

Materials design and selection for circular economy

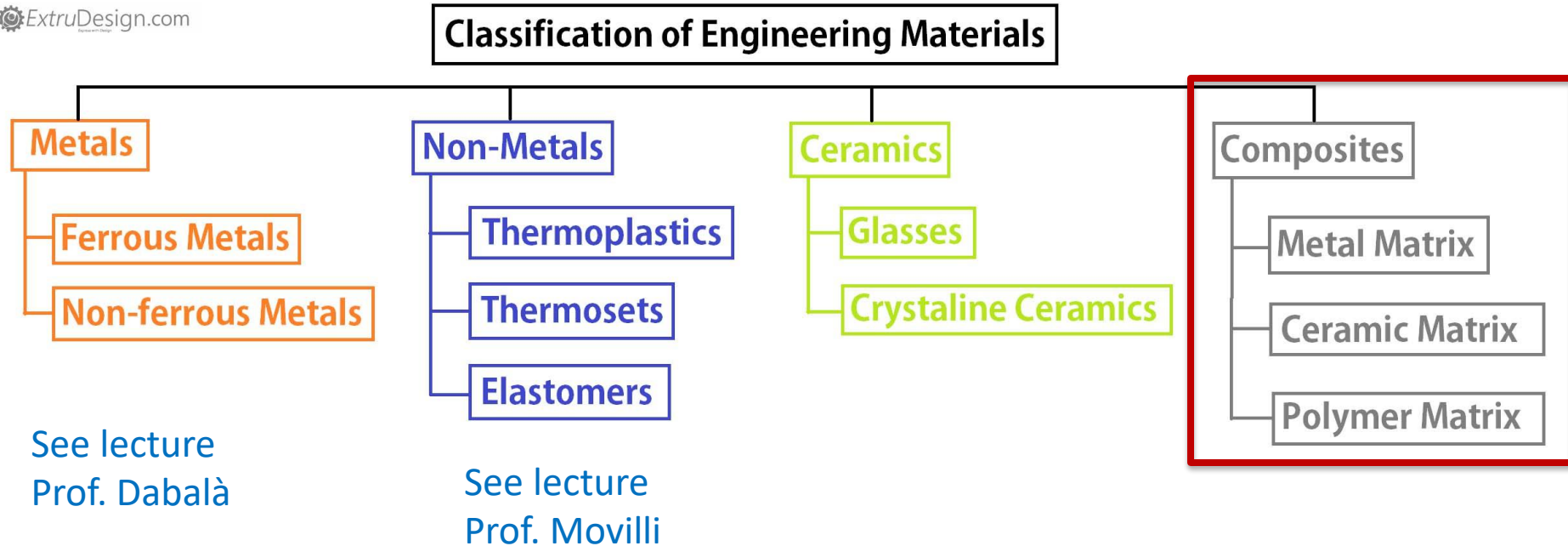
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Classification of materials



Source of the picture: <https://extrudesign.com/classification-of-materials-engineering-material-classification/>

Composites

Composites are considered to be **combinations** of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

COMPOSITE MATERIALS HANDBOOK, DoD, U.S. Government, MIL-HDBK-17-4, 1999

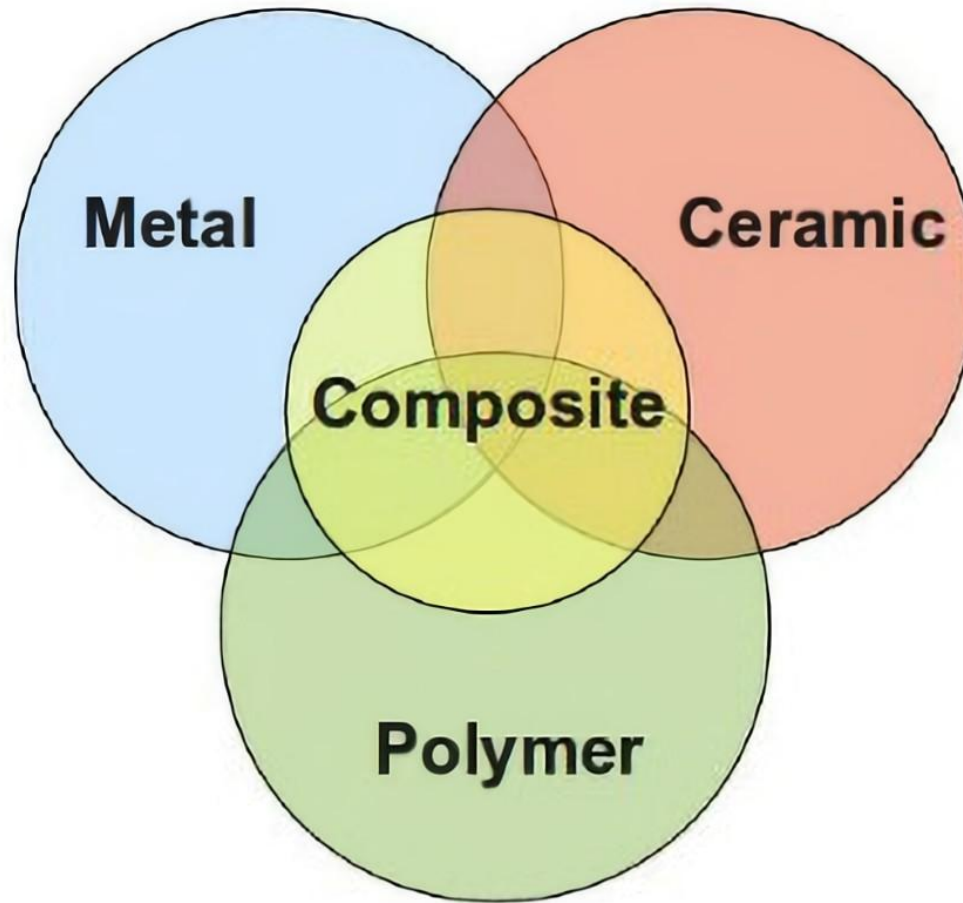
A composite material is defined in accordance with the ASTM D3878-15 Method as a substance **consisting of two or more materials**, insoluble in one another, which are combined with the aim to obtain a **useful engineering material** possessing certain properties not shown by the constituents taken separately.

https://link.springer.com/chapter/10.1007/978-3-319-58607-6_6

Composite is a material consisting of two or more distinct phases bonded together. This distinguishes composites from metal alloys in which constituents are dissolved in one another.

Comprehensive Composite Materials, Anthony Kelly and Carl Zweben, Editors-in-Chief, Pergamon Press, Elsevier Science, Oxford, 2000

Classification of composite materials



Source of the picture: Metallurgist

Composite/nanocomposite

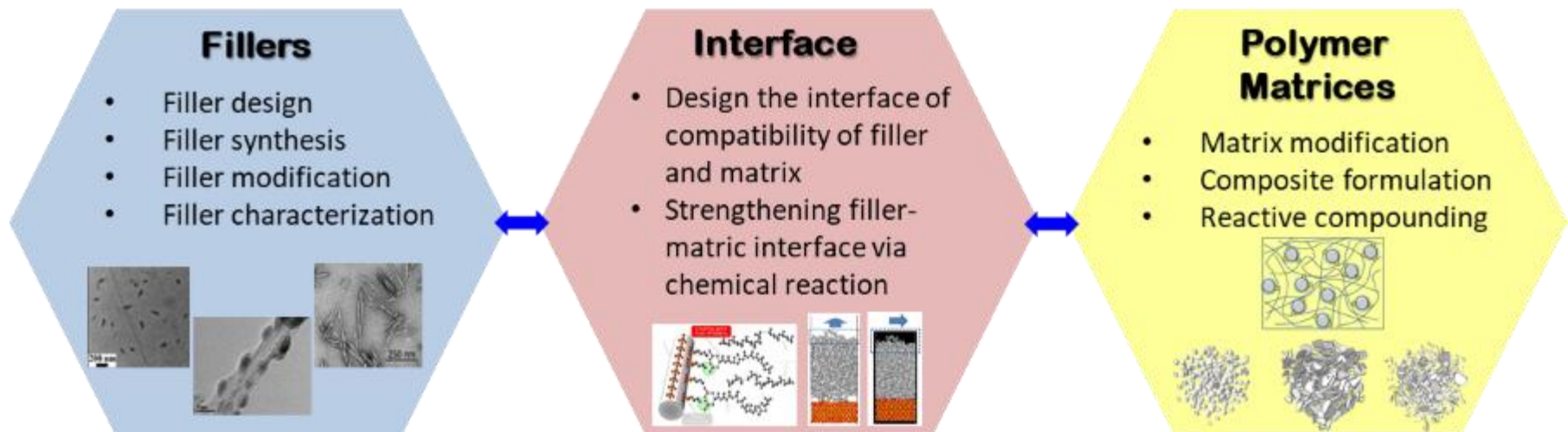
Nanocomposites

Nanocomposites are solid materials that have multiple phase domains and at least one of these domains has a **nanoscale** structure (i.e. 1-100 nm). The materials can have novel chemical and physical properties that depend on the morphology and interfacial characteristics of the component materials.

