heating elements

References to silicon carbide heating elements exist from the early 20th century when they were produced by Acheson's Carborundum Co. in the U.S. and EKL in Berlin. Silicon carbide offered increased operating temperatures compared with metallic heaters. Silicon carbide elements are used today in the melting of non-ferrous metals and glasses, heat treatment of metals, float glass production, production of ceramics and electronics components, igniters in pilot lights for gas heaters, etc.

Nuclear fuel particles

Silicon carbide is an important material in TRISO-coated fuel particles, the type of nuclear fuel found in high temperature gas cooled reactors (such as the Pebble Bed Reactor). A layer of silicon carbide gives coated fuel particles structural support and is the main diffusion barrier to the release of fission products.

Nuclear fuel cladding

Silicon carbide composite material has been investigated for use as a replacement for Zircaloy cladding in light water reactors. The composite consists of SiC fibers wrapped around a SiC inner layer and surrounded by an SiC outer layer.[52] Problems have been reported with the ability to join the pieces of the SiC composite.

Jewelry



A moissanite ring

As a gemstone used in jewelry, silicon carbide is called "synthetic moissanite" or just "moissanite" after the mineral name. Moissanite is similar to diamond in several important respects: it is transparent and

hard (9-9.5) on the Mohs scale (compared to 10 for diamond), with a refractive index between 2.65 and 2.69 (compared to 2.42 for diamond). Moissanite is somewhat harder than common cubic zirconia. Unlike diamond, moissanite can be strongly birefringent. This quality is desirable in some optical applications, but not in gemstones. For this reason, moissanite jewels are cut along the optic axis of the crystal to minimize birefringent effects. It is lighter (density 3.21 g/cm³ vs. 3.53 g/cm³), and much more resistant to heat than diamond. This results in a stone of higher luster, sharper facets and good resilience. Loose moissanite stones may be placed directly into wax ring moulds for lost-wax casting; unlike diamond, which burns at 800 °C, moissanite remains undamaged by temperatures up to 1800 °C. Moissanite has become popular as a diamond substitute, and may be misidentified as diamond, since its thermal conductivity is much closer to that of diamond than any other diamond substitute. Many thermal diamond-testing devices cannot distinguish moissanite from diamond, but the gem is distinct in its birefringence and a very slight green or yellow fluorescence under ultraviolet light. Some moissanite stones also have curved string-like inclusions, which diamonds never have.[54]

Steel production



Piece of silicon carbide used in steel making

Silicon carbide, dissolved in a basic oxygen furnace used for making steel, acts as a fuel. The additional energy liberated allows the furnace to process more scrap with the same charge of hot metal. It can also be used to raise tap temperatures and adjust the carbon and silicon content. Silicon carbide is cheaper than of a combination of ferrosilicon and carbon, produces cleaner steel and less emissions due to low level of trace elements, has a low gas content, and does not lower the temperature of steel.[55]

Catalyst support

The natural resistance to oxidation exhibited by silicon carbide, as well as the discovery of new ways to synthesize the cubic β -SiC form, with its larger surface area, has led to significant interest in its use as a heterogeneous catalyst support. This form has already been employed as a catalyst support for the oxidation of hydrocarbons, such as n-butane, to maleic anhydride.

Carborundum printmaking

Silicon carbide is used in carborundum printmaking – a collagraph printmaking technique. Carborundum grit is applied in a paste to the surface of an aluminium plate. When the paste is dry, ink is applied and trapped in its granular surface, then wiped from the bare areas of the plate. The ink plate is then printed onto paper in a rolling-bed press used for intaglio printmaking. The result is a print of painted marks embossed into the paper

Graphene production

Silicon carbide is used to produce epitaxial graphene by graphitization at high temperatures. This is considered as one of the promising methods to synthesize graphene at large scale for practical applications.

Silicon nitride

Silicon nitride



Properties

Molecular formula	N_4Si_3
Molar mass	$140.28 \text{ g mol}^{-1}$
Appearance	grey, odorless powder
Density	3.2 g/cm^3 , solid

Melting point 1900 °C, 2173 K, 3452 °F (decomposes)

Refractive index (n_D) 2.016^[1]

Related compounds

Other **anions** [silicon carbide](#), [silicon dioxide](#)

Other **cations** [boron nitride](#)

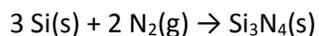
Silicon nitride is a chemical compound of [silicon](#) and [nitrogen](#). If powdered silicon is heated between 1300 °C and 1400 °C in an atmosphere of nitrogen, trisilicon tetranitride, Si₃N₄ is formed. The silicon sample weight increases progressively due to the chemical combination of silicon and nitrogen. Without an iron catalyst, the reaction is complete after several hours (~7), when no further weight increase due to nitrogen absorption (per gram of silicon) is detected. In addition to Si₃N₄, several other silicon nitride phases (with chemical formulas corresponding to varying degrees of nitridation/Si oxidation state) have been reported in the literature, for example, the gaseous disilicon mononitride (Si₂N); silicon mononitride (SiN), and silicon sesquinitride (Si₂N₃), each of which are stoichiometric phases. As with other [refractories](#), the products obtained in these high-temperature syntheses depends on the reaction conditions (e.g. time, temperature, and starting materials including the reactants and container materials), as well as the mode of purification. However, the existence of the sesquinitride has since come into question.^[2]

The Si₃N₄ phase is the most chemically inert (being decomposed by dilute HF and hot H₂SO₄). It is also the most thermodynamically stable of the silicon nitrides. Hence, Si₃N₄ is the most commercially important of the silicon nitrides^[3] and is generally understood as what is being referred to where the term "silicon nitride" is used.

