Plastics and Composite Materials

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FOR PARTICLE ACCELERATORS AND DETECTORS

Plastic (polymeric) Materials

We rely on this material category for clothing, protection, and transport in our **everyday life**, but plastics are also key components of **cutting-edge technologies** that have powered the space program, created the bulletproof vest or are widely used in surgical implants to mention a few

Why are they so interesting?

- Easy to fabricate, durable, versatile, resistant to corrosion, lightweight, resilient…
- Provide good protection and preservation…
- Thermal, electric, acoustic insulation value…
- Different formats like fibers, sheets, foams, or complex moulded parts

What are polymers?

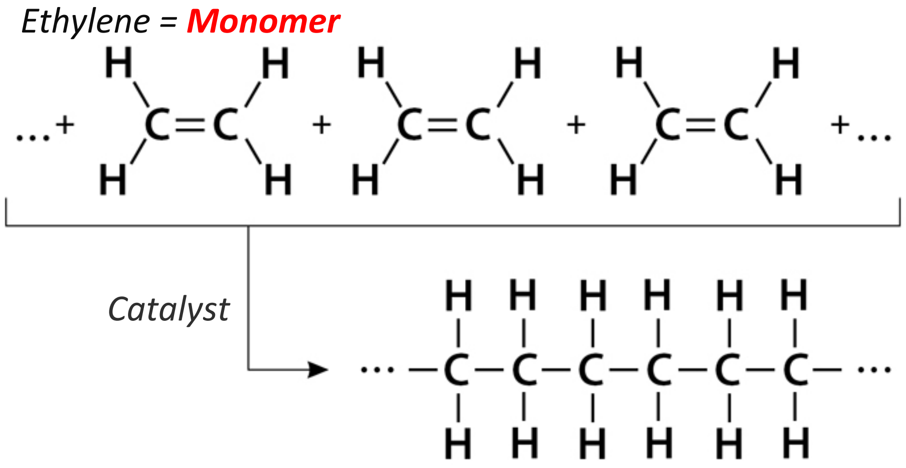
Natural polymers: cotton, cellulose, latex…
19th century → Chemically modified: rayon, celluloid, vulcanized rubber
1907 first totally synthetic polymer: Bakelite

Polymeric materials (commonly known as **plastics**) consist of macromolecular organic compounds that can be manufactured **synthetically** or transformed from **natural** products

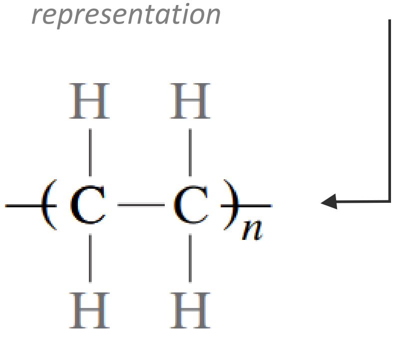
Polymer refers to molecules held together by covalent bonds and composed by small units which are repeated many times to form very large molecules

- **Monomer:** HC molecules derived from fossil fuels (ethylene, propylene, butylene…) from which the polymer is synthesized
- **Repeat unit ("mer"):** Entity successively repeated along the chain

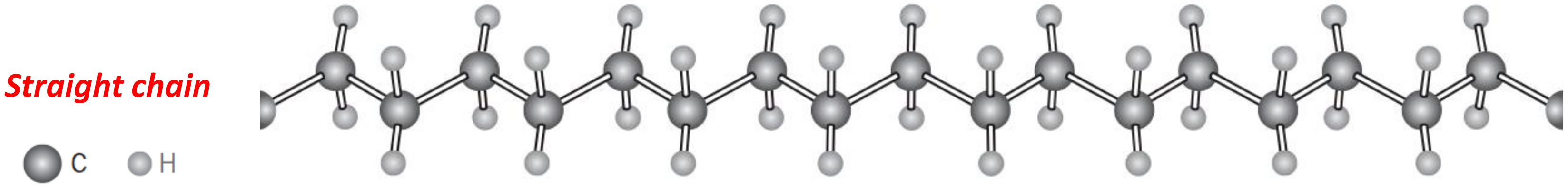
The **polymerisation** process consists in the aggregation of monomers that are chemically bonded into chains. There are two different mechanisms for polymerisation: **Addition** and **Condensation**



Polyethylene chain structure schematic representation



Repeat Unit



Polyethylene chain structure indicating the zigzag back-bone structure. W. D. Callister [1]

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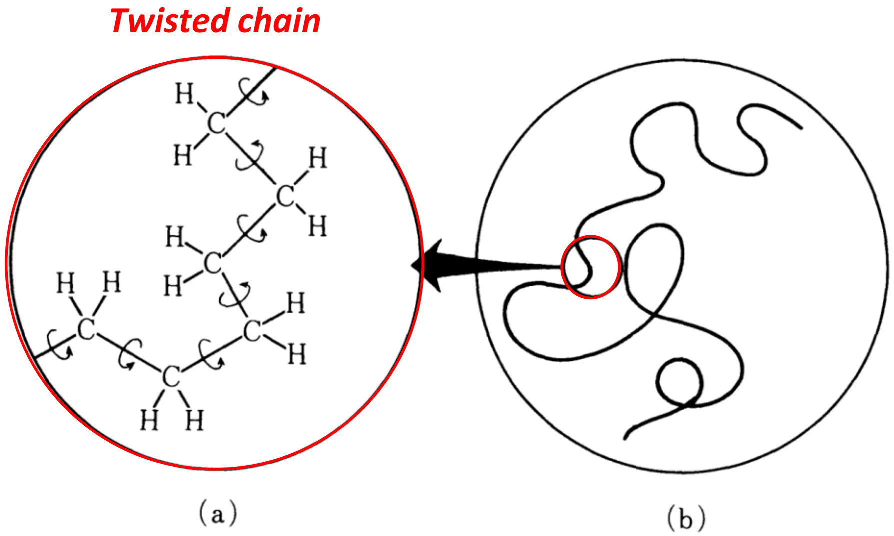
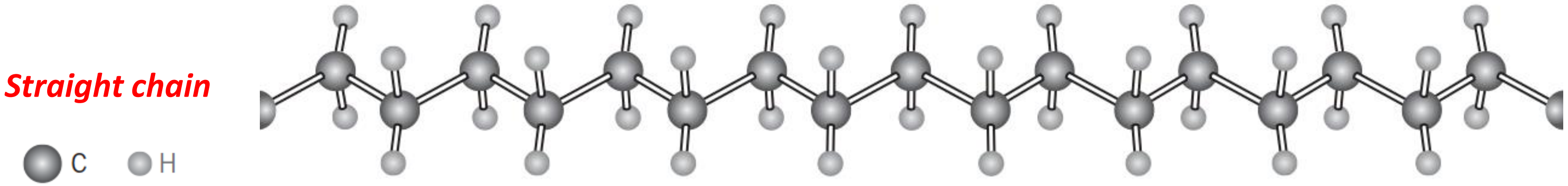


a) Atomic structure of the polyethylene molecule and b) An overall view of the molecule. M. Doi [2]



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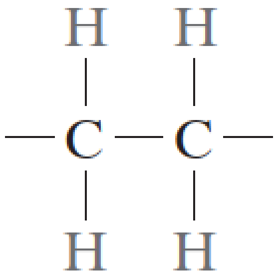
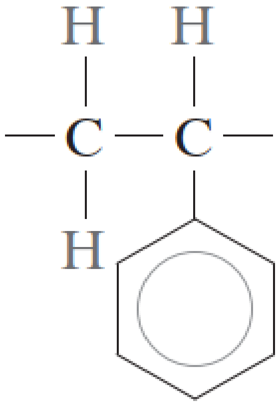
***Analysis techniques** (molecular level):*
Infrared (IR) and Nuclear Magnetic Resonance (NMR) Spectroscopy

Polymers: Structure

PE repeat unit



PS repeat unit



The molecular chains can **bend, coil,** and **entangle**. This structure leads to unique properties (i. e. the large elastic extensions in rubber)

Some of the **mechanical** and **thermal characteristics** of polymers are a function of the ability of chain segments to experience rotation in response to applied stresses or thermal vibrations

Rotational flexibility is dependent on repeat unit structure and chemistry

Example: *Polystyrene (PS) chains are more resistant to rotational motion than polyethylene (PE) chains due to the introduction of a (bulky) phenyl side group of atoms that restricts the rotational movement*

Polymers: Structure

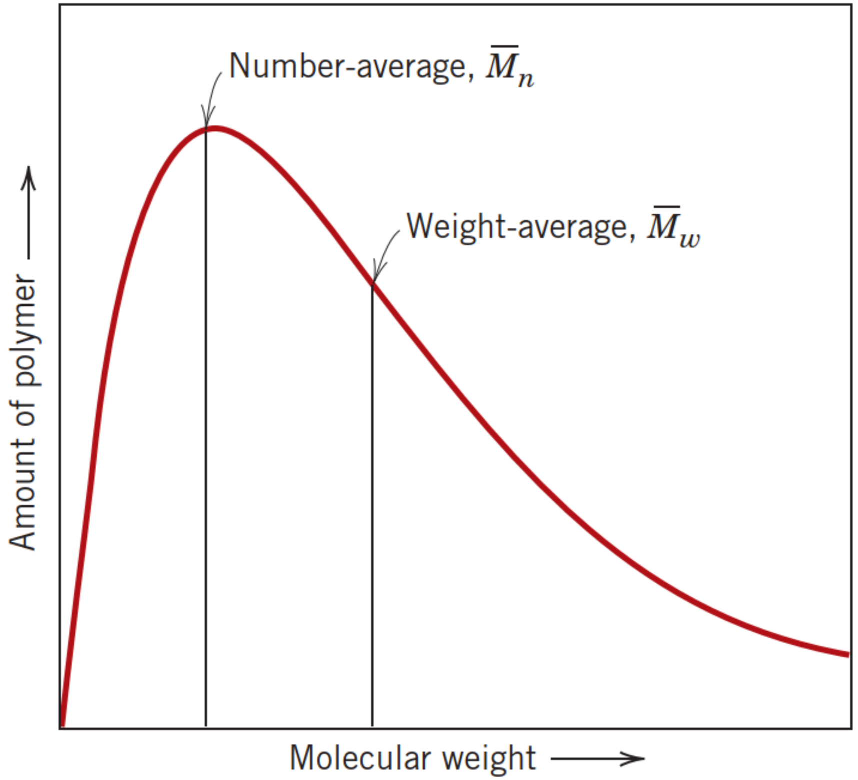
Polymerization results in varying chain lengths and the **average molecular weight (M_n)** is used to describe this distribution

M_n is calculated experimentally from the mole fraction distribution of different sized molecules in a sample, and the **weight average molecular weight (M_w)** from the weight fraction distribution of different sized molecules

An alternate way of expressing average chain size of a polymer is as the **degree of polymerization (DP)** which represents the average number of repeat units in a chain

M ~ 100 g/mol → generally exist as liquids
M ~ 1.000 g/mol → waxy solids (such as paraffin wax) and soft resins
10.000 g/mol < M < Several Million g/mol → Solid polymers
M ≤ 100.000 g/mol → the melting/softening temperature increases with M

***Analysis techniques**:*
Osmometry, Light Scattering Technique, End Group Analysis…



$$\overline{M}_n = \Sigma x_i M_i \qquad \overline{M}_w = \Sigma w_i M_i \qquad DP = \frac{\overline{M}_n}{m}$$

M_i represents the mean (middle) molecular weight of size range i, and x_i is the fraction of the total number of chains within the corresponding size range, w_i denotes the weight fraction of molecules within the same size interval [1]

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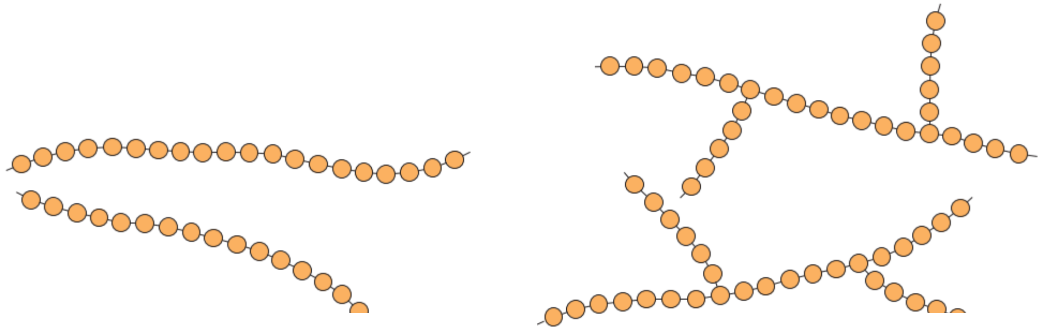
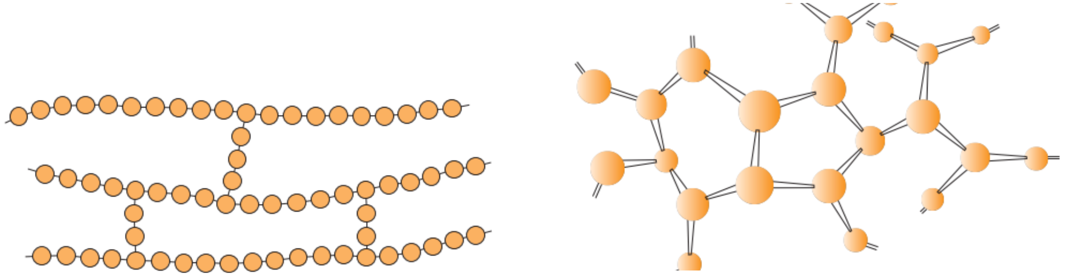
Four different polymer molecular chain structures:

Linear (long continuous chain without any branches), **branched** (main chain with smaller chains as branches), **crosslinked** (adjacent linear chains are joined one to another at various positions by covalent bonds) and **network polymers** (form three-dimensional networks and polymers that are highly crosslinked may also be classified like this)



Linear
i.e. polystyrene, PVC

Branched
i.e. polypropylene



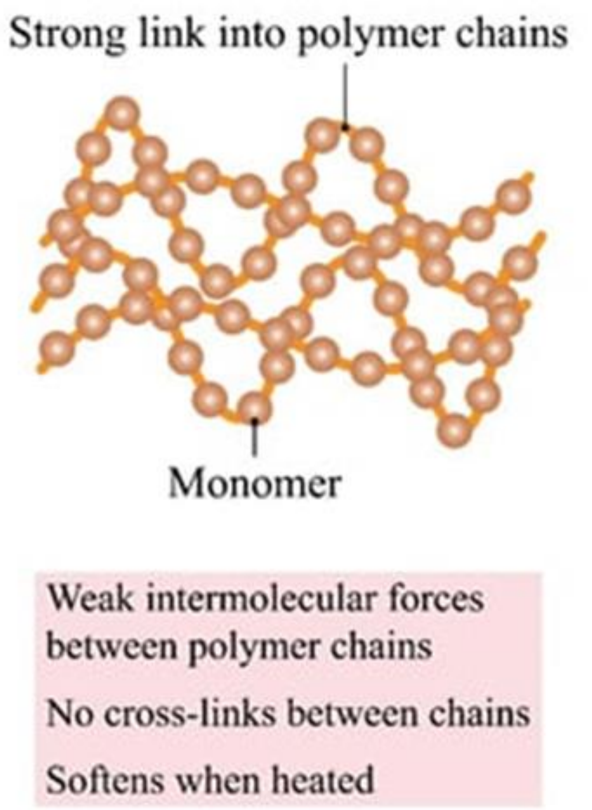
(Lightly) ***Crosslinked***
i. e. rubbers (vulcanization)

Network
(heavily cross-linked)
i. e. the epoxies

Molecular chain structure representation: linear, branched, cross-linked and network [1]

