American Carbon Society

HOW WELL DOES CARBON HANDLE STRESS?

A BRIEF OVERVIEW OF CARBONS IN STRUCTURAL APPLICATIONS

PLENARY LECTURE

CARBON2004

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Report Documentation Page

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Attempt to give an overview that provides a flavor for the breadth of structural applications. Note that many times other properties, such as thermal-shock resistance, conductivity, etc. will also be required for application. Will not be all-inclusive Polycrystalline forms, sintered mesophase, and carbon fiber reinforced composites will be covered in some detail but nanocarbons will not be included. Many groups are working on reinforcement, thread, ropes, and nanocomposites. These are being covered in this meeting and apart from a few examples, such as, Hyperion and Applied Sciences have not yet been commercialized. They will be a subject for a future meeting.

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Scope Of Presentation

Attempt to give an overview that provides a flavor for the breadth of structural applications.

Note that many times other properties, such as thermal-shock resistance, conductivity, etc. will also be required for application.

Will not be all-inclusive

Polycrystalline forms, sintered mesophase, and carbon fiber reinforced composites will be covered in some detail but nanocarbons will not be included.

Many groups are working on reinforcement, thread, ropes, and nanocomposites. These are being covered in this meeting and apart from a few examples, such as, Hyperion and Applied Sciences have not yet been commercialized. They will be a subject for a future meeting.

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Carbons Can Be Tailored To Possess A Wide Variety Of Properties

CARBON CAN

be **lubricating** --graphite powder & seals ...or **abrasive**--diesel soot

have **high surface area**--activated carbon (2000 m^2/g)...**or low-**-fibers (0.5 m^2/g)

be **hydrophobic**--carbon surface...or **hydrophilic**--oxygenated carbon surface

be **porous**--activated carbon…or **nonporous**--HOPG

have **high thermal conductivity**--HOPG- (*a*-direction) or pitch fiber...or **low thermal conductivity**--HOPG (*c*-direction) or PAN Fiber

be **anisotropic**--graphite or HOPG....or **isotropic**--polycrystalline graphite

be **hard** -- diamonds or chars...or **soft**-- carbon blacks

be **strong**-- PAN fibers… or **weak**--aerogel

be **stiff**—pitch carbon fibers...or **flexible**--Grafoil

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What Do All These Things Have In Common??

Sintering Furnace
Satellite Structures
Fission And Fusion Reactors
High Temp. Furnace Hardware
Nuclear Fuel Particle Coatings
Golf Clubs And Tennis Rackets
Tanks And Pressure Vessels
Planes, Trains, And Automobiles
Steel And Aluminum Production
Rocket Motor Nozzles And Exit Cones
Leading Edges of Hypersonic Craft

Clutches
Nuts And Bolts
Highway Bridges
Heart Valves
Pistons
Bearing Cages
Artificial Joints
ICBM Nose Tips
Motorcycles
Turbine Blades
Brakes

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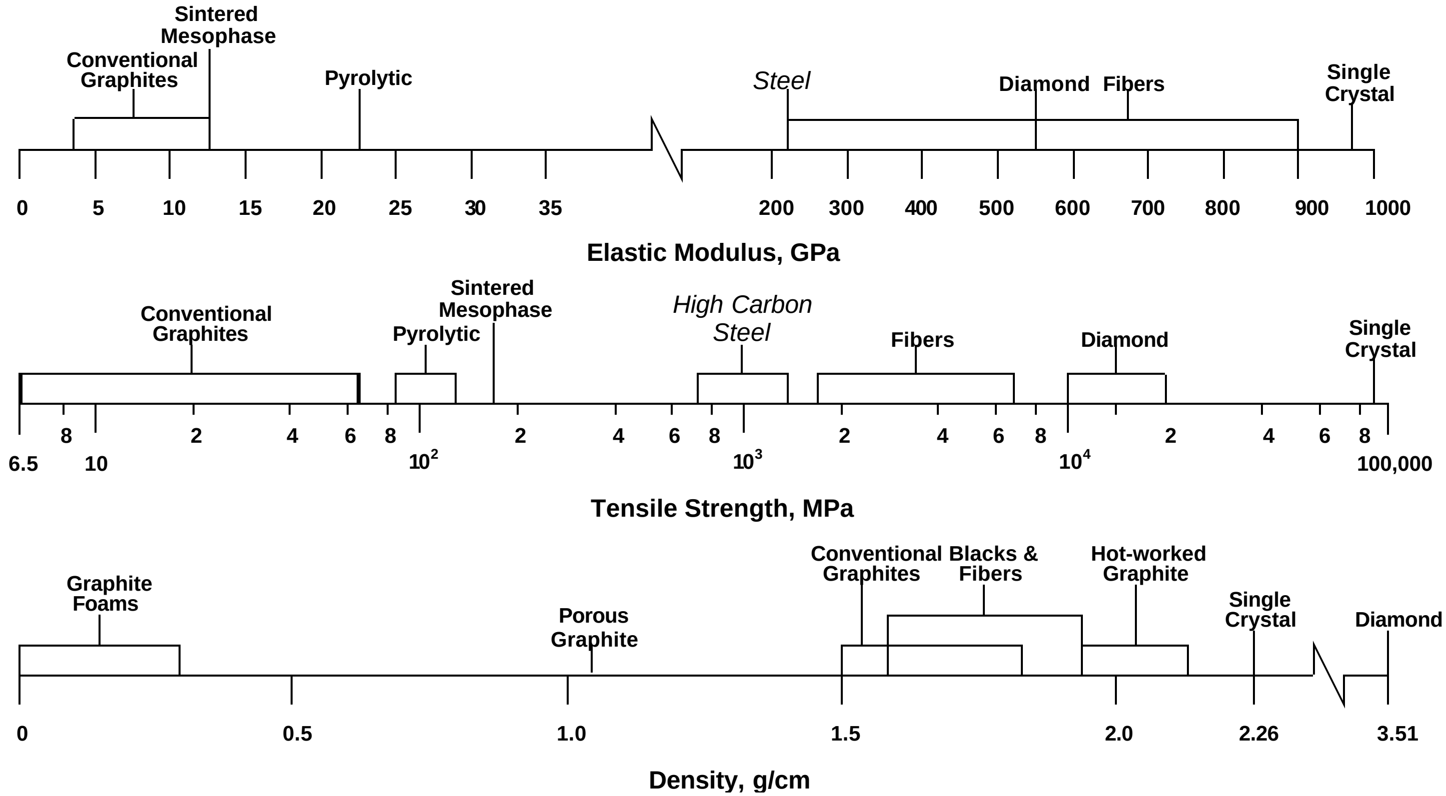
Structural Properties



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POLYCRYSTALLINE GRAPHITE

Carbon Electrodes

The electrodes for the steel and aluminum industries can weigh up to two tons and must support their own weight. Electrodes in center are 30" in diameter by 110" long. On left diameter is 20" while on right it is 24"

Carbon electrodes are usually extruded from a mixture of petroleum coke and coal tar pitch binder and are used for the Aluminum, Steel, Magnesium, Fluorine, Chlorine, Sodium, and Uranium Industries.

