CHEMISTRY

70th Class, 10-12-2021

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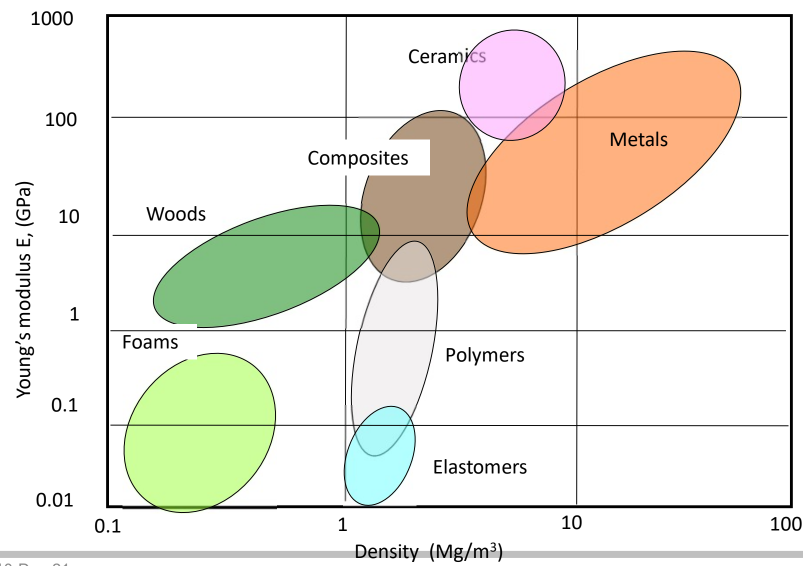
Last class

- Metal matrix composite materials
- Reinforcements used
- AMCs
- Synthesis and applications

Young's modulus vs Density Graph



In this class

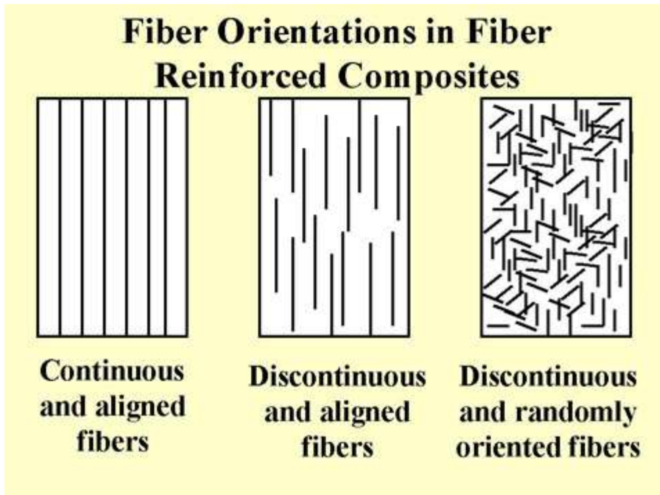
- ❑ Ceramic matrix composites
- ❑ Synthesis and applications

Fiber-reinforced Composites

- **Fiber – High length-to-diameter ratio, Its diameter approximates its crystal size**.
- **Whiskers are similar in diameter to fibers, but in general, they are short and have low length-to-diameter ratios, barely exceeding a few hundreds.**
- Modern composites exploit the fact that small scale samples of most of the materials are much stronger than bulk materials. Thus, **thin fibers of glass are 200-500 times stronger than bulk glass.**

Fiber-reinforced Composites

- Fibers are significantly stronger than bulk materials because: – **They have a far more "perfect" structure**, i.e. **their crystals are aligned along the fiber axis.**
- There are **fewer internal defects, lesser number of dislocations**.
- For this reason fibers of several engineering materials are far more strong than their equivalent bulk material samples.