<https://www.nature.com/subjects/nanocomposites>

Degrees of freedom in composite production

- composition of the inorganic component (guest, filler)
- composition of the polymer host matrix (host, matrix)
- relative amount of the two (or more) components
- interactions at the interface (covalent, eletrostatic, van der Walls....)
- granulometry and morphology of the two components



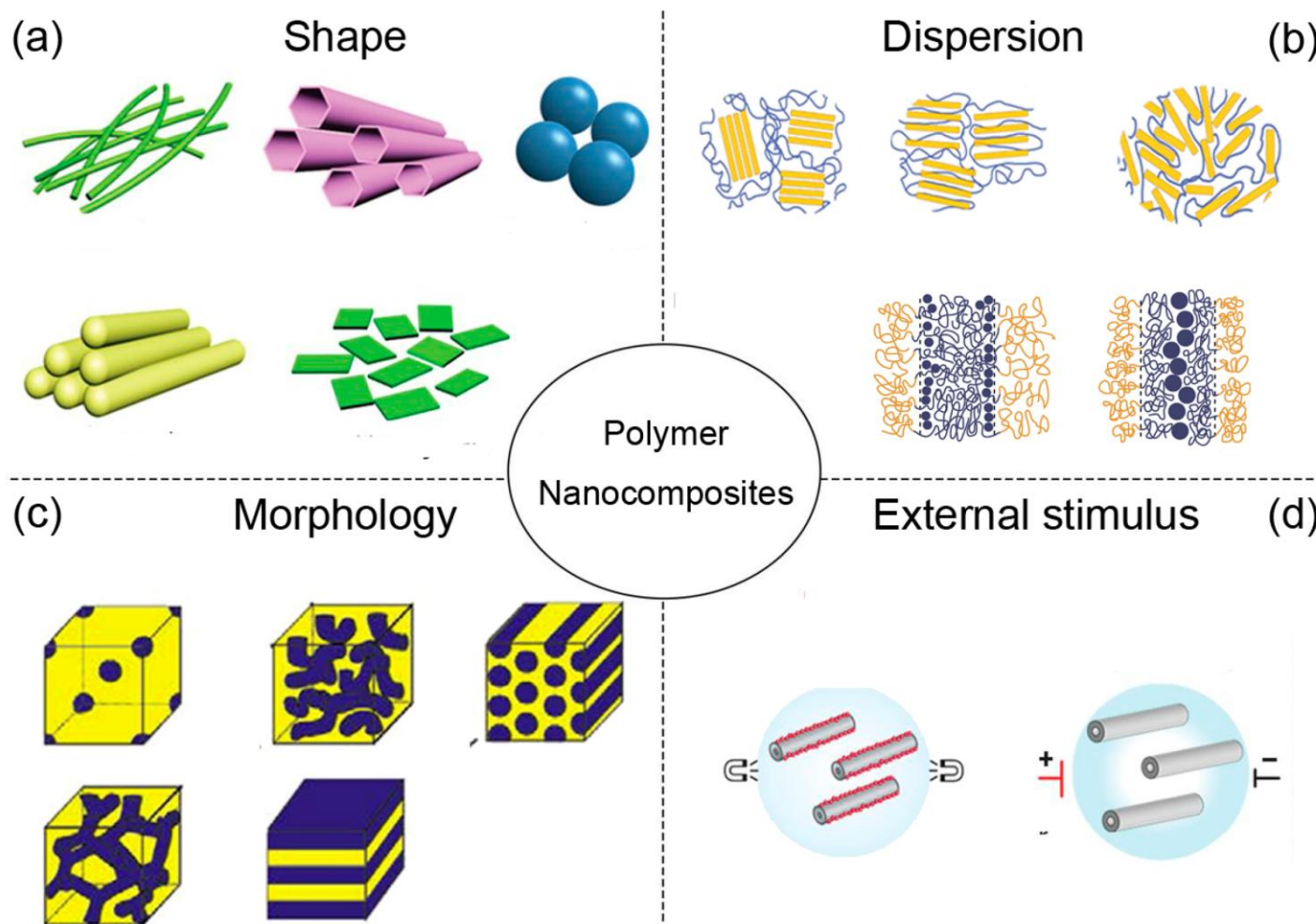
Source of the picture: <https://www.a-star.edu.sg/imre/research-departments/polymer-composite-department/advanced-composite-materials>

Degrees of freedom in composite production

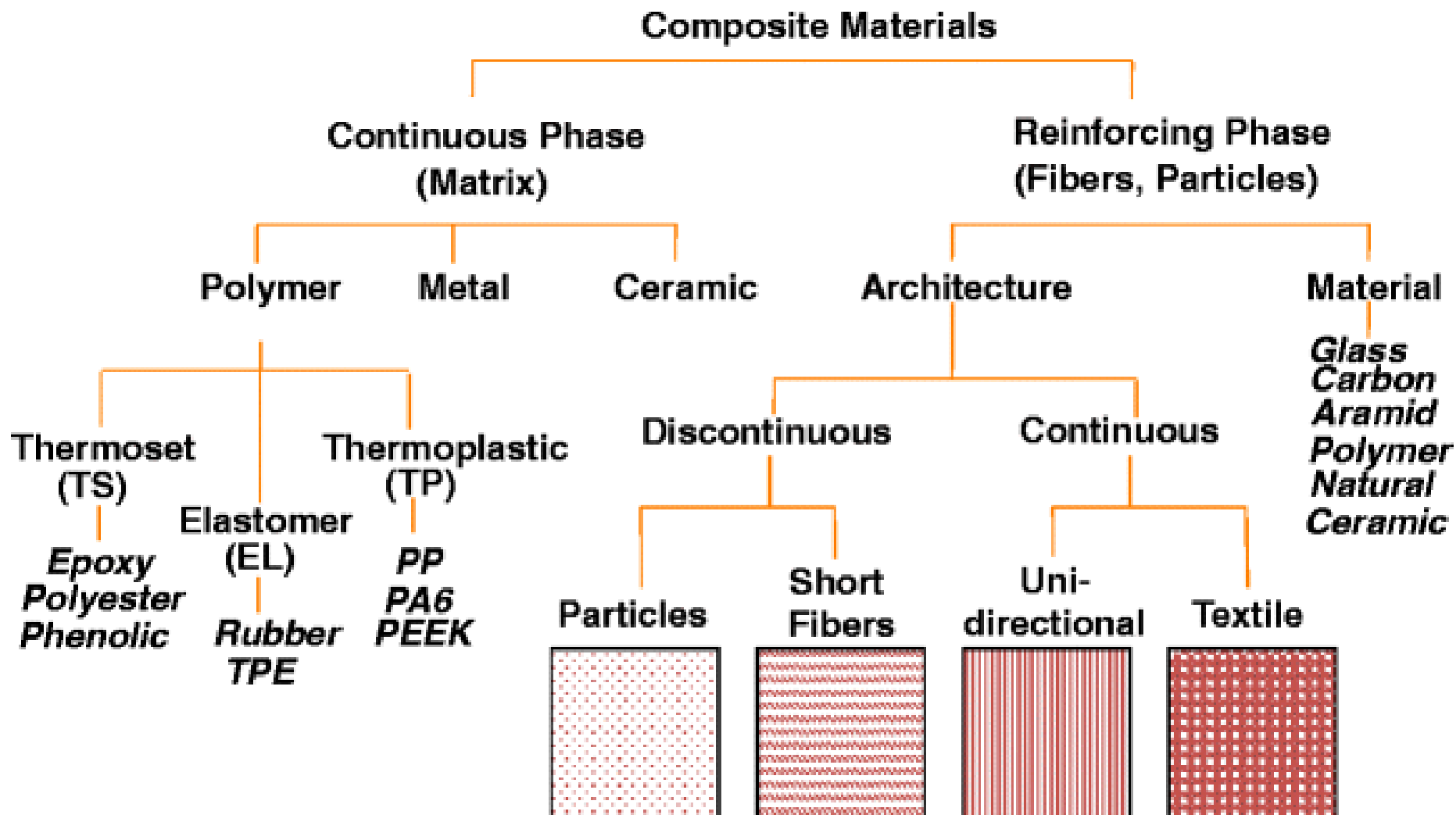
REINFORCEMENT	MATRIX			
	Polymer	Metal	Ceramic	Carbon
Polymer	X	X	X	X
Metal	X	X	X	X
Ceramic	X	X	X	X
Carbon	X		X	X