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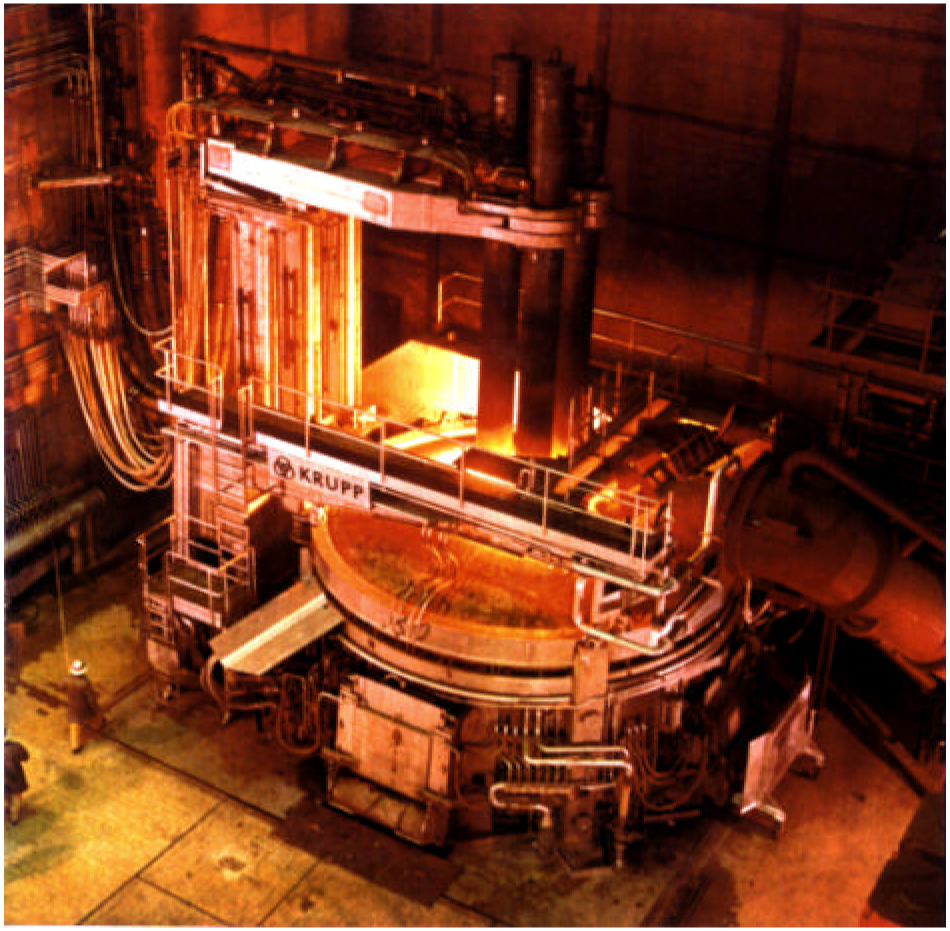
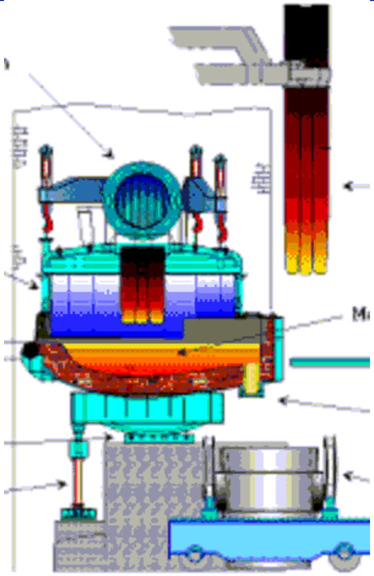
Graphite Electrodes
Electric arc Furnace





Graphite electrodes are used to reduce iron and make steel. (24” diameter shown)

Also, It requires one pound of carbon to reduce bauxite ore and produce two pounds of aluminum.

Chicago Pile One

- **First sustained nuclear reaction at the University of Chicago in December 1942 produced half a watt. Pile consisted of 57 layers of graphite blocks, half of them seeded with uranium.**

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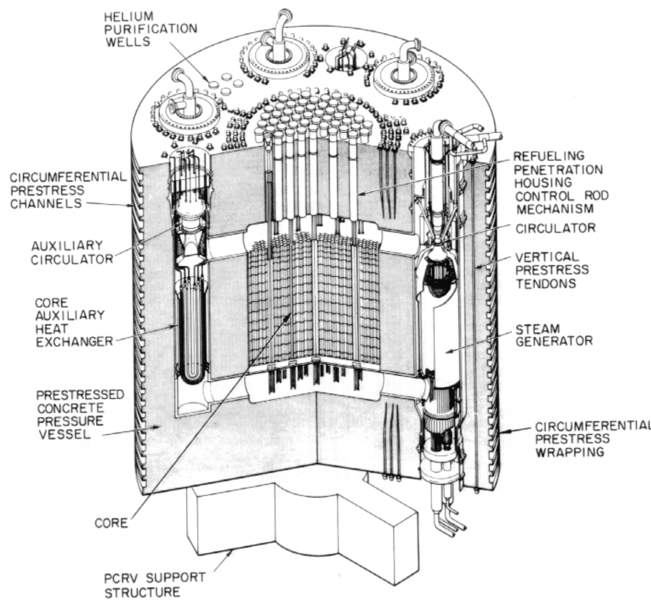
1160 MW Reactor



- **Carbon plays an essential role in the high temperature gas-cooled nuclear reactor. It serves as moderator, structural material, and as a fuel particle coating.**

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PYROLYTIC GRAPHITE

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Pyrolytic Carbon

- As the name implies, this carbon is formed through the cracking or pyrolysis of hydrocarbons.

$$CH_4 \longrightarrow C + 2H_2$$

- Carbon has a bad name in some fields because in the chemical field (especially in petroleum cracking) it is an undesirable by-product that must be burned away.
- However, this process utilizing principally methane and propylene for making carbon is important in the manufacture of HOPG, composites, nuclear fuel particles, and in the biomedical field

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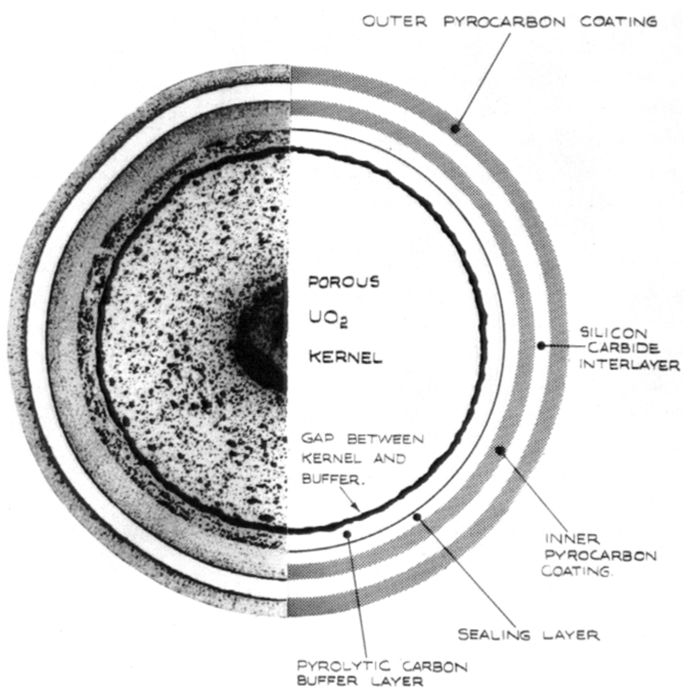
Nuclear Fuel Particle



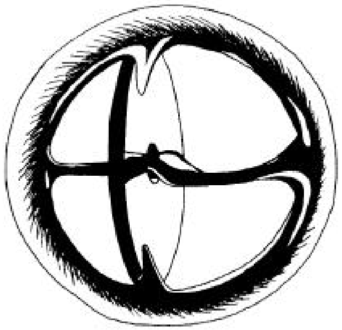
- **Photomicrograph of equatorial section of typical UO2-coated particle and designation of the components of the particle. Note inner porous carbon layer and impervious outer layer**