Silicon nitride (i.e. Si₃N₄) is a hard [ceramic](#) having high strength over a broad temperature range, moderate [thermal conductivity](#), low [coefficient of thermal expansion](#), moderately high [elastic modulus](#), and unusually high [fracture toughness](#) for a ceramic. This combination of properties leads to excellent thermal shock resistance, ability to withstand high structural loads to high temperature, and superior [wear resistance](#). Silicon nitride is mostly used in high-endurance and high-temperature applications, such as gas turbines, car engine parts, [bearings](#) and metal working and cutting tools. Silicon nitride bearings were used in the main engines of the [NASA Space shuttles](#). Thin silicon nitride films are a popular insulating layer in silicon-based electronics and silicon nitride cantilevers are the sensing parts of [atomic force microscopes](#).

Synthesis

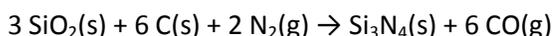
Silicon nitride can be obtained by direct reaction between [silicon](#) and [nitrogen](#) at temperatures between 1300 and 1400 °C:^[5]



by [diimide](#) synthesis:^[5]

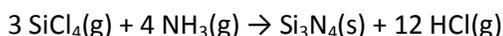
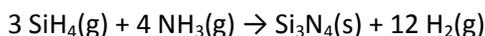


or by [carbothermal reduction](#) in nitrogen atmosphere at 1400–1450 °C:^[5]



The nitridation of silicon powder was developed in the 1950s, following the "rediscovery" of silicon nitride and was the first large-scale method for powder production. However, use of low-purity raw silicon caused contamination of silicon nitride by [silicates](#) and [iron](#). The diimide decomposition results in amorphous silicon nitride, which needs further annealing under nitrogen at 1400–1500 °C to convert it to crystalline powder; this is now the second-most important route for commercial production. The carbothermal reduction was the earliest used method for silicon nitride production and is now considered as the most-cost-effective industrial route to high-purity silicon nitride powder.^[5]

Electronic-grade silicon nitride films are formed using [chemical vapor deposition](#) (CVD), or one of its variants, such as [plasma-enhanced chemical vapor deposition](#) (PECVD):^{[5][9]}



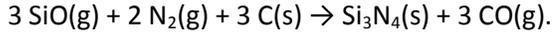
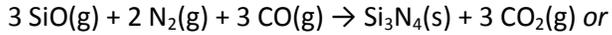
For deposition of silicon nitride layers on semiconductor (usually silicon) substrates, two methods are used:^[9]

1. Low pressure chemical vapor deposition (LPCVD) technology, which works at rather high temperature and is done either in a vertical or in a horizontal tube furnace,^[10] or
2. Plasma-enhanced chemical vapor deposition (PECVD) technology, which works at rather low temperature and vacuum conditions.

The [lattice constants](#) of silicon nitride and silicon are different. Therefore [tension](#) or [stress](#) can occur, depending on the deposition process. Especially when using PECVD technology this tension can be reduced by adjusting deposition parameters

Silicon nitride [nanowires](#) can also be produced by [sol-gel](#) method using carbothermal [reduction](#) followed by nitridation of [silica gel](#), which contains ultrafine carbon particles. The particles can be produced by decomposition of [dextrose](#) in the temperature range 1200–1350 °C. The possible synthesis reactions are:^[12]



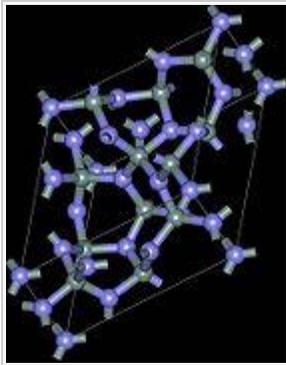


Processing

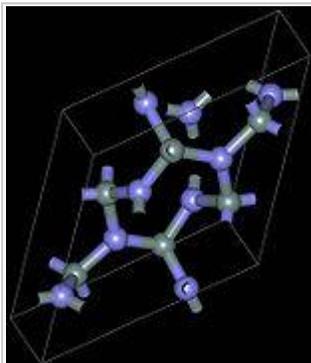
Silicon nitride is difficult to produce as a bulk material—it cannot be heated over 1850 °C, which is well below its [melting point](#), due to dissociation to silicon and nitrogen. Therefore, application of conventional [hot press sintering](#) techniques is problematic. Bonding of silicon nitride powders can be achieved at lower temperatures through adding additional materials (sintering aids or "binders") which commonly induce a degree of liquid phase sintering.^[13] A cleaner alternative is to use [spark plasma sintering](#) where heating is conducted very rapidly (seconds) by passing pulses of electric current through the compacted powder. Dense silicon nitride compacts have been obtained by this techniques at temperatures 1500–1700 °C.

Crystal structure and properties

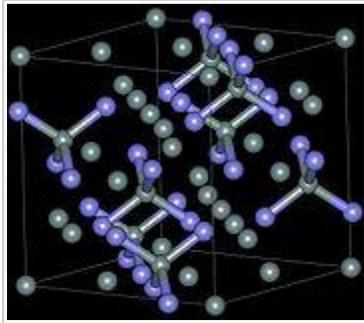
Blue atoms are nitrogen and grey are silicon atoms



trigonal α -Si₃N₄.