Homopolymers

Thermoplastic



Weak intermolecular forces between polymer chains

No cross-links between chains

Softens when heated

Amorphous or *semicrystalline*

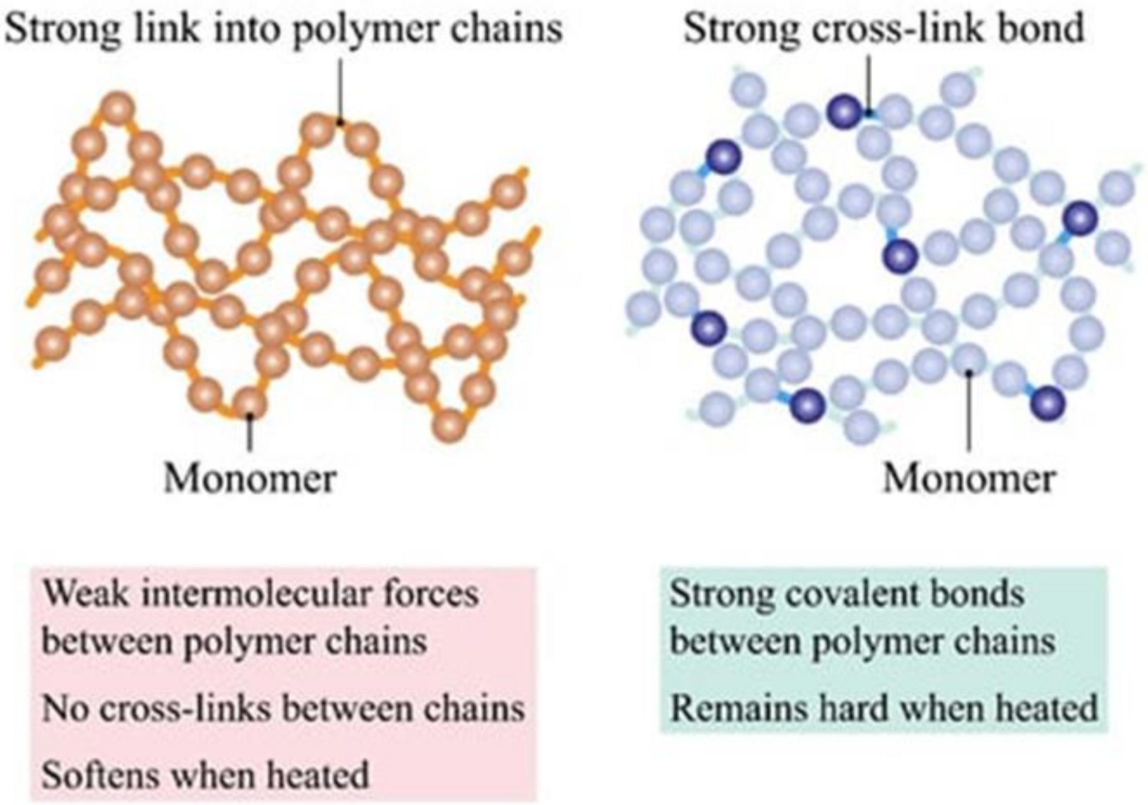
- **Thermoplastics** soften when heated and harden upon cooling
- This reversible process can be repeated multiple times without notable degradation. This feature gives thermoplastics a significant **recyclability advantage**

- **Most linear polymers** (and some branched) are thermoplastic. The lack of cross-linking allows the polymer chains to slide, making them softer and more flexible

Homopolymers

Thermoplastic

Thermosetting



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Strong covalent bonds between polymer chains

Remains hard when heated

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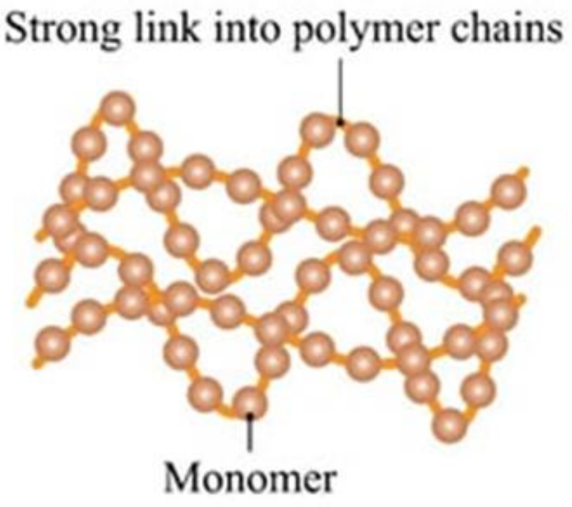
- **Thermosetting** polymers become permanently hard during their formation and do not soften upon heating
- They are generally harder and stronger than thermoplastics and have better dimensional stability
- **Most of the crosslinked** and **network** polymers are thermosets

Homopolymers

Thermoplastic



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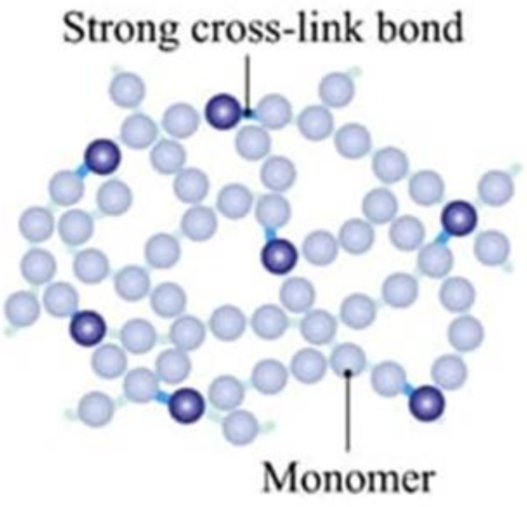
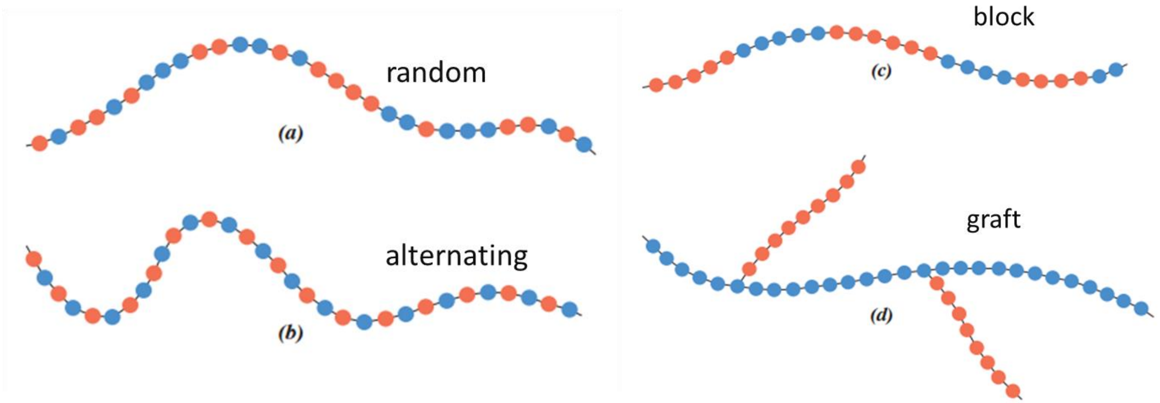


Strong covalent bonds between polymer chains

Remains hard when heated

Amorphous

Co-polymers



- A **co-polymer** is a polymer that is made up of two or more monomer species
- **Different sequencing arrangements** along the polymer chains are possible.
- For a copolymer, the degree of polymerization uses the average value "m"

$$DP = \frac{\overline{M}_n}{\overline{m}}$$

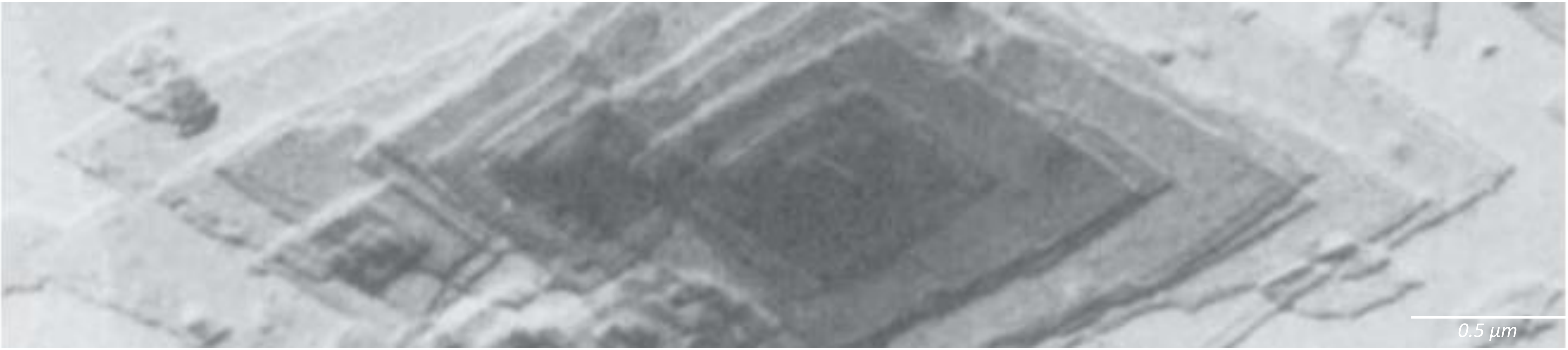
$$\overline{m} = \Sigma f_j m_j$$

f_j and m_j are, respectively, the mole fraction and molecular weight of repeat unit "j" in the polymer chain [1]

Crystallization, Melting, and Glass-Transition

Crystallization

Electron micrograph of a polyethylene single crystal. 20,000x.
(From A. Keller, R. H. Doremus, B. W. Roberts, and D. Turnbull 1958)



The **degree of crystallinity** may range from completely amorphous to almost entirely crystalline (up to about 95%) and can be determined from accurate **density measurements**

$$\% \text{ crystallinity} = \frac{\rho_c(\rho_s - \rho_a)}{\rho_s(\rho_c - \rho_a)} \times 100$$

ρ_c is the density of the perfectly crystalline polymer, ρ_s is the density of a specimen for which the percent crystallinity is to be determined, ρ_a is the density of the totally amorphous polymer [1]

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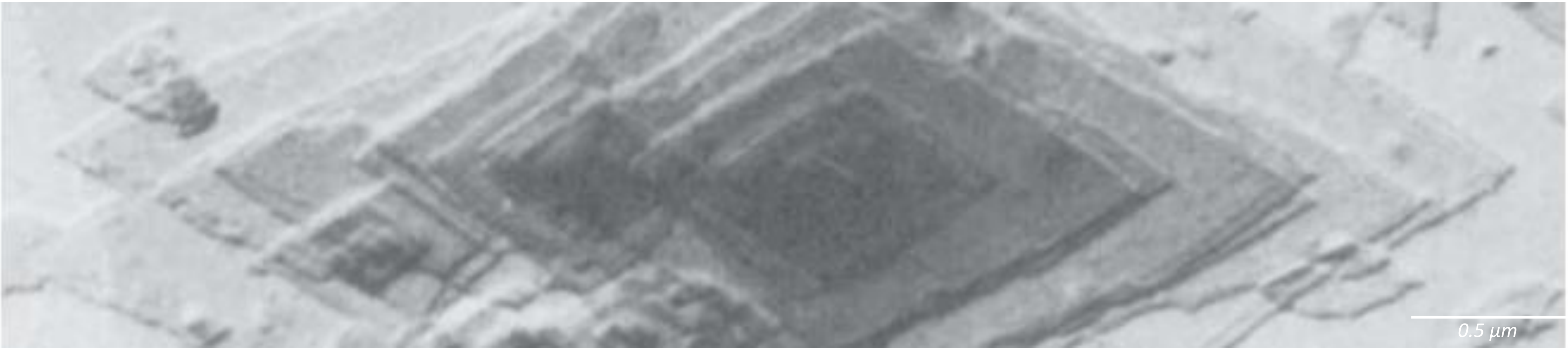

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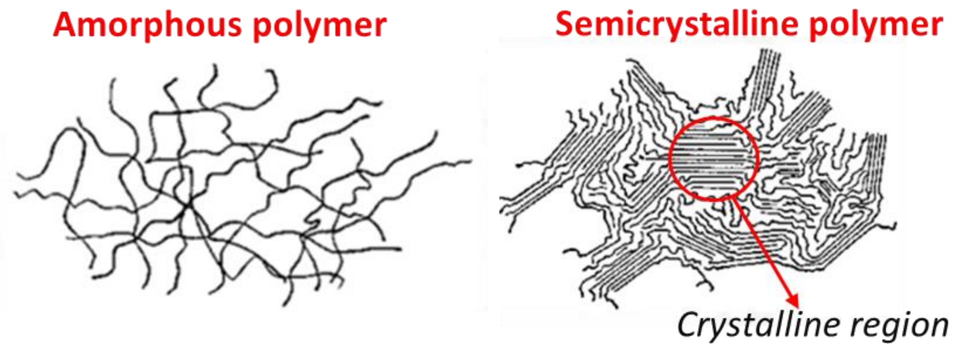
Semicrystalline polymers contain crystalline regions (**crystallites**) with linear chains structurally oriented, surrounded by amorphous domains of randomly oriented molecules.



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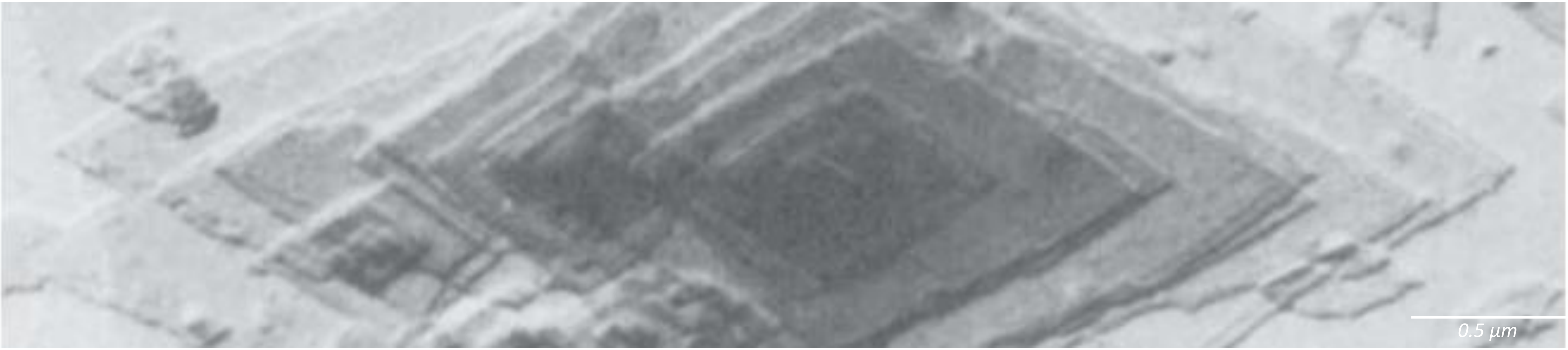
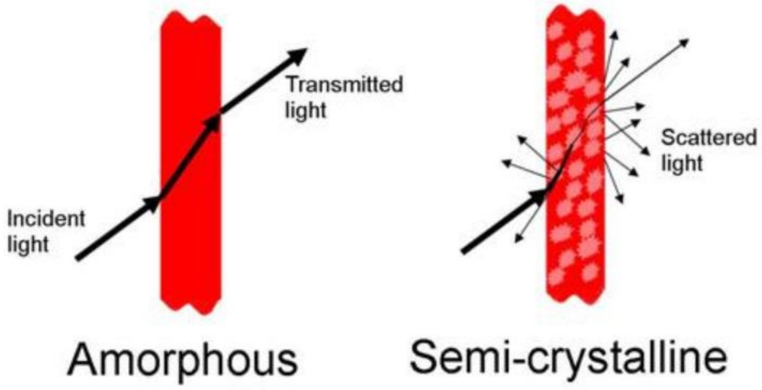


Different densities of the amorphous and crystalline regions will affect for example optical properties (transmitted light gets diffracted and scattered due to ≠ refractive indices)

Polymer crystallinity was firstly observed experimentally in the SEM by growing single crystals from a dilute solution. X-ray measurements indicated that the chains were perpendicular to the face of the lamellae…**But how?**



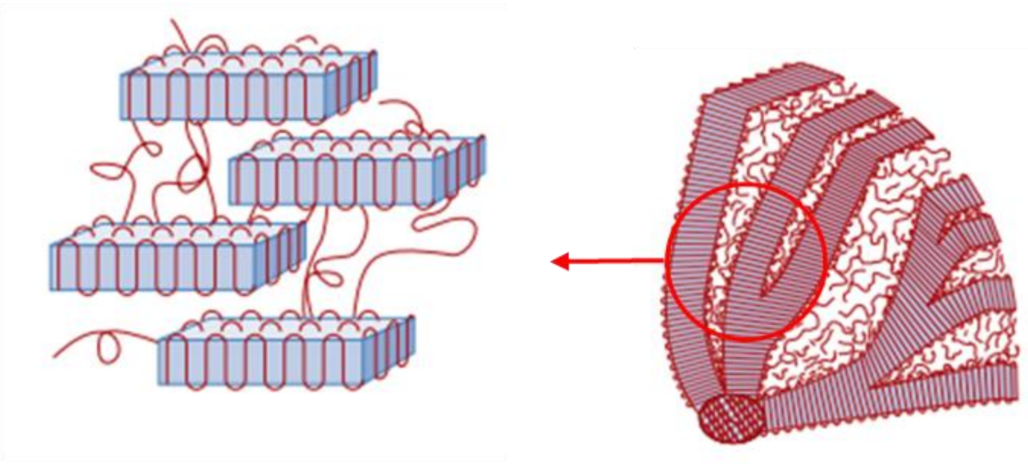
Crystallization, Melting, and Glass-Transition