Prosthetic Heart Valves

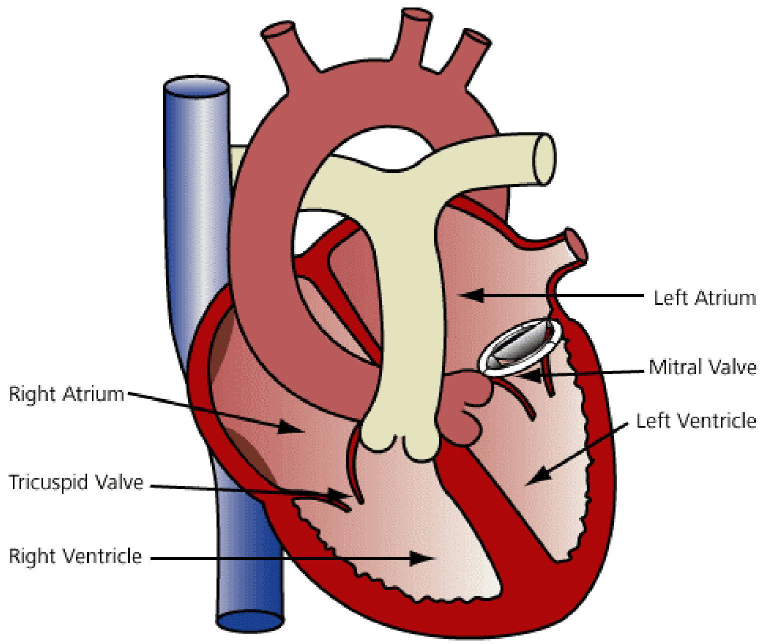
A tissue valve known as a xenograft, is a biological valve that has been taken from an animal heart (pig or cow)-- naturally biocompatible.

Mechanical heart valve are more durable and should last a lifetime but requires that the recipient take anticoagulation medicine (blood thinner) daily. Accounts for 60% of market.

The three principal mechanical designs are the Bileaflet, the Caged Ball, and the Tilting Disc



Prosthetic Heart Valves



Pyrolytic carbon is the preferred (5 million to date) material for the exterior surfaces of valves because of its hardness, strength, durability, and because it is hard for blood components to stick to the valve. Interior is usually Poco® graphite (isotropic, therm. exp.) or tungsten (radio-opaque).

Prosthetic Joints

The Ascension® MCP is a two-component, total joint replacement for the metacarpophalangeal (MCP) joint of the hand and is made of PyroCarbon over Poco® graphite and has properties ideally suited for making implants to replace the small joints of the hand and foot.

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Pyrolytic Graphite (PG) Washers

Up to 1m in diameter

Many people are familiar with pyrolytic graphite monochrometers as well as STM AFM standards, but PG washers are also used in furnaces as directional insulators and in solid rocket motors.

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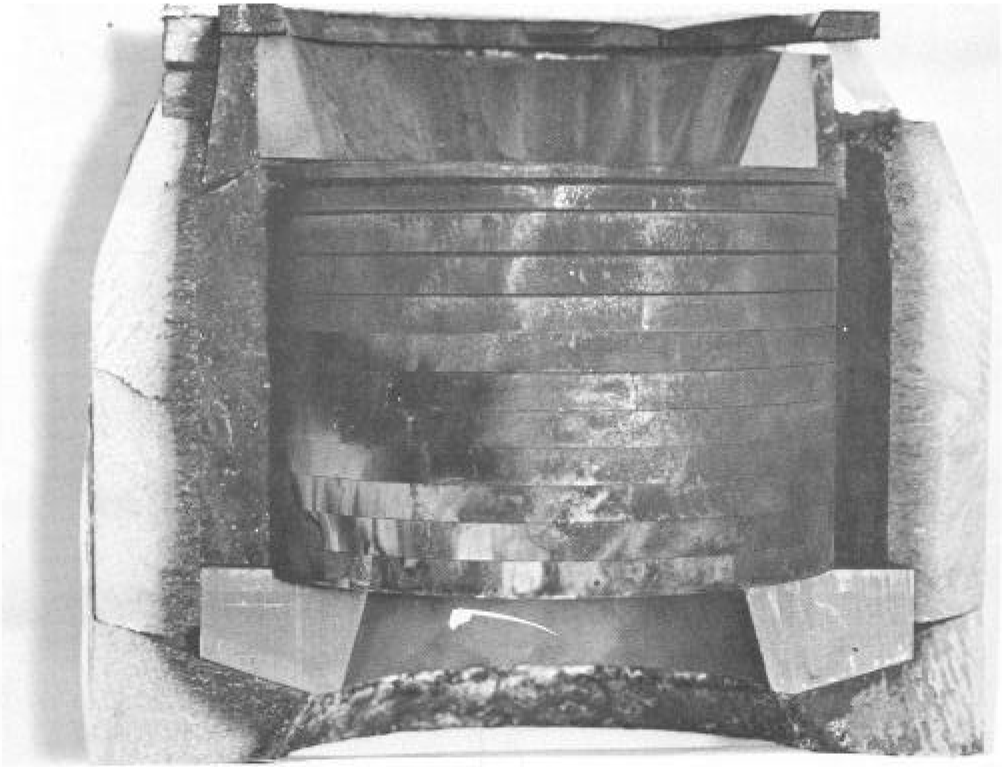
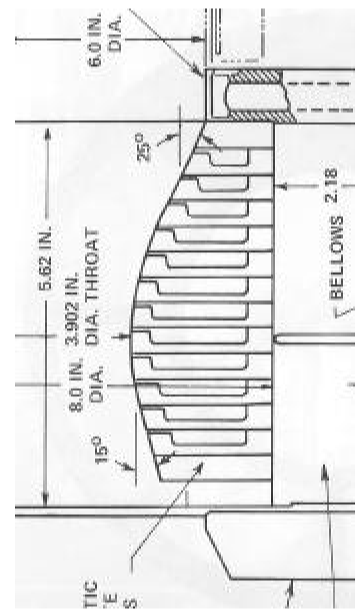
Pyrolytic Graphite (PG) Washers





In solid rocket motors the PG washers are stacked so that their internal diameters form the nozzle throat.

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SINTERED MESOPHASE

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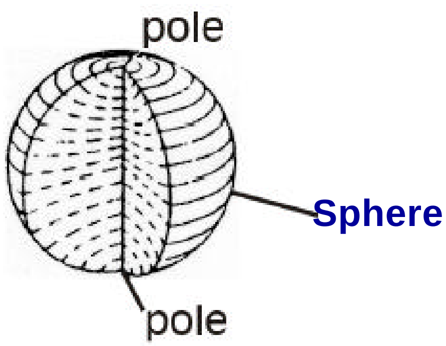
Sintered Mesophase

Mesophase-carbon is an anisotropic nematic discotic liquid crystalline polyaromatic material that can be produced from a variety of precursors,such as, coal tar or mineral oil pitches.

It forms as a second phase from isotropic pitch through polymerization and condensation reactions at ~350^{o}C.



After forming the mesophase sphereals from the isotropic phase, this process mills the resulting mixture and removes the isotropic phase by solvation leaving only mesophase powder, which is partially stabilized.

This powder is formed by compaction into a near-net-shaped part, the green body is machined slightly, and then sintered. After sintered it is machined again to bring part to final dimensions after extensive shrinkage.