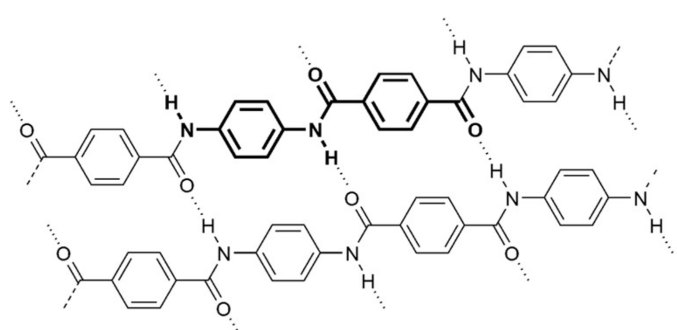


- **Carbon fiber composites are now quite common in commercial and military aviation. The Boeing 787 and Airbus A350 XWB have roughly 50% of their structure from composite materials**
- Fiber reinforced composites are used in high end sports cars
- Fiber glass has been the common material for recreational boats and yachts for many years.
- **Major advantage is its thermal expansion is basically zero**
- Carbon fiber composite structures **do not suffer any fatigue issues** if designed and dimensioned properly.
- **Does not corrode, which is a huge issue with metals**

- The strength of the composite depends primarily on the **amount, arrangement and type of fiber (or particle) reinforcement in the resin**
- Typically, **the higher the reinforcement content, the greater the strength**
- In some cases, glass fibers are combined with other fibers, such as **carbon or aramid (Kevlar29 and Kevlar49), to create a "hybrid" composite** that combines the properties of more than one reinforcing material.

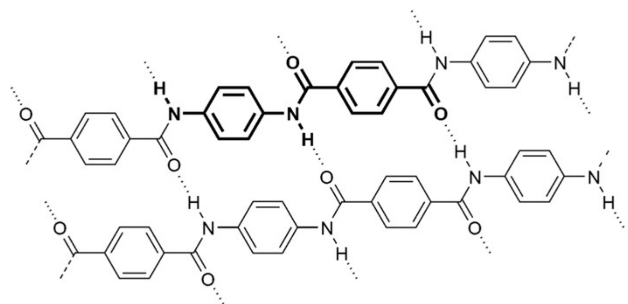
Kevlar

- Developed by Stephanie Kwolek at DuPont in 1965
- **Kevlar** is the registered trademark for a para aramid synthetic fiber, **Poly-paraphenylene terephthalamide**
- Replacement for steel in racing tires



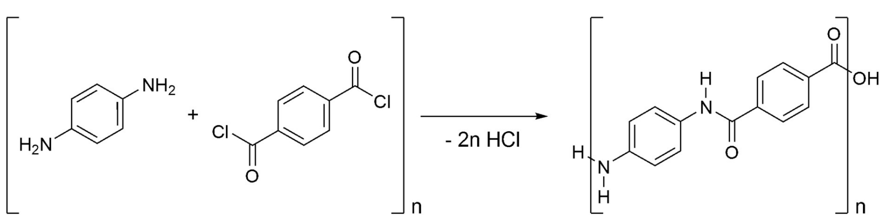
Kevlar

- ❑ High tensile strength to weight ratio; by this **measure it is 5 times stronger than steel**
- ❑ The polymer owes its high strength to the many inter-chain bonds : inter-molecular hydrogen bonds form between the carbonyl groups and N*H* centers



Kevlar – Synthesis

- ❑ In solution from the monomers **para-pheylenediamine and terephthaloyl chloride** in a condensation reaction
- ❑ Patent war with Akzo (solvents) – Leo Vollbracht and Wim Engelhard
- ❑ Hexamethylphosphoramide (DuPont), N-methyl pyrollidone with calcium chloride (Akzo)