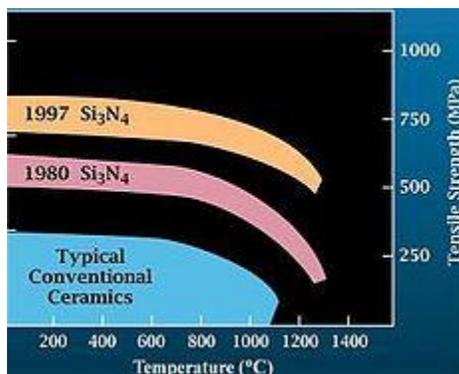


hexagonal β -Si₃N₄



cubic γ - Si_3N_4

There exist three [crystallographic](#) structures of silicon nitride (Si_3N_4), designated as α , β and γ phases.^[16] The α and β phases are the most common forms of Si_3N_4 , and can be produced under normal pressure condition. The γ phase can only be synthesized under high pressures and temperatures and has a hardness of 35 GPa.



The α - and β - Si_3N_4 have [trigonal](#) (Pearson symbol hP28, [space group](#) P31c, No. 159) and [hexagonal](#) (hP14, P6₃, No. 173) structures, respectively, which are built up by corner-sharing SiN_4 [tetrahedra](#). They can be regarded as consisting of layers of silicon and nitrogen atoms in the sequence ABAB... or ABCDABCD... in β - Si_3N_4 and α - Si_3N_4 , respectively. The AB layer is the same in the α and β phases, and the CD layer in the α phase is related to AB by a c-glide plane. The Si_3N_4 tetrahedra in β - Si_3N_4 are interconnected in such a way that tunnels are formed, running parallel with the c axis of the unit cell. Due to the c-glide plane that relates AB to CD, the α structure contains cavities instead of tunnels. The cubic γ - Si_3N_4 is often designated as c modification in the literature, in analogy with the cubic modification of [boron nitride](#) (c-BN). It has a [spinel](#)-type structure in which two silicon atoms each coordinate six nitrogen atoms octahedrally, and one silicon atom coordinates four nitrogen atoms tetrahedrally.

The longer stacking sequence results in the α -phase having higher hardness than the β -phase. However, the α -phase is chemically unstable compared with the β -phase. At high temperatures

when a liquid phase is present, the α -phase always transforms into the β -phase. Therefore, β - Si_3N_4 is the major form used in Si_3N_4 ceramics.

Applications

In general, the main issue with applications of silicon nitride has not been technical performance, but cost. As the cost has come down, the number of production applications is accelerating.

Automobile industry

One of the major applications of sintered silicon nitride is in automobile industry as a material for engine parts. Those include, in [Diesel engines](#), [glowplugs](#) for faster start-up; precombustion chambers (swirl chambers) for lower emissions, faster start-up and lower noise; [turbocharger](#) for reduced engine lag and emissions. In [spark-ignition engines](#), silicon nitride is used for [rocker arm pads](#) for lower [wear](#), turbocharger for lower inertia and less engine lag, and in [exhaust gas control valves](#) for increased acceleration. As examples of production levels, there is an estimated more than 300,000 sintered silicon nitride turbochargers made annually.

Bearings



Si_3N_4 bearing parts

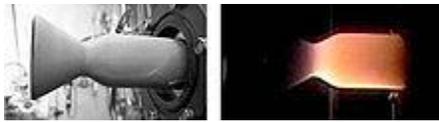
Silicon nitride bearings are both full ceramic bearings and [ceramic hybrid bearings](#) with balls in ceramics and races in steel. Silicon nitride [ceramics](#) have good [shock](#) resistance compared to other ceramics. Therefore, ball bearings made of silicon nitride ceramic are used in performance [bearings](#). A representative example is use of silicon nitride bearings in the main engines of the NASA's [Space Shuttle](#).

Silicon nitride ball bearings are harder than metal which reduces contact with the bearing track. This results in 80% less friction, 3 to 10 times longer lifetime, 80% higher speed, 60% less weight, the ability to operate with lubrication starvation, higher corrosion resistance and higher operation temperature, as compared to traditional metal bearings.^[20] Silicon nitride balls weigh 79% less than tungsten carbide balls. Silicon nitride ball bearings can be found in high end automotive bearings, industrial bearings, [wind turbines](#), motorsports, bicycles, rollerblades and

skateboards. Silicon nitride bearings are especially useful in applications where corrosion, electric or magnetic fields prohibit the use of metals. For example, in tidal flow meters, where seawater attack is a problem, or in electric field seekers.

Si_3N_4 was first demonstrated as a superior bearing in 1972 but did not reach production until nearly 1990 because of challenges associated with reducing the cost. Since 1990, the cost has been reduced substantially as production volume has increased. Although Si_3N_4 bearings are still 2–5 times more expensive than the best steel bearings, their superior performance and life are justifying rapid adoption. Around 15–20 million Si_3N_4 bearing balls were produced in the U.S. in 1996 for machine tools and many other applications. Growth is estimated at 40% per year, but could be even higher if ceramic bearings are selected for consumer applications such as in-line skates and computer disk drives.