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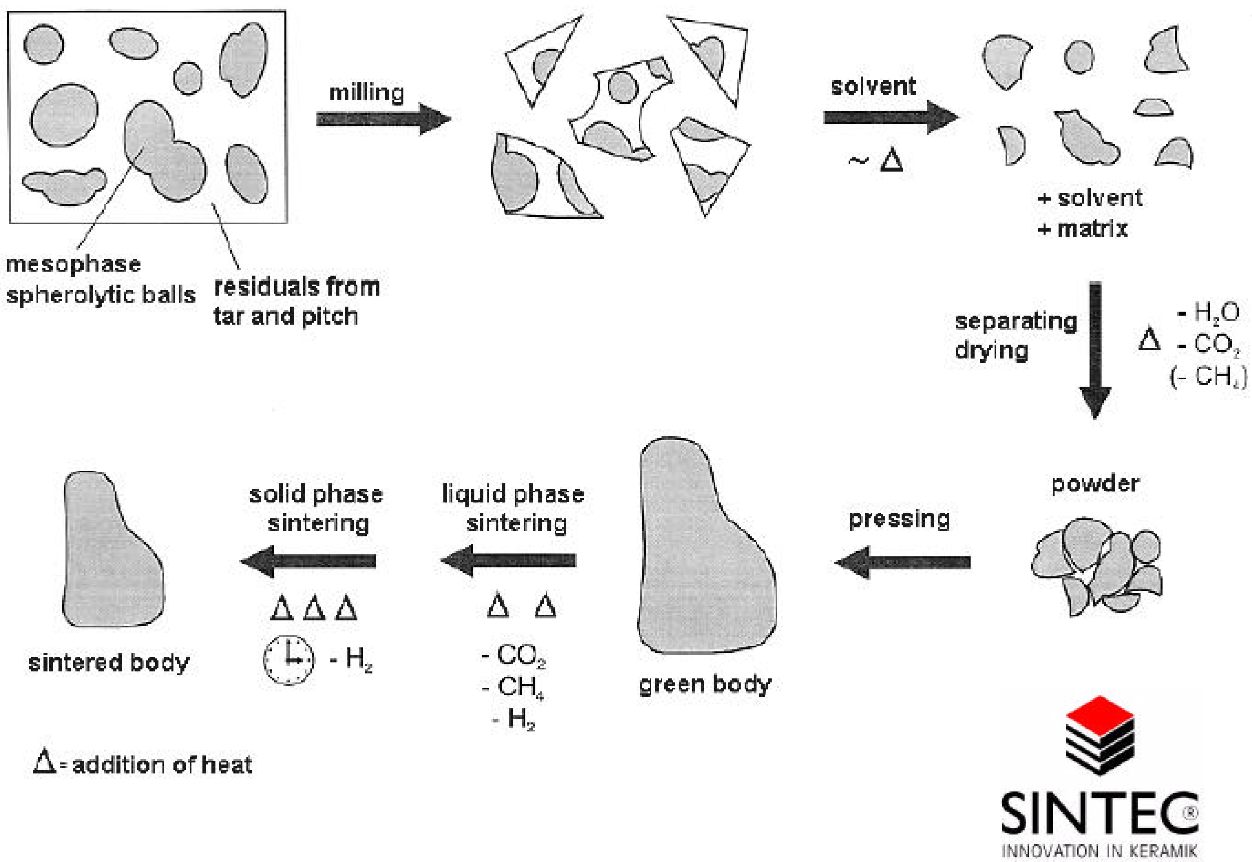
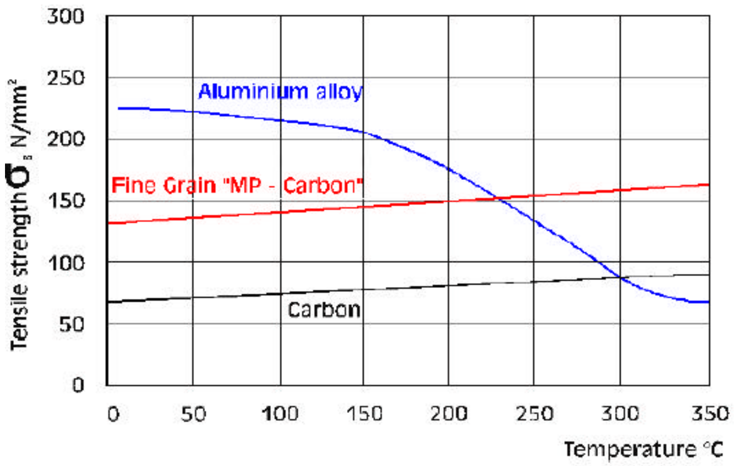
Sintered Mesophase Production



Sintered Mesophase Properties



Low thermal expansion

Low density

Good thermal shock behavior

Increase of strength with increasing temperature

These properties along with the fact that the piston is self –lubricating due to the open pores acting as reservoirs made this an excellent piston material.

Properties	Unit	Aluminium Alloy	Fine Grain Graphite	Mesophase Carbon
Density	g/cm³	2,7	1,86	1,89
Flexural Strength (RT)	MPa	220	50	127
Flexural Strength (570K)	MPa	80	90	180
Young's Modulus	GPa	80	12	12,2
Thermal Conductivity	W/mK	155	70	44
Thermal Expansion	$x10^{-6}K^{-1}$	20	3,3	5,7

Sintec Keramik GmbH & Co. KG

Sintered Mesophase Piston

The use of self-lubricating mesophase pistons in two-stroke engines improves fuel efficiency and increases power while decreasing lubricant consumption and combustion emissions (CO, NO_x, and HC).

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DIAMOND FILMS

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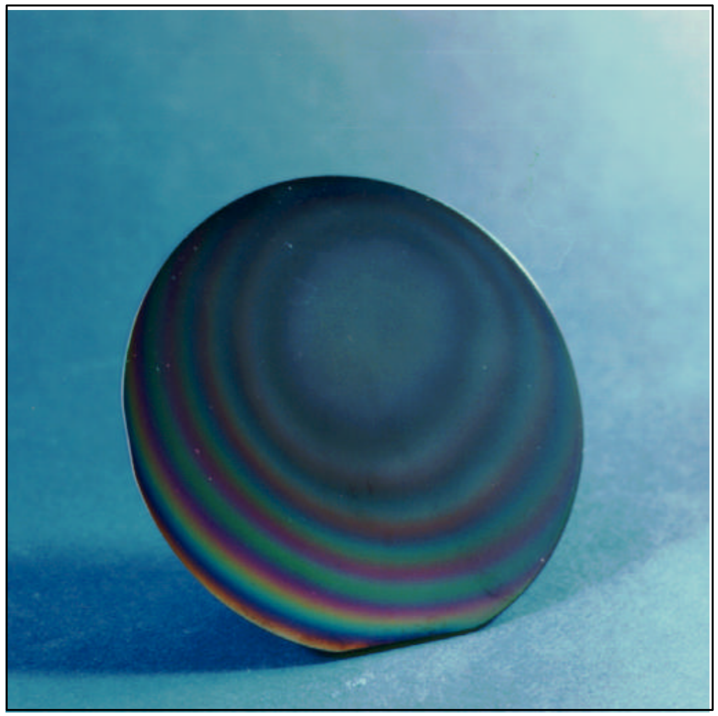
Diamond Coatings



Diamond film coatings are hard and scratch-resistant. Used for contact surfaces such as bearings, wire drawing dies, as well as for tool coatings for cutting, grinding, drilling, etc.