Crystallization

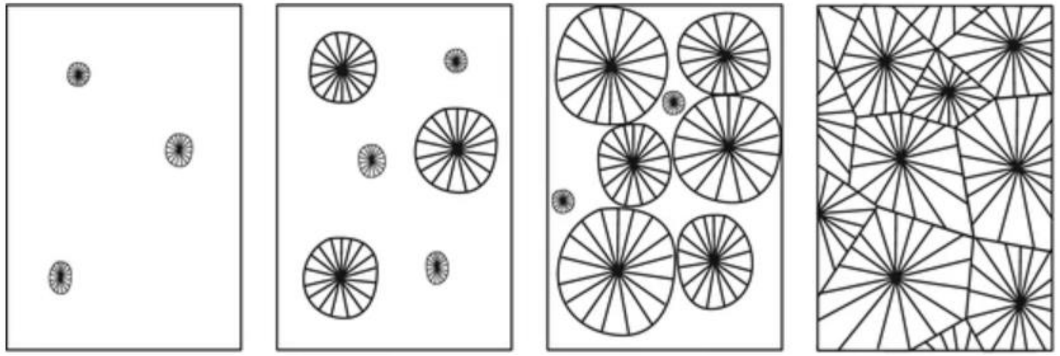
Chain-folded model: Crystals are regularly shaped in thin platelets (**lamellae**) about 10-20 nm thick and ~10 µm long. The molecular chains within each platelet fold back and forth on themselves, with folds occurring at the faces

In many cases, crystals are arranged in larger aggregates known as **spherulites** that grow radially from nucleation points until they meet other spherulites

The temperature range for crystallization is between the glass transition temperature and the crystalline melting temperature



Schematic representation of the detailed structure of a spherulite [1]



Spherulites grow radially until another spherulite is encountered. Hal F. Brinson [3]

$$y = 1 - \exp(-kt^n)$$

In many polymers the progress of the crystallization from the melt with time (crystallized fraction “”) is described by the Avrami equation where “k” and “n” are time-independent constants dependant on the crystallizing system [1]

Crystallization, Melting, and Glass-Transition

Melting (crystalline phase)

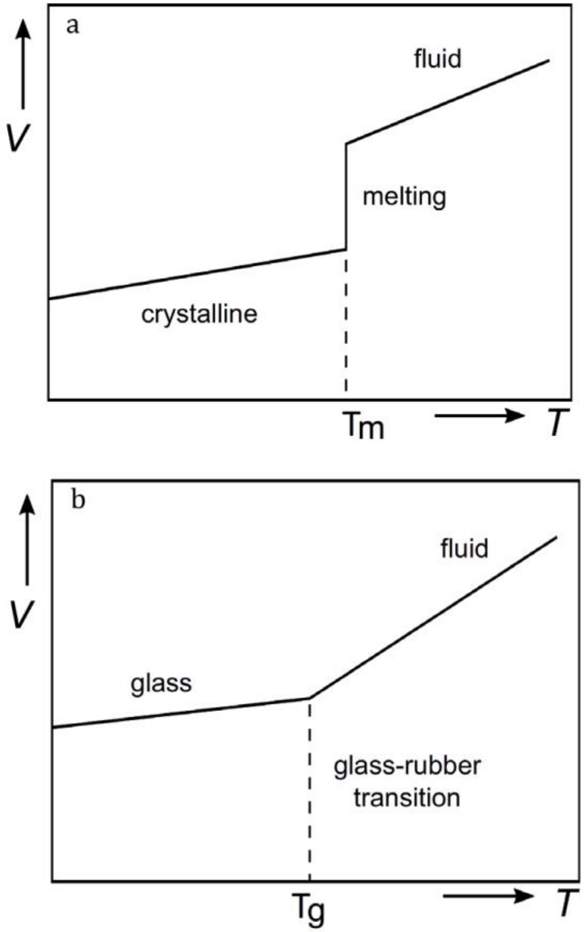
The **melting of a polymer** corresponds to the transformation of a solid material into a viscous liquid. This phenomenon occurs on the crystalline regions upon heating at the **melting temperature (T_m)**

Melting behaviour depends on many variables like the crystallization temperature or annealing treatment, thickness the lamellae, heating rate or impurities/imperfections in the crystals

Glass transition (amorphous phase)

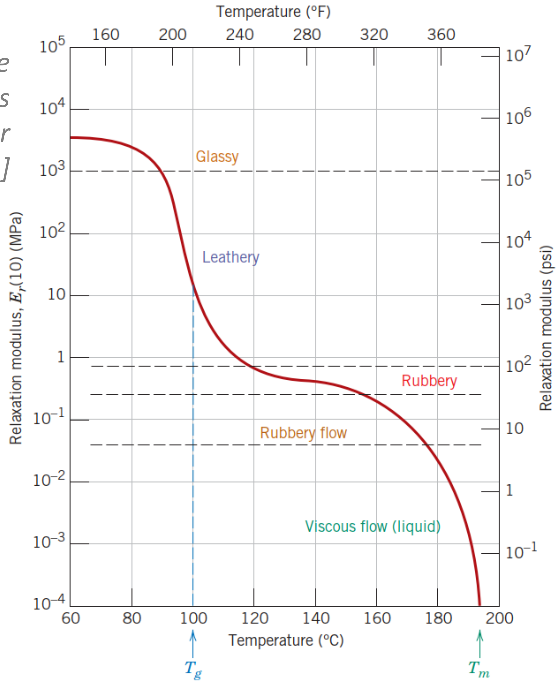
The **glass transition** occurs in the amorphous regions and is due to a reduction in motion of large segments of molecular chains with decreasing temperature. The temperature at which the polymer experiences the transition is the **glass transition temperature (T_g)**

T_g is governed by the competition between **thermal mobility** and the **attraction forces between the chains**. Abrupt changes in other physical properties accompany this glass transition like stiffness, heat capacity, coefficient of thermal expansion (CTE)…



Volume as a function of temperature: Crystalline material (top), Amorphous polymer (bottom). L. E. Govaert [4]

Other important properties



Logarithm of the relaxation modulus versus temperature for amorphous PE [1]

Viscosity

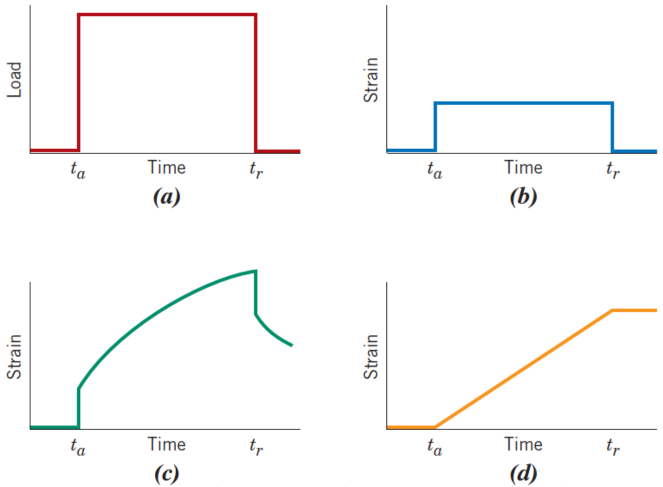
Measure of a material’s **resistance to flow** by shear forces. The viscosity of liquid polymers is very low and depends strongly on their molecular weight

It is a key property for the **processing technology** as most of the techniques are carried out in the fluid phase (lower viscosity → better processability)

Viscoelastic Creep

Many polymeric materials are susceptible to **time-dependent deformation** when the stress level is maintained constant. Creep results are represented as a time-dependent creep modulus $E_c(t)$

The creep modulus is also temperature sensitive ↓ $E_c(t)$ ↔ ↑ T and susceptibility to creep decreases ↑ $E_c(t)$ ↔ ↑ % of crystallinity



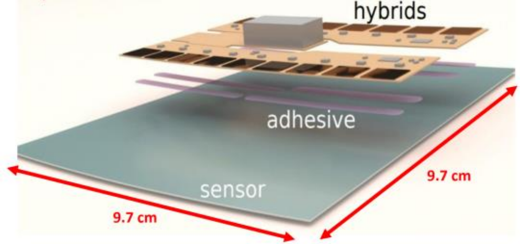
Load versus time, where load is applied instantaneously at time t_a and released at t_r. For the load–time cycle in (a), the strain-versus-time responses are totally elastic (b), viscoelastic (c), and viscous (d) behaviours [1]

Thermal expansion

Polymers generally have higher thermal expansivities than metals and ceramics and their thermal expansion coefficients are not truly constants (the polymers expand in a nonlinear way with temperature)

Example at CERN: Adhesive in sensors

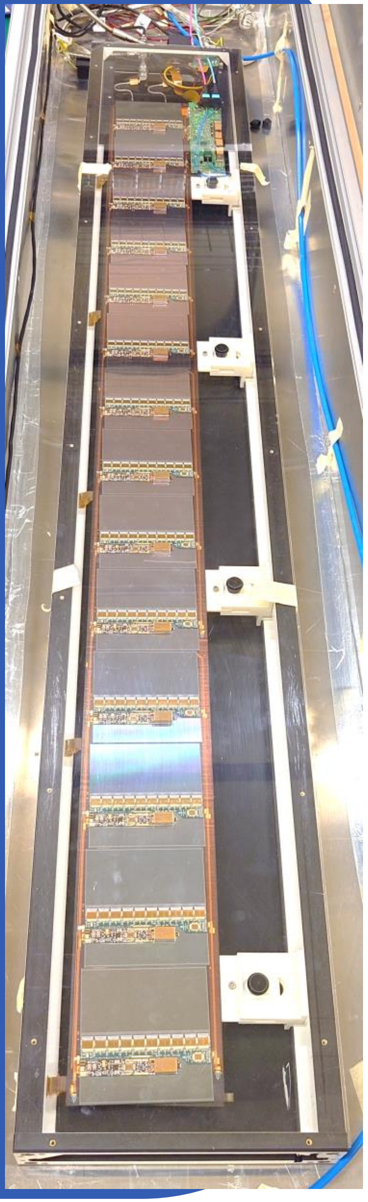
Basic building block of the ITk detector. Courtesy of G. Sciolla [5]



What? Adhesive SE4445 in ATLAS Inner Tracker (ITk)
Where? Silicon modules are glued on “stave cores” support structures

Why? The adhesive material is applied as a low-viscosity liquid, to cover the adherend surfaces evenly and completely and allow for maximum bonding interactions to position the modules and provides thermal conductivity (titanium cooling pipes into the support structures carry CO_2 at −40C).

Case of Study: Failure analysis on cracked modules.



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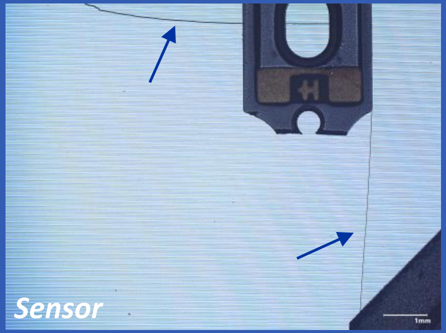

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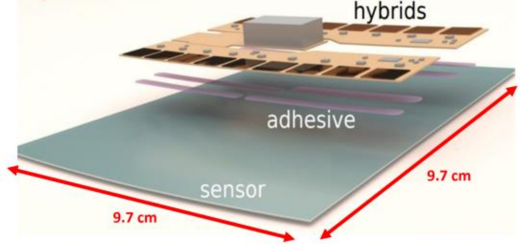
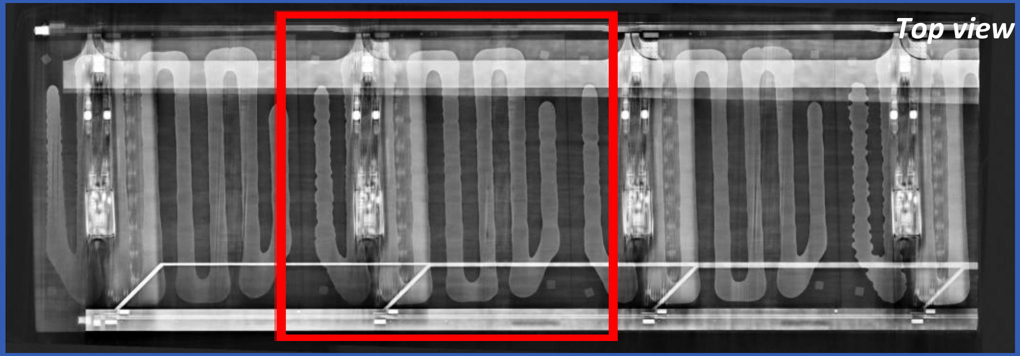
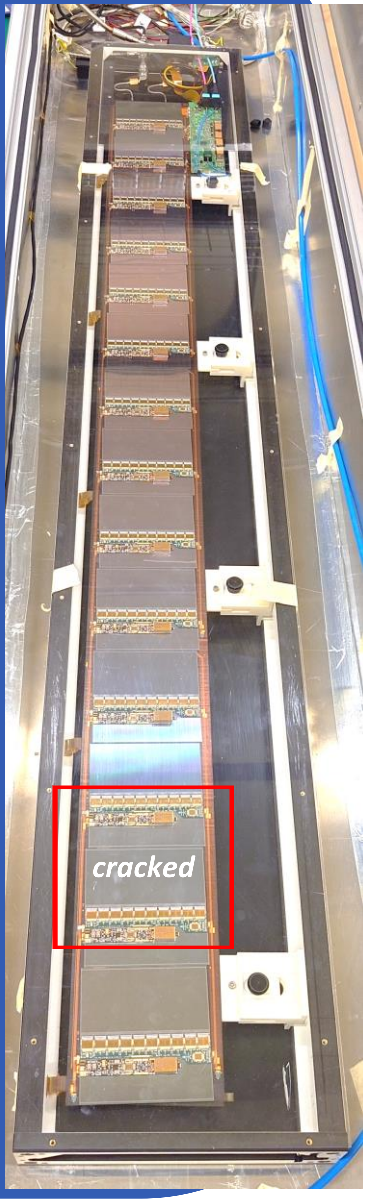


Optical microscopy (OM) and Computed Tomography (CT) for glue pattern evaluation [6] Images courtesy of M. Celuch CERN





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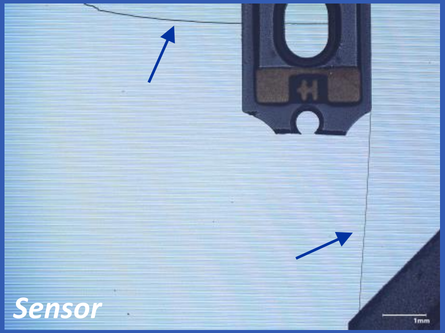
The CT pointed out that the pattern, procedure and/or parameters used for the adhesive application, did not resulted in the desired surface coverage.

The elevated viscosity might have limited the adhesive displacement leading to different local behaviour when subjected to thermomechanical solicitations and resulting in some modules cracked.

Additional analyses are on-going to solve the issue



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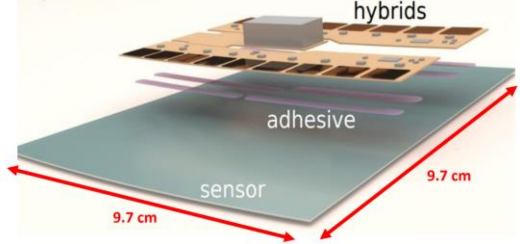

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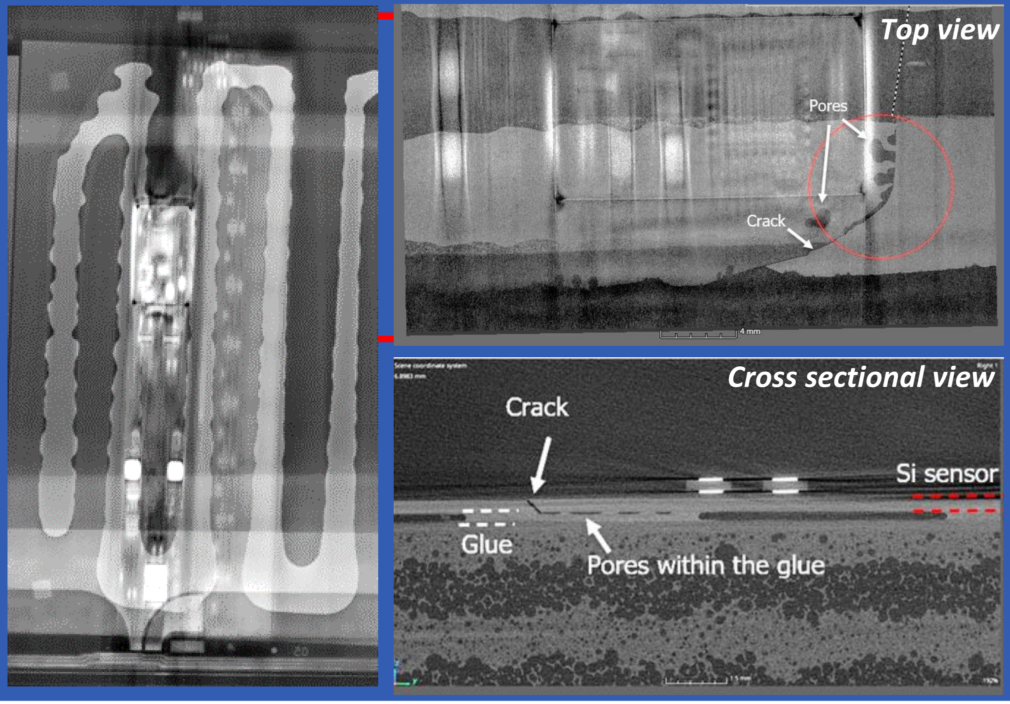
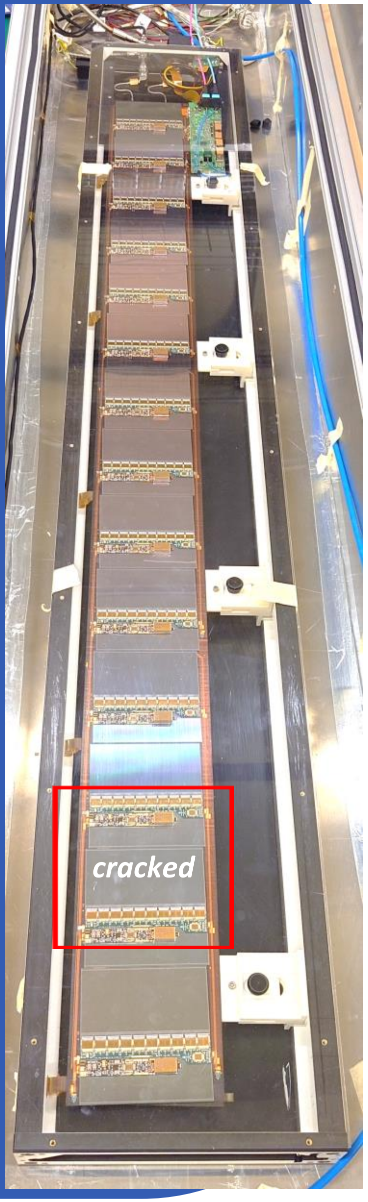