High-temperature material



Silicon nitride thruster. Left: Mounted in test stand. Right: Being tested with H_2O_2 propellants

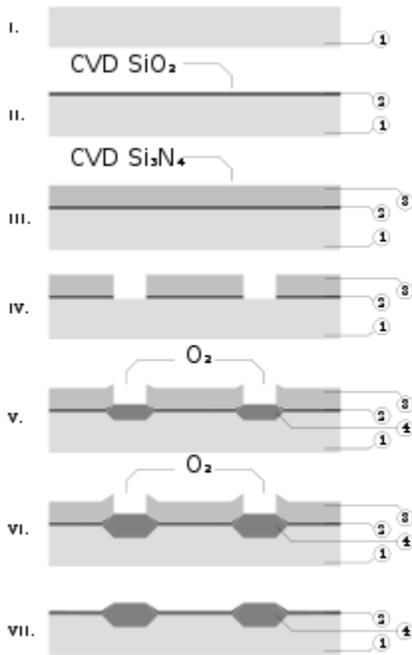
Silicon nitride has long been used in high-temperature applications. In particular, it was identified as one of the few monolithic ceramic materials capable of surviving the severe thermal shock and thermal gradients generated in hydrogen/oxygen rocket engines. To demonstrate this capability in a complex configuration, NASA scientists used advanced rapid prototyping technology to fabricate a one-inch-diameter, single-piece combustion chamber/nozzle (thruster) component. The thruster was hot-fire tested with hydrogen/oxygen propellant and survived five cycles including a 5-minute cycle to a 1320 °C material temperature.

Metal working and cutting tools

The first major application of Si_3N_4 was abrasive and cutting tools. Grinding, milling, and boring of metals constitute the major cost of manufacturing. A study in the early 1970s estimated that there were 2,692,000 metal-cutting machine tools in the United States with an annual operating cost of \$64 billion

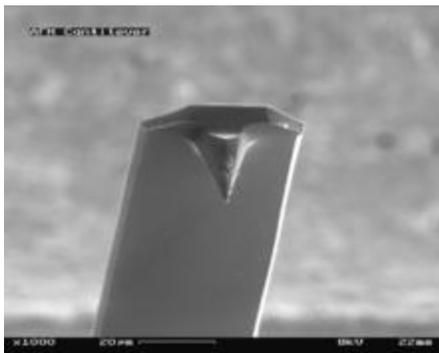
Bulk, monolithic silicon nitride is used as a material for **cutting tools**, due to its hardness, thermal stability, and resistance to **wear**. It is especially recommended for high speed **machining** of **cast iron**. Hot hardness, fracture toughness and thermal shock resistance mean that sintered silicon nitride can cut cast iron, hard steel and nickel based alloys with surface speeds up to 25 times quicker than those obtained with conventional materials such as tungsten carbide.^[13] The use of Si_3N_4 cutting tools has had a dramatic effect on manufacturing output. For example, face milling of gray cast iron with silicon nitride inserts doubled the cutting speed, increased tool life from one part to six parts per edge, and reduced the average cost of inserts by 50%, as compared to traditional **tungsten carbide** tools.

Electronics



Example of [local silicon oxidation](#) through a Si₃N₄ mask

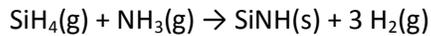
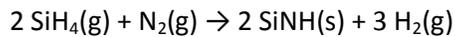
Silicon nitride is often used as an [insulator](#) and chemical barrier in manufacturing [integrated circuits](#), to electrically isolate different structures or as an [etch mask](#) in [bulk micromachining](#). As a passivation layer for microchips, it is superior to [silicon dioxide](#), as it is a significantly better [diffusion barrier](#) against water molecules and [sodium](#) ions, two major sources of corrosion and instability in microelectronics. It is also used as a [dielectric](#) between [polysilicon](#) layers in [capacitors](#) in analog chips.



Si₃N₄ cantilever used in atomic force microscopes

Silicon nitride deposited by LPCVD contains up to 8% hydrogen. It also experiences strong tensile [stress](#), which may crack films thicker than 200 nm. However, it has higher [resistivity](#) and dielectric strength than most insulators commonly available in microfabrication (10^{16} Ω -cm and 10 MV/cm, respectively).

Not only silicon nitride, but also various ternary compounds of silicon, nitrogen and hydrogen (SiN_xH_y) are used insulating layers. They are plasma deposited using the following reactions:^[9]



These SiNH films have much less tensile stress, but worse electrical properties (resistivity 10^6 to 10^{15} Ω -cm, and dielectric strength 1 to 5 MV/cm).^{[9][25]}

Silicon nitride is also used in [xerographic process](#) as one of the layer of the photo drum.^[26] Silicon nitride is also used as an ignition source for domestic gas appliances.^[27] Because of its good elastic properties, silicon nitride, along with silicon and silicon oxide, is the most popular material for [cantilevers](#) — the sensing elements of atomic force microscopes.

Silicon Nitride, Si_3N_4 Material Properties

Silicon nitride is a man made compound synthesized through several different chemical reaction methods. Parts are pressed and sintered by well developed methods to produce a ceramic with a unique set of outstanding properties. The material is dark gray to black in color and can be polished to a very smooth reflective surface, giving parts with a striking appearance. High performance silicon nitride materials were developed for automotive engine wear parts, such as valves and cam followers and proven effective. The cost of the ceramic parts never dropped enough to make the ceramics feasible in engines and turbochargers. The very high quality bodies developed for these demanding high reliability applications are available today and can be used in many severe mechanical, thermal and wear applications.