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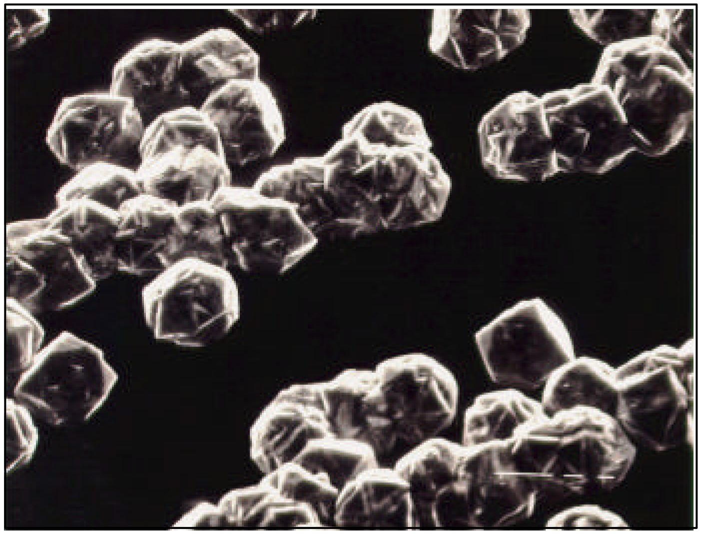
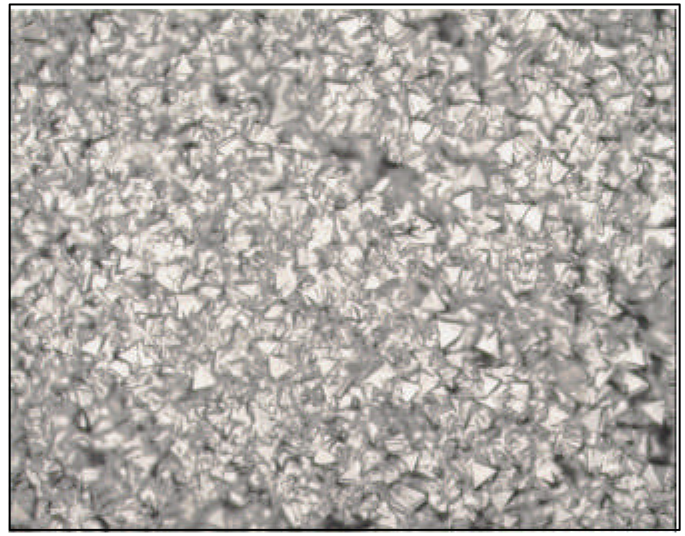
CVD Diamond



Discrete Crystals



Diamond Film

A surface can be coated with diamonds using a diamond paste or by employing the Chemical Vapor Deposition (CVD) of diamond and diamond-like carbon using microwave plasma and hot-filament techniques.

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FIBER REINFORCED COMPOSITES

CARBON FIBERS

Polymer Precursor:

Formed by carbonization of a polymer fiber such as rayon or PAN (polyacrylonitrile). These fibers, which are relatively low cost, are not graphitizable so they have high strength but low moduli.

Pitch Precursor:

These fibers are formed from mesophase, petroleum or coal tar pitch. Through heat treatment to temperatures > 2000^{o}C these fibers are graphitized giving them very high moduli (up to 900 GPa) and high thermal conductivity (three times that of copper).

Catalytic fibers:

Formed by the pyrolysis of hydrocarbons on a catalyst particle. The high purity fiber, which grows out of the particle, has similar properties to the pitch fiber, but offers a lower processing cost.

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Comparison With Other Fibers

Fiber	Strength (MPa)	Modulus (GPa)	Diameter (u)	Density (g/cc)
S- Glass	4585	86	10	2.48
Kevlar 149	3450	228	12	1.47
PAN, T-300	3660	231	7	1.76
Pitch, P-25	1400	160	11	1.9
Pitch, P-120	2410	828	10	2.18

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Carbon Fiber Reinforced Composites

Consist of carbon fibers surrounded by a matrix material, which can be a polymer (usually epoxy or phenolic), carbon, cement, or a metal.

For structural applications, the fibers are incorporated to add strength and stiffness.

For example, C-C composites are stronger than steel, stiffer than steel, and lighter than aluminum. Properties maintained (and actually increased) to > 3000o C.

Carbon fiber reinforcement can be chopped and random or can be continuous.

In a continuous fiber composite, the carbon fibers are usually oriented to carry the load while the matrix binds the fibers together transmitting the load among the fibers. The matrix also decreases the density.

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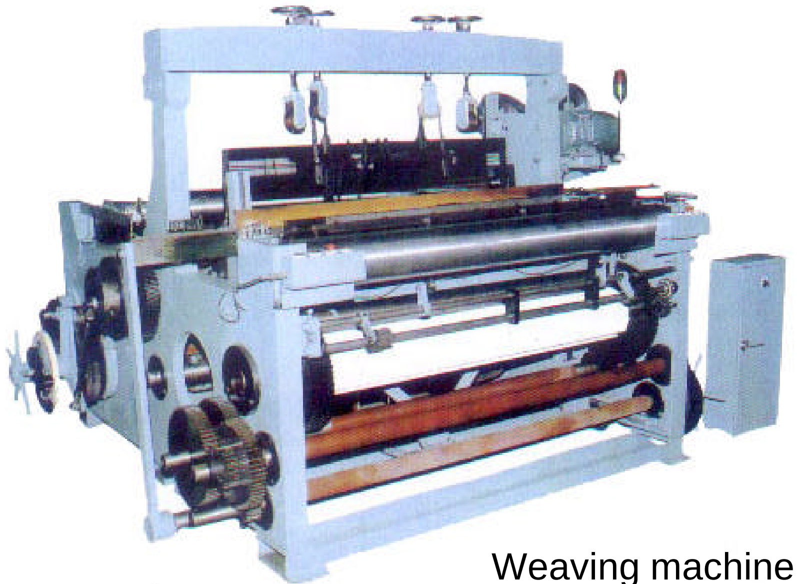
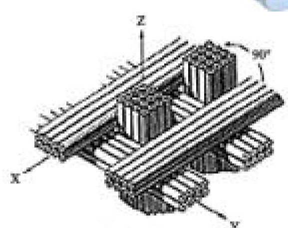
Carbon Composite Preform Fabrication

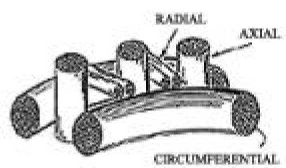


Weaving machine

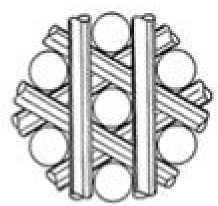
In composite fabrication, the first step is to form a carbon fiber preform with the fibers oriented for the desired mechanical properties. The preforrm can be formed as a felt or as a 2-D cloth lay-up. Alternatively the fibers can be braided, woven, filament wound