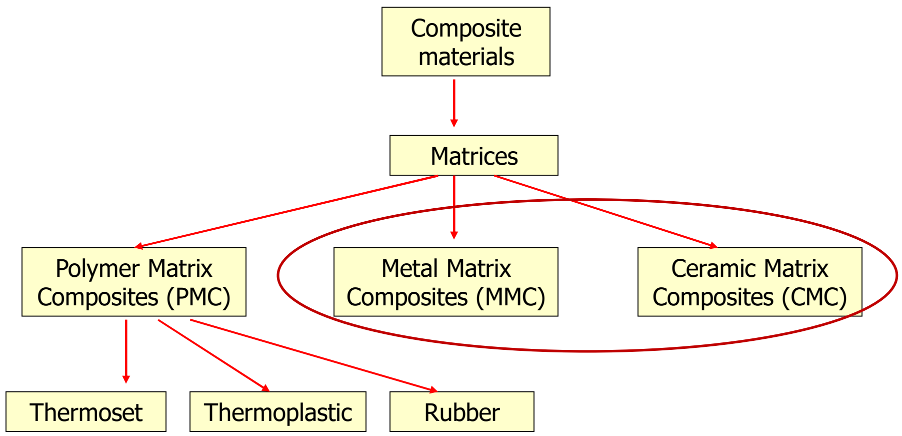


Kevlar

Most Common Fibers for FRP

Property	Glass	Carbon	Kevlar
Strength	Worst	In - between	Best
Stiffness	Worst	Best	In – between
Cost	Best	Worst	In – between
Weight	Worst	Best	In-between

Classification based on Matrix



Matrix - Functions

- Holds the fibers together, protects the fibers from environment.
- Distribute the load evenly between fibers so that all fibers are subjected to the same amount of strain.
- Improves impact and fracture resistance of a component.
- Helps to avoid propagation of crack growth through the fibers.

Desired properties of a matrix

- Reduced moisture absorption
- Low shrinkage
- Excellent chemical resistance
- Low coefficient of thermal expansion
- Should be easily processable into the final composite shape
- Good flow characteristics so that it penetrates the fibre bundles completely and eliminates voids during the compacting/curing process
- Must be elastic to transfer load to fibres

Metal Matrix Composites (MMC)

- Metal matrix composites (MMCs) are a class of materials comprised of a metal fused with another substance.
- The two components appear in differing phases that are physically & chemically distinct; base material - metal matrix, reinforcing material- fibers or particulates

Aluminium – graphite particle composite piston

Metal matrix composites for rocket nozzle

Composite Materials – Metal Matrix

- Metal matrix: Al, Ti, Mg, Fe, Cu, Ni
- Example: Al-SiC (silicon carbide) CERMETS
- Example: Al-Al_2O_3 (aluminum oxide)
- High strength, high stiffness, abrasion resistance, dimensional stability, high temperature and toughness.

Composites – Metal Matrix

The metal matrix composites offer higher modulus of elasticity, ductility, and resistance to elevated temperature than polymer matrix composites. But, they are heavier and more difficult to process.

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

Examples of Metal Matrix Composites

- **Aluminium MMC** - Ex: aluminium-graphite composite & aluminium-beryllium composites
- **Magnesium MMC**– Ex: magnesium-silicon carbide (Mg-SiC), magnesium-aluminium oxide ($Mg\text{-}Al_2O_3$) & magnesium-titanium carbide (Mg-TiC).
- **Titanium MMC** - Pure titanium is already a strong material in itself, but its composite form may enhance its superior strength.
- **Other MMCs** - Other less common but highly useful matrix base materials used for composites include **copper, cobalt, nickel, or a combination of metals**

Metal Matrix Composites (MMC)

- In **structural applications**, the matrix is usually composed of a lighter metal such as magnesium, titanium, or aluminum.
- In **high temperature applications**, cobalt and cobalt-nickel alloy matrices are common.
- **Continuous carbon, silicon carbide, or ceramic fibers** are some of the materials that can be embedded in a metallic matrix material.
- Typical **MMC's manufacturing** is basically divided into three types: solid, liquid, and vapor.

Reinforcements used in MMC

- Matrices based on most engineering metals have been explored, including **aluminum, magnesium, zinc, copper, titanium, nickel, cobalt and iron**.
- Reinforcements used in metal-matrix composites fall in four main categories: **continuous fibers, short fibers, whiskers, and equiaxed particles**
- Its size can also vary widely, from about **0.1 to more than 100 µm.**

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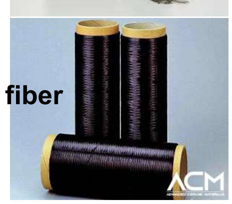
Reinforcements

Continuous Fibers

- Many continuous (organic & inorganic) fibers or filaments are used in MMC
- Almost all organic fibers have low density, flexibility, and elasticity.
- Inorganic fibers are of high modulus, high thermal stability and possess greater rigidity
- Ex :Glass fibers, silicon carbide fibers, alumina fibers, metal fibers, graphite fibers, boron fibers, aramid fibers