Key Silicon Nitride Properties

- ✓ High strength over a wide temperature range
- ✓ High fracture toughness
- ✓ High hardness
- ✓ Outstanding wear resistance, both impingement and frictional modes
- ✓ Good thermal shock resistance
- ✓ Good chemical resistance

Typical Silicon Nitride Uses

- ✓ Rotating bearing balls and rollers
- ✓ Cutting tools
- ✓ Engine moving parts — valves, turbocharger rotors
- ✓ Engine wear parts — cam followers, tappet shims
- ✓ Turbine blades, vanes, buckets
- ✓ Metal tube forming rolls and dies
- ✓ Precision shafts and axles in high wear environments
- ✓ Weld positioners

General Silicon Nitride Information

The material is an electrical insulator and is not wet by nonferrous alloys. Silicon nitride is a rather expensive material, but its performance to cost benefit ratio is excellent in the applications where it can outperform the normally utilized materials with long life and very reliable low maintenance operation.

Silicon Nitride Engineering Properties*

Silicon Nitride, Hot Pressed Properties			
Mechanical	SI/Metric (Imperial)	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.29	(205.4)
Porosity	% (%)	0	(0)
Color	—	black	—
Flexural Strength	MPa (lb/in ² x10 ³)	830	(120.4)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	310	(45)
Shear Modulus	GPa (lb/in ² x10 ⁶)	—	—
Bulk Modulus	GPa (lb/in ² x10 ⁶)	—	—

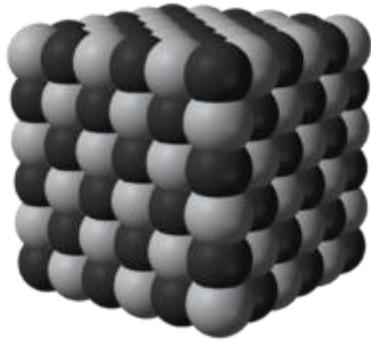
Poisson's Ratio	—	0.27	(0.27)
Compressive Strength	MPa (lb/in ² x10 ³)	—	—
Hardness	Kg/mm ²	1580	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	6.1	—
Maximum Use Temperature (no load)	°C (°F)	1000	(1830)
Thermal			
Thermal Conductivity	W/m•°K (BTU•in/ft ² •hr•°F)	30	(208)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	3.3	(1.8)
Specific Heat	J/Kg•°K (Btu/lb•°F)	—	—
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	—	—
Dielectric Constant	—	—	—
Dissipation Factor	—	—	—
Loss Tangent	—	—	—
Volume Resistivity	ohm•cm	—	—

Silicon Nitride, Pressureless Sintered Properties			
Mechanical	SI/Metric (Imperial)	SI/Metric	(Imperial)
Density	gm/cc (lb/ft ³)	3.27	(204)
Porosity	% (%)	0	(0)
Color	—	black	—
Flexural Strength	MPa (lb/in ² x10 ³)	689	(100)
Elastic Modulus	GPa (lb/in ² x10 ⁶)	310	(45)

Shear Modulus	GPa (lb/in ² x10 ⁶)	—	—
Bulk Modulus	GPa (lb/in ² x10 ⁶)	—	—
Poisson's Ratio	—	0.24	(0.24)
Compressive Strength	MPa (lb/in ² x10 ³)	—	—
Hardness	Kg/mm ²	1450	—
Fracture Toughness K _{IC}	MPa•m ^{1/2}	5.7	—
Maximum Use Temperature (no load)	°C (°F)	1000	(1830)
Thermal			
Thermal Conductivity	W/m•°K (BTU•in/ft ² •hr•°F)	29	(201)
Coefficient of Thermal Expansion	10 ⁻⁶ /°C (10 ⁻⁶ /°F)	3.3	(1.8)
Specific Heat	J/Kg•°K (Btu/lb•°F)	—	—
Electrical			
Dielectric Strength	ac-kv/mm (volts/mil)	—	—
Dielectric Constant	—	—	—
Dissipation Factor	—	—	—
Loss Tangent	—	—	—
Volume Resistivity	ohm•cm	—	—

Titanium carbide

Titanium carbide



Properties	
Molecular formula	TiC
Molar mass	59.89 g/mol
Appearance	black powder
Density	4.93 g/cm ³
Melting point	3160 °C, 3433 K, 5720 °F
Boiling point	4820 °C, 5093 K, 8708 °F
Solubility in water	insoluble in water

Structure	
Crystal structure	Cubic, cF8
Space group	Fm3m, No. 225
Coordination geometry	Octahedral

Titanium carbide, **TiC**, is an extremely **hard** (Mohs 9-9.5) **refractory** ceramic material, similar to **tungsten carbide**.

It is commercially used in **tool bits**. It has the appearance of black powder with **NaCl-type face centered cubic crystal structure**. It is mainly used in preparation of **cermets**, which are frequently used to **machine steel** materials at high cutting speed.

The resistance to **wear**, **corrosion**, and **oxidation** of a **tungsten carbide-cobalt** material can be increased by adding 6-30% of titanium carbide to tungsten carbide. This forms a **solid solution** that is more **brittle** and susceptible to breakage than the original material.

Tool bits without tungsten content can be made of titanium carbide in [nickel](#)-cobalt matrix cermet, enhancing the cutting speed, precision, and smoothness of the workpiece. This material is sometimes called high-tech [ceramics](#) and is used as a [heat shield](#) for [atmospheric reentry](#) of [spacecraft](#). The substance may be also polished and used in scratch-proof watches.

It can be [etched](#) with [reactive-ion etching](#).