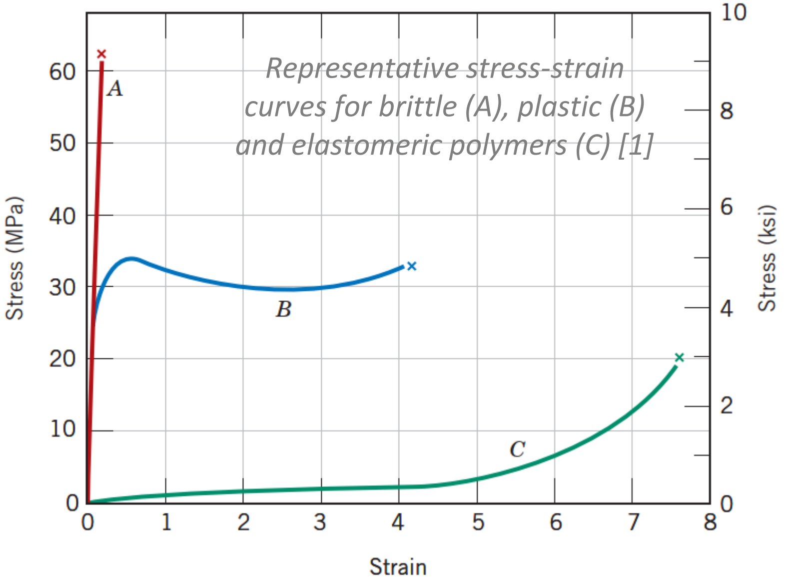
Polymeric vs metallic materials:
Modulus: Polymers < 4 GPa; Metals 48 - 410 GPa
TS: Polymers 100 MPa; Metals 4100 MPa
Elongation: Elastomers > 1000%; Metals < 100%

Mechanical behaviour of Polymers

Stress-Strain Behaviour

Three typically different types of stress–strain behaviour are found for polymeric materials: brittle (curve A), plastic (curve B), and highly elastic polymers – elastomeric - (curve C)

Elastic response: Stiffness of polymers is lower than in other materials → Relevant interactions are the **intermolecular interaction between chains** and the **entanglement (crosslink) network.** A further increase in modulus can be achieved by using particulate fillers (e. g. glass fibers), increasing cross-links (vulcanization) and by molecular orientation (e. g. HPPE commercially available in drawn fibers and tapes with moduli up to 200 GPa).



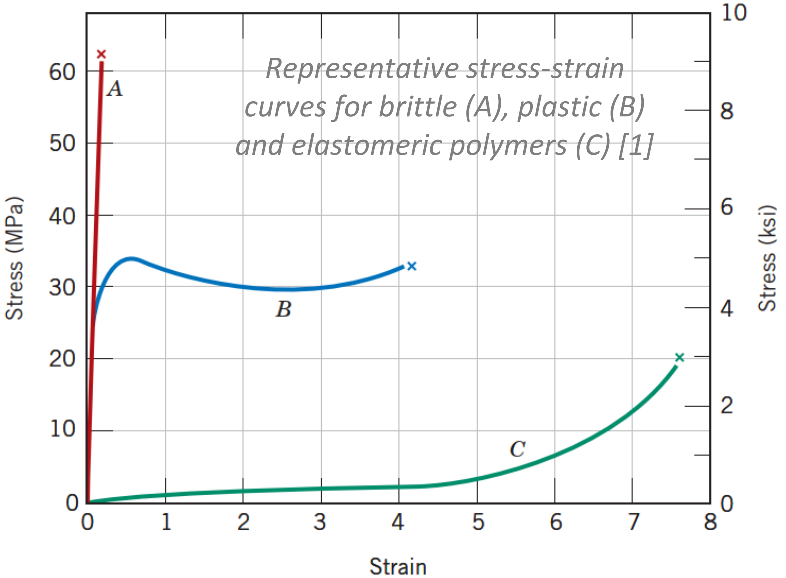
Representative stress-strain curves for brittle (A), plastic (B) and elastomeric polymers (C) [1]

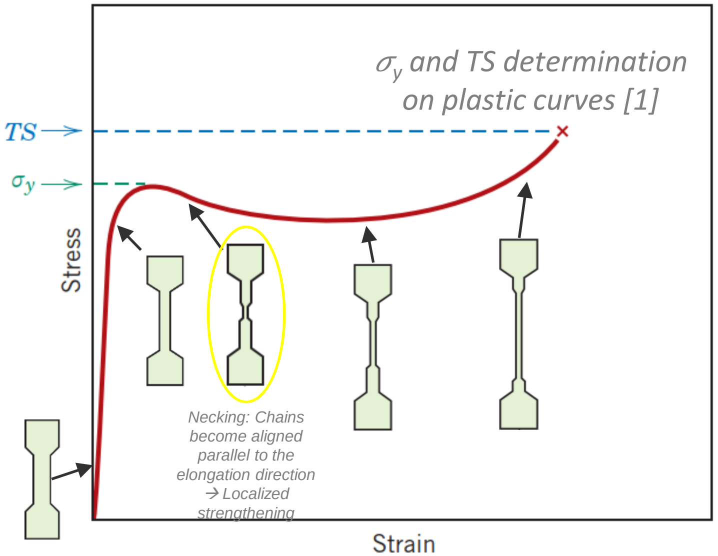
Mechanical behaviour of Polymers

Stress-Strain Behaviour

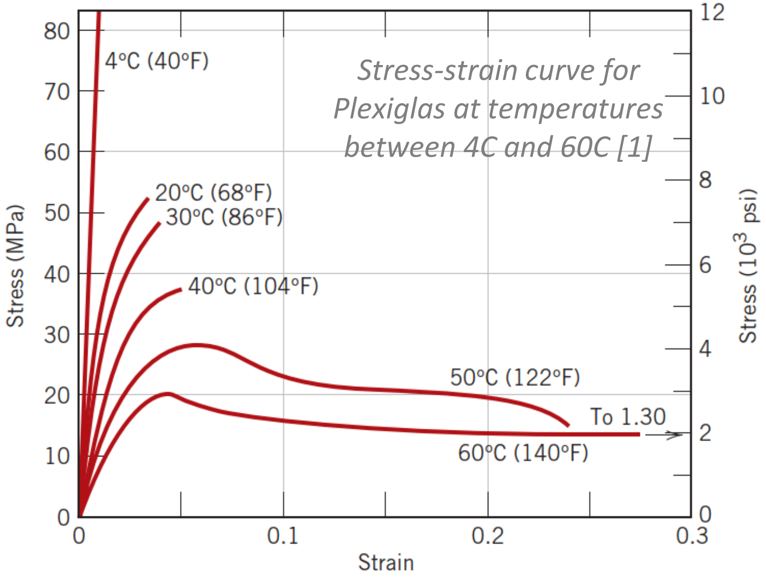
Three typically different types of stress–strain behaviour are found for polymeric materials: brittle (curve A), plastic (curve B), and highly elastic polymers – elastomeric - (curve C)

Beyond the elastic regime: the yield point is taken as a maximum on the curve, which occurs just after the linear-elastic region. The stress at this maximum is the yield strength (σ_y) and tensile strength (TS) corresponds to the stress at which fracture occurs. The mechanical characteristics of polymers are much more sensitive to temperature changes near room temperature


Representative stress-strain curves for brittle (A), plastic (B) and elastomeric polymers (C) [1]


σ_y and TS determination on plastic curves [1]

Necking: Chains become aligned parallel to the elongation direction → Localized strengthening


Stress-strain curve for Plexiglas at temperatures between 4C and 60C [1]

Example at CERN: Epoxy resin

What? Epoxy resin system CTD101K (Composite Technology Development Inc.)

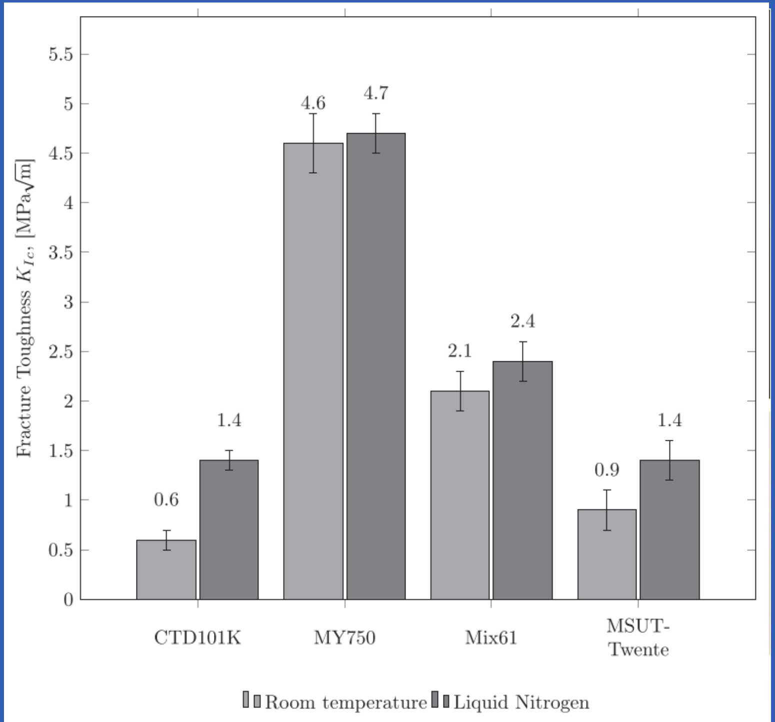
Where? Specifically developed for the impregnation of high-field magnet coils

Why? Epoxy resin is used for electrical insulation [7] and to provide mechanical stability, stiffness and protection to the coil during handling and operation. Important property of the resin system is the ability to resist crack formation and crack propagation.

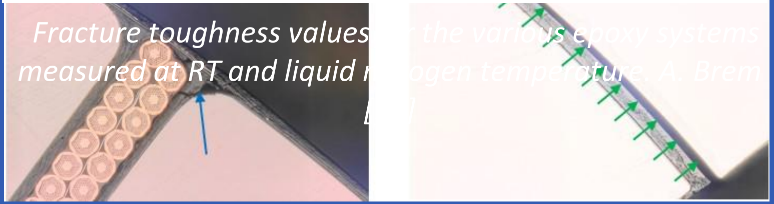
- ***Low viscosity*** → *For void free impregnation (long coil length + geometry)*
- ***Improved adhesion*** *property* → *To reduce bond failure with other components*
- ***Moderate "pot life"*** → *time that passes from initial mixing to reaching a target viscosity*
- ***Low temperature cure*** → *to reduce internal thermal stresses*
- ***Toughness and resistance to cracking at RT and 1.9K*** → *FT, shock test…*
- ***Acceptable strength and flexibility after irradiation*** → *The epoxy is the first magnet material to incur radiation damage*

We need well-balanced overall combination of properties! → New formulations

[7] Electrical Insulation for Magnets: dielectrics, design and construction (Lecture by R. Piccin CAS Magnet Nov. 2023)

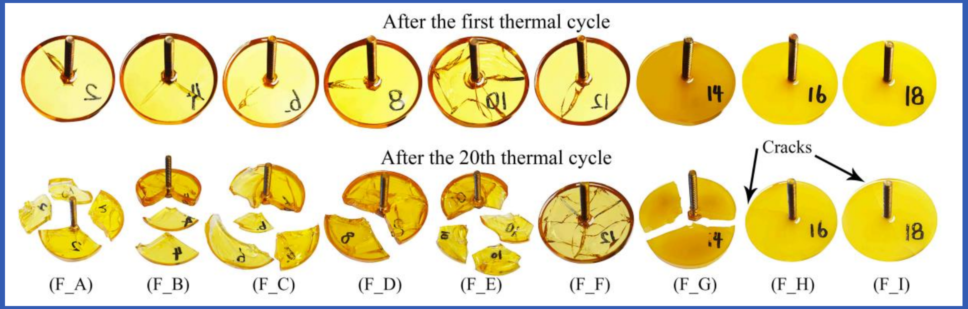


Fracture toughness values for the various epoxy systems measured at RT and liquid nitrogen temperature. A. Brem



Side view of coil section cut from a 11 T dipole magnet GE13. The flat Rutherford cables can be seen encased in cured CTD101K epoxy with some defects highlighted: a) Shrinkage cavities and metal-to-metal crack across the coil interlayer b) Metal-to-metal crack and a large decohesion c) Conductor–to–pole crack d) Large decohesion between resin and pole piece I. Avilés et al. [8]

Thermal shock samples with brass bolts after the 1st thermal cycle and the 20th thermal cycle. Y. Shijian et al. [9]



Polymer additives

Foreign substances intentionally introduced to enhance or modify the polymer properties and render a polymer more usable

Fillers

- Added to improve tensile and compressive strengths, abrasion resistance, toughness, dimensional and thermal stability…but also to reduce the cost
- Particle sizes range from 10 nm to macroscopic, and fillers include wood flour, silica, sand, glass, clay, talc, limestone, and synthetic polymers

Plasticiser

- Added to improve the flexibility, ductility, and toughness of polymers reducing hardness and stiffness.
- Plasticizers are usually low vapor pressure, low molecular weight liquids that fit between large polymer chains, increasing interchain distance and reducing secondary intermolecular bonding

Colorants

- Added to provide a specific colour to a polymer in the form of dyes or pigments

Flame retardants

- Interfering with the combustion process either through the gas phase or by initiating a different → slowing or stopping the burning

Stabilizers

- Added to counteract deterioration processes due to environmental conditions like exposure to UV radiation
- Also, antioxidants that prevent the chemical interaction between the oxygen and the polymer molecules

Radiation on Polymers

Radiation modifies the structure of polymeric materials making them either softer or harder and causing gas production, acid formation, colour change, oxidation, and separation of multi-phase materials like greases.

A deep knowledge of the **radiation tolerance** of lubricants, glues, elastomeric sealants, resins, insulators for magnets, cables, vacuum components, etc. minimizes the risk of radiation-induced failures and reduces the design safety margins.

