Roles of interfaces on microstructural and structural integrity of advanced FRP and nano-fillers enhanced multiscales FRP composites

Presented by

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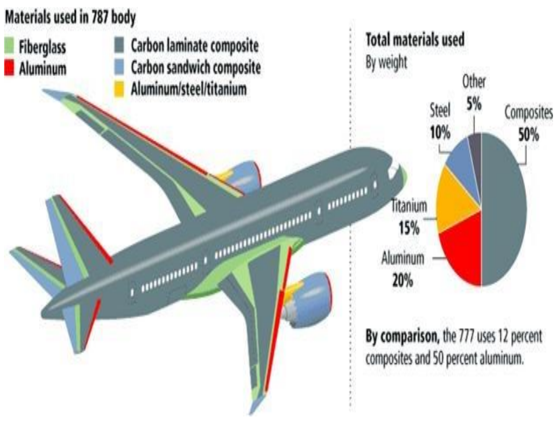
Introduction

Composite material - A composite is made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with improved properties from the individual components.

Nowadays, the fiber reinforced polymeric composites (FRP) are one among the peak used structural materials in the globe.

The typical properties of FRP's include high strength to weight ratio, high stiffness, low density, high corrosion resistance, high endurance limit, high fatigue resistance.



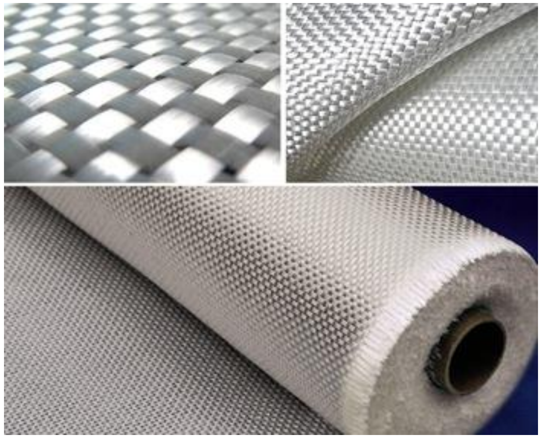
- Major constituents in a fiber-reinforced composite material are the reinforcing fibers and a matrix, which acts as a binder for the fibers. Other constituents that may also be found are coupling agents, coatings, and fillers.
- There are mainly three types of fibres used in composites. They are **Glass Fibre, Carbon fibre and Aramid Fibre.**
- These fibres are used for having some important properties. They are as follows:

  1. High tensile and compressive strength.
  2. Low density
  3. High chemical stability
  4. High thermal stability
- In case of fabric composites we mainly use WOVEN FABRICS .

Woven fabrics are generally used in high-performance composite to reinforce them. A wide range of different types of woven fabrics are used, the most familiar being plane weave, twill weave and satin weave. The density of the fibre and the type of weave critically influence the forming properties and the characteristics of the finished product.

Glass Fibres:

The Glass derived from the latin word "Glesum" means transparent,lustrous substance.
A uniform amorphous solid material, usually produced when a suitably viscous molten material cools very rapidly



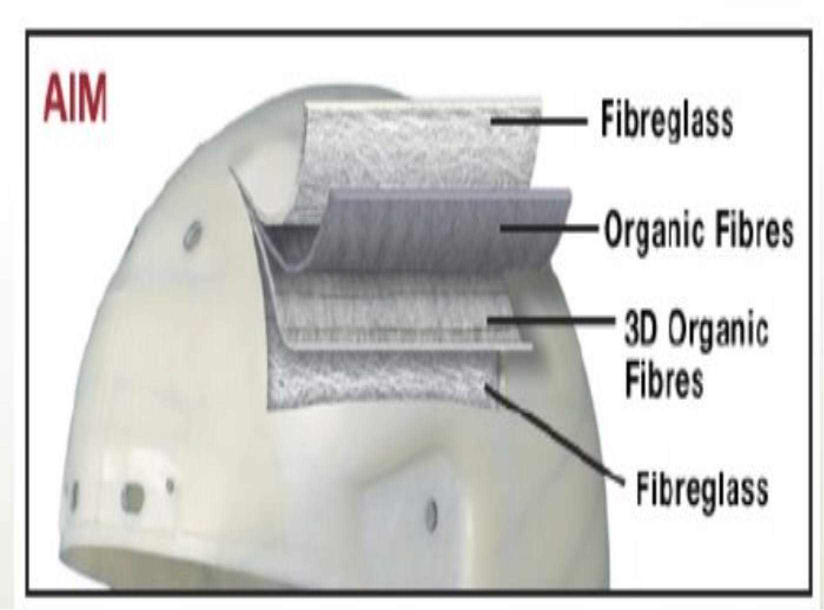
Mechanical Properties:

- Strength to weight ratio- 1307 kN.m/kg
- Tensile strength for, E – glass fibre is 3445 Mpa
  S- glass fibre is 4890 Mpa
- Tensile modulus: for E-glass fibre is 72.4 Gpa and
  for S- glass fibre is 86.9 Gpa

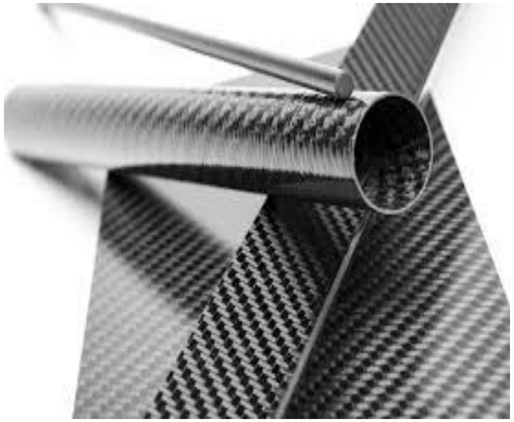
Thermal Properties

- For Glass fiber can have of thermal expansion coefficient depends upon type of the glass fibre
- For E- glass fibre 5 µm/m·°C
- For S-glass fibre 2.9 µm/m·°C

Applications Of Glass Fibres:



Carbon Fibres:



Carbon Fibres are made of carbon crystals aligned in a long axis. The honeycomb shaped crystals organize themselves in long flattened ribbons. This crystal alignment makes the ribbon strong in the long axis.

Mechanical Properties:

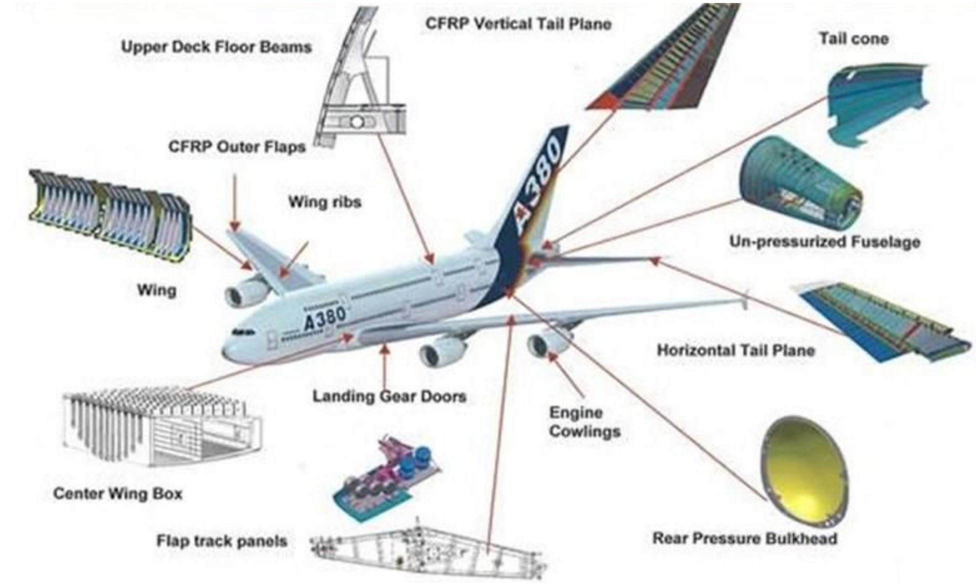
- High Strength to weight ratio- 2457 kN.m/kg This is attributed to orientation of the crystals of carbon fibre along long flat ribbon or narrow sheets of honeycomb crystals, so the strength is higher running lengthwise than across the fibre.
- High rigidity of carbon fibre: It is 4times stiffer than Glass reinforced plastic.
- Good tensile strength : ultimate tensile strength is typically 500 ksi (3.5 Gpa)
- The modulus of carbon fiber is typically 33 msi (228 GPa)

Thermal Properties:

- The variation in carbon fibre make it difficult to pinpoint the exact thermal conductivity. Carbon fiber can have a broad range of Cofficient of thermal Expansion is, -1 to 8+, depending on the direction measured, the fabric weave, the precursor material, Pan based or Pitch based

Applications Of Carbon Fibres:

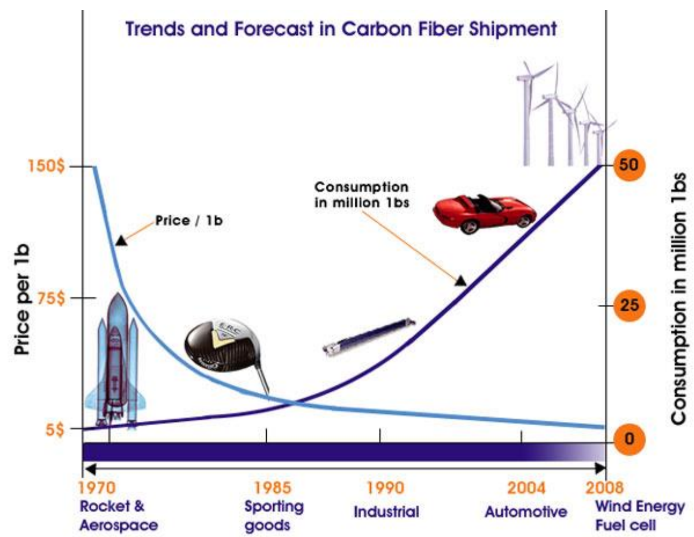
Sports equipment



Aerospace and aircraft industries

Automotive body

Wind mill blades



Aramid Fibre

Kevlar is an organic fiber in the aromatic polyamide family. The unique properties and distinct chemical composition of wholly aromatic polyamides (aramids) distinguish them and especially Kevlar from other commercial, man-made fibers

- Kevlar 49 filaments are manufactured by extruding an acidic solution of a proprietary precursor (a polycondensation product of terephthaloyol chloride (TCL) and p-phenylenediamine(PPD)) from a spinneret.

Mechanical Properties:

- High Strength to weight ratio- 2514 kN.m/kg
- Tensile strength of 3.62 Gpa for Kelver -49 and for kelver-149 3.45 Gpa
- Tensile modulus for kelvar-49 is 131 Gpa and for kelver-149 is 179 Gpa

Thermal Properties:

Determined by coefficient of thermal expansion which varies in longitudinal and radial direction of the Kevlar fibre , for kelvar-49 coefficient of the thermal expansion is -2 * 10^-6/ oC (longitudinal), and 59 * 10^-6/ oC (radial). For Kelvar-149 coefficient of thermal expansion is -6 * 10^-6/ oC in radial direction.

Applications Of Aramid Fibres:

BULLET / STAB PROOF VESTS

DIVING GLOVES

WALKING BOOTS

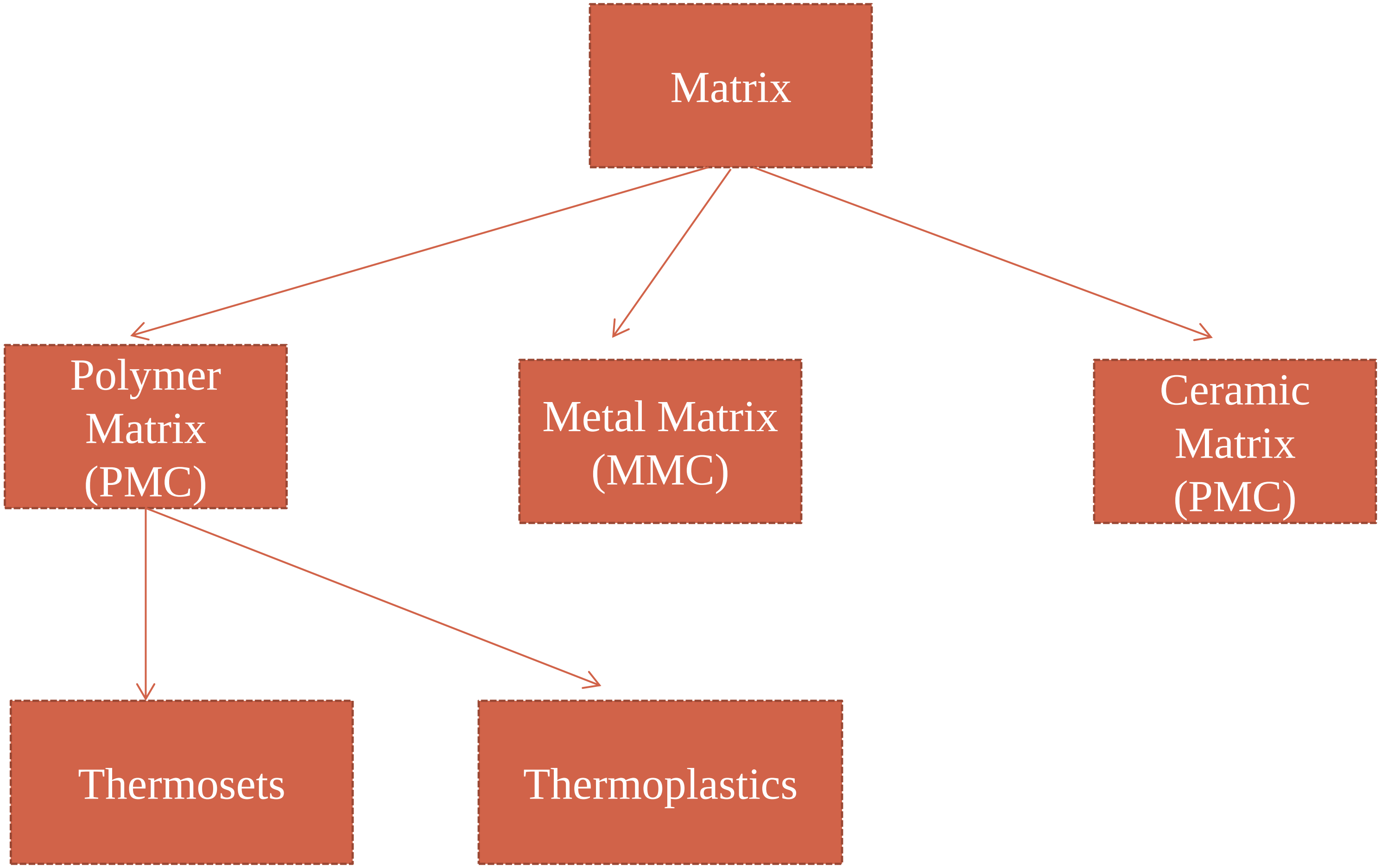
MILITARY HELMET

CUT RESISTANT GLOVES

BICYCLE TYRES

CAR TYRES

FIRE PROOF CLOTHING

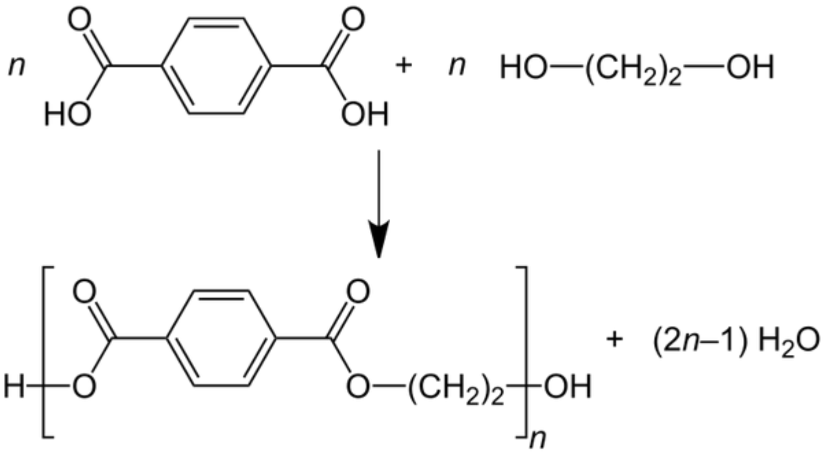


- In the fiber reinforced polymer (FRP) composite materials we generally consider the polymer matrix. Plastics that can be used as polymer matrix are PMMA, epoxy, polyethylene, polyester.