Degrees of freedom in composite production

Composite/nanocomposite

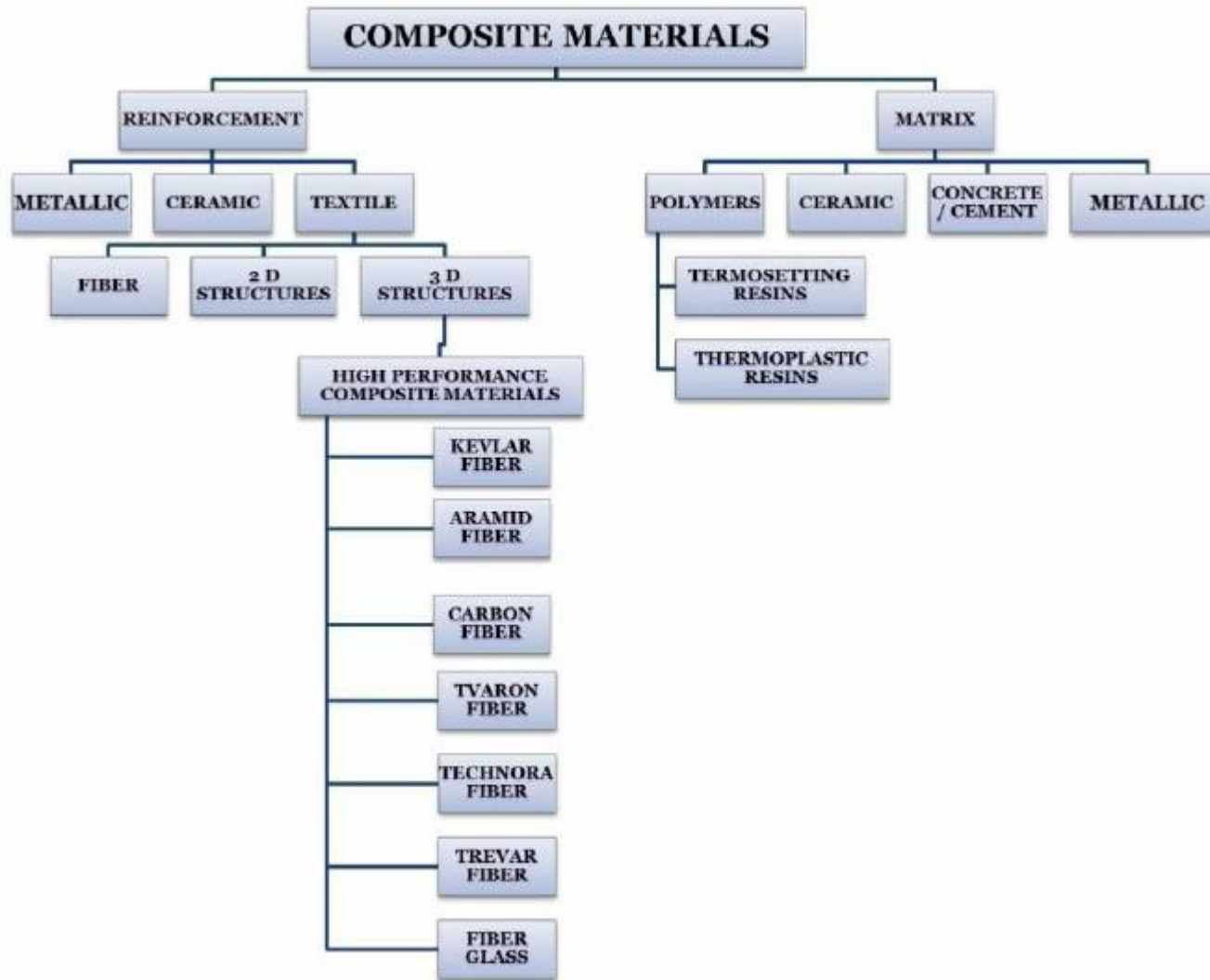


Degrees of freedom in composite production



Source of figure: Applied Composite Materials volume 20, 107–128 (2013)

Classification of composite materials



Source of the picture: Louisa, Ait & Kamel, Chaoui & Rachid, Chaib. (2015). Experimental Analysis of Cutting Tool's Wear Evolution.