Total absorbed dose of polymers during operation:

0.1 MGy threshold for many polymeric materials

> 1 MGy → experimentally tested radiation tolerance

> 10 MGy → avoid, or regular monitoring/ maintenance planned

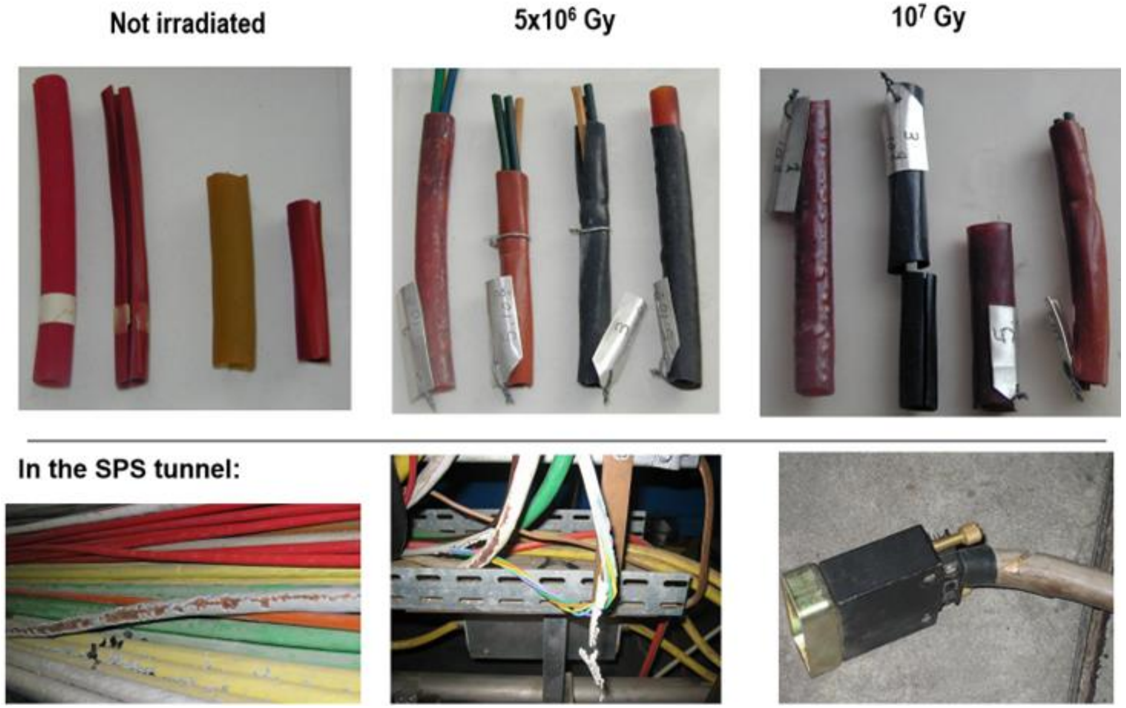
Important research activity at CERN in this field includes experimental testing of commercial and custom-made non-metallic materials (yellow reports [11][12][13], R2E Project [14], CARE Project,…)

External or in-house facilities

Total doses 0.1 MGy to 20 MGy

***Characterization techniques**:*

Characterization: Visual testing, mechanical testing, swelling test, Differential Scanning Calorimetry (DSC), outgassing……



Representative examples of installed cables subjected to different total absorbed dose. CARE Project. Courtesy of J. Gascón [15]

Radiation on Polymers

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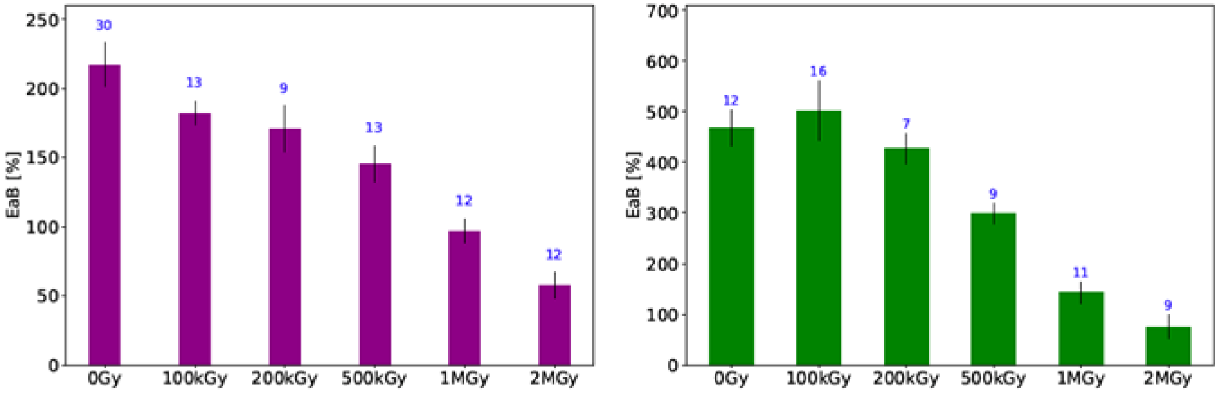
- **Formation of free radicals:** depending on chemical structure, crystallinity, solvent content, additives, plasticizer, stabilizers, temperature, oxygen, humidity…
- **Formation of hydrogen & light HC**
- **Formation of C-C bonds between molecules** (crosslinking)
- **Rupture of C-C bond** (chain scission)
- **Increase in unsaturation**
- **Breakdown of crystalline structure**
- **Discoloration**
- **Oxidation**



(a) Draka NE48 jacket. (b) Draka NE48 insulation.

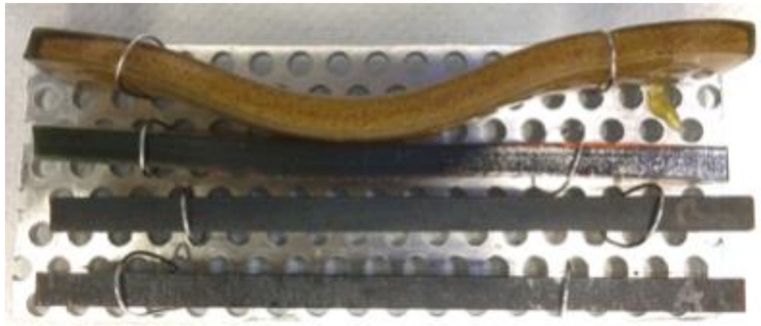
Elongation at break (EaB %) vs absorbed dose on cable jacket (EVA) and insulation (XLPE). Courtesy of J. Gascón

Radiation induced effects are usually described as a function of the **total absorbed dose**, but depend also on the irradiation conditions (radiation type, dose rate, temperature, humidity, oxygen, electrical or mechanical stress) and their **synergetic effect** (simultaneous stressors damage higher than sequential equivalent stressor damage separately)

Radiation on Polymers

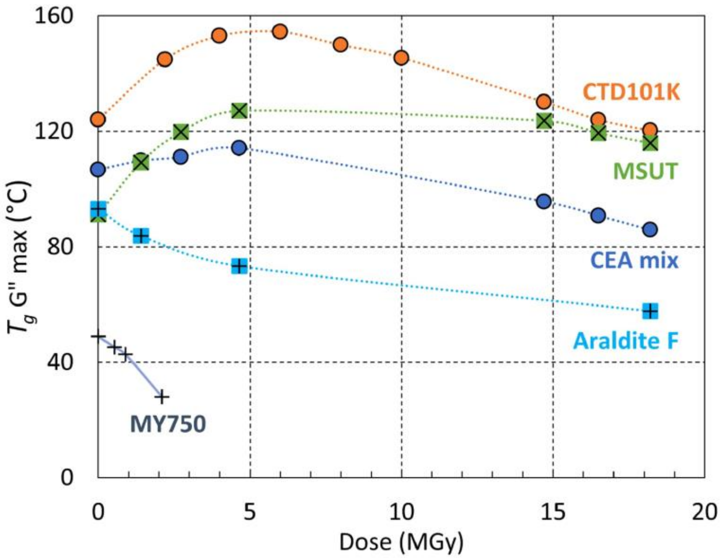
Understanding the effect of radiation on the properties of **epoxy resins** used in the vacuum impregnation of **magnet coils under relevant irradiation conditions** is crucial for the future accelerator facilities

In this case the irradiation source, temperatures (ambient and 4.2 K), atmosphere (absence of oxygen) or the specific additives can strongly influence the aging



Materials candidate for the protective covers of magnets after gamma irradiation at 10 MGy. Courtesy of C. L. Marraco Borderas [10]

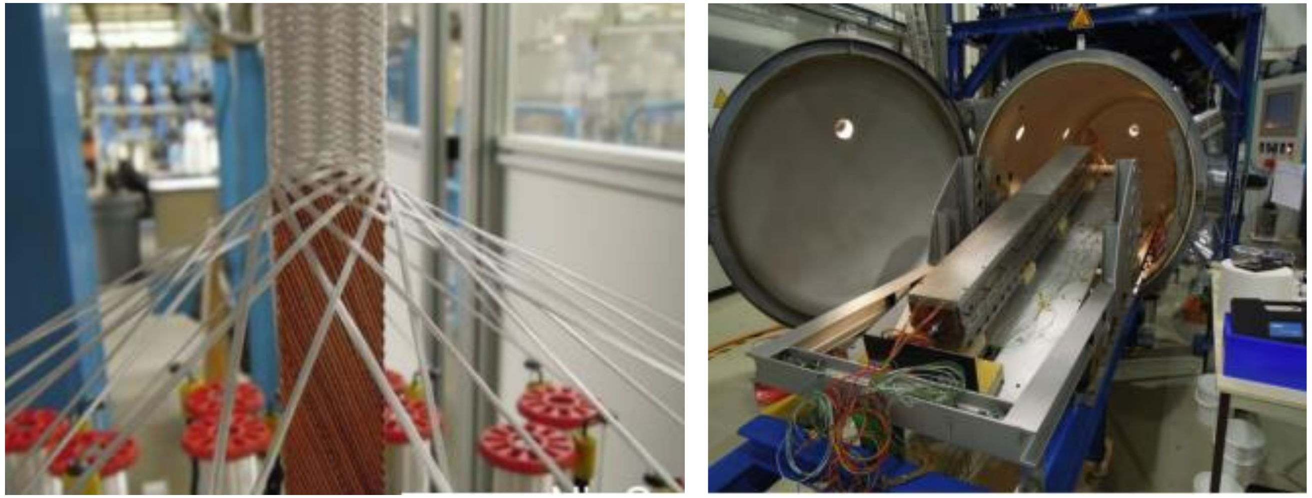
T_g vs dose evolutions allow to compare aging rates



Evolution of the Tg (G" max) of different epoxy resins as a function of the absorbed dose. D. M. Parragh et al. [16]

↑ T_g cross-linking
↓ T_g chain scission

Images from [7]



Knowledge of the behaviour of cable insulation and the thermo-mechanical properties of the **composite** is essential for the mechanical design of the magnet

Composite Materials

This relatively new family of materials marked a significant advancement in civil construction, energy or aeronautics…meeting the growing need for **stronger** yet lighter materials

Why are they so interesting?

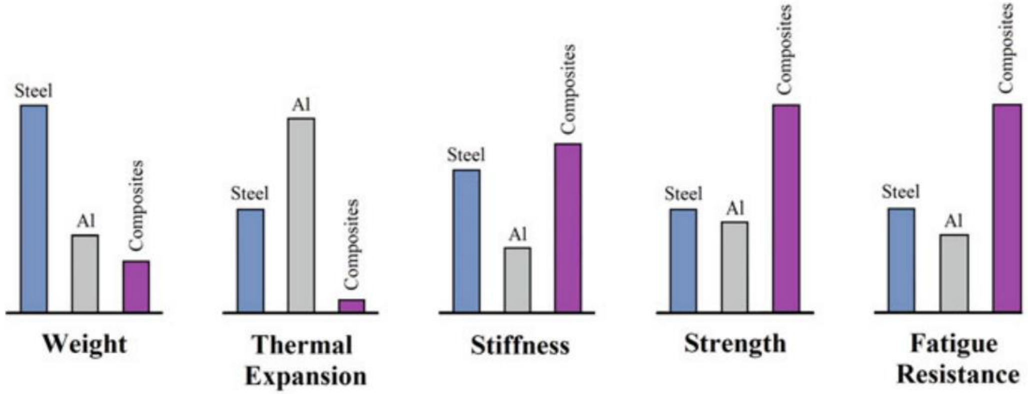
- Possible to achieve combinations of properties not attainable with metals, ceramics or polymers alone
- Design of materials with optimized properties
- Developed in parallel with high stiffness and strength fibers
- Can be produced by various processing techniques
- Large part size possible

What are composites?

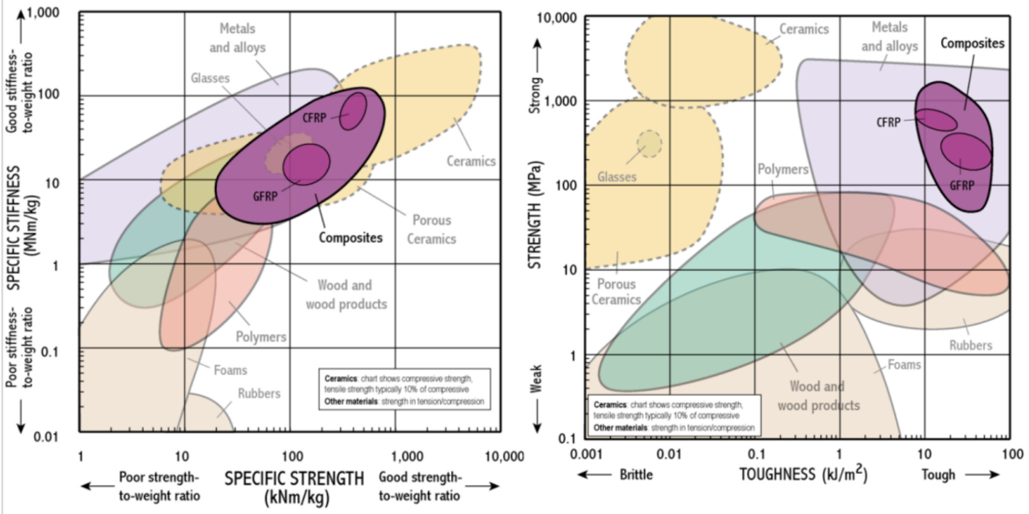
Composed of at least two phases: the **matrix**, which is continuous and surrounds the **dispersed phase**

The **properties of composites** are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase (shape and size of the particles, distribution, and orientation)

Classification according to the matrix (polymeric, metallic or ceramic, including the carbon-carbon composites) or to the **reinforcement geometry** (particle-reinforced, fiber- reinforced, structural and nanocomposites)



Comparison between conventional materials and composite materials.
K. Chawka [17]



Comparison of the mechanical properties of composites with other materials. (a) Specific stiffness versus specific strength and (b) strength versus fracture toughness. CFRP, carbon-fiber reinforced polymers; GFRP, glass–fiber reinforced polymer [18]

Polymer-Matrix Composites

Polymeric Matrix Composites (**PMCs**) consist in a plastic matrix with fibers as reinforcement and are the most widely used to manufacture composites.

Two types of matrix:

- **Thermoplastics** → low flow (difficult to infiltrate), expensive but good mechanical properties at high temperature (i. e. Polyetheretherketone-PEEK, Polyphenylene Sulphide-PPS and polyetherimide-PEI)
  - ➢ Film stacking, thermoforming, injection moulding…
- **Thermosets (resins)** → low viscosity before **curing**, cheap, resistant to chemical attack but brittle, very low fracture toughness and limited properties at high temperature (i. e. unsaturated polyester resins, epoxy resins and polyimides)
  - ➢ Produced by hand layup and spray techniques, filament winding, pultrusion, autoclave-based methods (“**prepreg**”)…

Most typical fibers are Glass Fiber–Reinforced Polymer (**GFRP**), Carbon Fiber–Reinforced Polymer (**CFRP**) and Aramid Fiber–Reinforced Polymer Composites

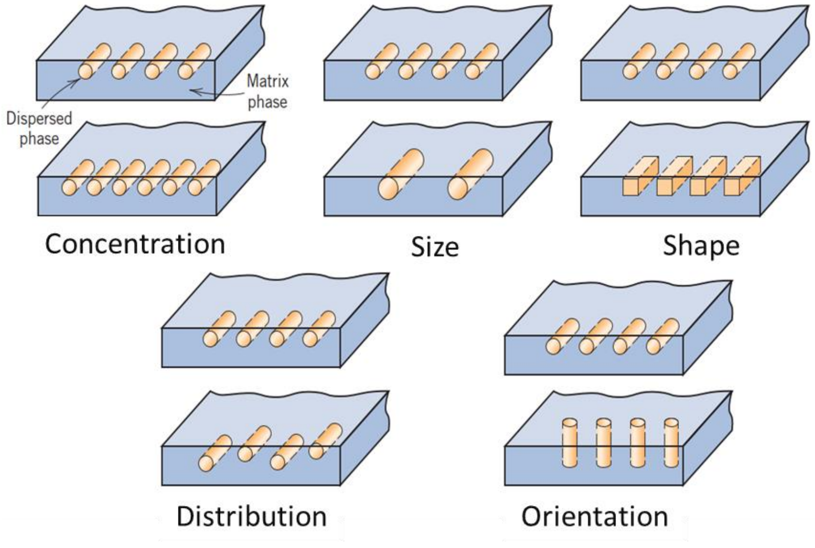
Fiber-Reinforced Composites

Continuous fibers → Maximum fiber volume fraction in real composites is in the range 60-70% (matrix infiltration becomes very difficult above these values)

- Highly **anisotropic** and the maximum strength and reinforcement are achieved along the alignment (longitudinal) direction
- Properties perpendicular to the fibers are controlled by the matrix

Short fibers → Length from 100 µm to few mm. The fiber volume fraction, average length and orientation are relevant parameters

- Fiber orientation (2D or 3D)



Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites [1]