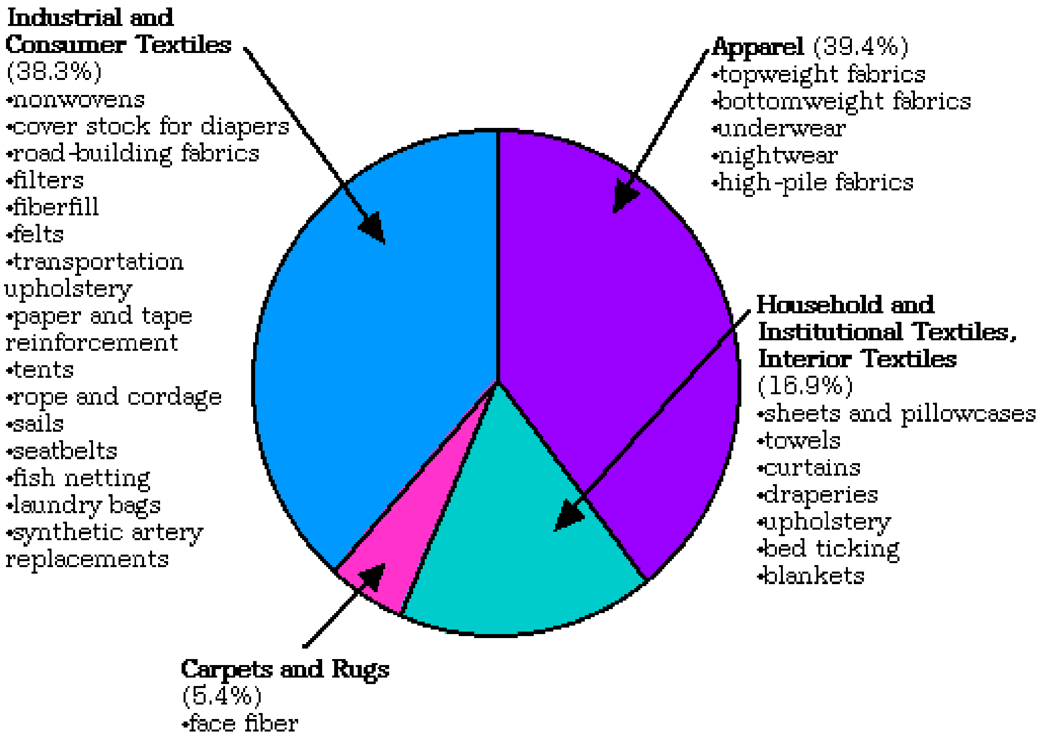
Polyester :

- It is a category of polymer containing the ester functional groups
- It can be thermoplastic or thermoset depending upon the chemical composition, thermoset polyesters include the **desmophen** brand from Bayer
  Examples : Polyethylene Tetraphthalate(PET), Polybutylene succinate (PBS), Polytrimethylene terephthalate (PTT)

- Properties:
  1. It has higher strength
  2. It is very durable, resistant to most chemicals, stretching
  3. It is hydrophobic in nature
- It is sold under the trade name of unsaturated polyester resin, allyester, PET.
- Usually synthesized by direct reaction, acid halide, Transesterification and Melt acidolysis



Applications

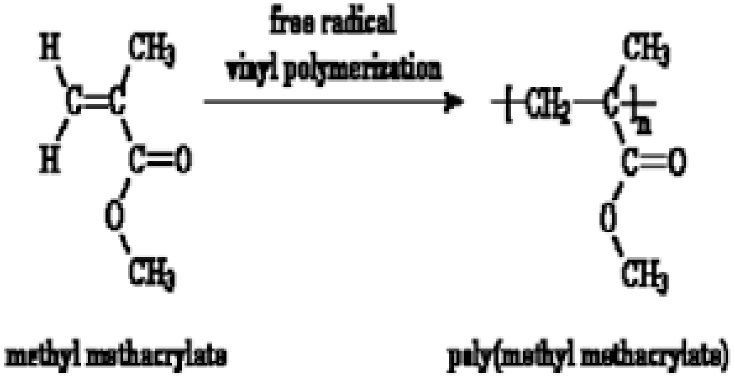


- The **Futuro** house was made of fibreglass-reinforced polymer **(FRP),** polyester-polyurethane, and poly methyl methacrylate were used as polymer matrix which was found to be degrading by Cyanobacteria and Archaea

PMMA

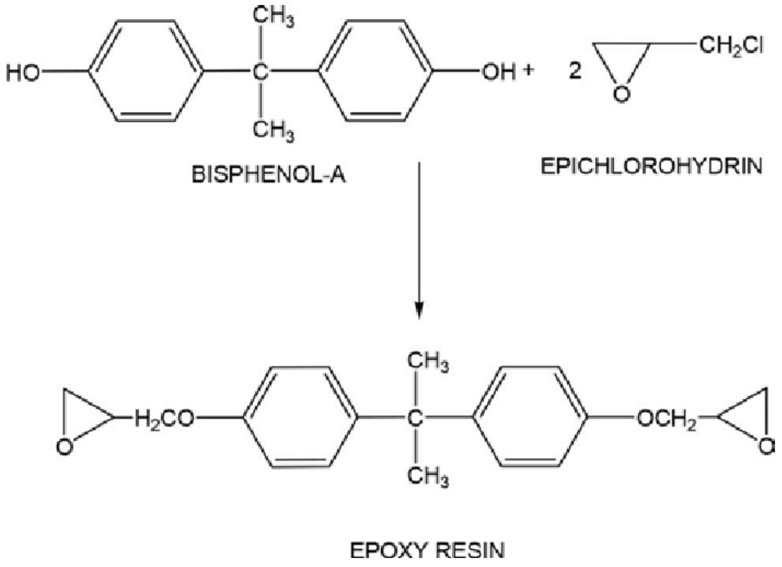
- Poly methyl methacrylate a thermoplastic and transparent plastic. Chemically it is a synthetic polymer of methyl methacrylate.
- Properties of PMMA:
  1. It is strong and lightweight
  2. Weatherable and scratch resistance
  3. Good impact strength

- It is sold in the market under the trade names of Plexiglass, R-Cast, Perspex, Plazeryl, Limacryl, Acrylex, Acrylite, Acryplast, Altuglass.
- It is a non-toxic material synthesized by the process of free radical vinyl polymerization.



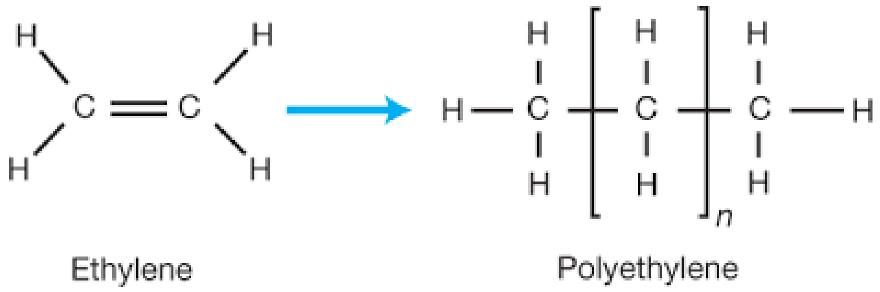
Epoxy

- Epoxy is a polymer that contains an epoxide group in its chemical structure is a reactive resin which can be considered as hardener (also called as curing agent)
  Example: DGEBA (Diglcidyl ether of Bisphenol A)
- Properties of Epoxy:
  1. Better moisture resistance
  2. Low shrinkage
  3. Good adherence with reinforcement
- It is sold under the trade names Allaco, Allibond, Epocap, Epocure, Tracon, Resiweld.
- The most commonly used epoxide monomer is the diepoxide prepared by treating one mole of bisphenol A with two moles of epicholohydrin



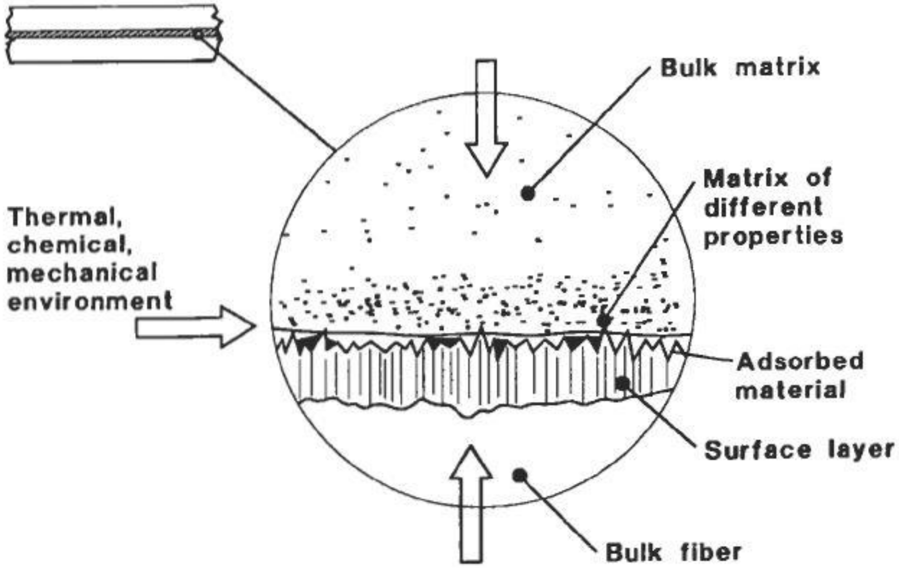
Polyethylene

- Polyethylene is most common plastic have simple structure simplest of all commercially available polymers having ethylene as the monomer
- Properties of polyethylene:
  1. Low strength, hardness and rigidity
  2. High ductility and impact strength
  3. Strong creep resistance
- It is available under the trade names Novapol, Chevron Phillips LLC Marlex, Nova Chemicals Sclair.
- It is also known as polyethene synthesized by the suitable polymerization of ethylene.



Interface - Importance

- “An **interface** is the region of significantly changed chemical composition that constitutes the bond between the matrix and reinforcement”.
- A classic definition of the ***interface*** in fiber composites is a surface formed by a common boundary of reinforcing fiber and matrix that is in contact with and maintains the bond in between for the transfer of loads.



How Interface Affects?

- The growing number of uses for fiber reinforced composites in many engineering applications has made the issue of interface (or more properly termed, interphase)
- Interfaces influences the fracture toughness in both transverse and interlaminar fractures, and strength and stiffness of fiber composites in various failure mode
- Taking advantage of the high strength and high stiffness of fibers, which are combined with matrix materials of similar/dissimilar natures in various ways, creating the use of interfaces which forms a bonding between the fibre and a matrix.
- The bond formed may be due to :

  a. Wettability of surface

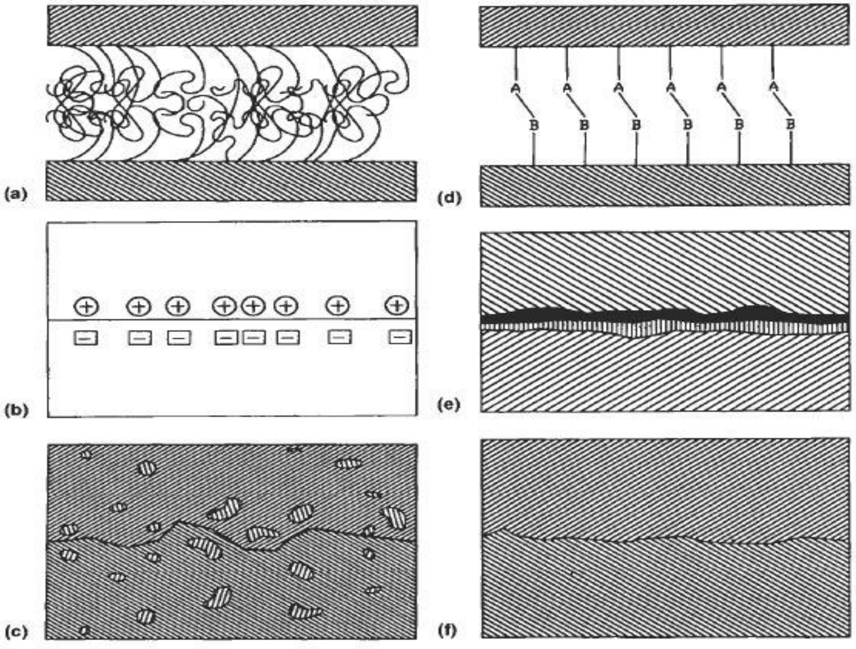
  b. Interdiffusion of atoms

  c. Electrostatic attraction

  d. Chemical bonding

  e. Reaction bonding

  f. Mechanical bonding



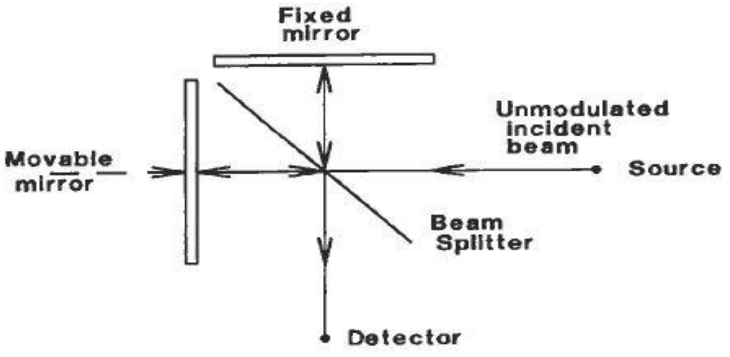
Characterization of interface

- A convenient way to characterize composite interfaces embedded within the bulk material is to analyze the surfaces of the composite constituents before they are combined together, or the surfaces created by fracture.
- Many factors such as process variables, contaminants, surface treatments and exposure to environmental conditions must be considered in the analysis.
- Amongst the currently available characterization techniques, the most useful ones for composite interfaces are:

  1. Infrared **(IR)** and Fourier transform infrared **(FTIR)** spectroscopy
  2. Laser Raman spectroscopy
  3. X-ray photoelectron spectroscopy **(XPS)**
  4. Auger electron spectroscopy **(AES)**
  5. Secondary ion mass spectroscopy **(SIMS)**
  6. Ion scattering spectroscopy **(ISS)**
  7. Solid state nuclear magnetic resonance **(NMR)** spectroscopy
  8. Wide-angle X-ray scattering **(WAXS)** and
  9. Small-angle X-ray scattering **(SAXS)**
  10. Atomic Force Microscope **(AFM)**

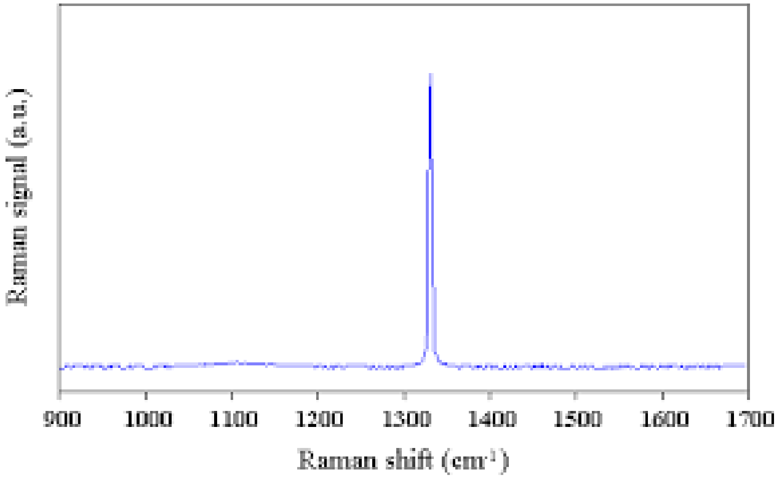
Infrared **(IR)** and Fourier transform infrared **(FTIR)** spectroscopy

- The absorption versus frequency characteristics are obtained when a beam of IR radiation is transmitted through a specimen.
- The absorption or emission of radiation is related to changes in the energy states of the material interacting with the radiation.
- In the IR region (between **800** nm and **250 pm** in wavelength), absorption causes changes in rotational or vibrational energy states. The components or groups of atoms that absorb in the IR at specific frequencies are determined, providing information about the molecular structure.
- The FTIR technique employs a moving mirror to produce an optical transformation of the IR signal, with the beam intensity after the interferometer becoming sinusoidal. FTIR has been extensively used for the study of adsorption on polymer surfaces, chemical modification and irradiation of polymers on the fiber surfaces



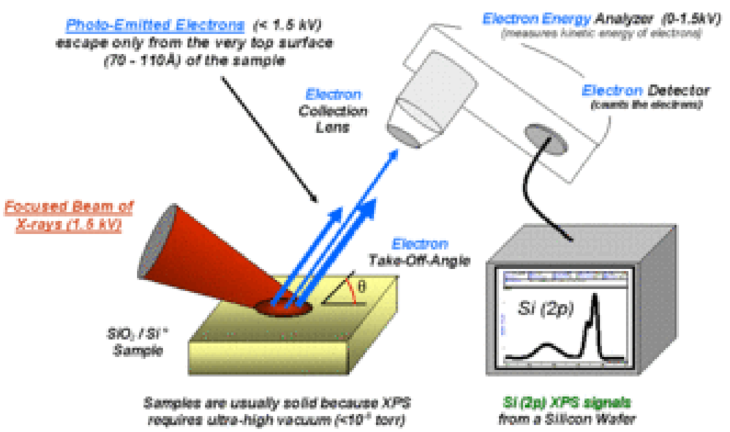
Laser Raman spectroscopy

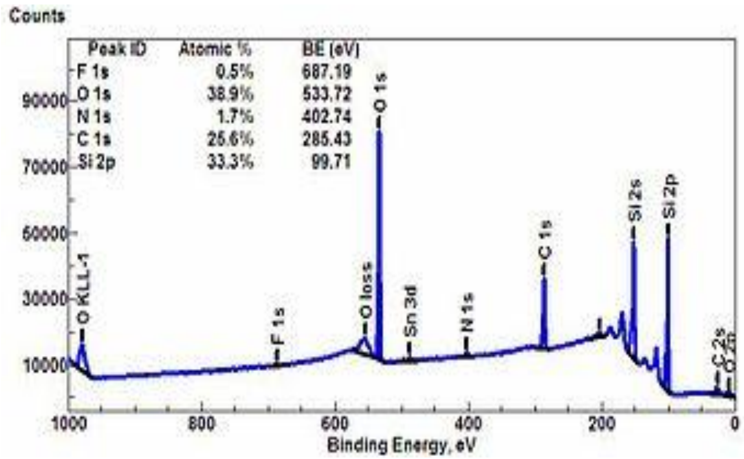
- The collision between a photon of energy and a molecule results in two different types of light scattering: the first is Rayleigh scattering and the second is Raman scattering.
- The Raman effect is an inelastic collision where the photon gains energy from or loses energy to the molecule that corresponds to the vibrational energy of the molecule.
- Surface-enhanced Raman spectroscopy has been successfully used to obtain information about adsorption of polymers onto metal surfaces, polymer-polymer interaction and Interdiffusion, surface segregation, stress transfer at the fiber-matrix interface, and surface structure of materials.



X-ray photoelectron spectroscopy **(XPS)**

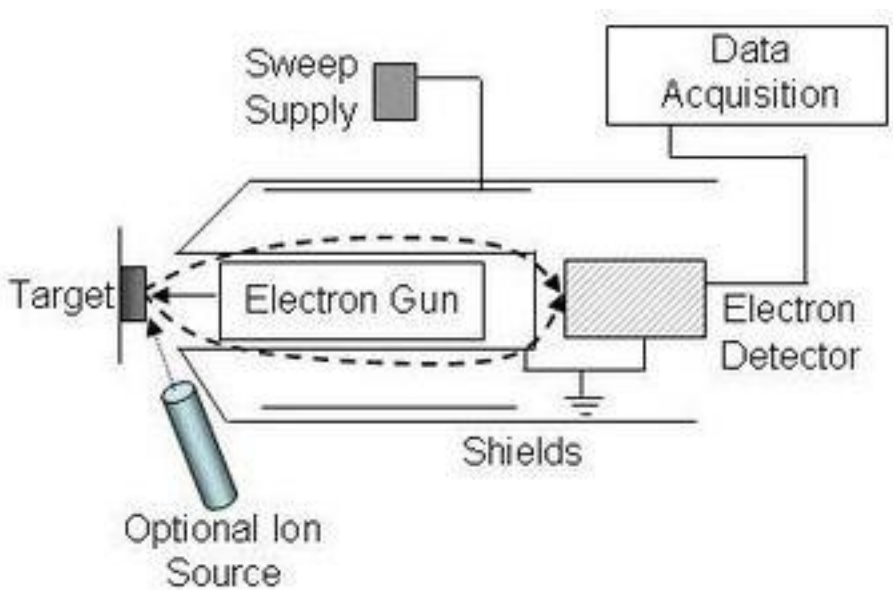
- When a sample maintained in a high vacuum is irradiated with soft X-ray, photoionization occurs, and the kinetic energy of the ejected photoelectrons is measured.
- Output data and information related to the number of electrons that are detected **as** a function of energy are generated.
- Interaction of the soft X-ray photon with sample surface results in ionization from the core and valence electron energy levels of the surface elements

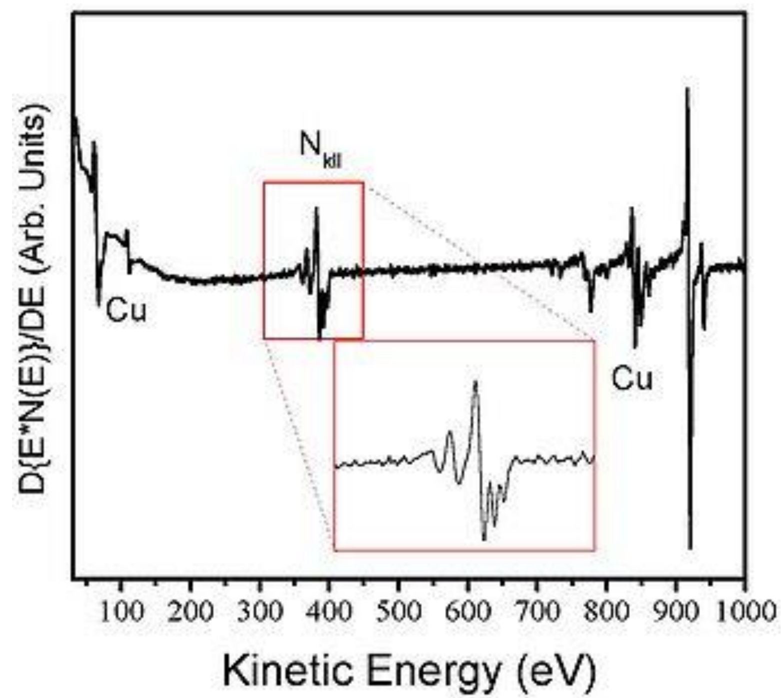




Auger electron spectroscopy **(AES)**

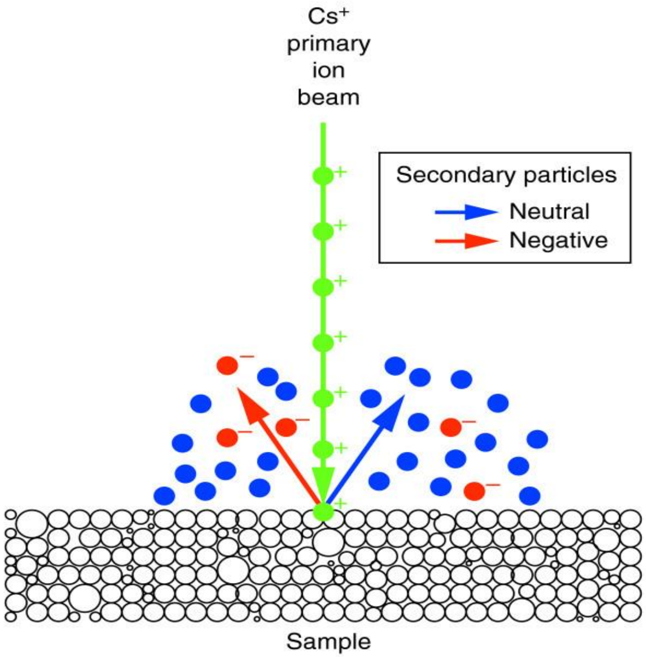
- The sample surface is bombarded with an incident high energy electron beam, and the action of this beam produces electron changes in the target atoms, the net result is the ejection of Auger electrons, which are the characteristics of the element.
- Because of the small depth and small spot size of analysis, this process is most often used for chemical analysis of microscopic surface features.

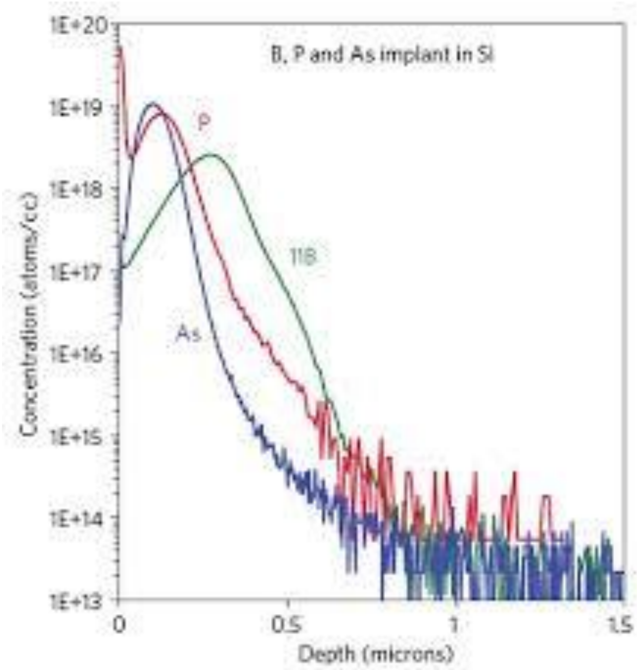




Secondary ion mass spectroscopy **(SIMS)**

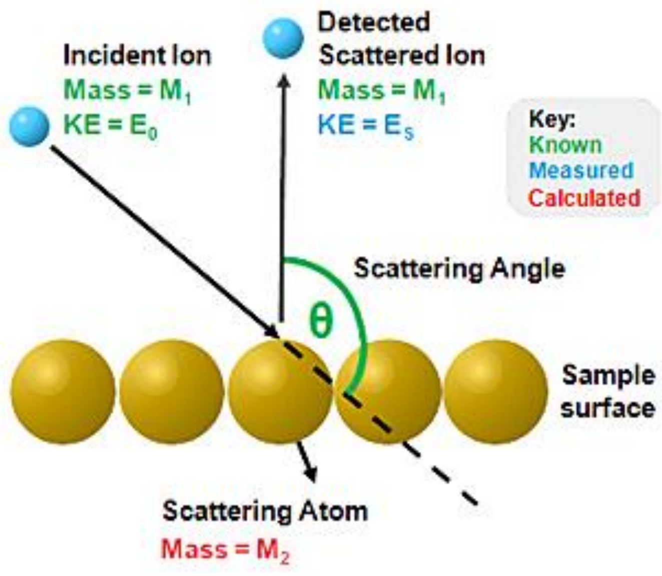
- The sample surface is bombarded with a beam of around **1** keV ions of some gas such as argon and neon.
- The action of the beam sputters atoms from the surface in the form of secondary ions, which are detected and analyzed to produce a characterization of the elemental nature of the surface.
- The depth of the analysis is usually less than a nanometer, making this process the most suitable for analyzing extremely thin films