Metal fiber

Carbon fiber



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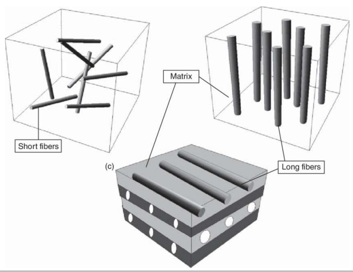
Reinforcements

Short Fibers

- Short fibers are less expensive, especially when they are mass-produced for other applications such as high-temperature thermal insulation.
- Their reinforcing efficiency in the matrix is also far lower. Short fibers used in engineering practice include chopped carbon fibers and alumina-silica fibers.



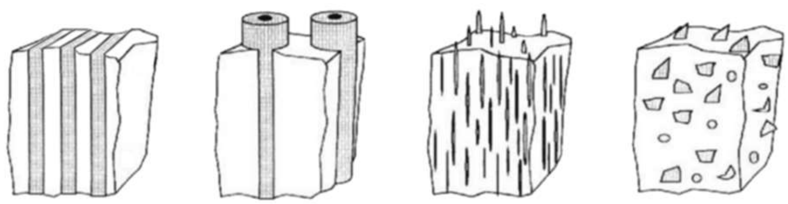
Composite - Components - Advantages

Composite	Components	Advantages
Aluminum-silicon carbide (particle)	Piston	Reduced weight, high strength & wear resistance
Aluminum-silicon carbide(whiskers)	Connecting rod	Reduced reciprocating mass, high specific strength and stiffness, low coefficient of thermal expansion
Magnesium-silicon carbide (particle)	Sprockets, pulleys, and covers	Reduced weight, high strength & stiffness
Aluminum-aluminum oxide (short fibers)	Piston ring	Wear resistance, high running temperature
Aluminum-aluminum oxide (long fibers)	Connecting rod	Improved strength & stiffness
Copper-graphite	Electrical contact strips, electronics packaging, bearings	Low friction and wear, low coefficient of thermal expansion
Aluminum-graphite	Cylinder, bearings	Reduced friction, wear & weight
Aluminum-titanium carbide (particle)	Piston, connecting rod	Reduced weight and wear
Aluminum-aluminum oxide fibers-carbon fibers	Engine block	Reduced weight, improved strength & wear resistance

Classification of metal matrix composites

Metal Matrix Composites(MMCs)

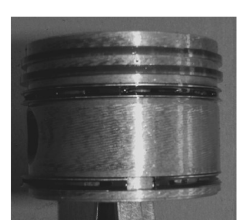
- Dispersion hardened and particles
- Layer composites
- Fiber composites
- Infiltration composites



Aluminium matrix composites (AMC)

- Aluminium matrix composites (AMCs) refer to the class of **light weight high performance** aluminium centric material systems.
- The reinforcement in AMCs can be **continuous/discontinuous fibres, whisker or particulates**, in **volume fractions ranging from a few percent to 70%**
- AMCs are intended to substitute monolithic materials including aluminium alloys, ferrous alloys & polymer based composites.

AMC Pistons



Types of AMCs

AMCs can be classified into four types depending on the type of reinforcement.

- Particle-reinforced AMCs (PAMCs)
- Whisker-or short fibre-reinforced AMCs (SFAMCs)
- **Continuous fibre-reinforced AMCs (CFAMCs)**
- Mono filament-reinforced AMCs (MFAMCs)