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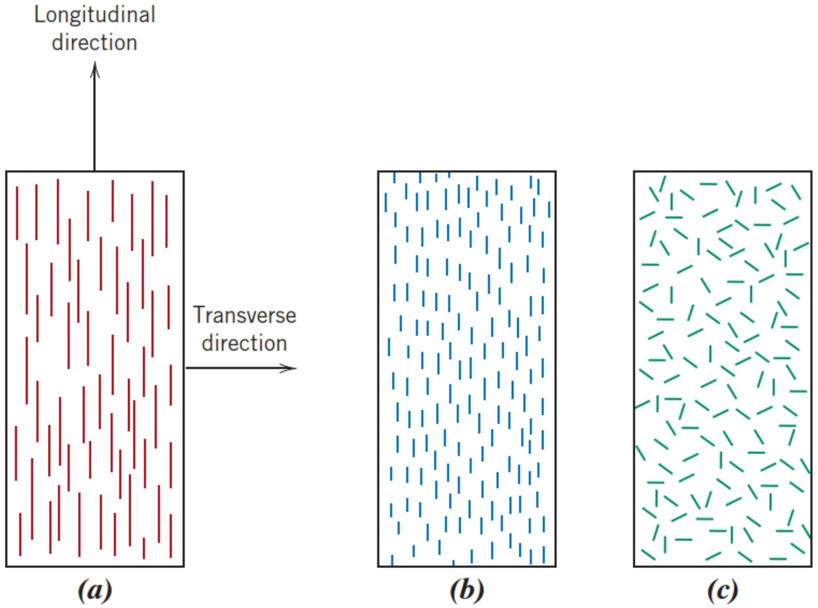
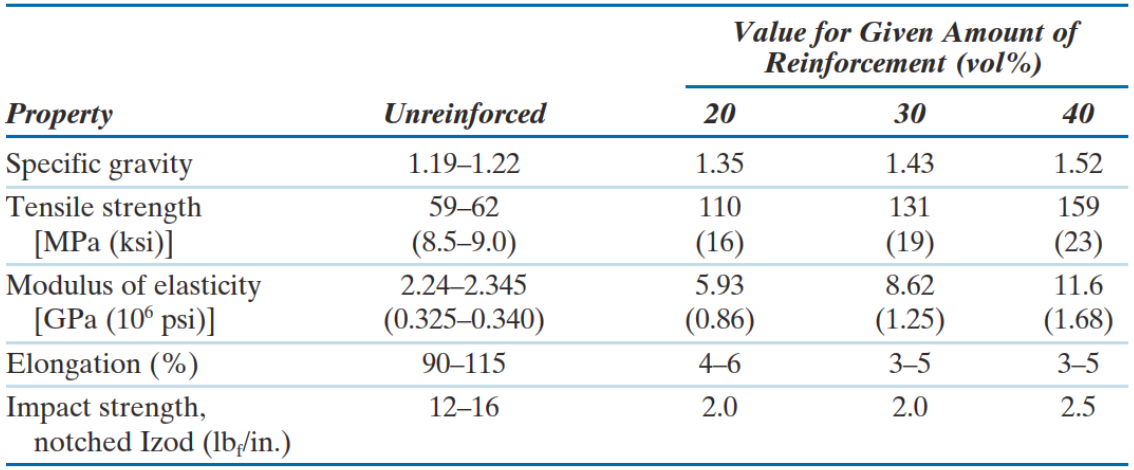
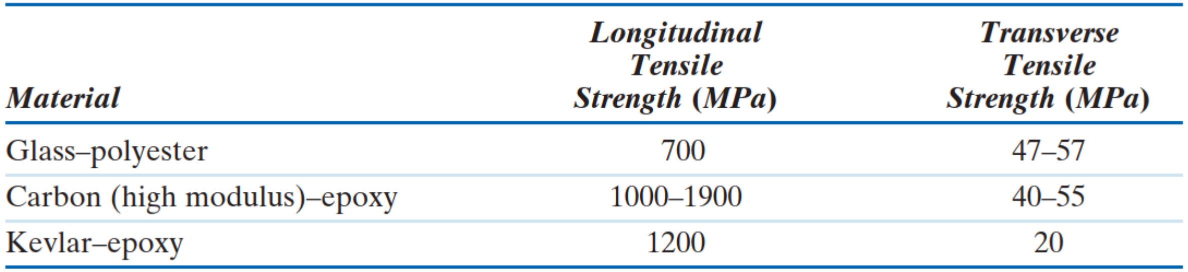


Schematic representations of (a) continuous and aligned, (b) discontinuous and aligned, and (c) discontinuous and randomly oriented fiber–reinforced composites [1]



Property	Unreinforced	Value for Given Amount of Reinforcement (vol%) 20	30	40
Specific gravity	1.19–1.22	1.35	1.43	1.52
Tensile strength [MPa (ksi)]	59–62 (8.5–9.0)	110 (16)	131 (19)	159 (23)
Modulus of elasticity [GPa (10^6 psi)]	2.24–2.345 (0.325–0.340)	5.93 (0.86)	8.62 (1.25)	11.6 (1.68)
Elongation (%)	90–115	4–6	3–5	3–5
Impact strength, notched Izod (lb_f/in.)	12–16	2.0	2.0	2.5

Properties of unreinforced and reinforced polycarbonates with randomly oriented glass fibers [1]



Material	Longitudinal Tensile Strength (MPa)	Transverse Tensile Strength (MPa)
Glass–polyester	700	47–57
Carbon (high modulus)–epoxy	1000–1900	40–55
Kevlar–epoxy	1200	20

Comparison of longitudinal and transverse tensile strength in various FRC [1]

Fiber-Reinforced Composites

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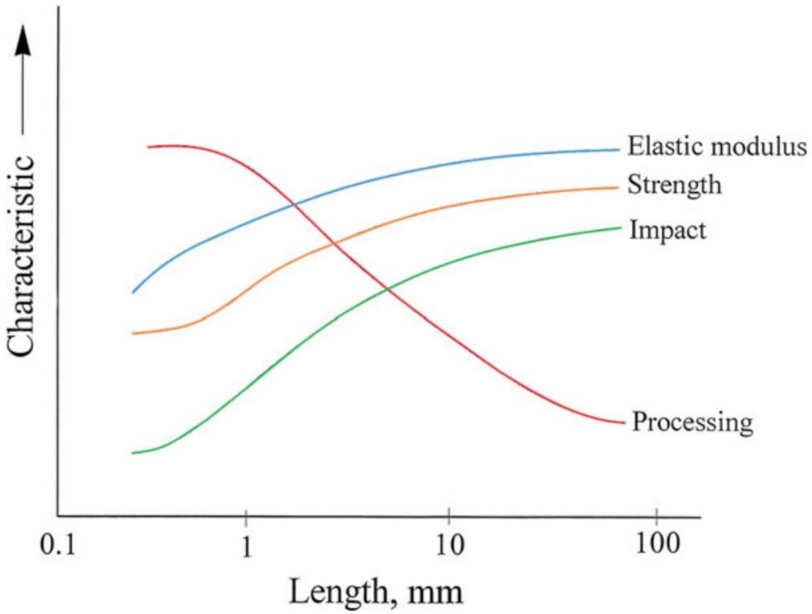
- Properties perpendicular to the fibers are controlled by the matrix

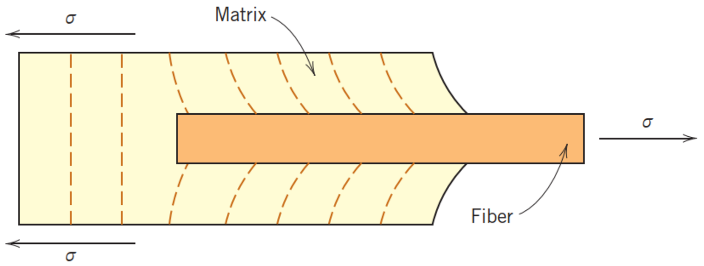
Short fibers → Length from 100 µm to few mm. The fiber volume fraction, average length and orientation are relevant parameters

- Fiber orientation (2D or 3D)
- Critical length “l_c” of the fiber



Variation of some mechanical properties of a composite as a function of fiber length [17]

The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load [1]



$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

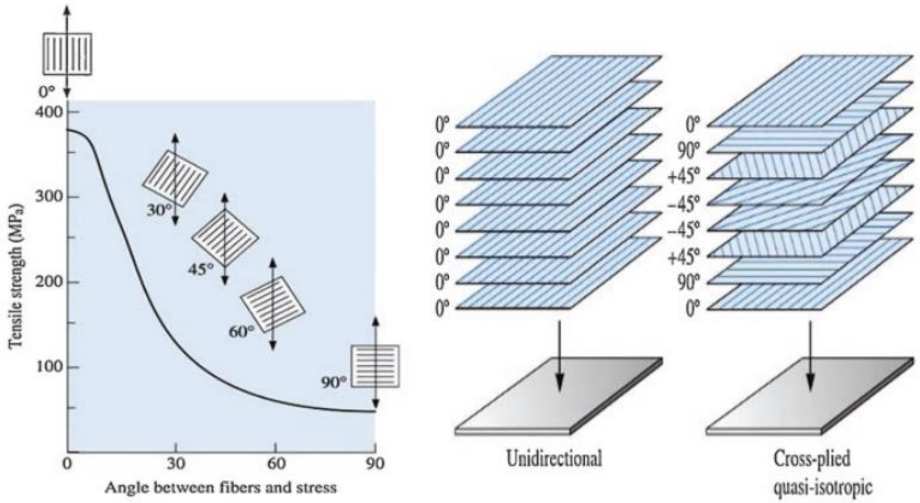
Where “d” is the fiber Ø and “σ^*_f” the ultimate (or tensile) strength and τ_c the fiber–matrix bond strength [1]

Fiber-Reinforced Composites

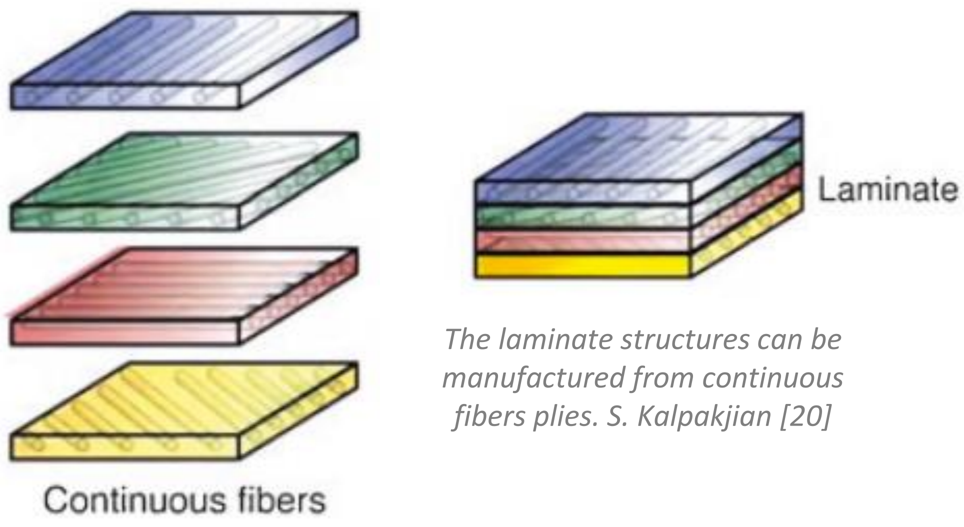
1D: Is the easiest fiber arrangement in a **unidirectional lamina** also called ply or layer

2D fabrics: Multidirectional laminates (built by stacking unidirectional lamina with different orientations and can provide quasi-isotropic properties)**,** woven fabrics, knit, braided, nonwovens (from a set of disordered fibers)

3D fabrics (woven fabrics, non-crimp fabrics, stitching)



Effect of fiber orientation on the tensile strength of E-glass fiber-reinforced epoxy composites. D. R. Askeland [19]



The laminate structures can be manufactured from continuous fibers plies. S. Kalpakjian [20]

Post-lay-up processing techniques include autoclave moulding, pressure-bag moulding, and vacuum-bag moulding to reduce the porosity

Example at CERN: PMCs

What? CFRP Composite

Where? ATLAS Inner Tracker (ITk) structural components

Why? The tracker needs to record particle paths with very high precision, yet be lightweight, to disturb the particles as little as possible → Very thin, robust and accurate carbon fiber profiles are needed

For small series production an important invest on the development phase the mechanical simulation is key to validate the configuration of the laminates arranged so that the maximum service stress lies in the direction that has the highest strength

Design and simulation

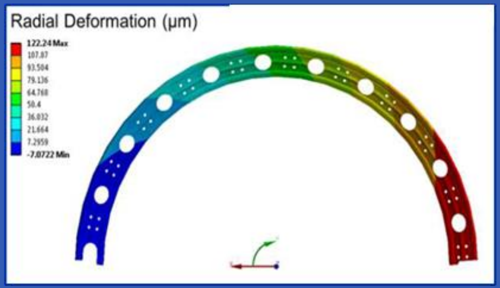
- *Definition of the material properties*
- *Definition of the stacking sequence*
- *Verify the compatibility with the detector envelope*

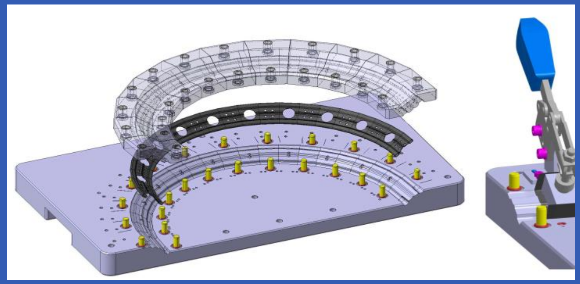
Tooling and mould

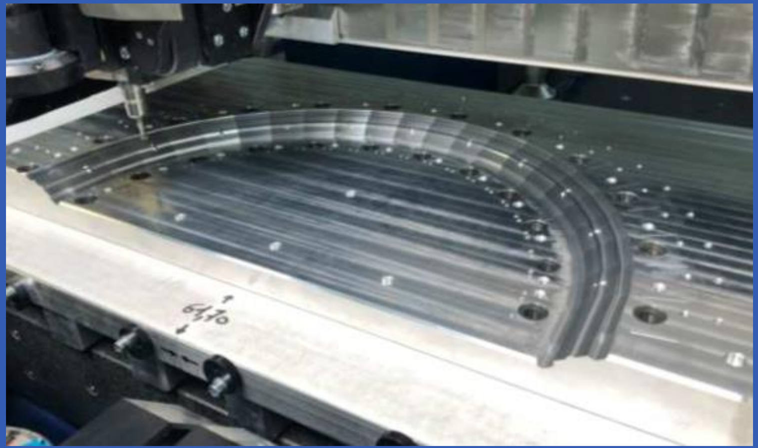
- *Conception of the different parts*
- *CNC machining*

Prototype production

- *Cutting of the carbon plies*
- *Lamination of the carbon plies*
- *Polymerization in autoclave*
- *Demoulding of the part*







"Prepreg" twill weave

Main design and manufacturing steps of structural ring from CFRP composite "pre-preg" raw material. Courtesy of F. Boyer Composite Laboratory at CERN

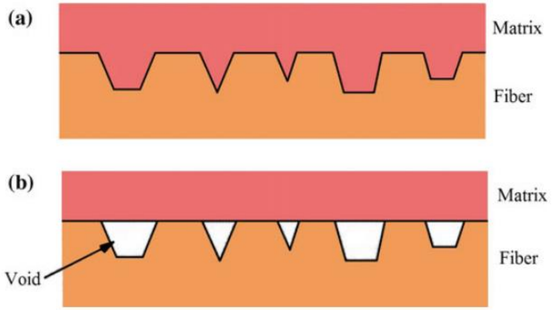
Fiber-Reinforced Composites

The **mechanical characteristics** of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase → **Matrix-fiber interface**

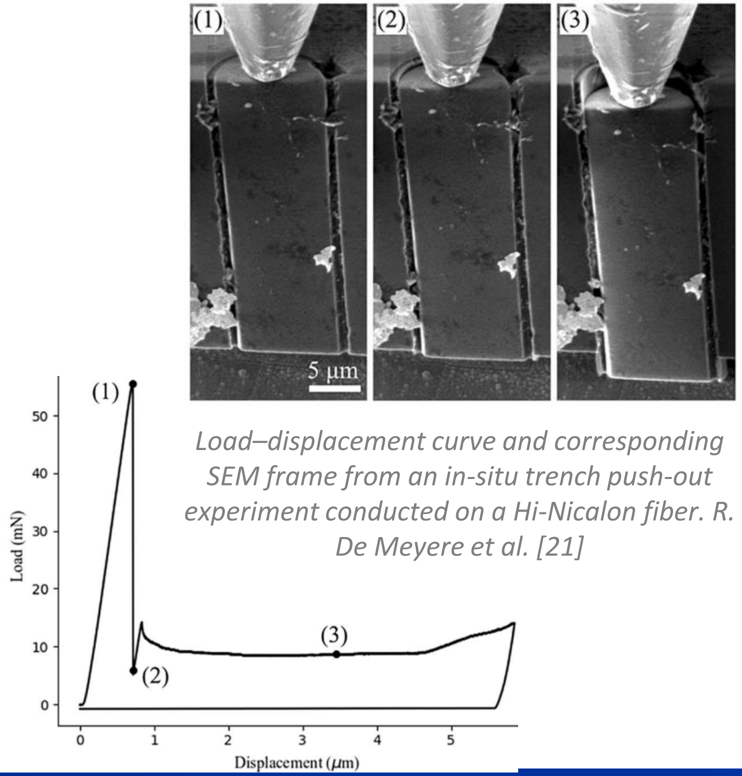
The **interface area is very large** in composites (100000 m^2/m^3) and is more important if the fiber radius decreases (i. e. nanotubes reinforcement). We need an **optimized bonding that improves the toughness** of the component