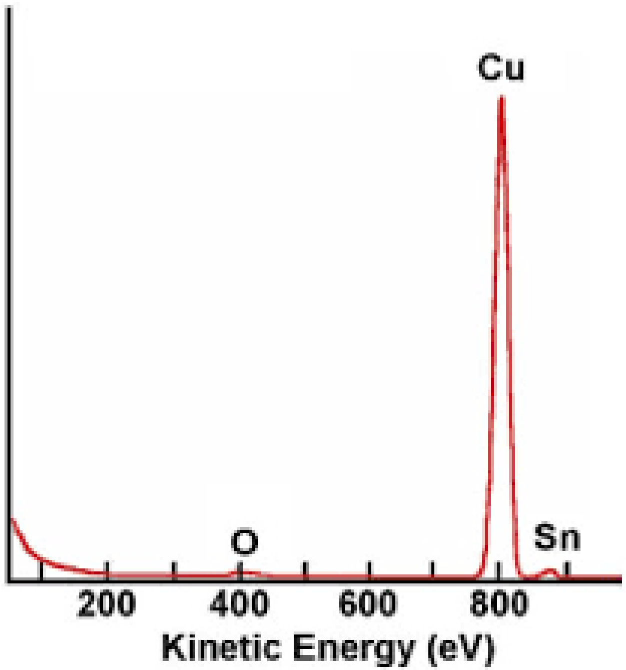




Ion scattering spectroscopy **(ISS)**

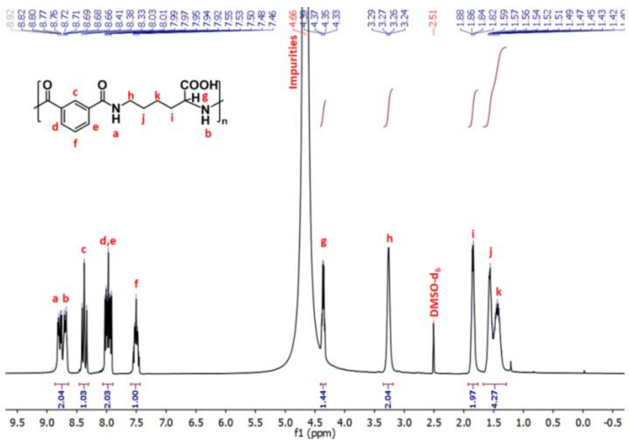
- In **ISS,** like in **SIMS,** gas ions such as helium or neon are bombarded on the sample surface at a fixed angle of incident.
- The **ISS** spectrum normally consists of a single peak of backscattered inelastic ion intensity at an energy loss that *is* characteristic of the mass of surface atom.
- From the pattern of scattered ion yield versus the primary ion energy, information about elements present on the sample surface can be obtained at ppm level.





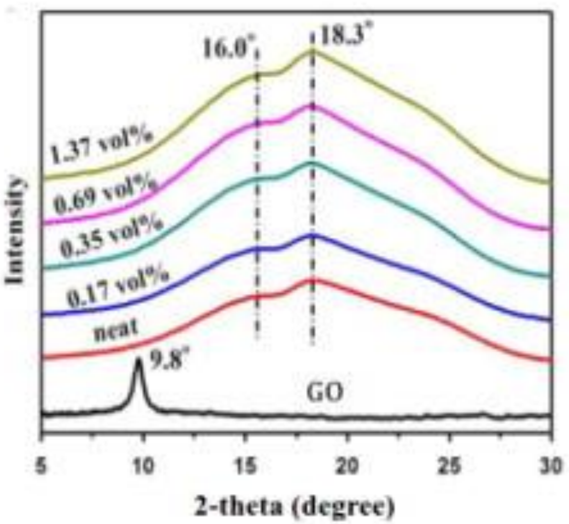
Solid state nuclear magnetic resonance **(NMR)** spectroscopy

- In NMR technique, a sample is placed in a magnetic field which forces the nuclei into alignment.
- When the sample is bombarded with radio waves, they are absorbed by the nuclei topple out of alignment with the magnetic field.
- By measuring the specific radiofrequencies that are emitted by the nuclei and the rate at which the realignment occurs, the spectroscope can obtain the information on molecular structure.



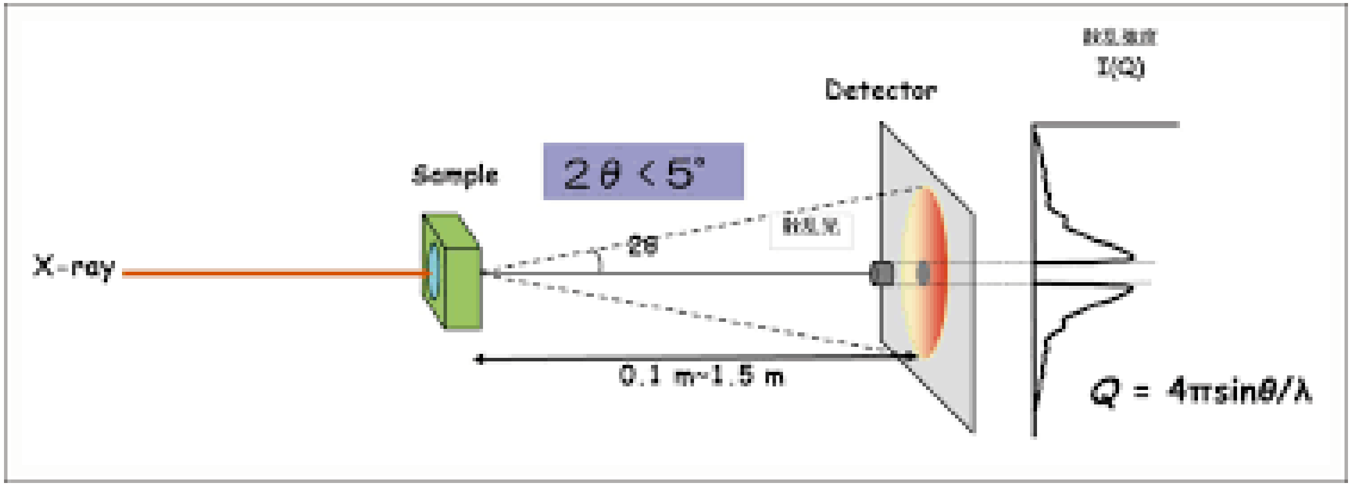
Wide-angle X-ray scattering **(WAXS)**

- A technique for the characterization of polymer crystallinity as a bulk material or around the stiff fibers/particulates in composites is based on **WAXS.**
- The **WAXS** method is actually more of a bulk analytical tool than a surface technique, but it has been developed mainly for monitoring crystallinity in thermoplastics and fiber composites made therefrom.



Small-angle X-ray scattering **(SAXS)**

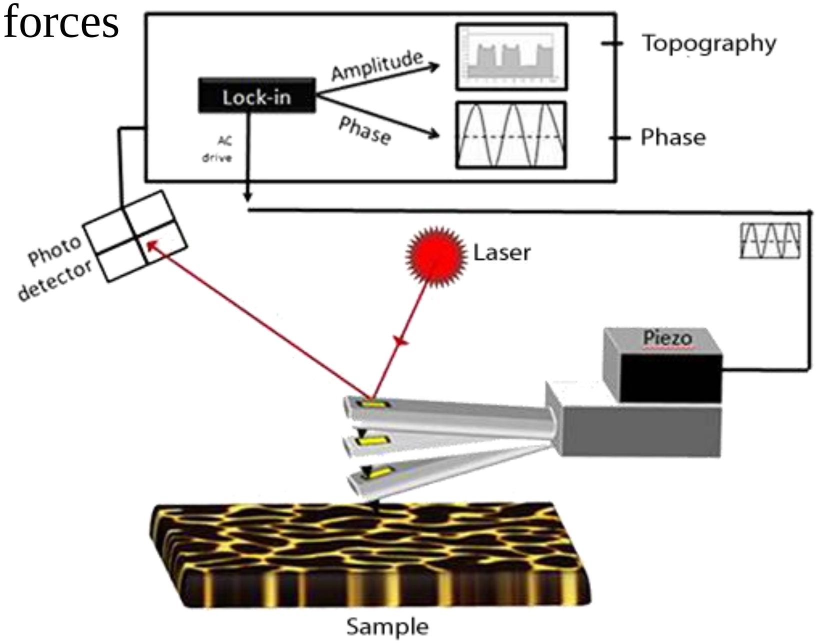
- Small-angle light scattering (SALS) is a technique developed to determine the morphological structures on a scale larger than the wave length 1-100 pm of the radiation used.
- Spherulites are structures of semi crystalline polymers that are in this size range.
- In SALS, a monochromatic, collimated and plane polarized laser beam is used to excite a thin polymer film.
- The scattered radiation is analyzed with a second polarizer, aligned with the first polarizer, and the scattering pattern is recorded on photographic film or by electron detectors. As light interacts with the polymer, there is polarization of the electronic charge distribution

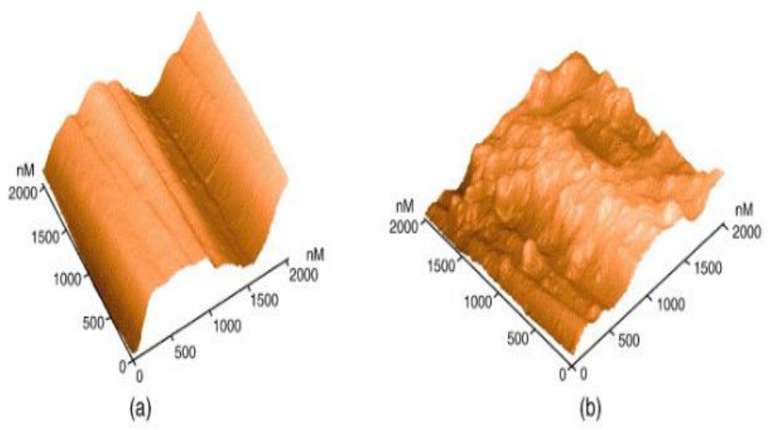


Atomic Force Microscope (**AFM**):

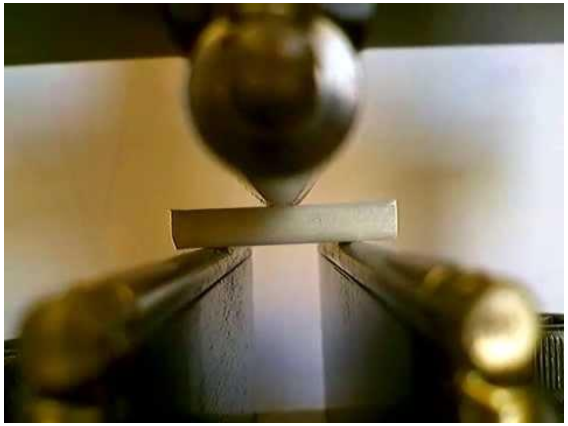
- AFM uses a cantilever with a very sharp tip to scan over a sample surface. As the tip approaches the surface, the close-range, attractive force between the surface and the tip cause the cantilever to deflect towards the surface. However, as the cantilever is brought even closer to the surface, such that the tip makes contact with it.

- Information obtained from AFM can be associated with physical-chemical and chemical processes, such as adhesion, van der Waals, electrostatic and even primary forces





Short beam shear test:

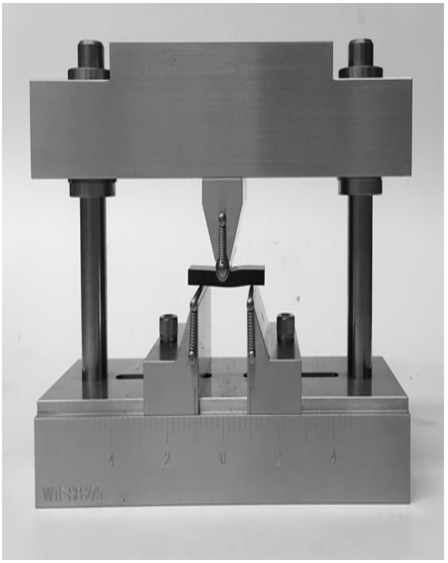


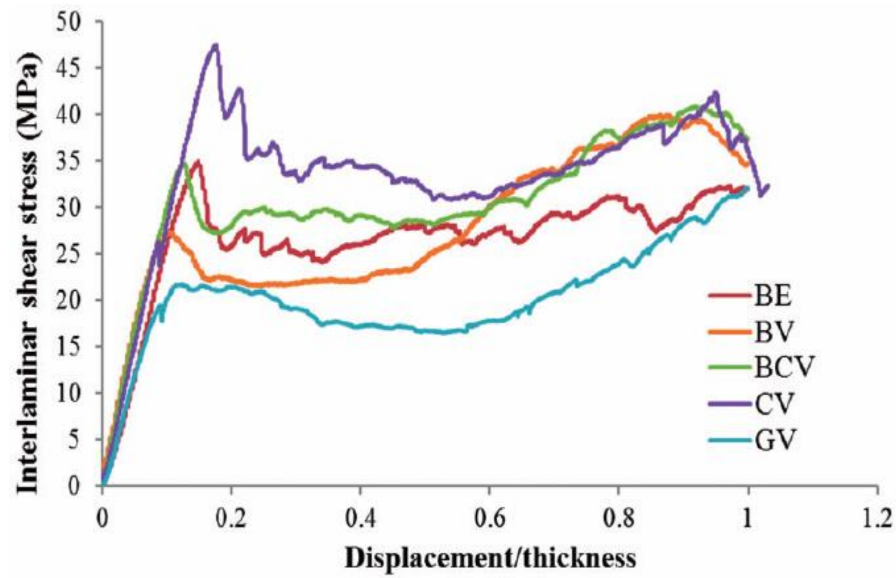
- Inter laminar shear stress (ILSS) of the composite is measured in terms of Short beam shear test with ASTM D2344 standard
- A flexural specimen of small span to depth (L/h) ratio is tested in three-point bending to produce a horizontal shear failure between the laminas
- Maximum normal stress can be calculated