Carbon fibre reinforced AMCs

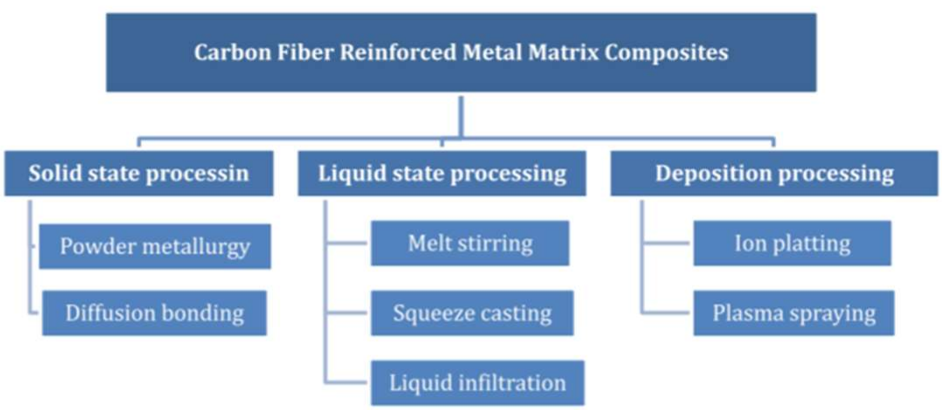
- Carbon fibres are generally produced by the thermal decomposition of various organic fibres like rayon, polyacrylonitrile (PAN)
- Carbon fibres are available in various forms: continuous, chopped, woven fabric or mat
- Aluminium, because of its low density, availability and low cost is extremely attractive for use as a matrix material.
- The matrix material has the dual function of maintaining the component shape and the transference of load to the fibres via shear processes at the interface.

Carbon Fiber Reinforced AMC

Fabrication of carbon fibre reinforced AMCs

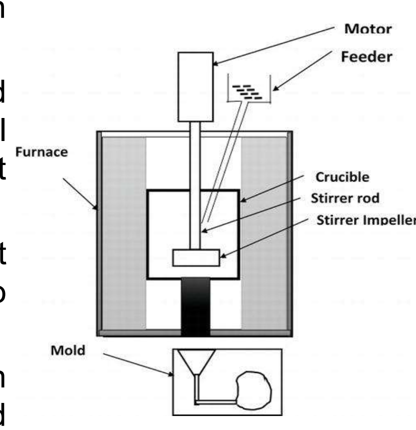
- The objective of a fabrication process
  - The fibres are introduced in the matrix without mechanical damage.
  - The fibres are aligned and distributed uniformly .
  - Adequate bonding between fibre and matrix is obtained.

- Fabrication processes is categorized into three types: **liquid-state fabrication, solid-state fabrication and deposition processing**



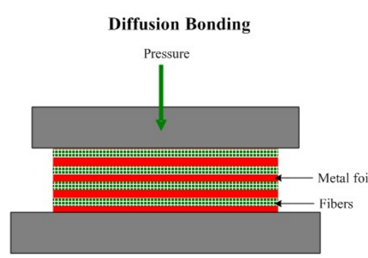
Liquid-state fabrication – Stir casting

- In stir casting the matrix metal is introduced into a furnace with stirring rod.
- Matrix material will be heated above its melting point, so metal is melted & stirrer will start rotating.
- Raw or preheated reinforcement material will be added slowly to the vortex.
- After some time molten composite melt will be poured into the mould and allow it to solidify.



Solid state fabrication

- Diffusion bonding is a solid state fabrication method,
- In which a matrix in form of foils and a dispersed phase in form of long fibers are stacked in a particular order and then pressed at elevated temperature.
- The finished laminate composite material has a multilayer structure.
- Diffusion bonding is used for fabrication of simple shape parts (plates, tubes).



Applications of Carbon fibre reinforced AMCs

- Automotive push rods, energy storage flywheels, retainer rings for high-speed motors and automotive brake calipers.
- In vehicles, such as valve covers, torque converter and transmission housings, crankcase, control arms, cradles, suspension links, door frames, steering, aluminium brake rotors and disc brakes.

Ceramic matrix composites (CMC)

- Ceramic matrix composites (CMCs) are a special type of composite material in which **both the reinforcement (refractory fibers) and matrix material are ceramics**.
- Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding.
- Typical reinforcing fiber materials include the following:
  - Carbon, C
  - Silicon Carbide, SiC
  - Alumina, Al_2O_3
  - Mullite, Al_2O_3-SiO_2

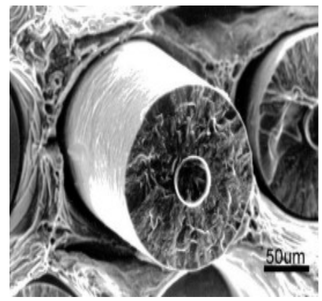
Composites – Ceramic Matrix

Ceramic matrix composites (CMC) are used in applications where **resistance to high temperature and corrosive environment is desired**. CMCs are strong and stiff but they lack toughness (ductility)

Matrix materials are usually **silicon carbide, silicon nitride and aluminum oxide, and mullite (compound of aluminum, silicon and oxygen). They retain their strength up to 3000 ^{o}F**.