The mineralogical form is very rare and called khamrabaevite - (Ti,V,Fe)C.

Titanium-carbon clusters

A surprisingly stable cluster with formula $\text{Ti}_8\text{C}_{12}^+$, was detected in 1992.^{[1][2]} The 20 atoms were conjectured to be arranged as the vertices of a [dodecahedron](#), with the titanium atoms at the corners of a [cube](#)^[1] However, this claim was soon disputed by [Linus Pauling](#)^[3] who proposed an alternative arrangement — with the Ti atoms still at the corners of a cube, but with the carbon atoms pushed inwards so as to be nearly coplanar with the faces of that cube.

Tungsten carbide

Tungsten carbide



Tungsten carbide milling bits

Properties

Molecular formula	WC
Molar mass	195.851 g/mol
Appearance	Grey-black lustrous solid
Density	15.63 g/cm ³
Melting point	2870 °C, 3143 K, 5198 °F

Boiling point 6000 °C, 6273 K, 10832 °F

Solubility in water Insoluble

Structure

Crystal structure Hexagonal, hP2,
space group = P6m2, No. 187^[1]

Hazards

EU classification Not listed

Related compounds

Other anions Tungsten boride
Tungsten nitride

Other cations Molybdenum carbide
Titanium carbide
Silicon carbide

Tungsten carbide (WC) is an inorganic chemical compound (specifically, a **carbide**) containing equal parts of **tungsten** and **carbon** atoms. In its most basic form, tungsten carbide is a fine gray powder, but it can be pressed and formed into shapes for use in **industrial machinery**, **cutting tools**, **abrasives**, other tools and instruments, and **jewelry**.

Tungsten carbide is approximately three times **stiffer** than **steel**, with a **Young's modulus** of approximately 550 GPa,^[2] and is much **denser** than steel or **titanium**. It is comparable with **corundum** (α -Al₂O₃) or **sapphire** in **hardness** and can only be polished and finished with abrasives of superior hardness such as **cubic boron nitride** and **diamond** amongst others, in the form of powder, wheels, and compounds.

Naming

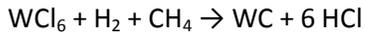
Colloquially among workers in various industries (such as **machining** and **carpentry**), tungsten carbide is often simply called *carbide* (without precise distinction from other carbides). Among the lay public, the growing popularity of tungsten carbide rings has led to some consumers calling the material just *tungsten*, despite the inaccuracy of the usage

Synthesis

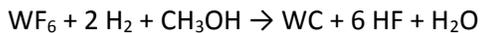
WC can be prepared by reaction of tungsten metal and carbon at 1400–2000 °C.^[3] Other methods include a patented fluid bed process that reacts either tungsten metal or blue WO₃ with CO/CO₂ mixture and H₂ between 900 and 1200 °C.^[4] WC can also be produced by heating WO₃ with

graphite in hydrogen at 670 °C following by carburization in Ar at 1000 °C or directly heating WO_3 with graphite at 900 °C.^[5] **Chemical vapor deposition** methods that have been investigated include:^[3]

- reacting **tungsten hexachloride** with hydrogen, as a **reducing agent**, and **methane**, as the source of carbon at 670 °C (1,238 °F)



- reacting **tungsten hexafluoride** with hydrogen, as reducing agent, and **methanol**, as source of carbon at 350 °C (662 °F)



Chemical properties

There are two well characterized compounds of tungsten and carbon, WC and **tungsten semicarbide**, W_2C . Both compounds may be present in coatings and the proportions can depend on the coating method.

At high temperatures WC decomposes to tungsten and carbon and this can occur during high-temperature **thermal spray**, e.g., in high velocity oxygen fuel (HVOF) and high energy plasma (HEP) methods.^[7]

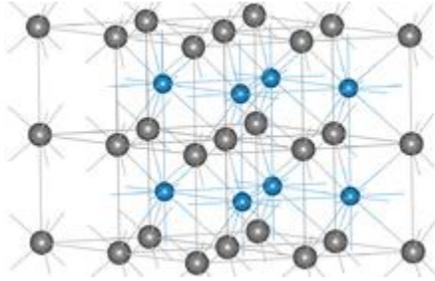
Oxidation of WC starts at 500–600 °C.^[3] It is resistant to **acids** and is only attacked by **hydrofluoric acid/nitric acid** (HF/HNO_3) mixtures above room temperature.^[3] It reacts with **fluorine** gas at room temperature and **chlorine** above 400 °C (752 °F) and is unreactive to dry H_2 up to its melting point.^[3]

Physical properties

Tungsten carbide is high melting, 2,870 °C (5,200 °F), extremely hard (~9 **Mohs scale**, 1700–2400 **Vickers number**^[8]) with low **electrical resistivity** ($\sim 2 \times 10^{-7}$ Ohm·m), comparable with that of some metals (e.g. **vanadium** 2×10^{-7} Ohm·m)

WC is readily **wetted** by both molten **nickel** and **cobalt**.^[10] Investigation of the phase diagram of the W-C-Co system shows that WC and Co form a pseudo binary **eutectic**. The **phase diagram** also shows that there are so-called η -carbides with composition $(\text{W},\text{Co})_6\text{C}$ that can be formed and the fact that these phases are brittle is the reason why control of the carbon content in WC-Co hard metals is important.