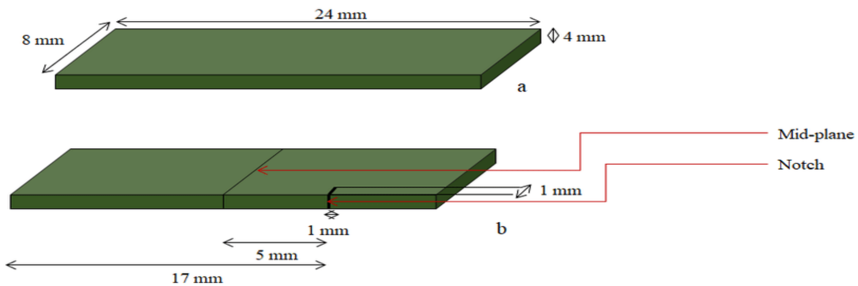
$$\sigma_{xx} = \frac{3PL}{2bh^2} = \frac{3P}{2bh}\left(\frac{L}{h}\right),$$

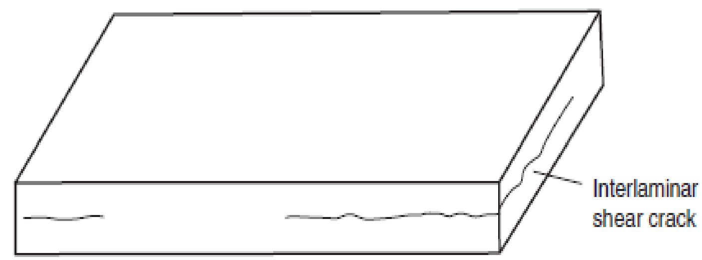
- Maximum shear stress $$\tau_{xz} = \frac{3P}{4bh}.$$
- It is noticed that the maximum normal stress in the beam decreases with decreasing L/h ratio and the maximum shear stress is not affected by the L /h ratio , so sufficiently small value of L/h ratio will reach ILSS of the fibre even though maximum normal stress is low.
- In short beam shear test a combination of failure modes, such as fiber rupture, microbuckling, and interlaminar shear cracking can be observed

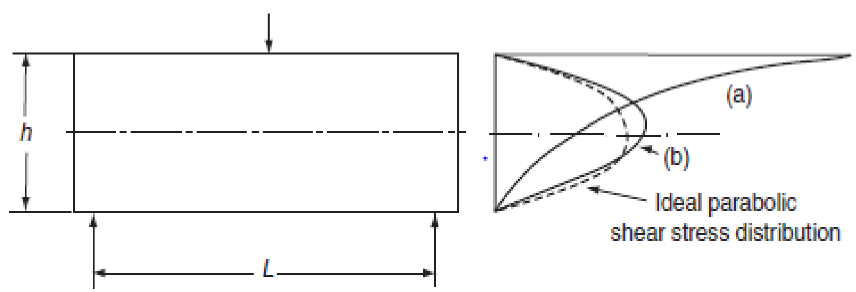
Pictorial representation of short beam shear test



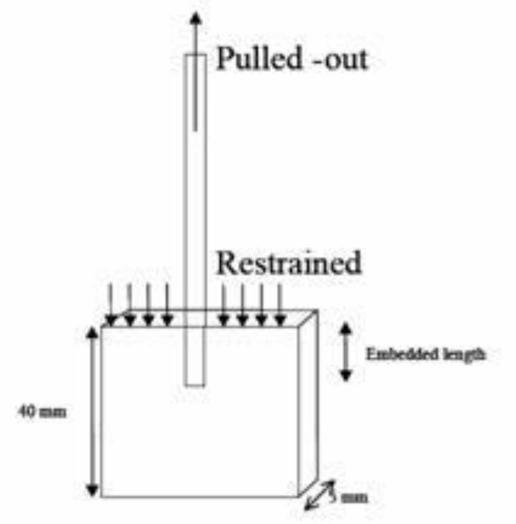




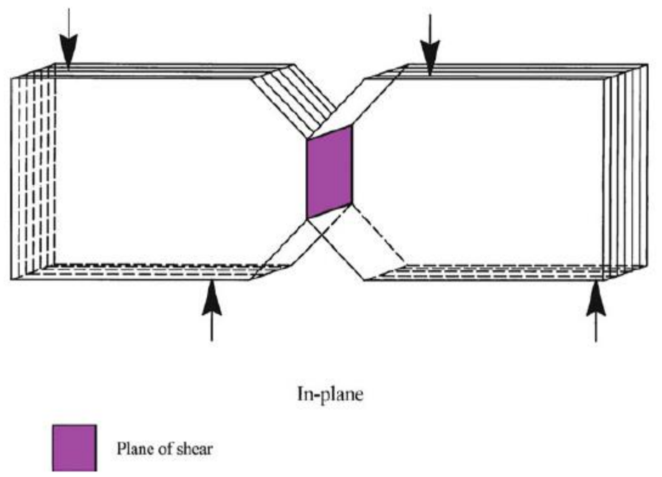


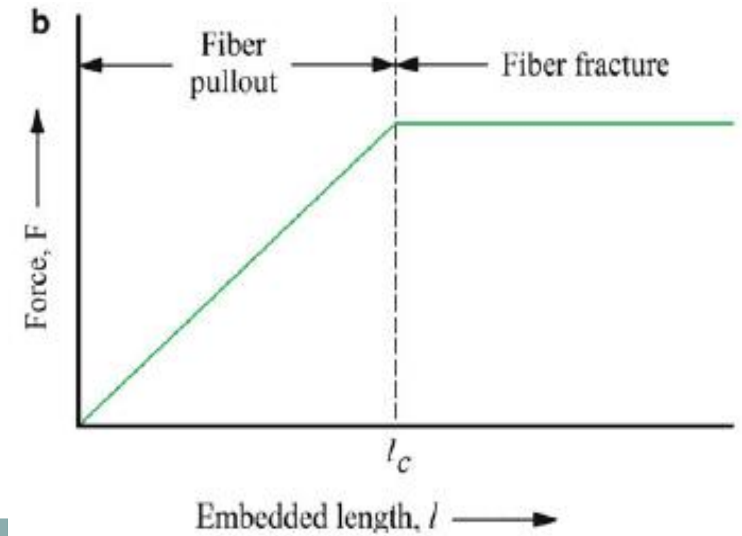


Fibre Pull Out test:



- Provide information about the interface strength in model composite system
- Fibre with length l is embedded in matrix and a pulling tensile force is applied
- If measured stress required to pull the fiber out of the matrix as a function of the embedded fiber length, stress required to pull the fibre is linearly increasing upto critical fibre length lc, fibre will fracture under tensile stress
- For l < lc, the fiber is pulled out and the interfacial shear strength $\sigma \pi r^2 = \tau 2 \pi r l.$ $\tau = \frac{\sigma r}{2l}.$
- At l > lc, fiber failure rather than pullout occurs $P = 2\pi r l \tau$



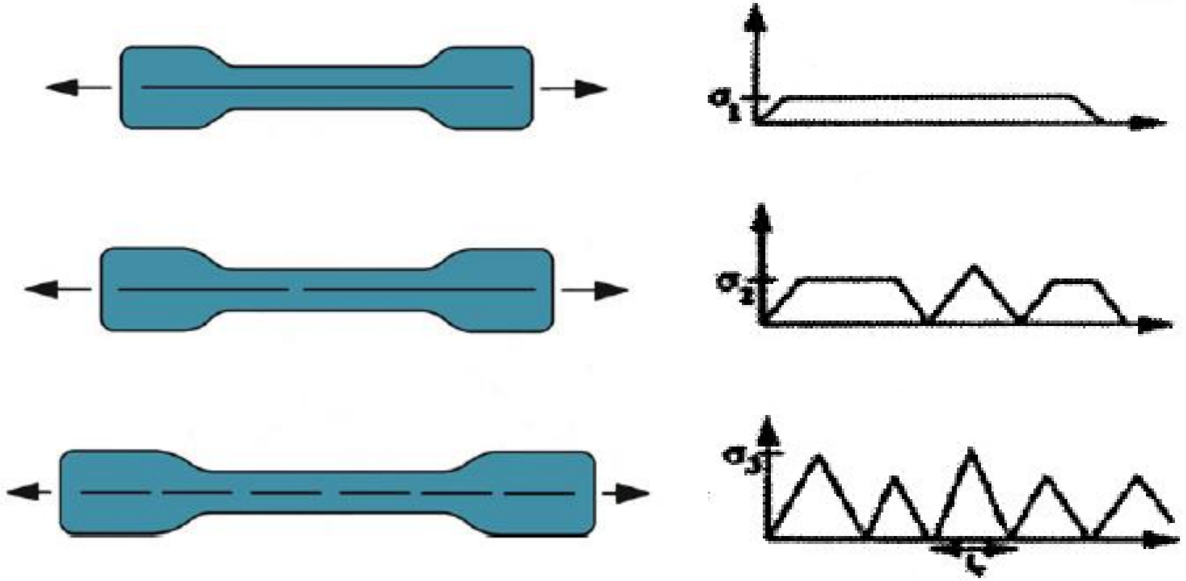


Fragmentation test:

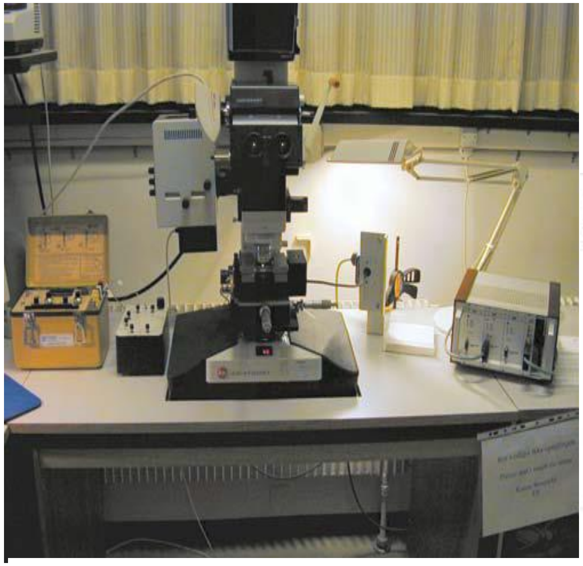
- Single fibre is embedded in a dog bone shape tensile sample matrix
- The applied load is transferred to the fiber via shear strains and stresses produced on planes parallel to the fiber/matrix interface.
- Tensile stress in the fibre reaches to its ultimate tensile stress it fragments into two parts, further under the application of load fiber continues to fragment into even smaller pieces until the fiber fragment length l = lc , to enable loading it to fracture
- Equilibrium of forces over an element dx of the fibre
- A transparent perfectly plastic matrix is required and failure strain of the fibre should be less than the matrix.

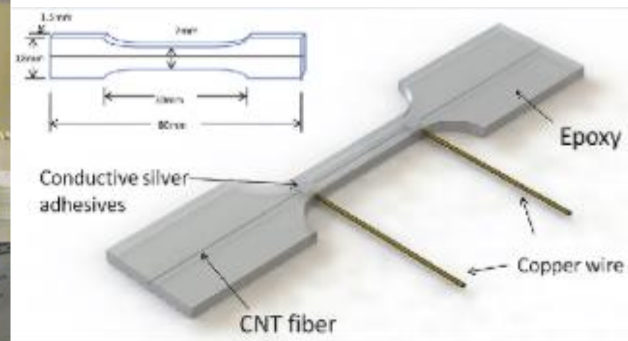
$$\pi r^2 \, d\sigma = 2\pi r \, dx \tau$$

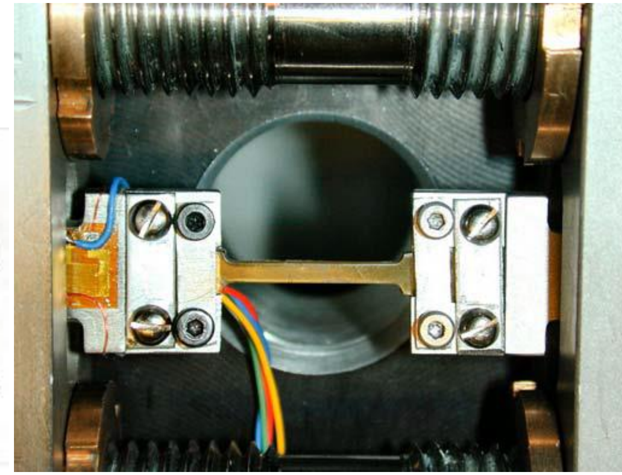
$$d\sigma / dx = 2\tau / r.$$

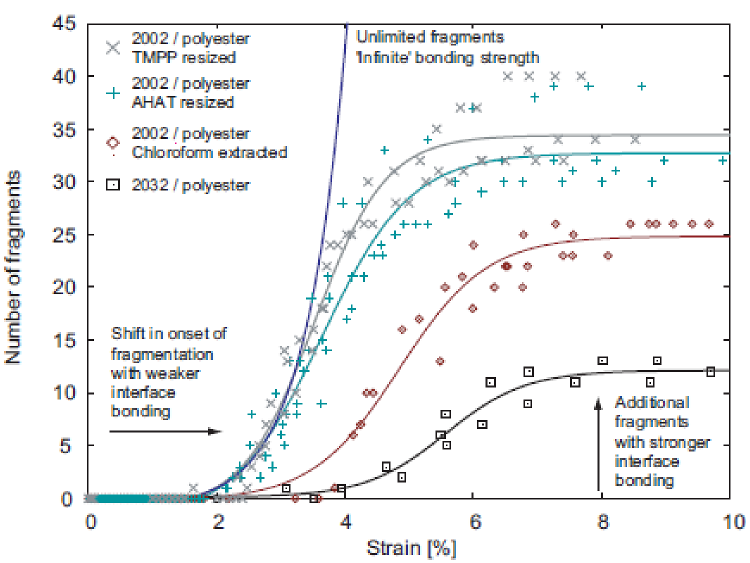


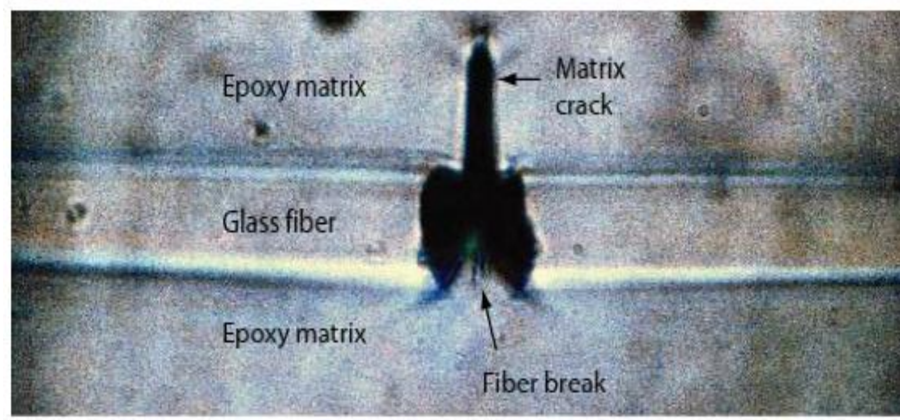
Pictorial Representation of single fibre fragmentation test