Families of nanocomposites

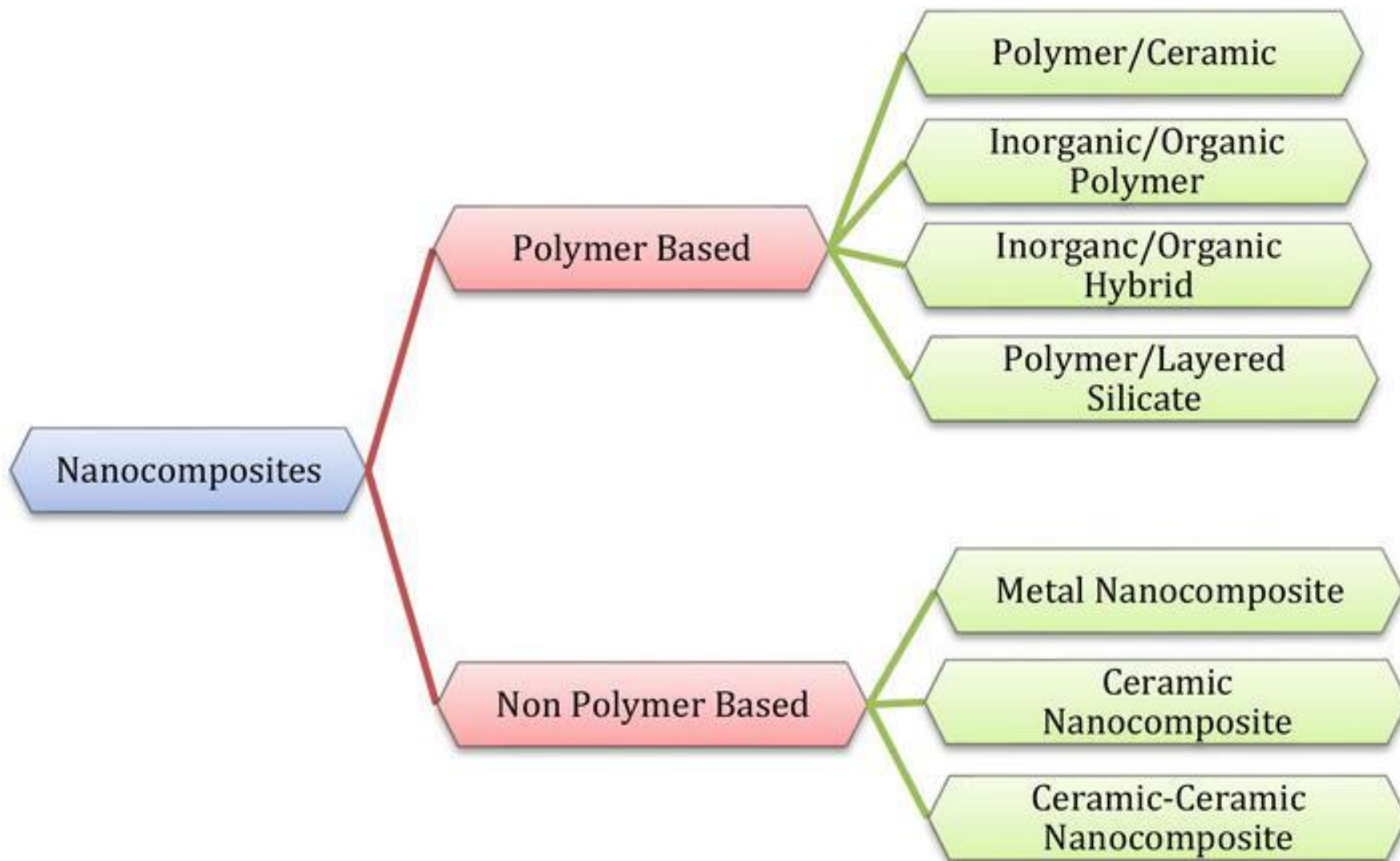


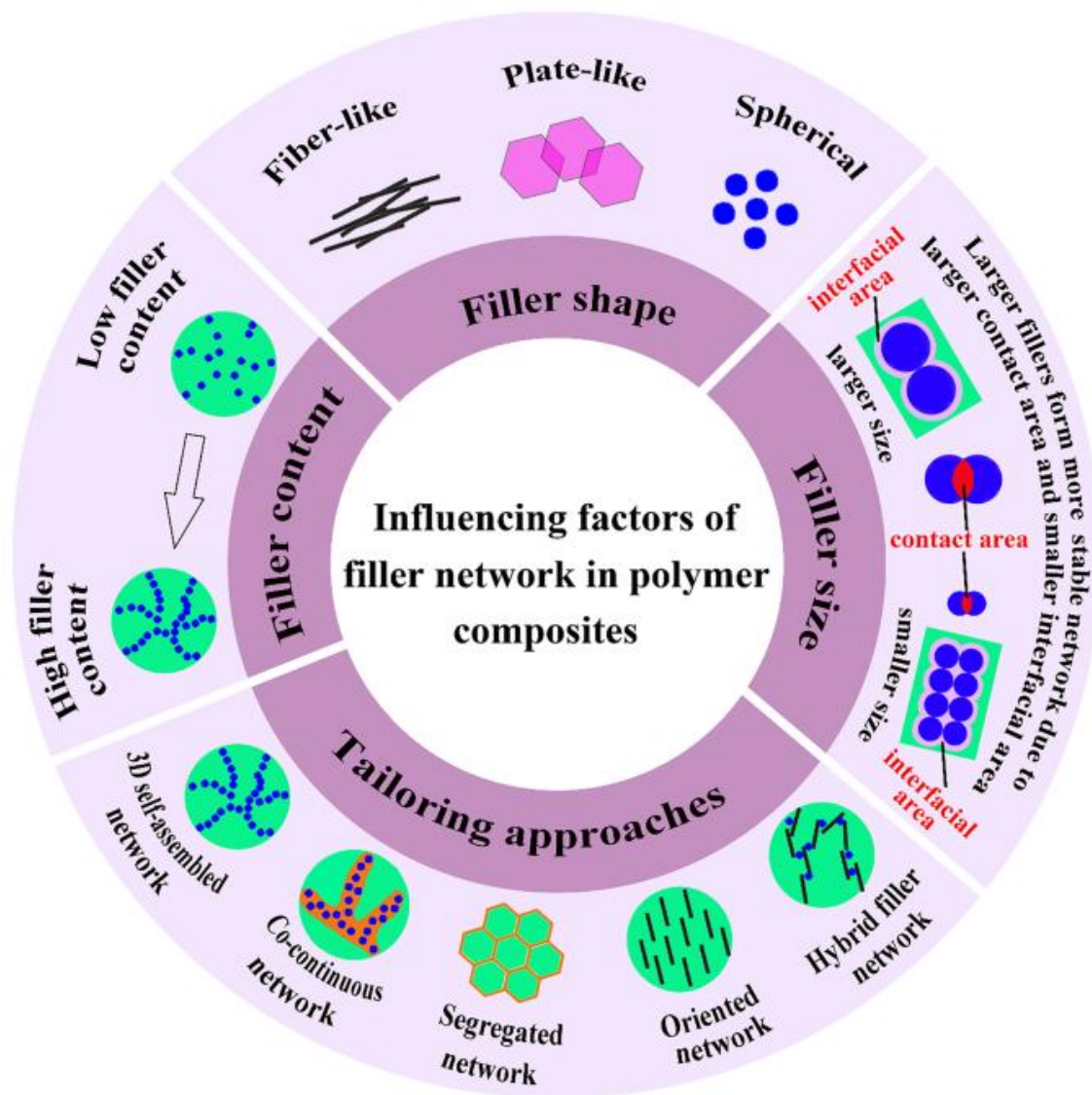
Table 4 Properties of Selected Thermosetting and Thermoplastic Matrices

	Density g/cm ³ (pci)	Modulus GPa (Msi)	Tensile Strength MPa (ksi)	Elongation to Break (%)	Thermal Conductivity W/m·K	Coefficient of Thermal Expansion ppm/K (ppm/°F)
Epoxy (1)	1.1–1.4 (0.040–0.050)	3–6 (0.43–0.88)	35–100 (5–15)	1–6	0.1	60 (33)
Thermosetting polyester (1)	1.2–1.5 (0.043–0.054)	2–4.5 (0.29–0.65)	40–90 (6–13)	2	0.2	100–200 (56–110)
Polypropylene (2)	0.90 (0.032)	1–4 (0.15–0.58)	25–38 (4–6)	>300	0.2	110 (61)
Nylon 6-6 (2)	1.14 (0.041)	1.4–2.8 (0.20–0.41)	60–75 (9–11)	40–80	0.2	90 (50)
Polycarbonate (2)	1.06–1.20 (0.038–0.043)	2.2–2.4 (0.32–0.35)	45–70 (7–10)	50–100	0.2	70 (39)
Polysulfone (2)	1.25 (0.045)	2.2 (0.32)	76 (11)	50–100	—	56 (31)
Polyetherimide (2)	1.27 (0.046)	3.3 (0.48)	110 (16)	60	—	62 (34)
Polyamideimide (2)	1.4 (0.050)	4.8 (0.7)	190 (28)	17	—	63 (35)
Polyphenylene sulfide (2)	1.36 (0.049)	3.8 (0.55)	65 (10)	4	—	54 (30)
Polyether etherketone (2)	1.26–1.32 (0.046–0.048)	3.6 (0.52)	93 (13)	50	—	47 (26)

Note: (1) = thermoset, (2) = thermoplastic.

Source of figure: Carl Zweben, Chapter 10 Composite Materials
Volume I. Materials and Engineering Mechanics, Part 1. Materials