Structure



α -WC structure, carbon atoms are gray.^[1]

There are two forms of WC, a **hexagonal** form, α -WC (**hP2**, **space group** P6m2, No. 187),^{[1][11]} and a **cubic** high-temperature form, β -WC, which has the **rock salt structure**.^[12] The hexagonal form can be visualized as made up of hexagonally close packed layers of metal atoms with layers lying directly over one another, with carbon atoms filling half the interstices giving both tungsten and carbon a regular trigonal prismatic, 6 **coordination**.^[11] From the unit cell dimensions^[13] the following bond lengths can be determined; the distance between the tungsten atoms in a hexagonally packed layer is 291 pm, the shortest distance between tungsten atoms in adjoining layers is 284 pm, and the tungsten carbon bond length is 220 pm. The tungsten-carbon bond length is therefore comparable to the single bond in $W(CH_3)_6$ (218 pm) in which there is strongly distorted trigonal prismatic coordination of tungsten.^[14]

Molecular WC has been investigated and this gas phase species has a bond length of 171 pm for $^{184}W^{12}C$.

Applications

Cutting tools for machining

Sintered tungsten carbide **cutting tools** are very abrasion resistant and can also withstand higher temperatures than standard **high speed steel** tools. Carbide cutting surfaces are often used for **machining** through materials such as **carbon steel** or **stainless steel**, as well as in situations where other tools would wear away, such as high-quantity production runs. Because carbide tools maintain a sharp cutting edge better than other tools, they generally produce a better finish on parts, and their temperature resistance allows faster machining. The material is usually called **cemented carbide**, hardmetal or tungsten-carbide cobalt: it is a **metal matrix composite** where tungsten carbide particles are the aggregate and metallic **cobalt** serves as the matrix. Manufacturers use tungsten carbide as the main material in some high-speed drill bits, as it can resist high temperatures and is extremely hard.^{[16][17]}

Ammunition

Tungsten carbide is often used in **armor-piercing ammunition**, especially where **depleted uranium** is not available or is politically unacceptable. W_2C projectiles were first used by **German**

[Luftwaffe tank-hunter](#) squadrons in [World War II](#). Owing to the limited German reserves of tungsten, W_2C material was reserved for making machine tools and small numbers of [projectiles](#). It is an effective penetrator due to its combination of great hardness and very high density.

Tungsten carbide ammunition can be of the [sabot](#) type (a large arrow surrounded by a discarding push cylinder) or a subcaliber ammunition, where [copper](#) or other relatively soft material is used to encase the hard penetrating core, the two parts being separated only on impact. The latter is more common in small-caliber arms, while sabots are usually reserved for [artillery](#) use.

Nuclear

Tungsten carbide is also an effective [neutron reflector](#) and as such was used during early investigations into nuclear chain reactions, particularly for weapons. A [criticality accident](#) occurred at [Los Alamos National Laboratory](#) on 21 August 1945 when [Harry K. Daghlian, Jr.](#) accidentally dropped a tungsten carbide brick onto a [plutonium](#) sphere, causing the [subcritical mass](#) to go supercritical with the reflected [neutrons](#).

Sports



A [Nokian](#) tire with tungsten carbide spikes. The spikes are surrounded by aluminum.

Hard carbides, especially tungsten carbide, are used by athletes, generally on poles that strike hard surfaces. [Trekking poles](#), used by many [hikers](#) for balance and to reduce pressure on leg joints, generally use carbide tips in order to gain traction when placed on hard surfaces (like rock); carbide tips last much longer than other types of tip.^[22]

While [ski pole](#) tips are generally not made of carbide, since they do not need to be especially hard even to break through layers of ice, rollerski tips usually are. [Roller skiing](#) emulates [cross country skiing](#) and is used by many skiers to train during warm weather months.

Sharpened carbide tipped spikes (known as studs) can be inserted into the drive tracks of [snowmobiles](#). These studs enhance traction on icy surfaces. Longer v-shaped segments fit into grooved rods called wear rods under each snowmobile ski. The relatively sharp carbide edges enhance steering on harder icy surfaces. The carbide tips and segments reduce wear encountered when the snowmobile must cross roads and other abrasive surfaces.

Some [tire](#) manufacturers offer bicycle tires with tungsten carbide studs for better traction on ice. These are generally preferred to steel studs because of their superior resistance to wear.

Tungsten carbide may be used in [farriery](#), the shoeing of [horses](#), to improve traction on slippery surfaces such as roads or ice. Carbide-tipped hoof nails may be used to attach the [shoes](#),^[25] or alternatively [borium](#), tungsten carbide in a matrix of softer metal, may be welded to small areas of the underside of the shoe before fitting.

Surgical instruments

It is also used for making surgical instruments meant for open surgery (scissors, forceps, hemostats, blade-handles, etc.) and laparoscopic surgery (graspers, scissors/cutter, needle holder, cautery, etc.). They are much costlier than their stainless-steel counterparts and require delicate handling, but give better performance.

Jewelry

Tungsten carbide, also called [cemented carbide](#), has become a popular material in the bridal jewelry industry due to its extreme hardness and high resistance to scratching. Unfortunately, this extreme hardness also means that it is very prone to shattering.^[28] Tungsten is extremely hard and dense. Combined with carbon and other elements, it becomes tungsten carbide, which registers between 8.9 - 9.1 on the Mohs hardness scale. It's roughly 10 times harder than 18k gold and four times harder than titanium and is equal to a natural sapphire's hardness. In addition to its design and high polish, part of its attraction to consumers is its technical nature.