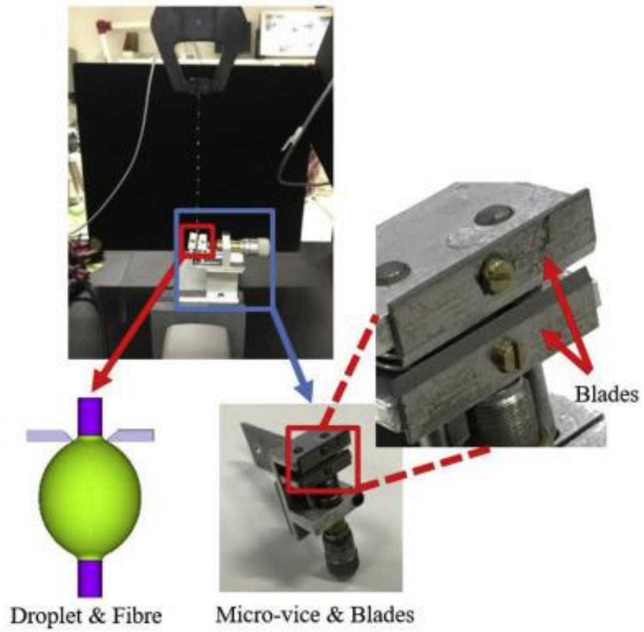


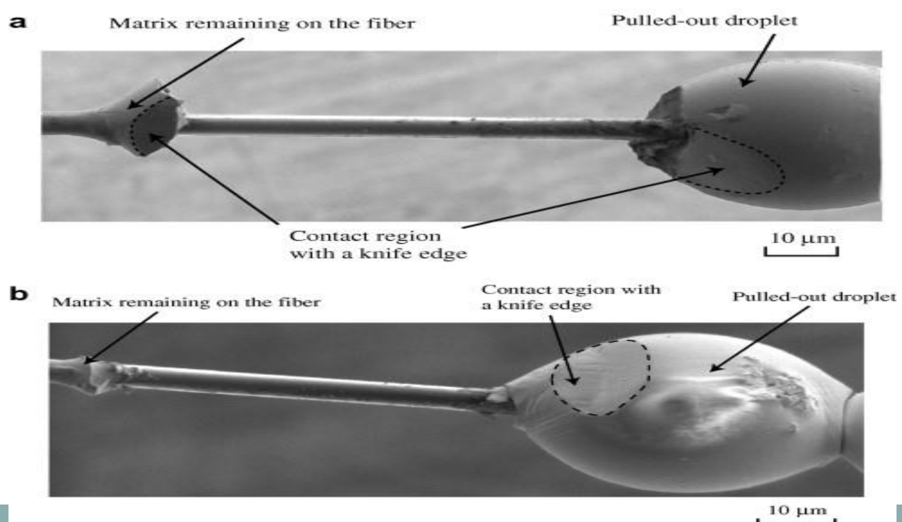


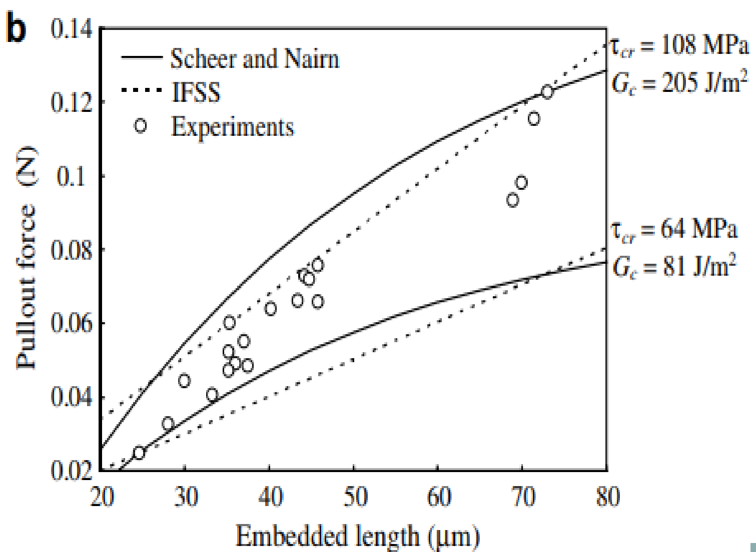


Microbond test:

- It is variation of fibre pull out test for polymer composites
- A droplet of polymer is formed on the fibre instead of the fibre passing through a supported disc
- The droplets normally form ellipsoid shape concentrically around the fibre, it retains their shape after curing
- The fibre specimens are then pulled out of the droplet just like fibre pull out test
- Average bond strength between an epoxy resin and fibres is determined





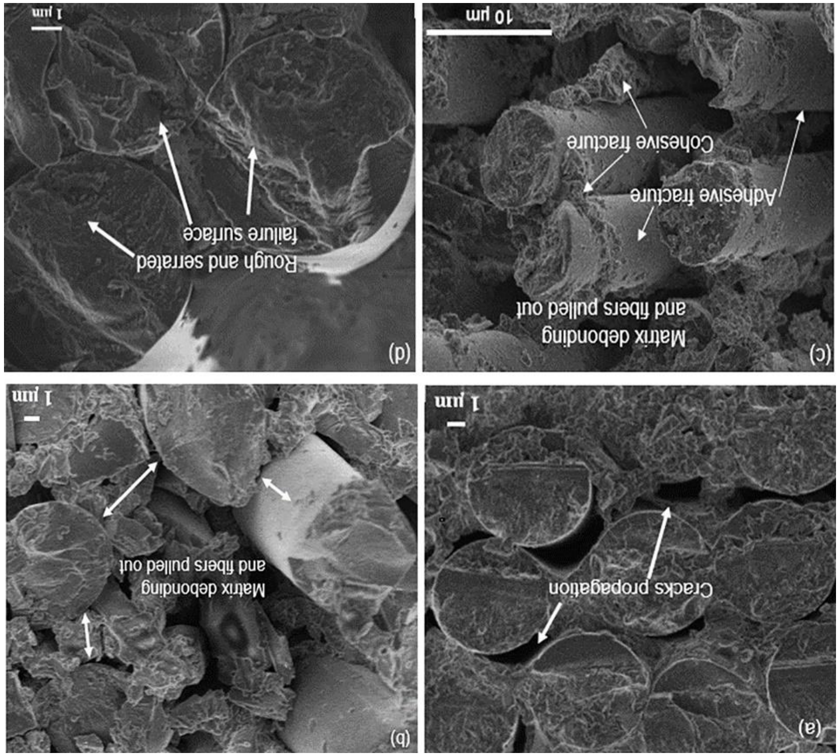


How to improve bonding?

- Decreasing the shear stiffness (defined as the elasticity modulus divided by the thickness) of adhesive layers could obviously improve the ultimate transferable load of the FRP composites-concrete interfaces thereby improves bonding.
- Increasing the effective bond length as well as by alleviating the stress concentration.
- The internal bonding strength of the interface of these composites can be enhanced by adding a small amount of material at the interface.
- Removing impurities on the surface of the fiber with surface treatment methods such as vapor phase oxidation, liquid phase oxidation, anodic oxidation and plasma treatment. After that the number of functional groups (carboxyl, carbonyl, and hydroxyl) enhancing the bonding force with the matrix is increased.
- A high bond strength does not necessarily lead to a high fracture toughness. Instead a compromise always has to be made in the bond strength to optimize the strength and toughness

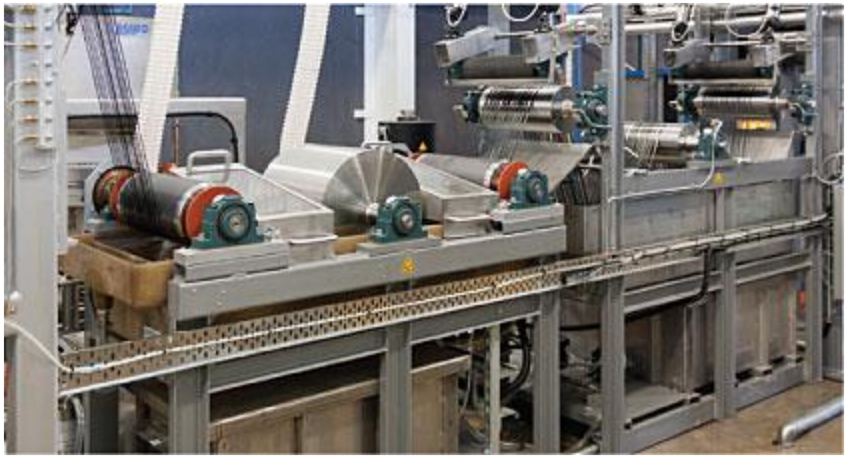
Interface Engineering

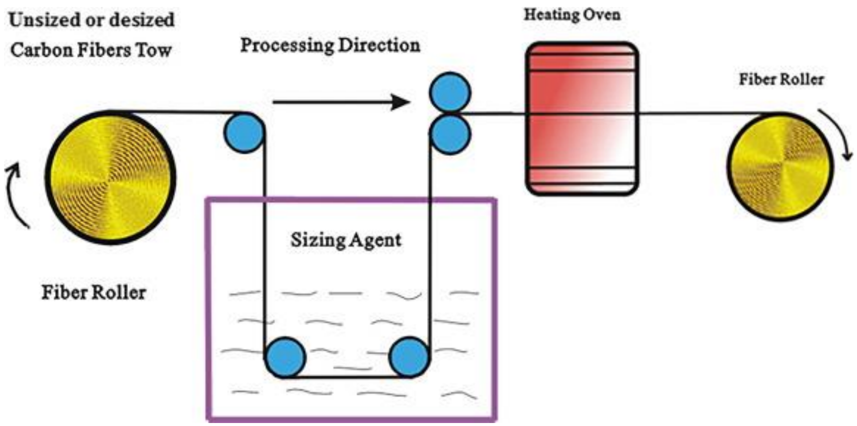
1. Fibre surface modification and surface coating are used for controlling the properties of fibre matrix interface
2. It provides a proper chemical bonding (adhesion) between matrix and fibre



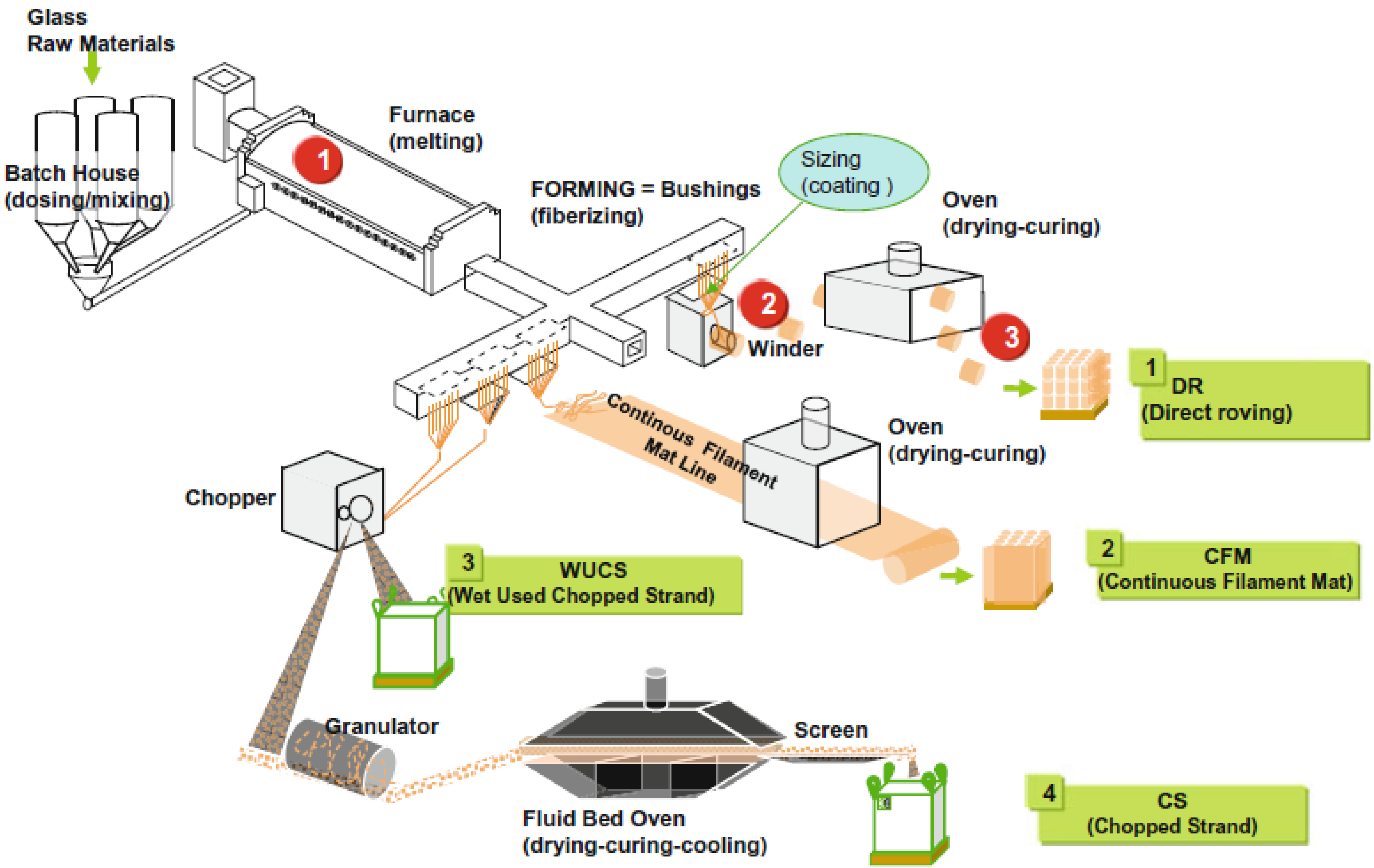
Sizing of fibres:

- To make the fibre easy to handle and to protect them against mechanical damage during processing
- The sizing that are applied on the fibre surface are mainly epoxide pre-polymer or polyvinyl alcohol
- Amount of coating vary between 0.5% to 5%
- The coating adheres to the carbon fibre by physical absorption and can be removed by chemical treatment with acetone, chloroform.