Second component: filler

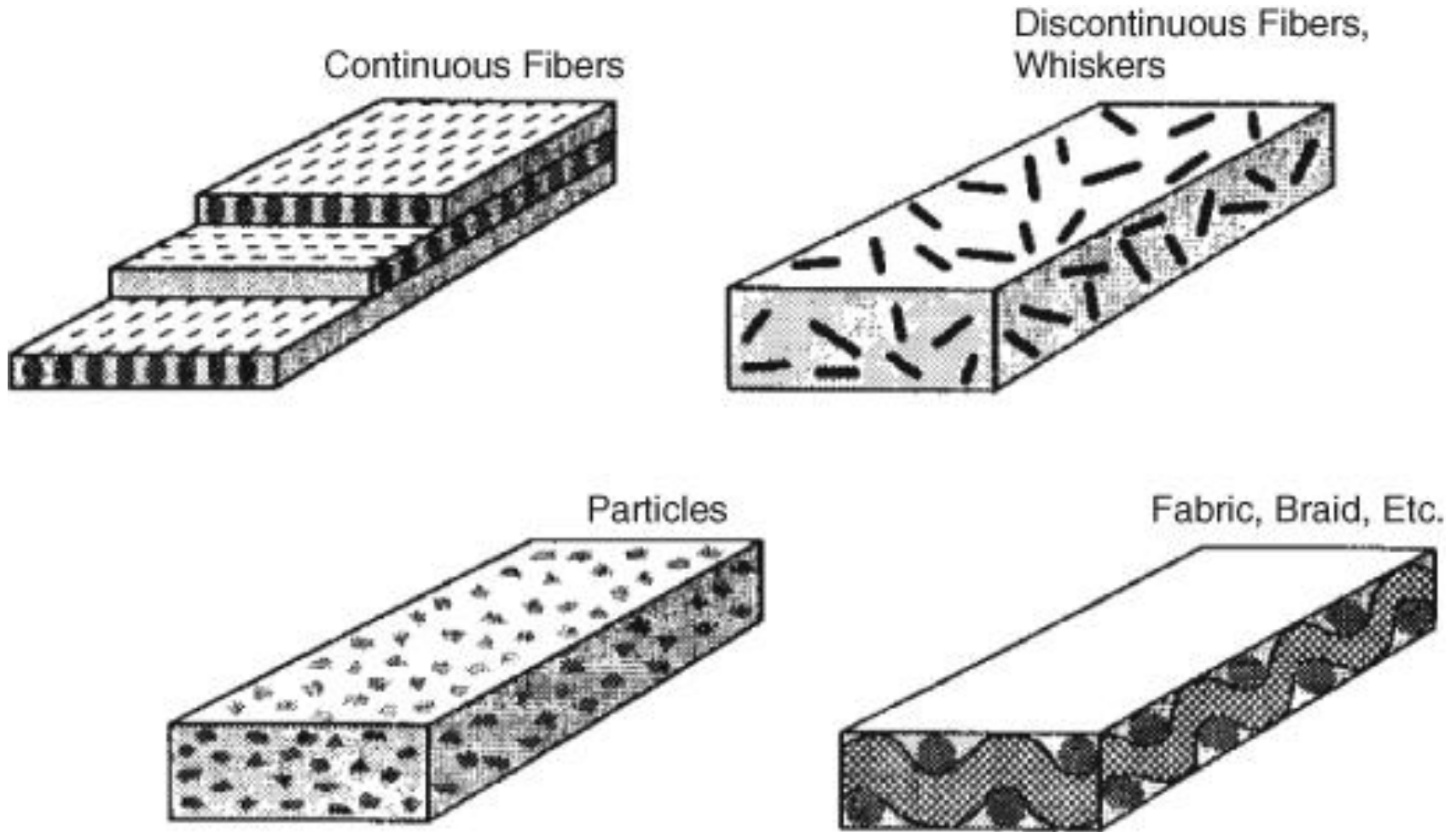


Source of the picture:

He, X., Ou, D., Wu, S. *et al.* A mini review on factors affecting network in thermally enhanced polymer composites: filler content, shape, size, and tailoring methods. *Adv Compos Hybrid Mater* **5**, 21–38 (2022).

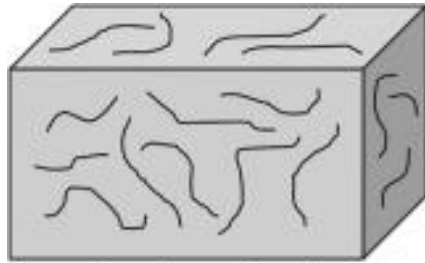
<https://doi.org/10.1007/s42114-021-00321-1>

Degrees of freedom in composite production



Source of figure: Carl Zweben, Chapter 10 Composite Materials
Volume I. Materials and Engineering Mechanics, Part 1. Materials

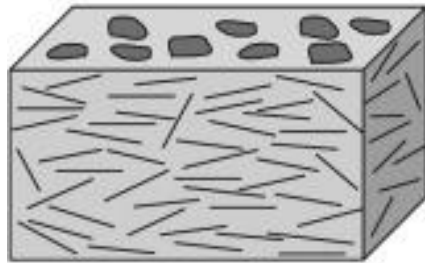
Second component: filler



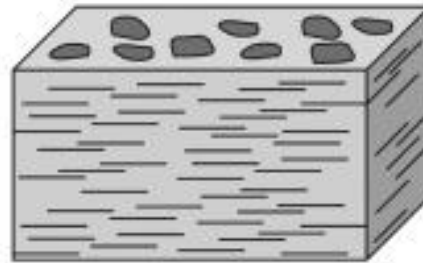
Random direction
Fiber composite



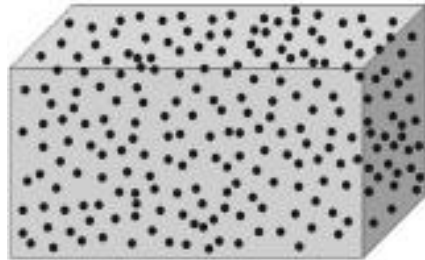
Aligned direction
Fiber composite



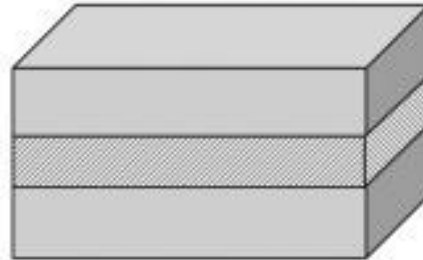
Random direction
Platelet composite



Aligned direction
Platelet composite



Particulate composite

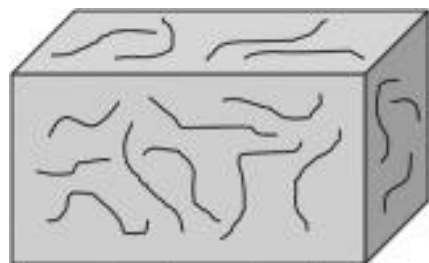


Laminate composite

Source of the picture:

Idrees, Humaira & Zohaib, Syed & Zaidi, Javaid & Sabir, Aneela & Khan, Rafi Ullah & Zhang, Xunli & Hassan, Sammer Ul. (2020). A Review of Biodegradable Natural Polymer-Based Nanoparticles for Drug Delivery Applications. *Nanomaterials*. 10. 1970.

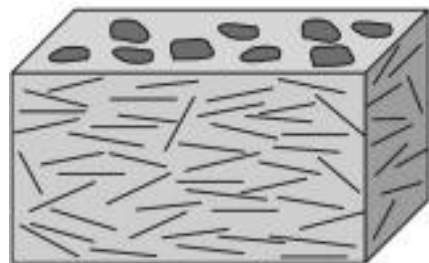
Second component: filler



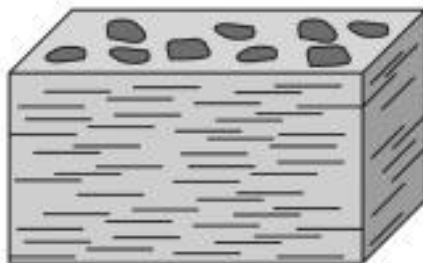
Random direction
Fiber composite



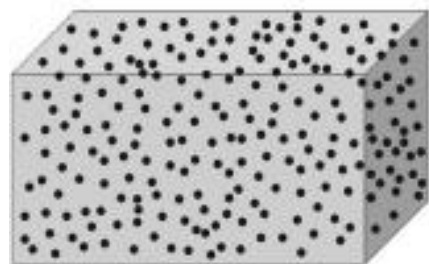
Aligned direction
Fiber composite



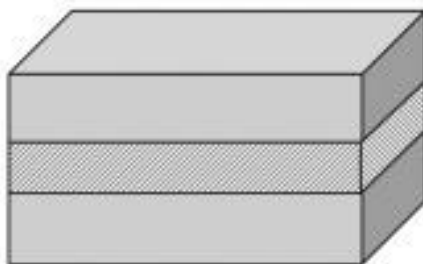
Random direction
Platelet composite



Aligned direction
Platelet composite



Particulate composite

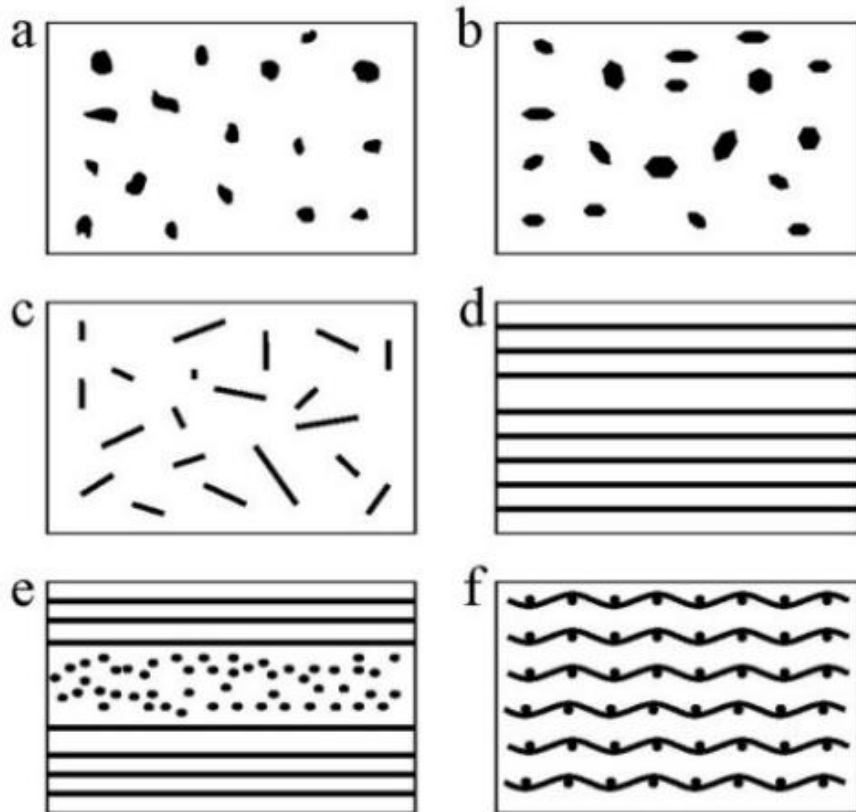


Laminate composite

Source of the picture:

Idrees, Humaira & Zohaib, Syed & Zaidi, Javaid & Sabir, Aneela & Khan, Rafi Ullah & Zhang, Xunli & Hassan, Sammer Ul. (2020). A Review of Biodegradable Natural Polymer-Based Nanoparticles for Drug Delivery Applications. *Nanomaterials*. 10. 1970.