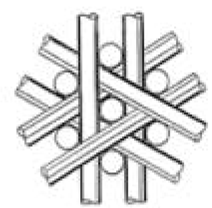
3-D Orthogonal



3-D Cylindrical

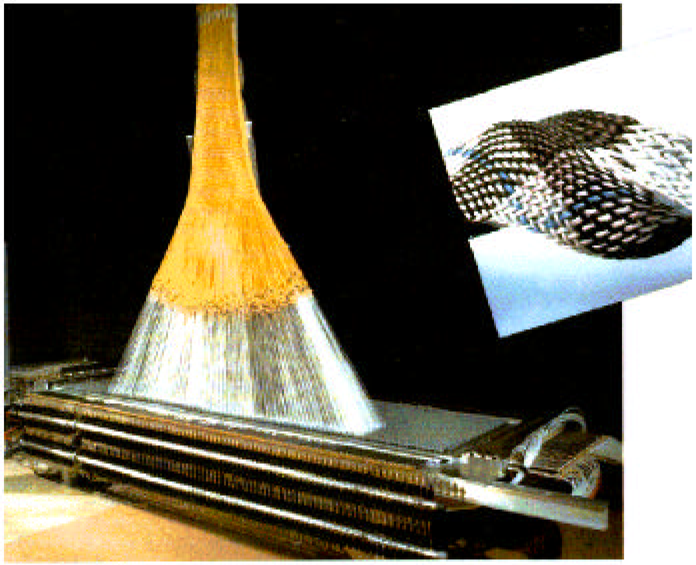


4-D In-Plane

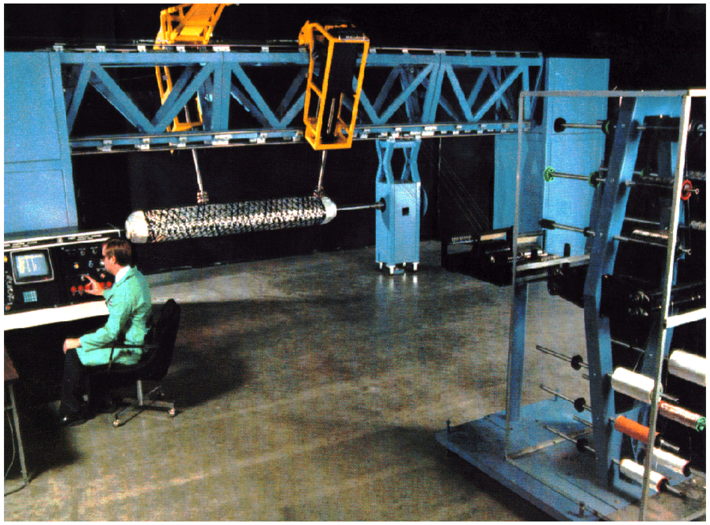


4-D Pyramidal

Carbon Composite Preform Fabrication



BRAIDING MACHINE



FILAMENT WINDING

In composite fabrication, the first step is to form a carbon fiber preform with the fibers oriented for the desired mechanical properties. The preform can be formed as a felt or as a 2-D cloth lay-up. Alternatively the fibers can be braided, woven, filament wound.

Carbon Composite Fabrication

After the preform is formed, the matrix or matrix precursor is used to fill the space between the fibers.

If a polymer matrix composite is desired, the polymer is used to fill the void space in the preform and then cured.

In a carbon-carbon composite, the carbon matrix is formed by a process called densification in which the matrix precursor is impregnated or infiltrated into the preform and then is converted to a char by a process called carbonization.

Depending on the application the carbon matrix is formed by pyrolysis of a polymer, hydrocarbon gas, or a pitch-based material.

During densification the composite may also experience machining and graphitization.

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Preform Impregnation/Infiltration Methods

Polymer Precursor:

A polymer is placed between the carbon fibers to produce a carbon fiber reinforced polymer (CFRP). If this matrix is carbonized a carbon-carbon composite results. (Not graphitizable)

Pitch Precursor:

A hydrocarbon pitch material, such as, petroleum pitch, coal-tar pitch, mesophase pitch, or refined pitch is forced into the fiber preform under pressure after raising the temperature to decrease viscosity. Alternatively, mesophase can be polymerized *In Situ*. The pitch is then carbonized to produce a carbon-carbon (C-C) composite. (Graphitizable)

Chemical Vapor Infiltration:

The fiber preform is surrounded in a furnace by a hydrocarbon gas, such as methane or propylene. At elevated temperature the gas precursor cracks to elemental carbon on the fiber surfaces ultimately filling the preform and resulting in a carbon-carbon (C-C) composite. (Graphitizable)

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Carbon Fiber Reinforced Sports Equipment

Graphite fibers decrease weight and add stiffness and speed to fishing rods, tennis racquets, hockey sticks, golf club and arrow shafts among others.

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Carbon Fiber Reinforced Toys

Graphite fibers decrease weight and add stiffness and speed to bicycles, motorcycles, and race cars

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Carbon Fiber Reinforced Pressure Vessels

Medical

9700 psi TVC tank for Delta Rocket

Escape slide
& Life raft

SCUBA

Carbon and graphite fibers decrease weight of pressure vessel up to 70% over that of steel cylinders. High-performance hoop-wrapped and full-wrapped composite gas cylinders are used in numerous domestic and space applications. No degradation in properties with time

Paintball-4500 psi

CNG and
Hydrogen Storage

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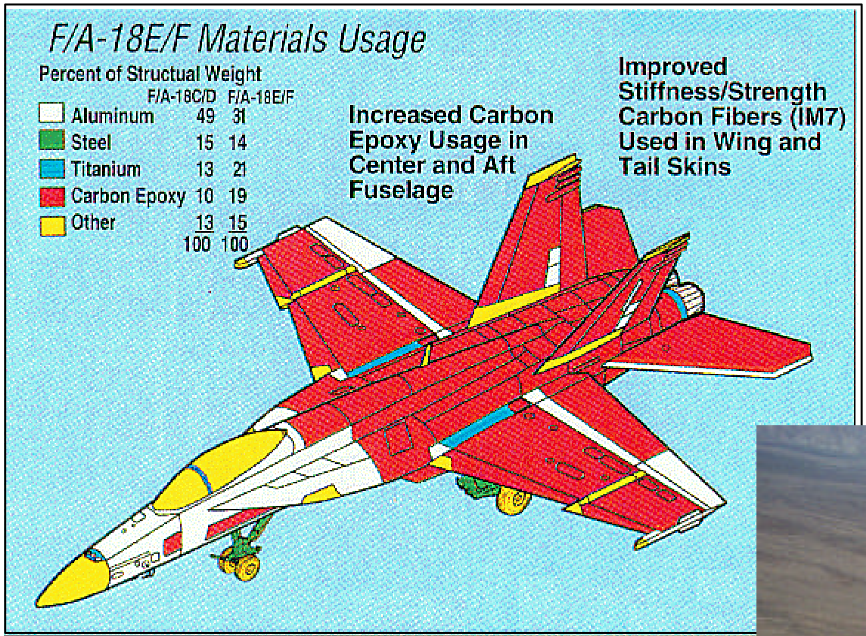
Carbon Fiber Reinforcement Aeronautics



- **Carbon-epoxy and carbon-phenolic are used in military aircraft.**

Carbon Fiber Reinforcement in Aeronautics

Gossamer Albatross

Carbon-epoxy and carbon phenolic were first used in high performance aircraft

Gossamer Penguin

Voyager

Carbon Fiber Reinforcement in Aeronautics

Carbon-epoxy and carbon phenolic are used in commercial aircraft.

Adam Aircraft

Carbon Fiber Reinforcement in Astronautics





AFRL/VS developed the technology for and produced the first isogrid stiffened payload fairing (shroud) by filament winding carbon fiber.

Carbon Fiber Reinforcement in Construction-Bridge Retrofits

Carbon fabric with epoxy matrix has been used to rehabilitate highway bridge decks, caps, and girders. The retrofit results in a structure that is at least 25% stronger and substantially increases the bridge life. It is accomplished at a fraction (~25%) of the cost of a conventional repair and requires no lane closures.