Fiber materials used commonly are carbon and aluminum oxide.

Applications are in jet and automobile engines, deep-see mining, cutting tools, dies and pressure vessels.



Properties of the ceramic matrix composites

- **Thermal resistance:** adding dimensional components (fibers & matrix) that enhance the thermal shocks resistance.
- **Lightweight:** compared with the previous composite technologies, ex: it is 1/3 the weight of nickel super alloys for a similar part.
- **Fracture toughness:** CMC material is less brittle than a conventional technical ceramic, since fibers contribute to bridge the cracks
- **Electrical insulation**
- **Chemical stability**

Aerospace industry –body flaps & shrouds

Reinforcements of CMC

- Reinforcing materials used for ceramic matrix composites include carbon, alumina, silicon carbide and alumina-silica.
- The refractory fibre can be in the form of whiskers, particles, long or short fibres.
- These fibres have a polycrystalline structure similar to that of ceramics.
- Continuous or long fibres provide better toughness as they can support a load even after the ceramic matrix undergoes cracking, thus slowing down the crack's propagation.
- This makes composites less sensitive to flaws.

Matrices for CMC

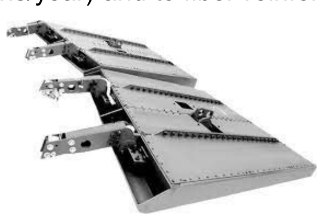
- The matrix materials used are the same as the reinforcements stated above, with the addition of non-oxide, ultra-high-temperature (UHT) ceramics used for special applications.
- The advanced ceramics are commonly used in the production of ceramic matrix composites to overcome the main disadvantage of traditional ceramics; namely, their brittleness.
- The most commonly used CMCs are non-oxide CMCs, such as carbon/silicon carbide (C/SiC), carbon/carbon (C/C), and silicon carbide/silicon carbide (SiC/SiC).

Classification of CMCs

- The type of matrix and fibers (oxide or non-oxide CMCs), the processing method or the fiber/matrix stiffness ratio, helps in differentiating CMCs into weak matrix composites (WMC) and weak interphase composites (WIC).
- The classification of CMCs according to their main constituents fibers and matrix results in two classes:
  - Non-oxide CMC (e.g., C/C, C/C-SiC, C/SiC, SiC/SiC).
  - Oxide CMCs (abbreviated Ox/Ox, OCMC or OFC, e.g., Al_2O_3/Al_2O_3)

Carbon reinforced ceramic matrix composites

- Carbon Fibre Reinforced Silicon Carbide Composites (C/SiC) AND carbon-fiber-reinforced carbon Silicon Carbide Composites (C/C-SiC COMPOSITES) are the major examples
- C/SiC materials are only used in niche applications and worldwide production of C/SiC (≈100 tons/year) is still low, compared to C/C (≈1000 tons/year) and to fiber-reinforced plastics (FRP >6 Mio tons/year)