- **Wettability →** Ability of the liquid to spread on a solid surface (infiltration!)
  - Important effect of surface roughness (intimate contact), and coupling agents are frequently used to improve the wettability between the components
- **Bonding →** Mechanical bonding (interlocking or mechanical gripping when the matrix contracts), physical bonding (van der Waals forces…), chemical bonding (dissolution bonding, and reaction bonding). Interlock effect between rough surfaces

Interface mechanical behaviour is characterized by shear stress (// to the interface), normal strength and interface fracture energy: Flexural test, bending test, interlaminar shear strength (ILSS), fibers push-in/push out test, pull-out test, instrumented indentation test…



a) Good mechanical bond and b) lack of wettability can make a liquid polymer or metal unable to penetrate the asperities on the fiber surface, leading to interfacial voids [17]



Load–displacement curve and corresponding SEM frame from an in-situ trench push-out experiment conducted on a Hi-Nicalon fiber. R. De Meyere et al. [21]

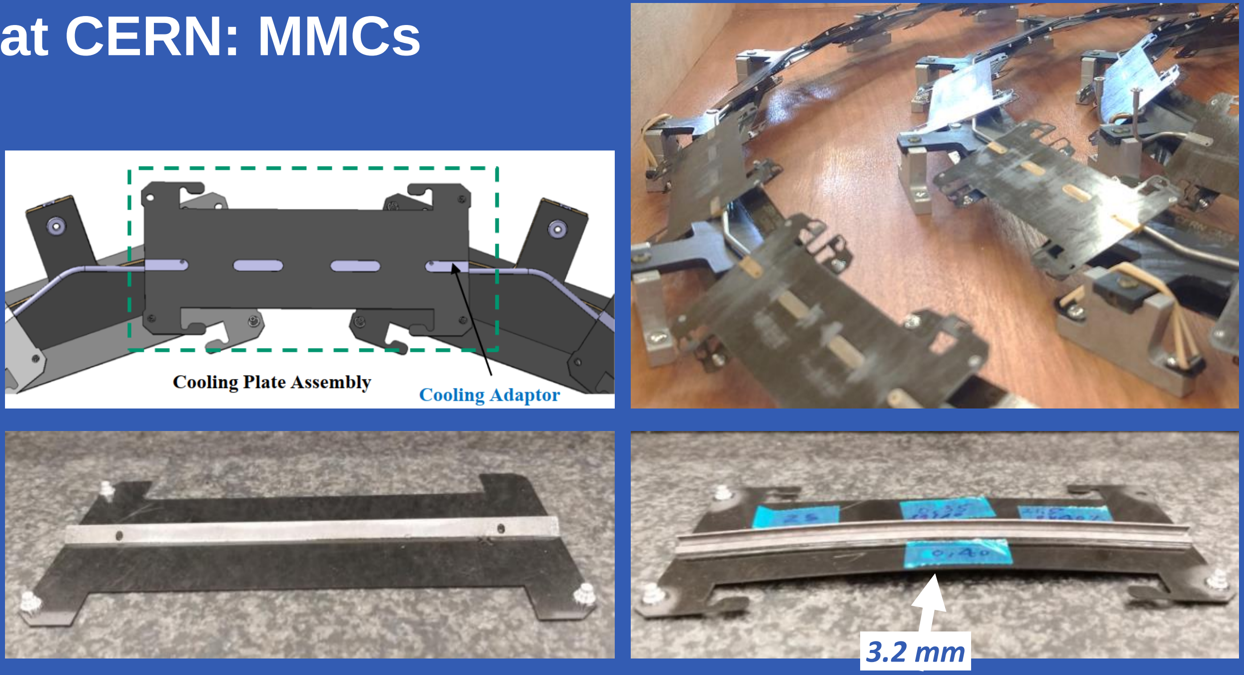
Example at CERN: MMCs

What? Cooling adaptors machined from MMC Aluminium-CF (Al-CF) with chopped fibers randomly oriented in XY plane (50 vol%)

Where? Outer tracker of the CMS detector with silicon sensors at -30C during operation

Why? Thermal expansion coefficient should match that of silicon to avoid deformations during cooling cycles, dimensional stability over time (few µm) and non-magnetic

Case of study: Material from two different providers A (Casted Al-CF) vs. B (Sintered Al-CF). Format from “B” (rectangular blocks) is more suitable for the application but important dimensional variations were observed with time.



Images from [22]

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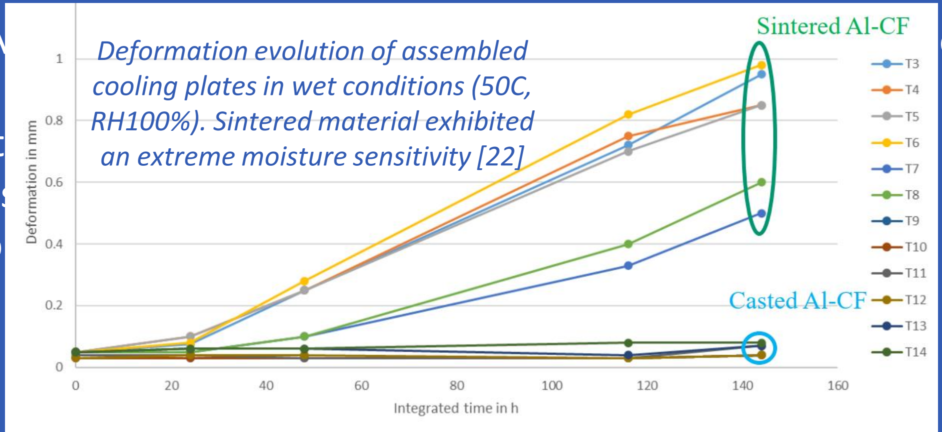
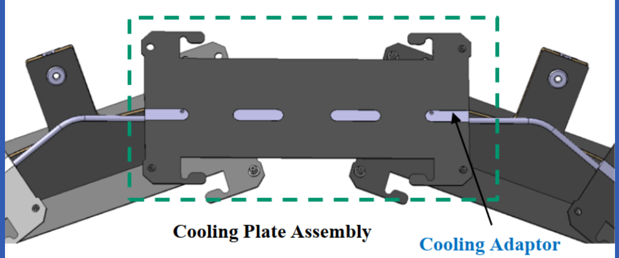
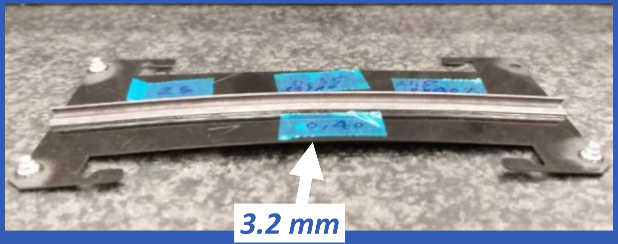
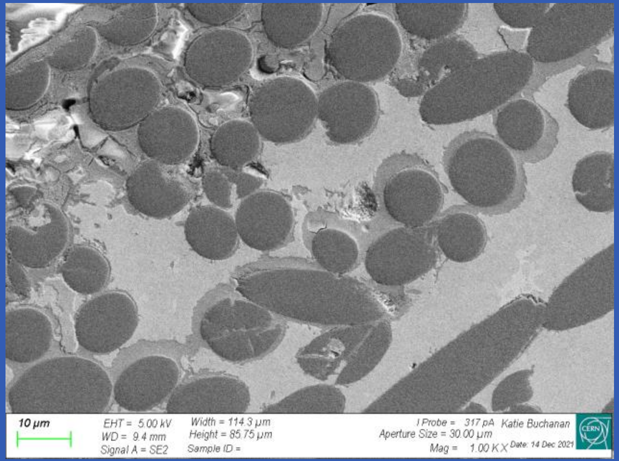

Deformation evolution of assembled cooling plates in wet conditions (50C, RH100%). Sintered material exhibited an extreme moisture sensitivity [22]

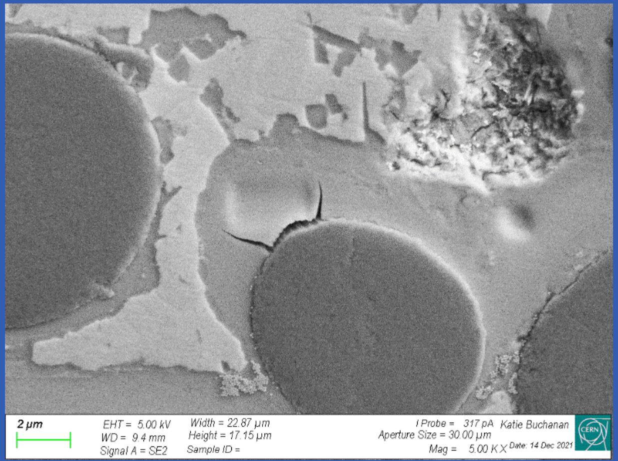




Images from [22]

SEM images after wet testing confirmed galvanic corrosion signs at the matrix-CF interface on sintered samples. K. Buchanan et al. [23]





Particle-Reinforced Composites

Large-particle composites

Polymers with fillers like synthetic rubber with carbon black particles in a tire, concrete used as structural building material…

Particle-matrix interactions are analysed using macroscopic mechanics

Dispersion-strengthened (DS) composites

Diameters between 10 and 100 nm

Particle–matrix interactions occur on the atomic or molecular level

The matrix carries most of the applied load, while the small dispersed particles hinder dislocation movement

Particle-Reinforced Composites

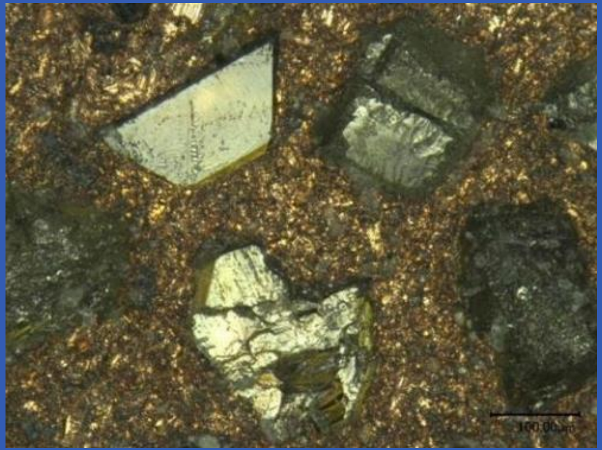
Large-particle composites

Example at CERN

What? CuCD with diamond particles dispersed in a Cu matrix

Where? Absorber material in beam intercepting devices (BIDs)

Why? Combination of properties provided by the two main material constituents—copper contributes to the thermal and electrical conductivity of the material, while the diamond particles further improve thermal conductivity and aid in reducing the density and the coefficient of thermal expansion



Microscopy image of CuCD, with diamond particles dispersed in a copper matrix. A. Bertarelli et al. [24]

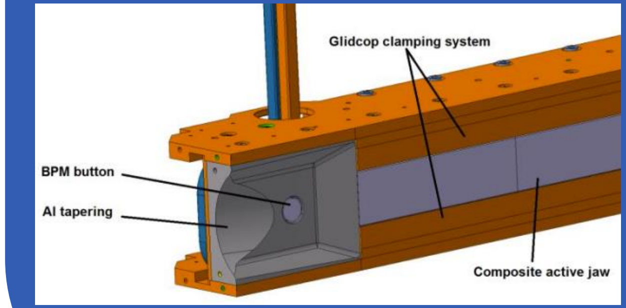
Dispersion-strengthened (DS) composites

Example at CERN

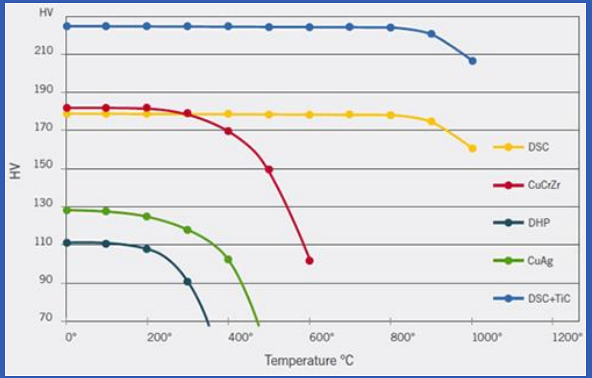
What? GLIDCOP® is the trademark for DS copper (DSC) containing Al_2O_3 particles. Fore CERN BID the grade Al-15 is of interest

Where? Collimators jaws

Why? The alumina particles are stable at high temperatures preventing the softening and of the copper when subjected to high temperatures and maintaining the requested jaw flatness to maintain their beam cleaning efficiency



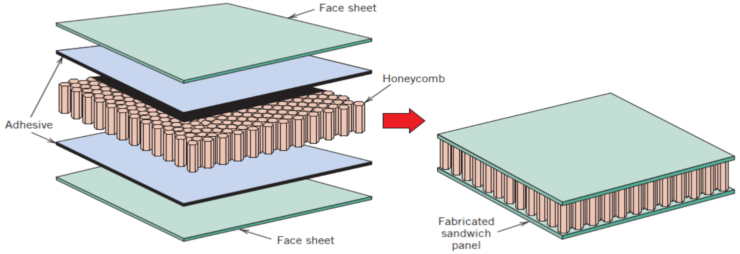
New secondary collimator, 3D view of the jaw. F. Carra et al. [25]



Comparison of hardness vs. T for different copper alloys and DSC. Total Materia [26]

Structural Composites:

- **Multilayered** and normally low-density composite used in applications requiring structural integrity, ordinarily high tensile, compressive, torsional strengths and stiffnesses
- The properties depend not only on the constituent materials, but also on the geometrical design of the structural elements (i. e. the core thickness)
    - **Sandwich panel** consists of two outer sheets (faces or skins) that are adhesively bonded to a thicker core (typically rigid polymeric foams, wood, and honeycombs)
    - **Laminar composite** produced by lay-up (i. e. laminate on fiber-reinforced composites)



Schematic diagram showing the construction of a honeycomb core sandwich panel [1]

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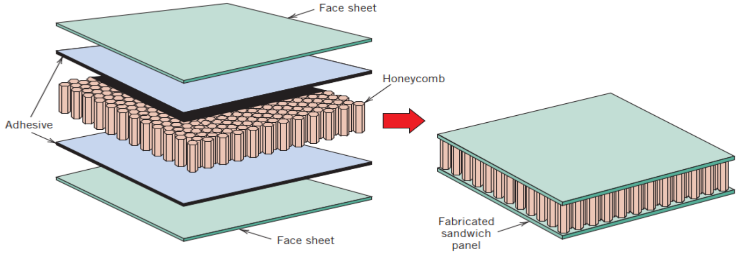


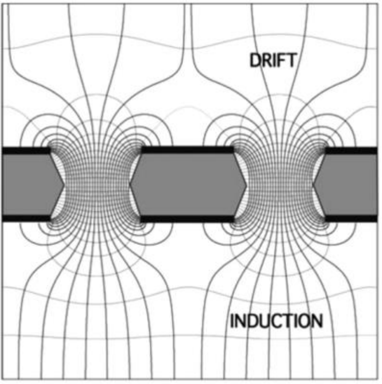
Schematic diagram showing the construction of a honeycomb core sandwich panel [1]

Example at CERN: Laminar

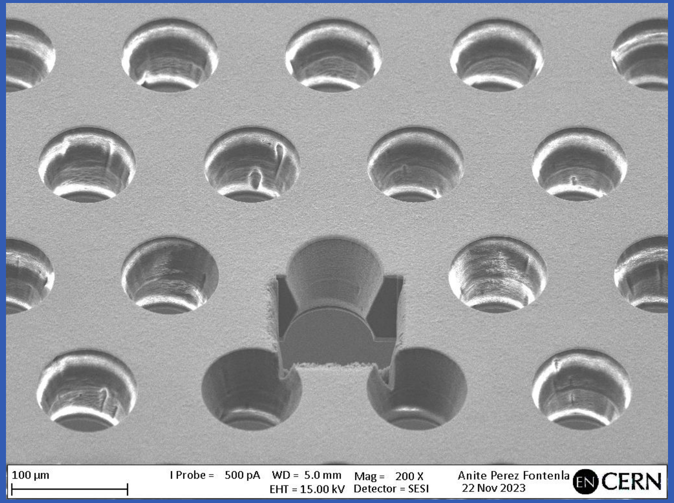
What? Gas Electrons Multiplier (GEM) thin composite sheet with a thin polymer foil (insulator) metal-coated on both sides and pierced with a high density of holes (50 µm Kapton with 5 µm Cu)

Where? The multiplier can be used as detector on its own, or as a preamplifier in a multiple structure

Why? The component can reach large overall gains in harsh radiation environment. The sensors are durable and easy to assemble using prefabricated components. They offer various configurable options, enabling customization of sensor parameters to meet specific needs. Flexible detector shape, robust and low cost



Electric field in the region of the holes of a GEM electrode. F. Sauli [27]



FIB-SEM cross sectional view on GEM composite as part of provider qualification. A. Pérez