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Carbon Fiber Reinforcement in Construction-Curtain Wall

A curtain wall system is a lightweight exterior cladding which is hung on the building structure, usually from floor to floor. High performance curtain walls now incorporate cement with chopped carbon fiber

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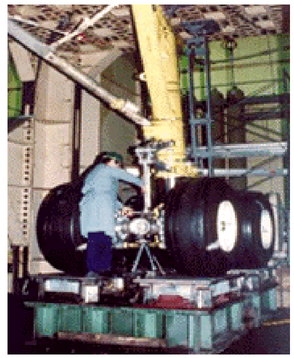
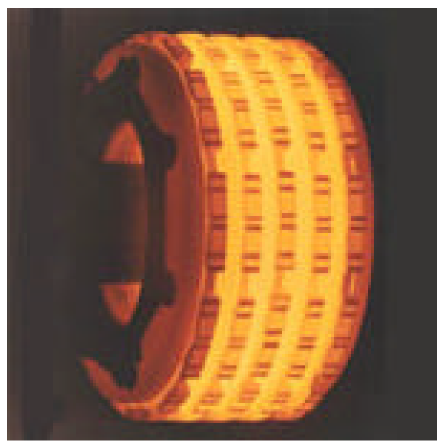
Carbon- Carbon Composites in Transportation

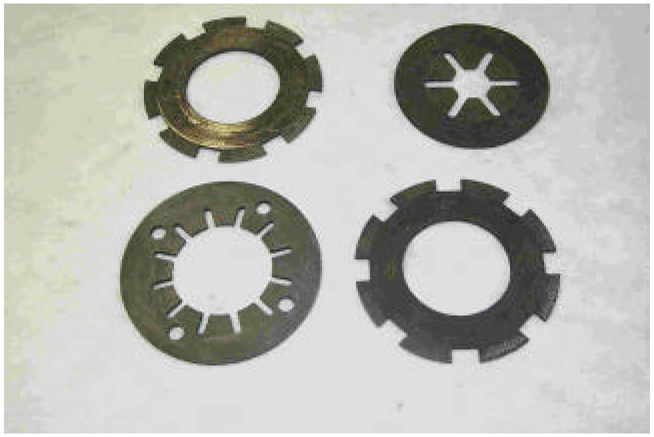


Carbon-carbon aircraft brakes are used in all military aircraft and a vast majority of the commercial fleet. This is by far the largest application of carbon-carbon composites.



Carbon- Carbon Composites in Transportation

Carbon-carbon is also used for brakes and clutches in race cars and motorcycles as well as for high temperature hardware



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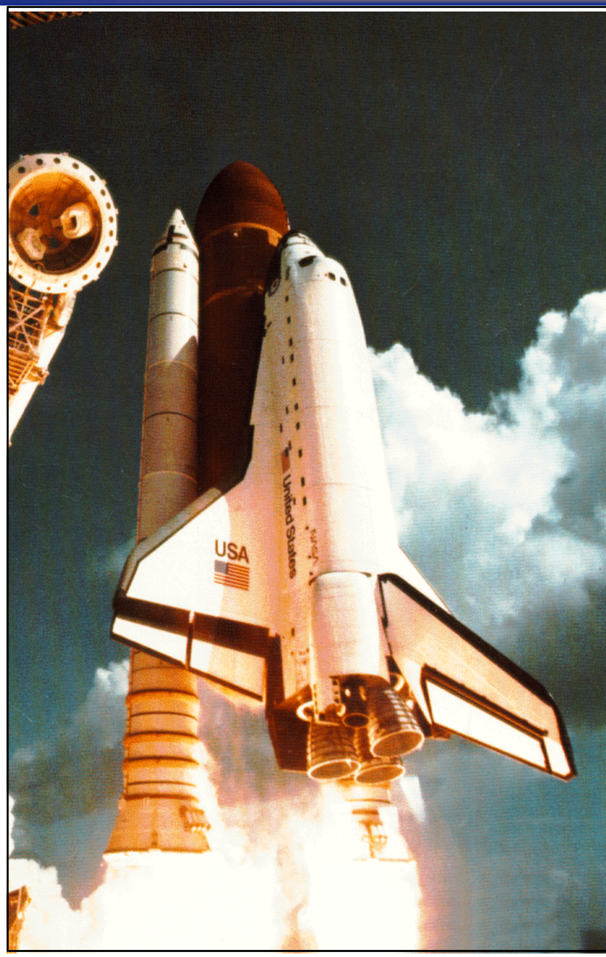
Carbon-Carbon Composites in Astronautics



Carbon-carbon in nose-tips, leading edges, nozzles and exit cones.

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Carbon-Carbon Composites in Astronautics

TABLE 1	Graphite Composite (aerospace grade)	Graphite Composite (commercial grade)	Fiberglass Composite	Aluminum 6061 T-6	Steel, Mild
Cost $/LB	$20-$250+	$5-$20	$1.50-$3.00	$3	$.30
Strength (psi)	90,000-200,000	50,000-90,000	20,000-35,000	35,000	60,000
Stiffness (psi)	10×10^6 - 50×10^6	8×10^6 - 10×10^6	1×10^6 - 1.5×10^6	10×10^6	30×10^6
Density (lb/in^3)	.050	.050	.055	.10	.30
Specific Strength	1.8×10^6 - 4×10^6	1×10^6 - 1.8×10^6	363,640 - 636,360	350,000	200,000
Specific Stiffness	200×10^6 - $1{,}000 \times 10^6$	160×10^6 - 200×10^6	18×10^6 - 27×10^6	100×10^6	100×10^6
CTE (in/in-F)	-1×10^{-6} - 1×10^{-6}	1×10^{-6} - 2×10^{-6}	6×10^{-6} - 8×10^{-6}	13×10^{-6}	7×10^{-6}

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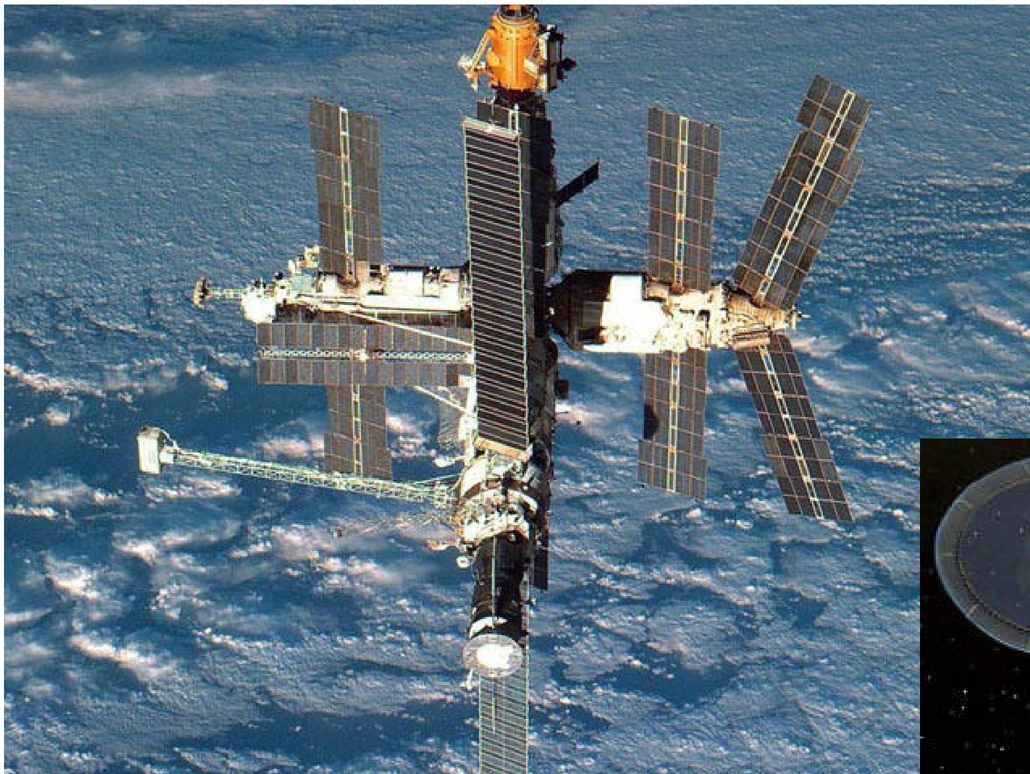
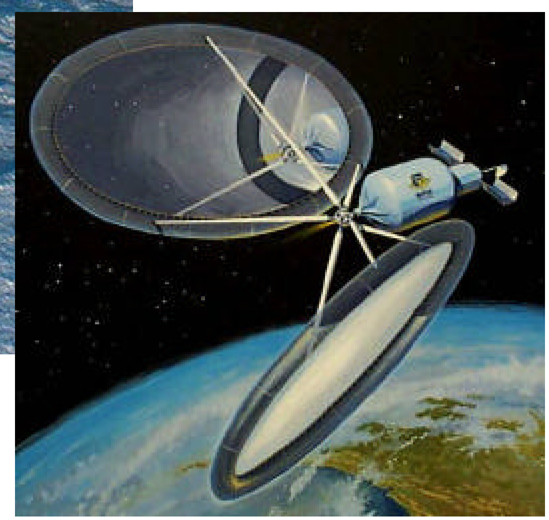
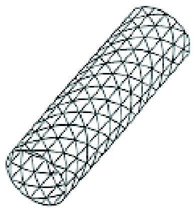
Carbon-Carbon Composites in Astronautics