Procedure:



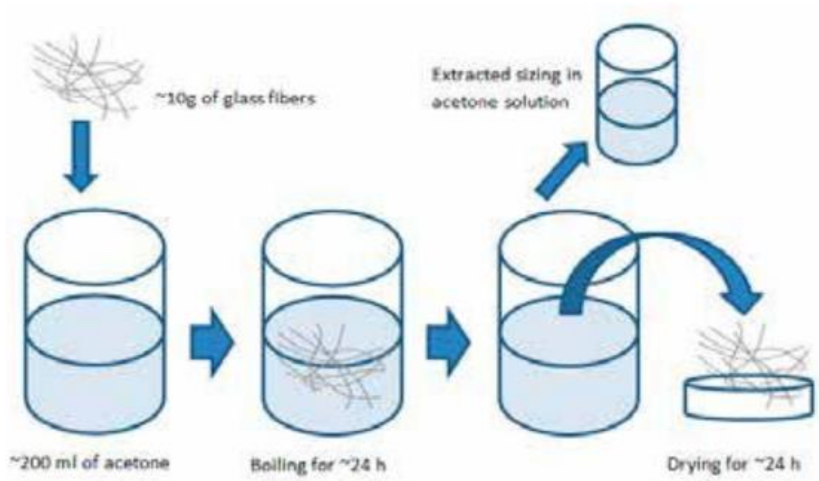
Glass
Raw Materials
Batch House
(dosing/mixing)
Furnace
(melting)
1
FORMING = Bushings
(fiberizing)
Sizing
(coating)
Oven
(drying-curing)
2
Winder
3
1
DR
(Direct roving)
Continous Filament
Mat Line
Oven
(drying-curing)
Chopper
2
CFM
(Continuous Filament Mat)
3
WUCS
(Wet Used Chopped Strand)
Granulator
Screen
Fluid Bed Oven
(drying-curing-cooling)
4
CS
(Chopped Strand)

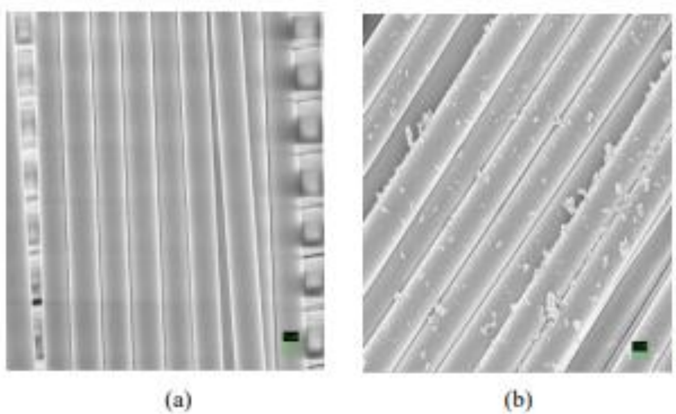
Silane Coating:

Purpose : increase the surface roughness ,good transfer load

Procedure:

- Two pure organosilanes were used 3-aminopropyltrimethoxysilane, 3-glycidoxypropyltrimethoxysilane for chemical treatment with fibres
- Initially the silane modified fibers were dried in a vacuum oven at 0.2 bars and 80°C for 2 h
- Five dry crucibles with 10 gm of dry fibers were placed in a furnace at 565°C for 3 h
- Sizing of the glass fibre involve burning of dried fibres, burn off experiment was performed with five fold determination
- Burning of fiber will remove all organic materials and organic functional groups leaving the part of the sizing that is strongly bonded to the fiber surface ,through Si-O bonds

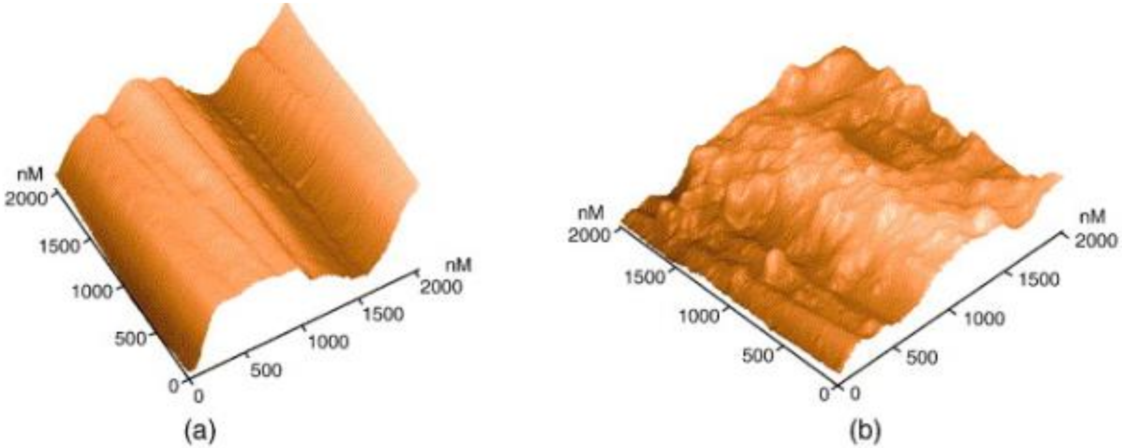




SEM micrographs of the glass fiber (a) non-treated glass fiber; (b) silane treated

Polymer Coating:

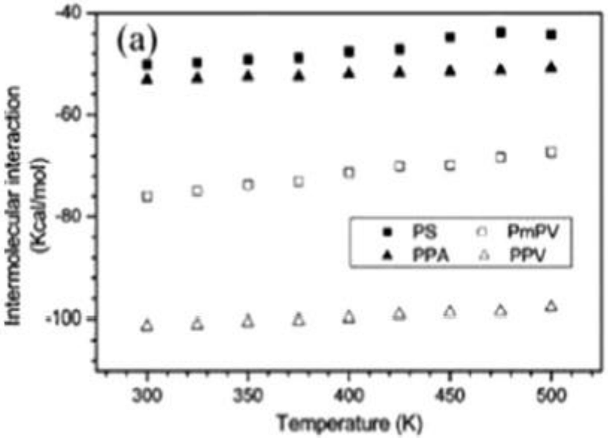
- Polymer coating provide higher mechanical interlocking between fibre and matrix by removal of surface contaminants
- Plasma treatment are known polymer coating ,significantly enhance the adhesion of polymer fibres to epoxy resin
- Carbon fibres can be plasma treated from acrylonitrile and styrene monomers
- Plasma coated single fibre interface testing results indicate a 100% increase in Interfacial shear strength. The ILSS of epoxy composites improved approximately 30% with minimal degradation in flexural properties
- Provide higher tensile strength, lower contact angle, increased functionality
- Fibre surface also can be coated with thin layer of polymer by electro polymerization process. Moderate improvements of ILSS property and impact strength of the composite

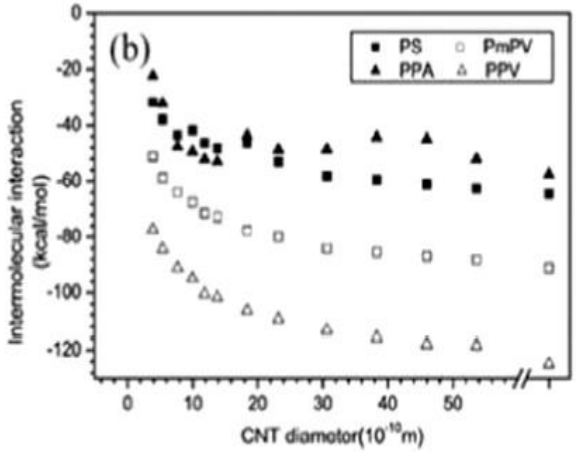


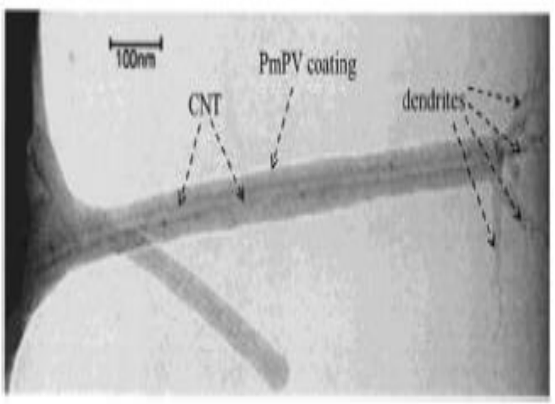
AFM study of (a) carbon fibre as received (b) plasma treated carbon fibres for 5 min

Nano scale interface modification:

- Polymer coating around the CNT surface provides a good interfacial bonding between the CNT/polymer
- The possible improvement in CNT/polymer interaction may be enhanced by covalent or non-covalent bonding characteristics between the polymer and CNT. In general, non-covalent bonding may be developed by bridging, wrapping and increasing the interfacial area
- The structurally modified polymer close to the interfacial region shows again remarkably higher strength than that of the bulk polymer. This in-turn makes the nanotube pull out energy to be significantly higher.
- Thus enhances the fracture toughness of the composite material.





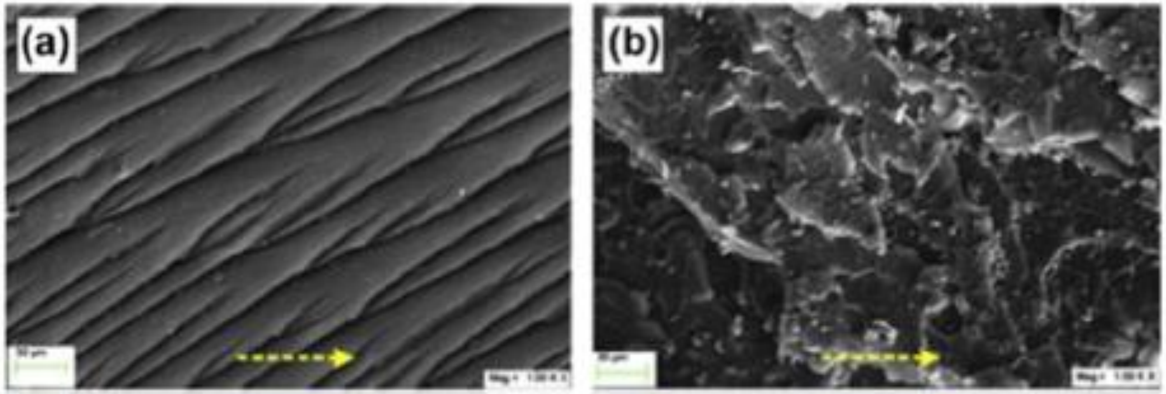


Functionalization:

- Functionalization is basically achieved by attachment of one end of functional group onto the nanofillers (Carbon Nano Tubes Graphene) surface other side will interact with polymer surface.
- Functionalized nanofilers will be attaced to polymer surface by Vander walls bonding
- Functional group will provide reactive bridge between carbon atoms (nanofillers-CNT or graphene) and polymer matrix results enhancement of interfacial shear strength and lowering critical length for effective load transfer.
- Two types depending upon chemical bonding presence between nanofillers and functional group

  (a) Covalent functionalization: strong chemical bonding

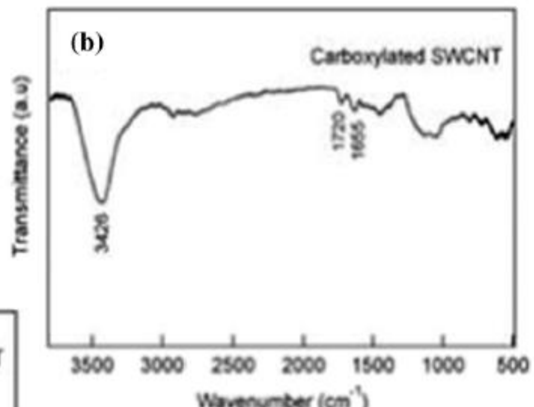
  (b) Non Covalent functionalization: vander walls, π-π such weak iteractions.

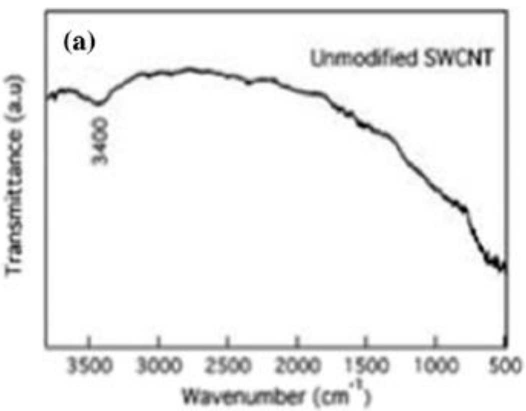


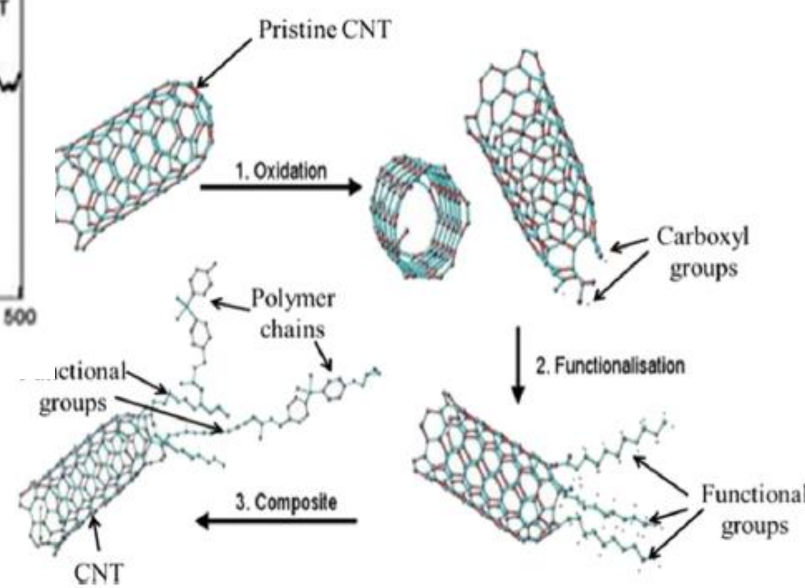
SEM images of fractured surface of (a) neat epoxy and (b) epoxy reinforced with 0.3% amine functionalized MWCNT

Procedure: (CNT functionalization)

- Ozone mediated process is used for functionalization of the non reactive polymers
- In the this process the nonreactive polymer chains are subjected to ozonisation which results in the formation of alkylperoxide and hydroperoxide groups
- Under the application of heat this groups decompose and then form a linkage between polymer and CNT, further plasma enhanced chemical
- vapor deposition (PECVD) and microwave irradiation have been employed for improving the interaction between CNT and non-reactive polymer.
- Functionalized groups: -COOH, -NH2,-OH