Reinforcing fibers



Of the various reinforcement types, those based on continuous **fibers** provide the best mechanical properties, when loaded parallel to the fiber direction. **Particulate** systems, although locally heterogeneous in nature, remain predominantly isotropic in their physical and mechanical behavior. Short fiber systems are often planar isotropic. Continuous fiber systems exhibit considerable anisotropy, i.e. the **properties along the fiber direction are very different** from those perpendicular to the fiber direction.

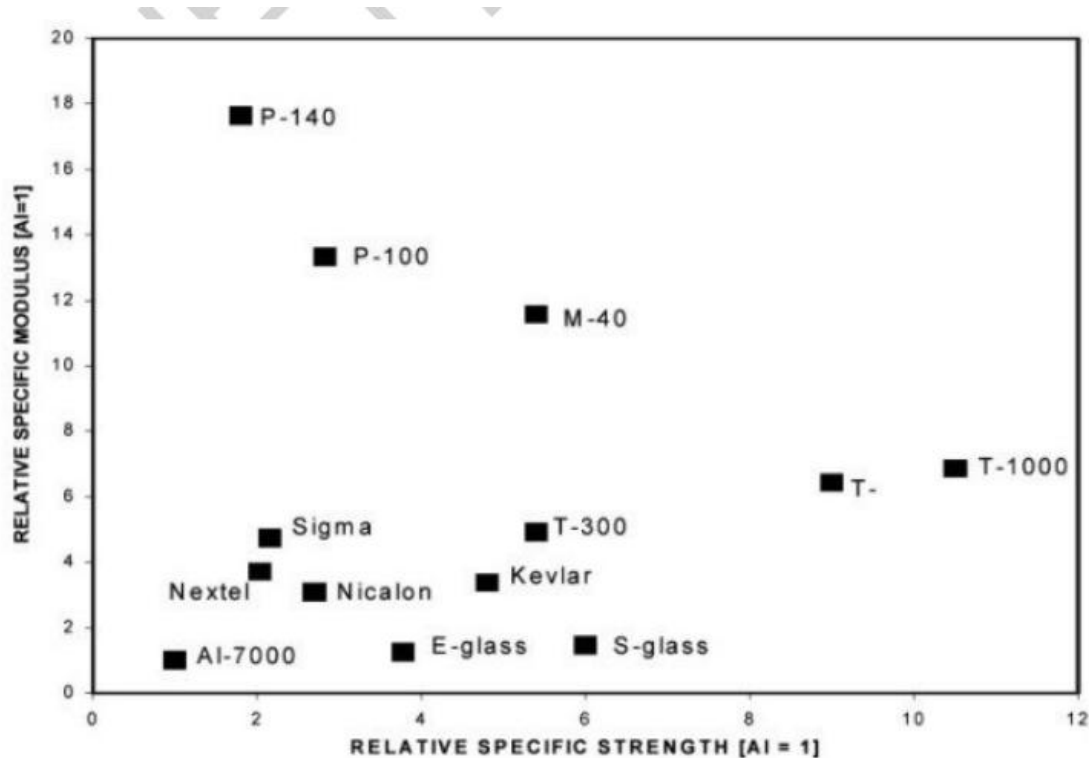
Schematic and not-to-scale diagrams showing the various formats available for the reinforcing phase: (a) particles, (b) platelets, (c) whiskers or short fibers, (d) unidirectional continuous fibers, (e) cross-ply continuous fibers and (f) woven tows of fibers. (a) to (d) show plan views while (e) and (f) are edge views. Source: MATERIALS SCIENCE AND ENGINEERING – Vol. II – Benefits of Fiber and Particulate Reinforcement - P.A.Smith and J.A.Yeomans

Table 2 Properties of Key Reinforcing Fibers

Fiber	Density g/cm ³ (pci)	Axial Modulus GPa (Msi)	Tensile Strength MPa (ksi)	Axial Coefficient of Thermal Expansion ppm/K (ppm/°F)	Axial Thermal Conductivity W/m·K
E-glass	2.6 (0.094)	70 (10)	2000 (300)	5 (2.8)	0.9
HS glass	2.5 (0.090)	83 (12)	4200 (650)	4.1 (2.3)	0.9
Aramid	1.4 (0.52)	124 (18)	3200 (500)	−5.2 (−2.9)	0.04
Boron	2.6 (0.094)	400 (58)	3600 (520)	4.5 (2.5)	—
SM carbon (PAN)	1.7 (0.061)	235 (34)	3200 (500)	−0.5 (−0.3)	9
UHM carbon (PAN)	1.9 (0.069)	590 (86)	3800 (550)	−1 (−0.6)	18
UHS carbon (PAN)	1.8 (0.065)	290 (42)	7000 (1000)	−1.5 (−0.8)	160
UHM carbon (pitch)	2.2 (0.079)	895 (130)	2200 (320)	−1.6 (−0.9)	640
UHK carbon (pitch)	2.2 (0.079)	830 (120)	2200 (320)	−1.6 (−0.9)	1100
SiC monofilament	3.0 (0.11)	400 (58)	3600 (520)	4.9 (2.7)	—
SiC multifilament	3.0 (0.11)	400 (58)	3100 (450)	—	—
Si–C–O	2.6 (0.094)	190 (28)	2900 (430)	3.9 (2.2)	1.4
Si–Ti–C–O	2.4 (0.087)	190 (27)	3300 (470)	3.1 (1.7)	—
Aluminum oxide	3.9 (0.14)	370 (54)	1900 (280)	7.9 (4.4)	—
High-density polyethylene	0.97 (0.035)	172 (25)	3000 (440)	—	—
Basalt	2.7 (0.099)	100 (15)	2900 (430)	5.5 (3.1)	1.7

Source of figure: Carl Zweben, Chapter 10 Composite Materials
Volume I. Materials and Engineering Mechanics, Part 1. Materials

First component: polymers



Plot of normalized specific modulus against normalized specific strength for a range of different fiber types (reference material is an aluminum alloy from the 7000 series - Al-7000). The data are for room temperature and may refer to a range of products with the general fiber specification.

Source: MATERIALS SCIENCE AND ENGINEERING – Vol. II – Benefits of Fiber and Particulate Reinforcement - P.A.Smith and J.A.Yeomans

Second component: filler

Different fillers assolve different functions:

- powdered metals (electrical and thermal conductivity)
- alumina, zirconia (thermal, mechanical reinforcement, abrasion resistance)
- silica (cost reduction, minor strength enhancement, reduction of wear rates)
- mica (electrical resistance)
- talc and calcium carbonate (cost reduction)
- barium sulfate (barites, density control)
- carbon and graphite powders (lubricity, electric conductivity)
- aluminum hydroxide (flame retardancy)
- glass fibers, rock fibers (thermal, mechanical reinforcement)

Second component: filler

- Reinforcing fillers can be added often in large amounts. Some plastics may contain as much as **60% wt. reinforcing fillers**.
- Frequently, **fibrous materials**, such as glass or carbon fibers, are added to resins to create reinforced grades with enhanced properties. For example, adding 30% short glass fibers by weight to nylon 6 improves creep resistance and increases stiffness by 300%. These glass-reinforced plastics usually suffer some loss of impact strength and ultimate elongation, and are more prone to warping because of the relatively large difference in mold shrinkage between the flow and cross-flow directions.
- Plastics with **non-fibrous fillers**, such as glass spheres or mineral powders, generally exhibit higher stiffness characteristics than unfilled resins, **but not as high as fiber reinforced grades**.
- Resins with **particulate fillers** are less likely to warp and show a decrease in mold shrinkage. Particulate fillers typically reduce shrinkage by a percentage roughly equal to the volume percentage of filler in the polymer, an advantage in tight tolerance molding.