] Other

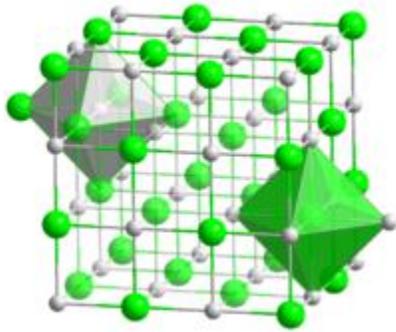
Tungsten carbide is sometimes used to make the rotating ball in the tips of [ballpoint pens](#) that disperse ink during writing.

English guitarist [Martin Simpson](#) is known to use a custom made tungsten carbide slide for playing [slide guitar](#). The hardness, weight, and density of the slide give it superior [sustain](#) and volume compared to standard glass, steel, ceramic, or brass slides.

WC has been investigated for its potential use as a [catalyst](#) and it has been found to resemble [platinum](#) in its catalysis of the production of water from hydrogen and oxygen at room temperature, the [reduction](#) of [tungsten trioxide](#) by hydrogen in the presence of water, and the [isomerisation](#) of 2,2-dimethylpropane to 2-methylbutane.^[31] It has been proposed as a replacement for the [iridium](#) catalyst in [hydrazine](#) powered [satellite thrusters](#).

Tantalum carbide

Tantalum carbide



Other names[hide][hide]

tantalum (IV) carbide

Properties	
Molecular formula	TaC _x
Appearance	brown-gray odorless powder 14.3 g/cm ³ (TaC)
Density	15.1 g/cm ³ (TaC) ^[1]
Melting point	3880 °C (TaC) 3327 °C (TaC _{0.5}) ^[1]
Boiling point	4780 °C (TaC) ^[1]
Solubility in water	insoluble
Solubility	HF-HNO ₃ mixture ^[1]
Structure	
Crystal structure	rock salt (TaC) trigonal (TaC _x)

Tantalum carbides form a family of [binary](#) chemical compounds of [tantalum](#) and [carbon](#) with the empirical formula TaC_x, where x usually varies between 0.4 and 1. They are extremely [hard](#), brittle, [refractory ceramic](#) materials with metallic [electrical conductivity](#). They appear as brown-gray powders which are usually processed by [sintering](#). Being important [cermet](#) materials, tantalum carbides are commercially used in [tool bits](#) for cutting applications and are sometimes added to [tungsten carbide](#) alloys.^[2] The melting points of tantalum carbides peak at about 3880 °C depending on the purity and measurement conditions; this value is among the highest for binary compounds.^{[3][4]} Only [tantalum hafnium carbide](#) has a distinctly higher melting point of about 4215 °C, whereas the melting point of [hafnium carbide](#) is comparable to that of TaC.

Preparation

TaC_x powders of desired composition are prepared by heating a mixture of tantalum and graphite powders in vacuum or inert gas atmosphere ([argon](#)). The heating is performed at temperature of about 2000 °C using a furnace or an arc-melting setup. An alternative technique is [reduction](#) of

[tantalum pentoxide](#) by carbon in vacuum or hydrogen gas atmosphere at a temperature of 1500-1700 °C. This method was used to obtain tantalum carbide back in 1876, but it lacks control over the stoichiometry of the product.

Crystal structure

TaC_x compounds have a [cubic](#) (rock-salt) crystal structure for $x = 0.7-1.0$; ^[8] the lattice parameter increases with x . ^[9] TaC_{0.5} has two major crystalline forms symmetry. The more stable one has an anti-[cadmium iodide](#)-type trigonal structure which transforms upon heating to about 2000 °C into a hexagonal lattice with no long-range order for the carbon atoms. ^[5]

Formula	Symmetry	Type	Pearson symbol	Space group	No	Z	ρ (g/cm ³)	a (nm)	c (nm)
TaC	Cubic	NaCl ^[9]	cF8	Fm3m	225	4	14.6	0.4427	
TaC _{0.75}	Trigonal ^[10]		hR24	R3m	166	12	15.01	0.3116	3
TaC _{0.5}	Trigonal ^[11]	anti-CdI ₂	hP3	P3m1	164	1	15.08	0.3103	0.4938
TaC _{0.5}	Hexagonal ^[6]		hP4	P6 ₃ /mmc	194	2	15.03	0.3105	0.4935

Here Z is the number of formula units per unit cell, ρ is the density calculated from lattice parameters.

Properties

The bonding between tantalum and carbon atoms in tantalum carbides is a complex mixture of ionic, metallic and covalent contributions, and because of the strong covalent component these carbides are very hard and brittle materials. For example, TaC has a microhardness of 1600-2000 kg/mm²^[12] (~9 Mohs) and an [elastic modulus](#) of 285 GPa, whereas the corresponding values for tantalum are 110 kg/mm² and 186 GPa. The hardness, [yield stress](#) and [shear stress](#) increase with the carbon content in TaC_x.^[13] Tantalum carbides have metallic electrical conductivity, both in terms of its magnitude and temperature dependence. TaC is a [superconductor](#) with a relatively high transition temperature of $T_C = 10.35$ K.

The magnetic properties of TaC_x change from diamagnetic for $x \leq 0.9$ to paramagnetic at larger x . An inverse behavior (para-diamagnetic transition with increasing x) is observed for HfC_x, despite it has the same crystal structure as TaC_x.

These details completely from internet sources,.

Veerapandian.K

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