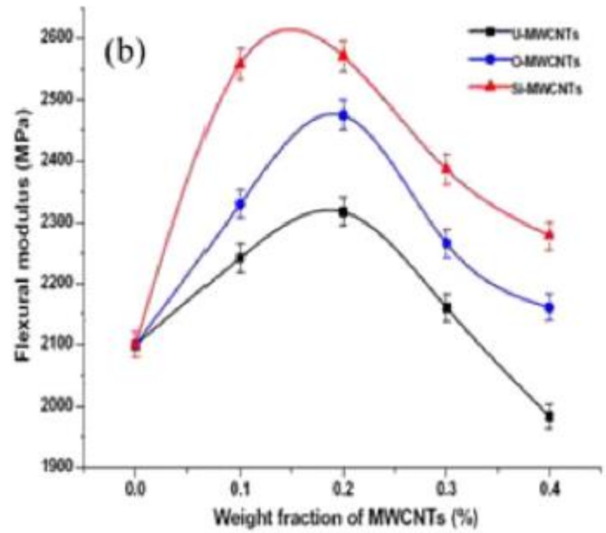


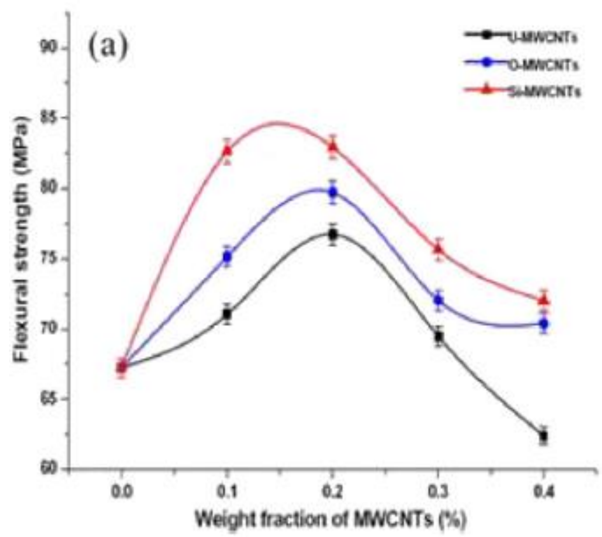


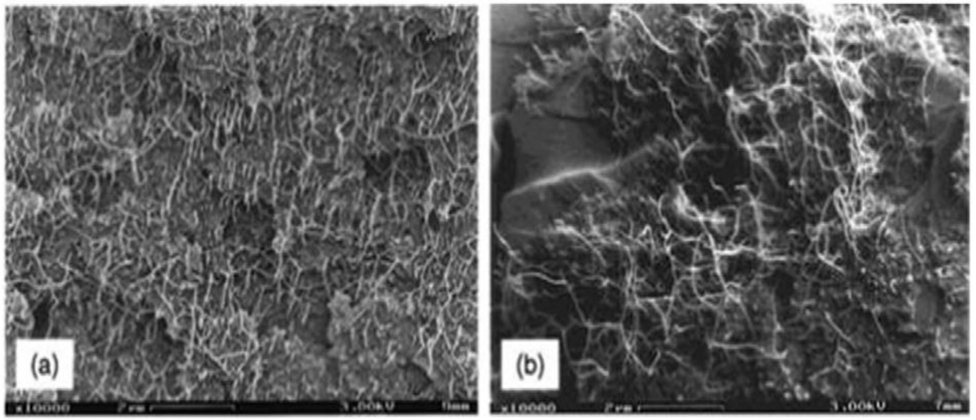


Results:

- In one of the studies Gojny et al. have reported that a superior ILSS for GFRP laminated was obtained by using small amount (0.1 and 0.3 wt.%) of amino functionalized DWCNT (DWCNT-NH2) in the epoxy matrix.
- Addition of 0.1% amino functionalized CNT exhibited 49% and 33% improved strength and modulus respectively, over the composite with 0.1% pristine CNT
- As per Kim et al. addition of 2% silanized CNTs resulted in 55% and 15% improvement in flexural strength in comparison to carbon/epoxy and carbon/2% oxidized CNT/epoxy composites respectively.



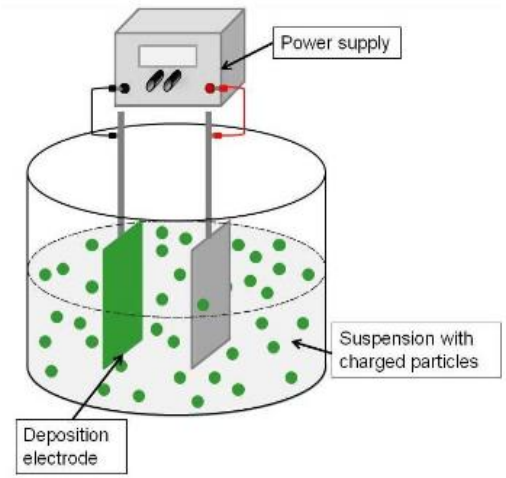


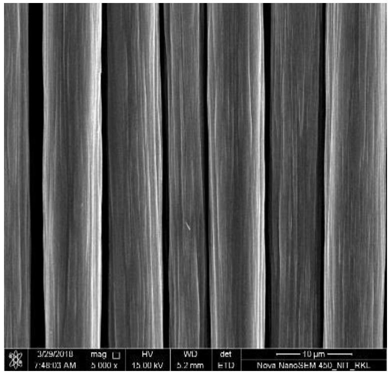


Fracture morphology of CNT/epoxy composite (a) with surfactant and (b) without surfactant

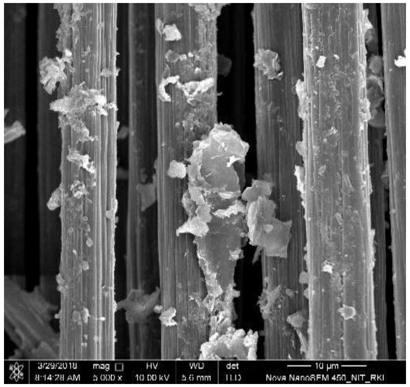
Electrophoretic Phoretic Deposition :

- Surface treatment also influence chemical structure of fibers and enhance chemical bonding with matrix
- EPD method has a number of advantages in the preparation of thin films from charged colloidal suspensions, such as high deposition rate, good thickness controllability, good uniformity, and simplicity of scale up.
- The electric charge of the dispersed particles may be either positive or negative. Depending upon that the process has been categorized into 2 different types:-
- (a) **Cathodic:** positively charged particles are attracted to the cathode and it results in a deposition of coatings with very low metallic contamination.
- (b) **Anodic :** deposition of negatively charged particles. It produces coatings of good aesthetic appearance



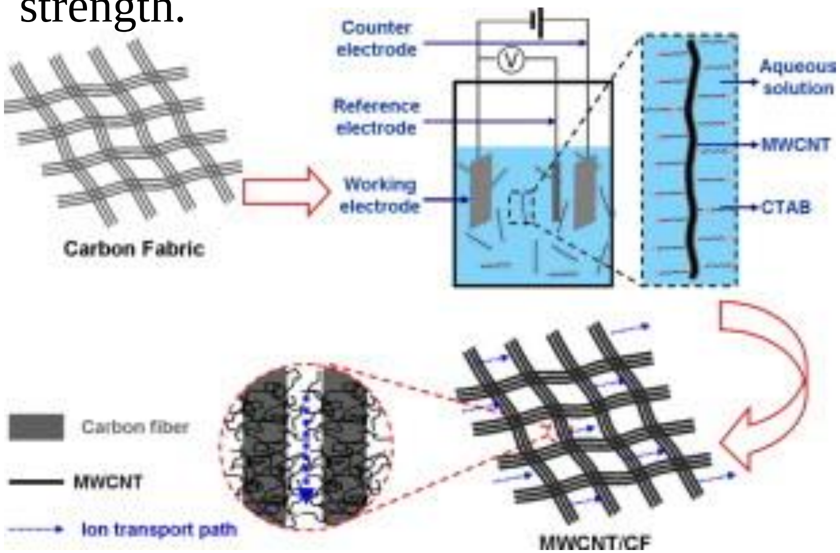


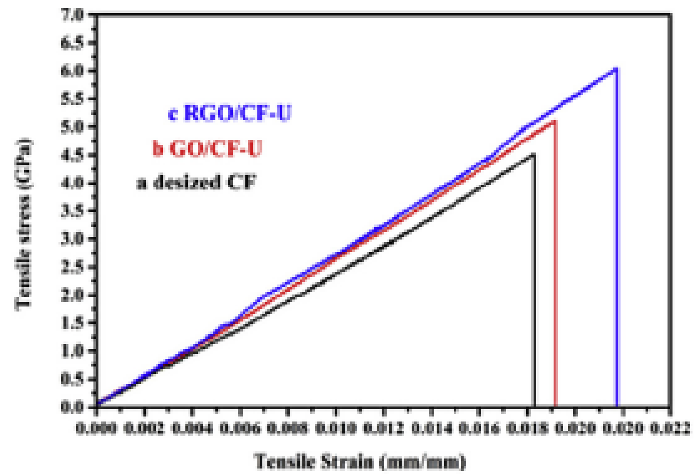
SEM of neat carbon fibre

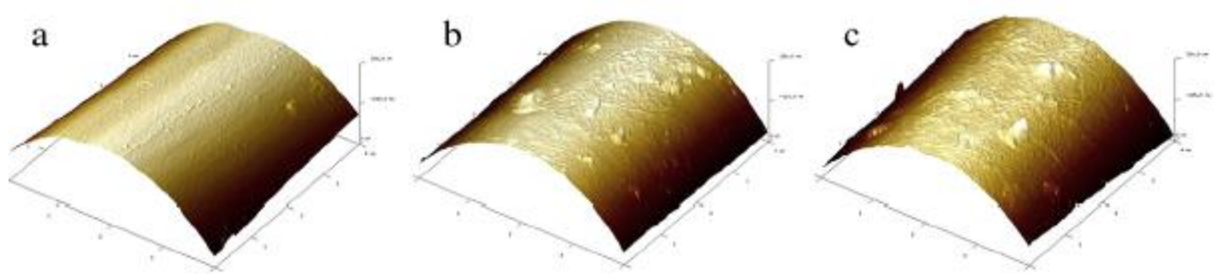


SEM of carbon fibre with Graphene-Oxide

- Improvement of the inter laminar shear strength and flexural strength of the composite
- Lower the contact angle increase the wettability of the carbon fibre
- Short beam tests were performed on the carbon fibres with electrophoretically deposited Graphene Oxide and epoxy composite shows enhancement of flexural strength.



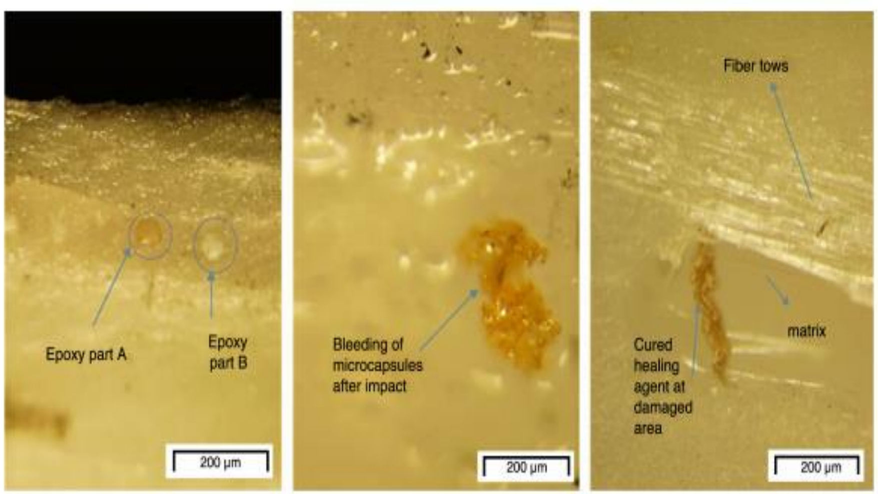




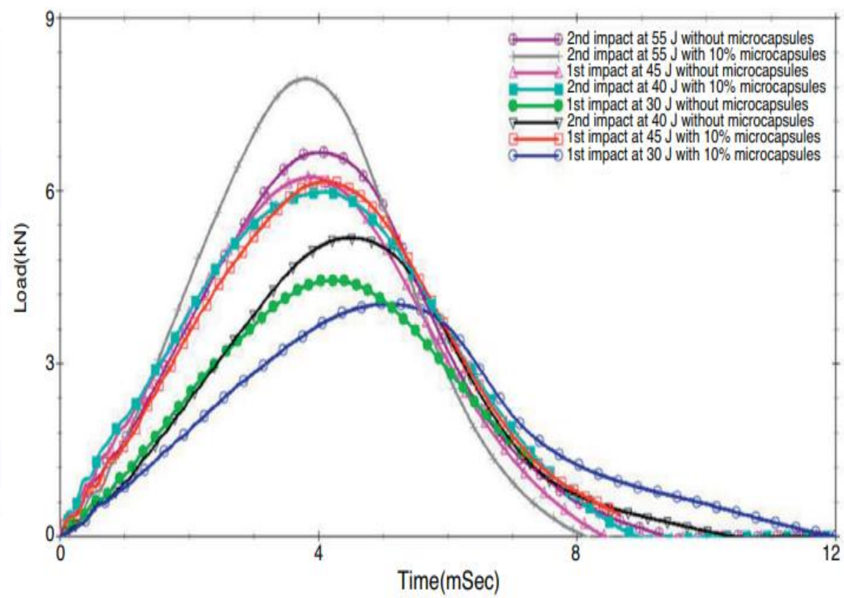
AFM images of carbon fiber: (a) desized; (b) GO deposited without ultrasonic; and (c) GO deposited with ultrasonic

Introducing Self Healing Property:

- Low velocity impact damage is common in fiber reinforced composites, which leads to micro-crack and interfacial debonding, introducing self-healing property at the interface of composites can be a way of overcoming this limitation and extending the life expectancy while expanding their usage in structural applications
- Contribute greatly to the safety and durability of polymeric components
- Built in capability to substantially recover their load transferring ability after damage
- Restoring the material performance, especially the recovery of properties such as fracture toughness, tensile strength.



Optical micrographs for damaged area recovery after impact by releasing of healing agent



SELF HEALING MECHANISM

INTRINSIC

- ✓ Crosslinking or crystallization

Heat Welding

Thermo-reversible chemical reaction

EXTRINSIC

- ✓ Dispersion of functional substances

Microencapsulation

Hollow fiber

Microvascular Network