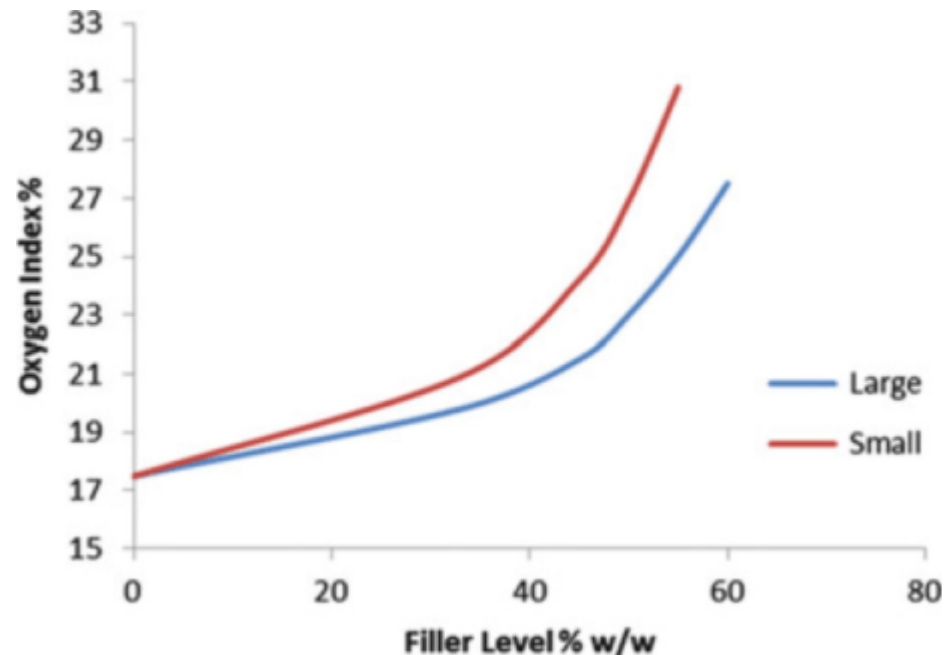
In depth: flame retardancy

Flame-retardant testing is a complex topic, but illustrative results showing the effect of adding aluminum hydroxide (ATH), a widely used flame-retardant fillers to a cross-linked PMMA matrix on a widely used test (oxygen index) are presented. **The higher the oxygen index, the more flame retardant a composite is** and the results show that:

- ATH is an effective flame retardant (water release).
- High levels are needed to achieve a significant effect.
- There is a small particle size effect, with smaller sizes giving better results.

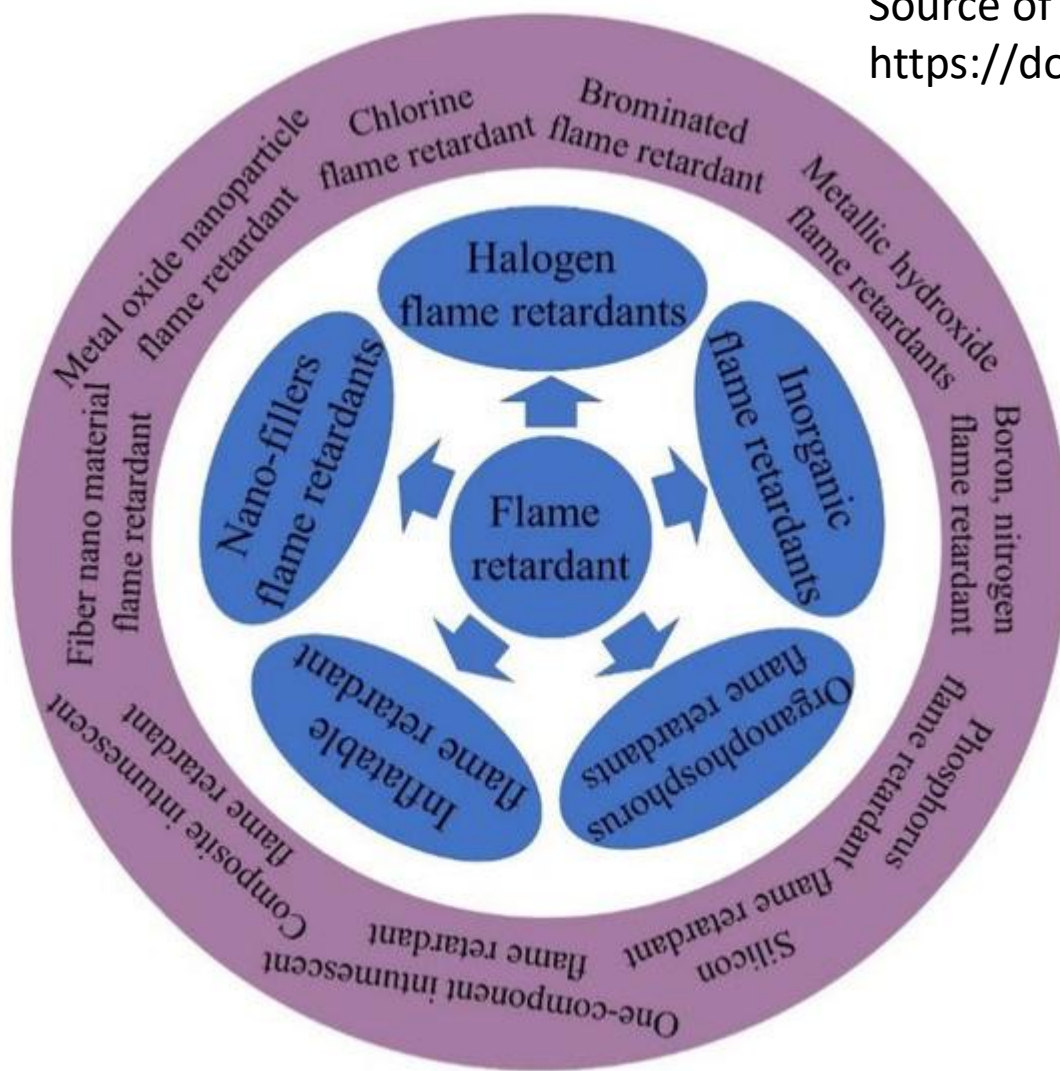
One of the main reasons for using ATH as a flame retardant is that, unlike some other systems (notably halogens) it gives low smoke levels when the composite burns. This is important in many applications in construction and transport, where smoke can seriously affect escape times.

Source of figure:
https://ebrary.net/66580/education/flame_retardancy



In depth: flame retardancy

Source of the figure: Polymers 2022, 14(1), 82;
<https://doi.org/10.3390/polym14010082>



Limiting Oxygen Index

Limiting oxygen index (LOI) is defined as the minimum amount of oxygen in a nitrogen–oxygen mixture (in vol%) required to sustain flaming combustion of a material.

The LOI is a fire reaction property used to quantify the **flammability of organic polymers** and composite materials. The LOI is defined as the minimum percentage of oxygen needed to sustain flaming combustion.

The test procedure, which was first proposed by Fenimore and Martin and is governed by standards ASTM D2863 and ISO 4589, consists of placing a sample vertically within a glass cylinder with a stream of air (nitrogen-oxygen mixture) flowing upwards, igniting the top edge of the sample, and gradually decreasing the oxygen concentration until burning stops; the oxygen concentration at which burning stops is the limiting oxygen index (LOI).

Higher LOI values indicate lower flammability and better flame retardance.

An LOI of 21% has a practical significance: the oxygen concentration in air is approximately 21 vol%, so materials with lower indexes are readily combustible, while those with higher values do not burn under ambient conditions without an external source of energy.