Space shuttle body flap

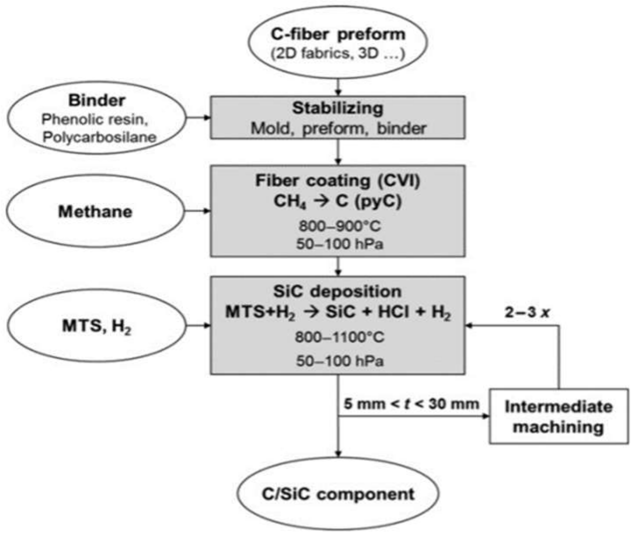
C/SiC disc barke

Manufacturing methods

- Manufacture of C/SiC materials have been adapted for the buildup of SiC matrices in fibrous preforms
- There are two main manufacturing methods:
  - CVI (Chemical Vapor Infiltration) = Deposition of gaseous SiC precursors
  - MI (Melt Infiltration) = Reaction of molten Si with C
- In principal, all the different manufacturing methods for C/SiC materials are based on three main process steps:
  - Manufacture of a C fiber preform or CFRP preform.
  - Buildup of a weak fiber/matrix interphase.
  - Buildup of a SiC matrix.

Chemical Vapor Infiltration (CVI)

- The CVI process is subdivided into three main process steps
  - 1. Manufacture and stabilizing of a carbon fiber preform.
  - 2. Deposition of fiber coating (interphase).
  - 3. Deposition of the SiC matrix
- In the first step, a porous preform made of carbon fibers is made in near net shape geometry. High fiber contents between 40 and 60 vol.% is required
- Binders like phenolic resin or polycarbosilane are used and laminated or filled in a mold, where they are formed to near net shape geometry
- Densified to a certain fiber volume content in the range of 15–25% (short fibers) up to 30–50% (fabrics)



Chemical Vapour Infiltration (CVI)

- In the third step of the CVI process, the porous fiber preform is set inside an infiltration chamber, and heated to a temperature typically between 800 deg C and 1100 deg C.
- The gaseous precursor passes through the infiltration chamber and penetrates into the porous fiber preform.
- Parallel to the infiltration, the chemical reaction of the process gas is activated at the hot surface of the porous fiber preform and SiC is deposited

Melt infiltration (MI)

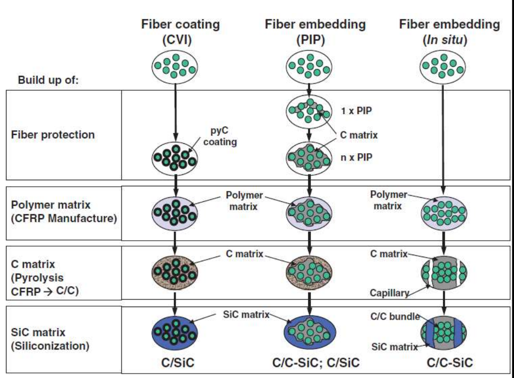
- MI technique is used for manufacturing of C/C-SiC & C/SiC materials.
- This method ensures both, minimal fiber damage during siliconization and complete densification with a homogeneously distributed SiC matrix
- The characteristics of the MI method are the infiltration of a porous C/C preform with molten Si and the buildup of the SiC matrix by an exothermic chemical reaction of the liquid silicon with the solid carbon:

$$Si_{liquid} + C_{solid} \rightarrow SiC_{solid}\ [\Delta H = -68\ kJ/mol]$$

Melt infiltration (MI) process

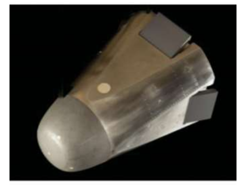
The MI process can be subdivided in four main process steps

- Buildup of fiber/matrix interphase, for example, by fiber coating.
- Manufacture of a CFRP preform.
- Pyrolysis of the CFRP preform to a C/C preform.
- Siliconization of the C/C preform



Applications of Carbon-fiber-reinforced SiC

- **Space Applications**
  - Thermal Protection Systems
  - Space Propulsion
  - Satellite Structures
- **Applications in Aeronautics**
  - Body flaps
  - Thrust vector control (TVC) system
- **Applications in Friction System** (Brakes)



Thank you all for your attention

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