Carbon-Carbon is used in space applications, such as platforms, booms, mirror and support structures because it is strong, stiff, light, and has low thermal expansion



Carbon-Carbon Composites in Astronautics

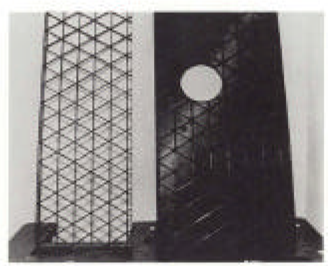


Isogrid structures are light, strong, and rigid. They can be made inexpensively using filament winding techniques.

Carbon-Carbon is used in space applications, such as platforms, booms, mirror and support structures because it is strong, stiff, light, and has low thermal expansion

Cylinder

Cone

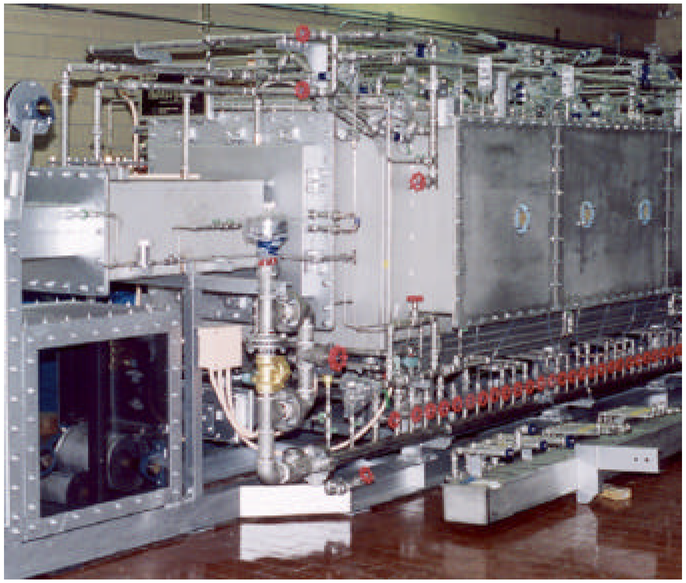


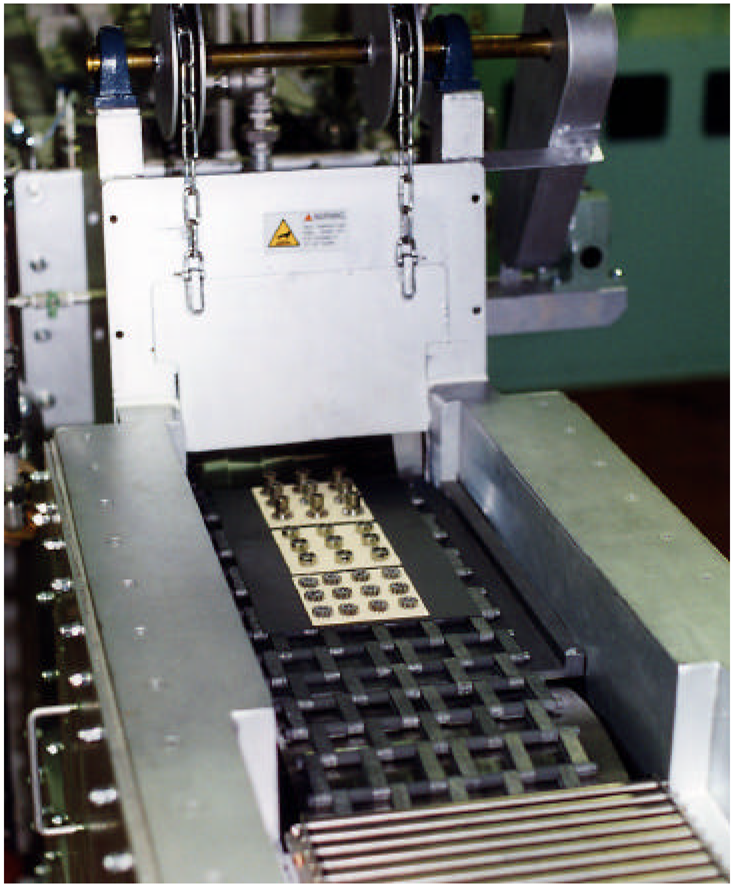
Panel

Rigidization on command inflatable structures with UV cure in Sunlight

A2705V2004.

KYK Oxynon®
Sintering Furnace





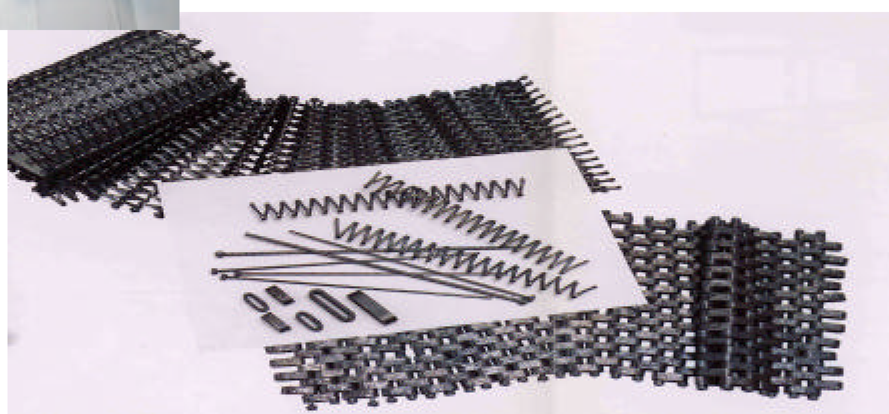
•Can sinter & braze up to 2000ºC.
•Continuous graphite channel is 25cm wide & 12.5cm high.
•Belt speed up to 25 cm/min.
•Eliminating refractory metal oxide lining allows low oxygen partial pressure operation.

KYK
KANTO YAKIN KOGYO CO. LTD.

KYK Oxynon® Sintering Furnace

Low Thermal Mass
High Strength
Thermal Shock Resistant
Energy Efficient
Fast Heating and Cooling
Max Temperature- 2600°C
Max load– 12 kPa (250 lb/ft^2)

Belt consists of light weight, high strength carbon composite links and threaded rods.



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2004 CORVETTE

The Model Z06 has a carbon fiber reinforced hood (bonnet). It has a 1.2 mm thick skin. First high gloss paint application.

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Conclusion

Carbon is a very diverse, useful and important material. Modern society as we know it could not function without numerous structural carbon products.