Nanocomposites:

Diameters < 100 nm

Properties depend on both matrix and nanoparticle, nanoparticles properties + shape + content + matrix/nanoparticle interface

Most of today’s **commercial nanocomposites** use nanocarbons, nanoclays, and particulate nanocrystals (typically inorganic oxides such as silica, alumina, zirconia, halfnia, and titania)

For most applications, the nanosized particles must be dispersed uniformly and homogeneously within the matrix → **Big challenge!**

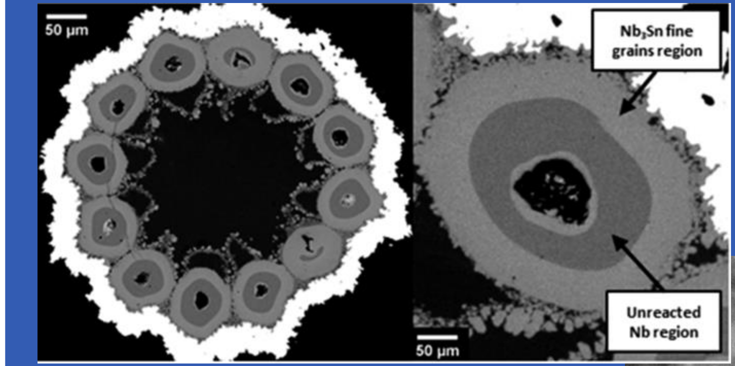
Novel fabrication techniques are constantly being developed

Example at CERN: SC wires

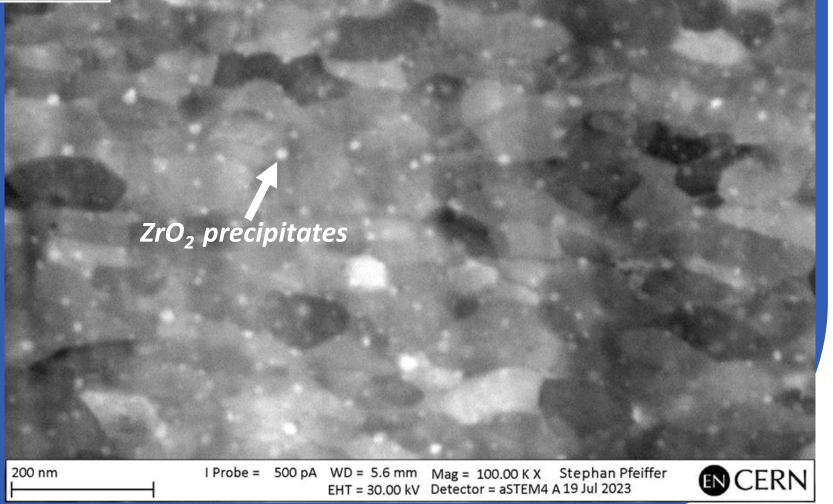
What? Artificial Pinning Center (APC) Nb_3Sn wires

Where? Development studies for future 100 TeV hadron collider

Why? The presence of a uniformly distributed oxygen source (OS) during the thermal treatment reduces the average Nb_3Sn grain size, leading to an enhancement of the layer critical current density (Jc) at 4.2 K [28][29][30]



SEM image of a heat treated Zr-core OS wire (700 °C × 50 h) and detail of filament with the central unreacted Nb-alloy surrounded by a region of Nb_3Sn fine grains and then the large grains of $Nb3_Sn$ and other phases.
F. Lonardo et al. [30]



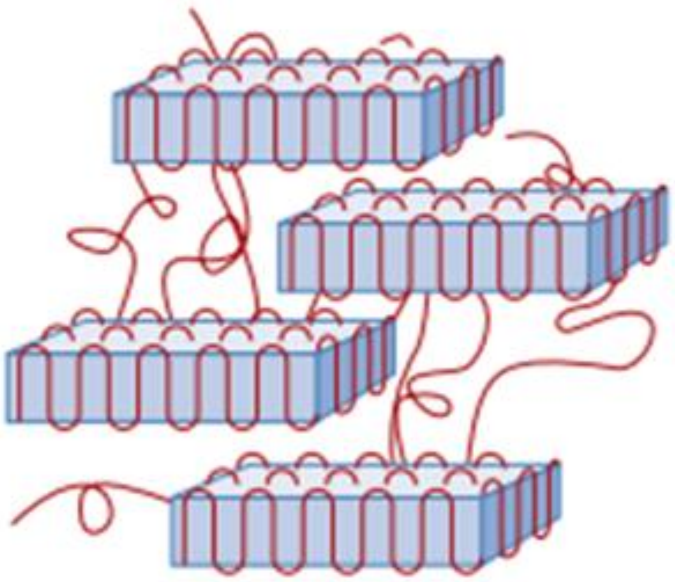
STEM image (Collaboration CERN – UNIGE on dimensional assessment of nano particles in APC Nb_3Sn wires).
Courtesy of S. Pfeiffer and A. Moros

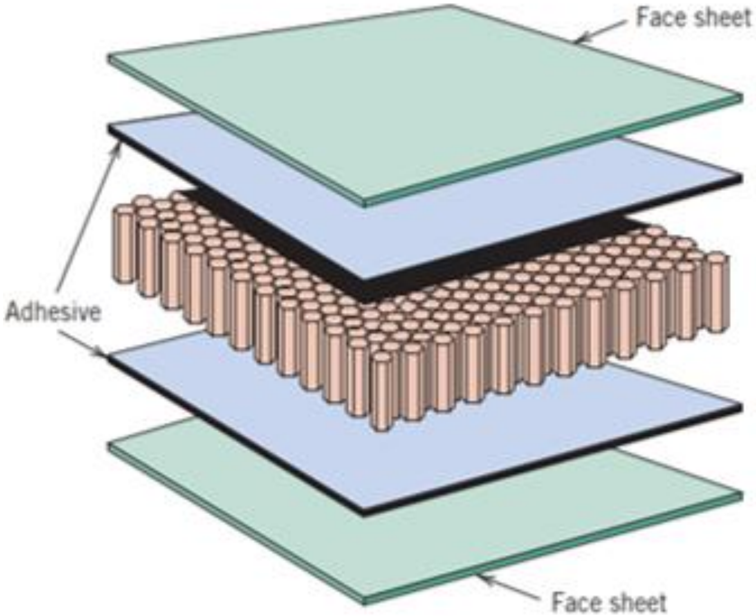
Conclusions

Understanding polymer and composite structures helps us to understand our component properties and performance

An overview of their typical classification, strengths and limitations of each type was presented

Specific examples of those materials use in accelerator complex has been provided





Thanks!

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[30] Influence of the Heat Treatment on the Layer J_C of Internal-Sn Nb_3Sn Wires With Internally Oxidized Nanoparticles, F. Lonardo et al. (2024)

Fiber-Reinforced Composites

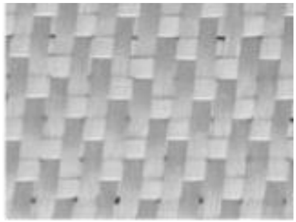
1D: Is the easiest fiber arrangement in a **unidirectional lamina** also called ply or layer → Maximum fiber volume fraction 60-70%

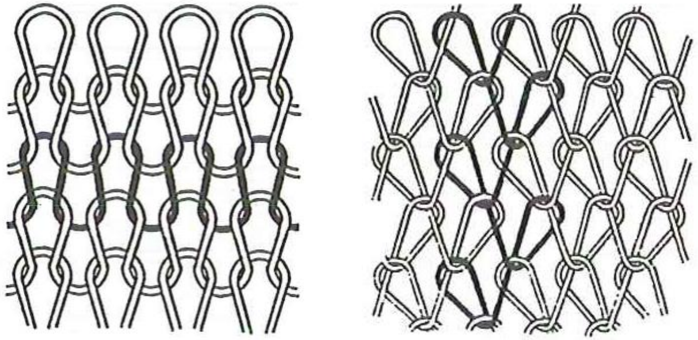
2D fabrics: Multidirectional laminates (built by stacking unidirectional lamina with different orientations and can provide quasi-isotropic properties)**,** woven fabrics, knit, braided, nonwovens (from a set of disordered fibers)

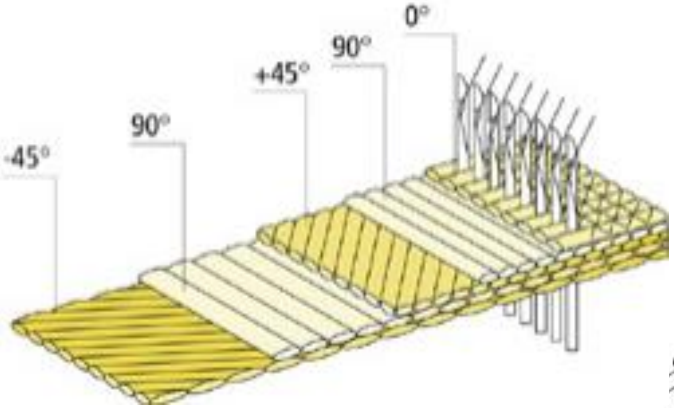
3D fabrics (woven fabrics, non-crimp fabrics, stitching)

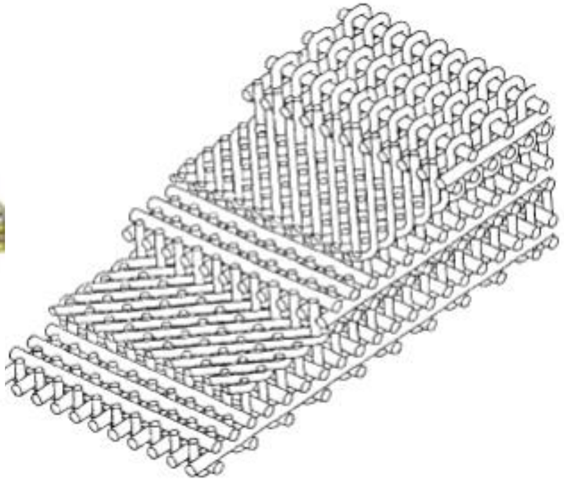

plain

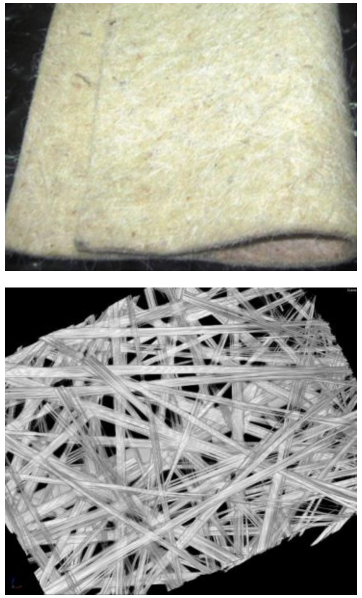

twill

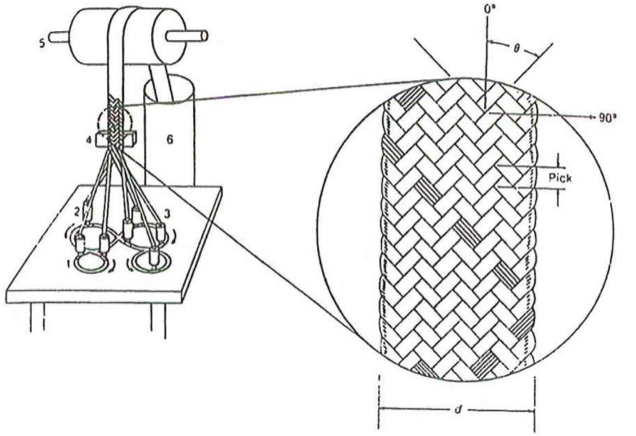

satin





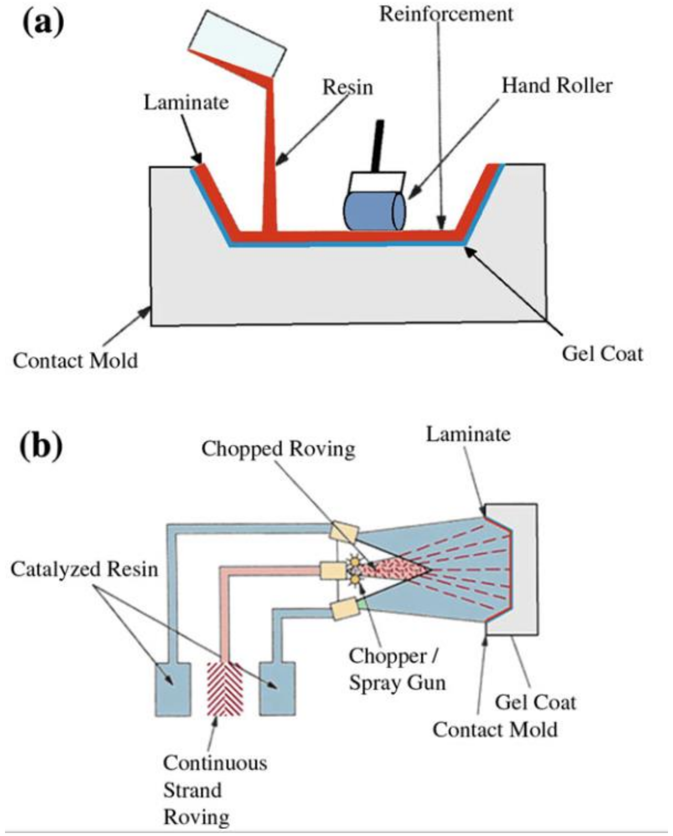




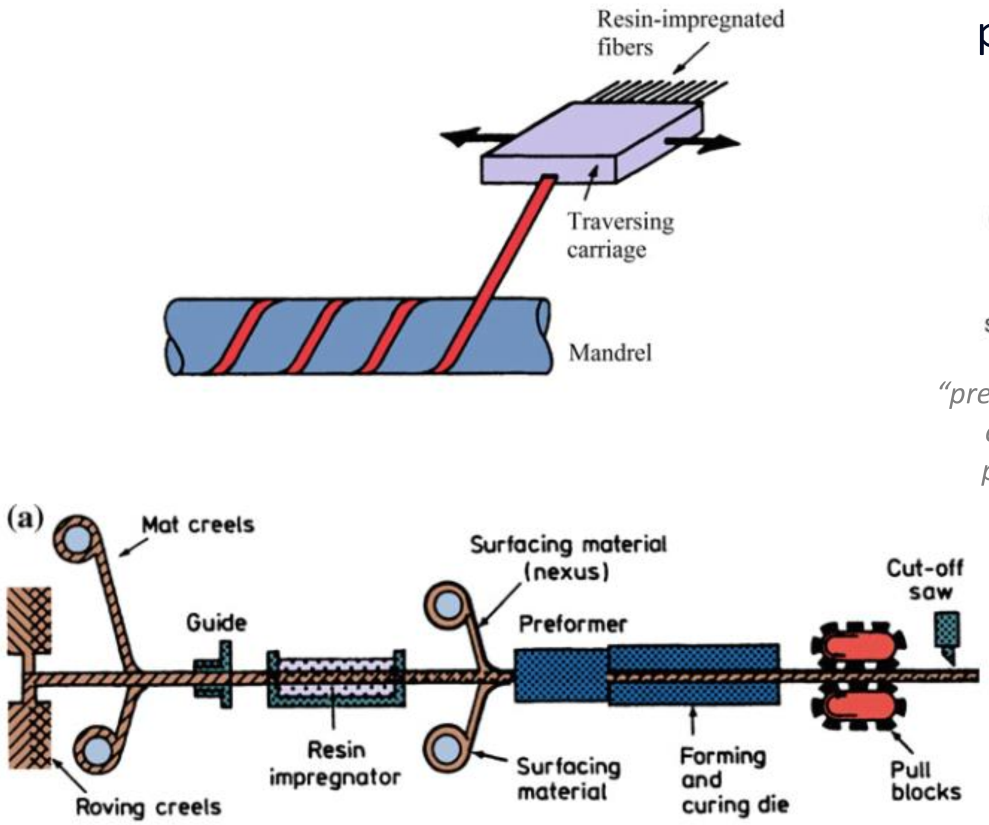


Polymer-Matrix Composites

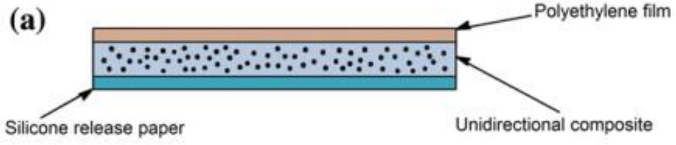
Autoclave or bag moulding processes → curing under (high) pressure and temperature → low content of air inclusions



a) In hand layup, fibers are laid onto a mould by hand, and the resin is sprayed or brushed on. b) In spray-up, resin and fibers (chopped) are sprayed together onto the mould surface [17]



Schematic of filament winding process (up) and schematic of the pultrusion process 9down) [17]



"prepreg" is thin sheet or lamina of unidirectional (or occasionally woven) fiber/polymer composite protected on both sides with easily removable separators

A large autoclave that is used to make the wings of Boeing 787