From: Bio-Based Flame-retardant Technology for Polymeric Materials, 2022

<https://www.youtube.com/watch?v=OAZBa2EL7yQ>

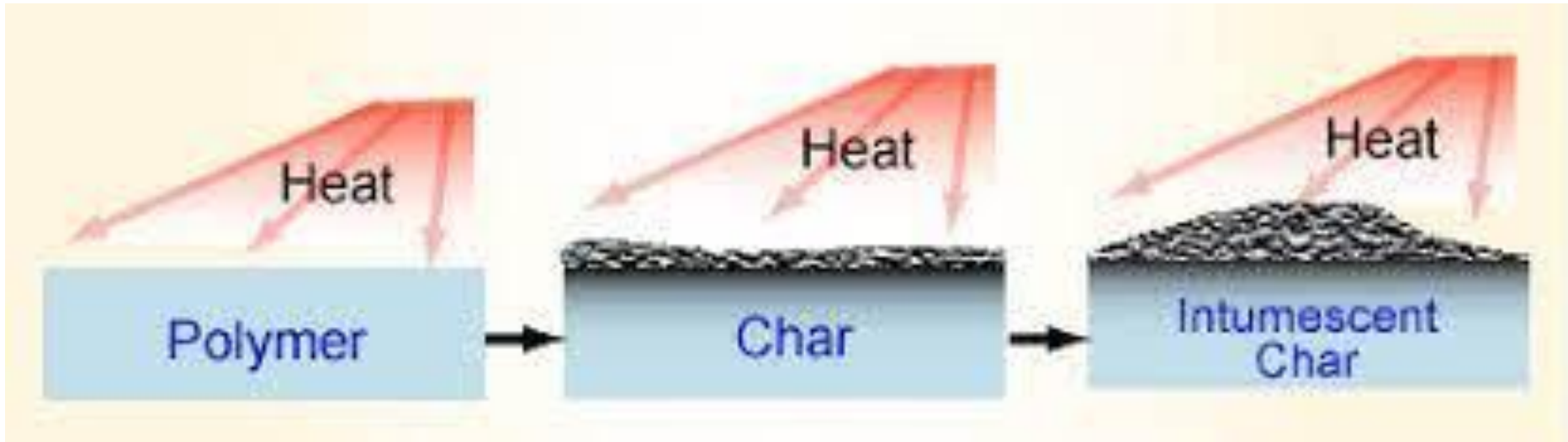
MECHANISM OF ACTION OF FLAME RETARDANTS

Flame retardants are generally designed to provide a particular level of resistance to ignition or flame spread. This is achieved **by suppressing oxygen availability**, building up of **char** at the surface, inhibiting the combustion reaction within the flame area, or by other mechanisms:

- The endothermic decomposition of aluminum hydroxide primarily leads to the cooling of polymer and the formation of a **protective and refractory layer of aluminum oxide**.
- The formation of water vapour decreases the oxygen concentration near the surface, hindering the combustion reaction.
- Simple and high volume fire retardant additives are hydroxides of aluminum and magnesium. Upon decomposition, they remove heat and release water vapor due to their endothermic nature.
- Large amounts of these additives are needed to achieve the desired effect.
- Major disadvantages of inorganic FRs are their relatively low decomposition temperature and requirement of a large fraction of material to give sufficient flame retardant performance in most polymers.

MECHANISM OF ACTION OF FLAME RETARDANTS

Source of figure: <http://fr.polymerinsights.com/home/mechanisims>



[Intumescence](https://www.sciencedirect.com/topics/chemical-engineering/intumescent-material) can be described as fire-retardant technology which causes an otherwise flammable material to foam, forming an insulating barrier when exposed to heat. A common characteristic of intumescent materials is that heat exposure initiates a chemical process that makes the material intumesce. It is the intumesced and porous part of the material which gives the insulation effect. <https://www.sciencedirect.com/topics/chemical-engineering/intumescent-material>

Intumescent coatings

Intumescent coatings were first reviewed in 1970s and primarily applied to paint. Intumescent materials provide a **thick fire protection layer by a decomposition process at high temperatures**, which causes the material **to swell into a thermally stable char layer**. Intumescent coatings have an appearance similar to paint and consist of combinations of different products such as:

- an inorganic acid source which releases an organic acid when heated,
- a binder which leaves a thick liquid, and
- a blowing agent (spumific) compound which releases non-flammable gases.

These compounds undergo a series of decomposition mechanisms and physical processes. The flame retardancy of intumescent coatings occurs by:

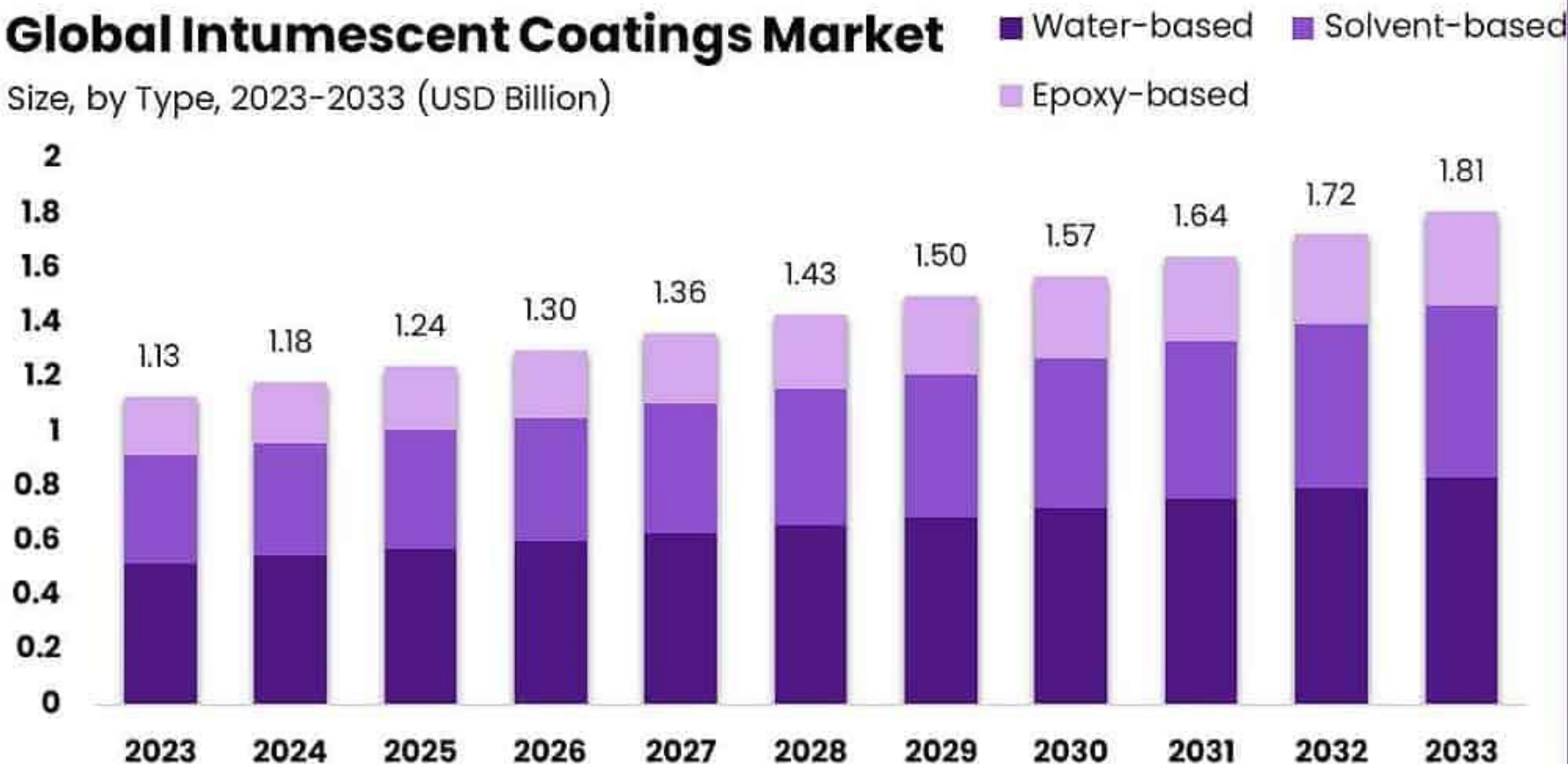
- the inorganic acid releasing the acid between 150 °C and 250 °C,
- esterification of carbon rich compounds at higher temperatures (above the acid-release temperature),
- melting of the materials during esterification,
- **carbonizing the material into foam due to the released gases of the above reactions and**
- foam strengthening and solidifying through gelation.

The majority of intumescent coatings use zinc borate, ammonium phosphate, melamine phosphate, and organic esters as the acid source. Blowing agents are generally nitrogen compounds such as urea, melamine, and guanidine. Intumescent coating systems are mostly based on ammonium polyphosphate (acid source) melamine and its derivatives (as blowing agent) and pentaerythritol derivatives are often used as char forming agents.

Intumescent coatings

Global Intumescent Coatings Market

Size, by Type, 2023-2033 (USD Billion)



The Market will Grow
At the CAGR of:

4.8%

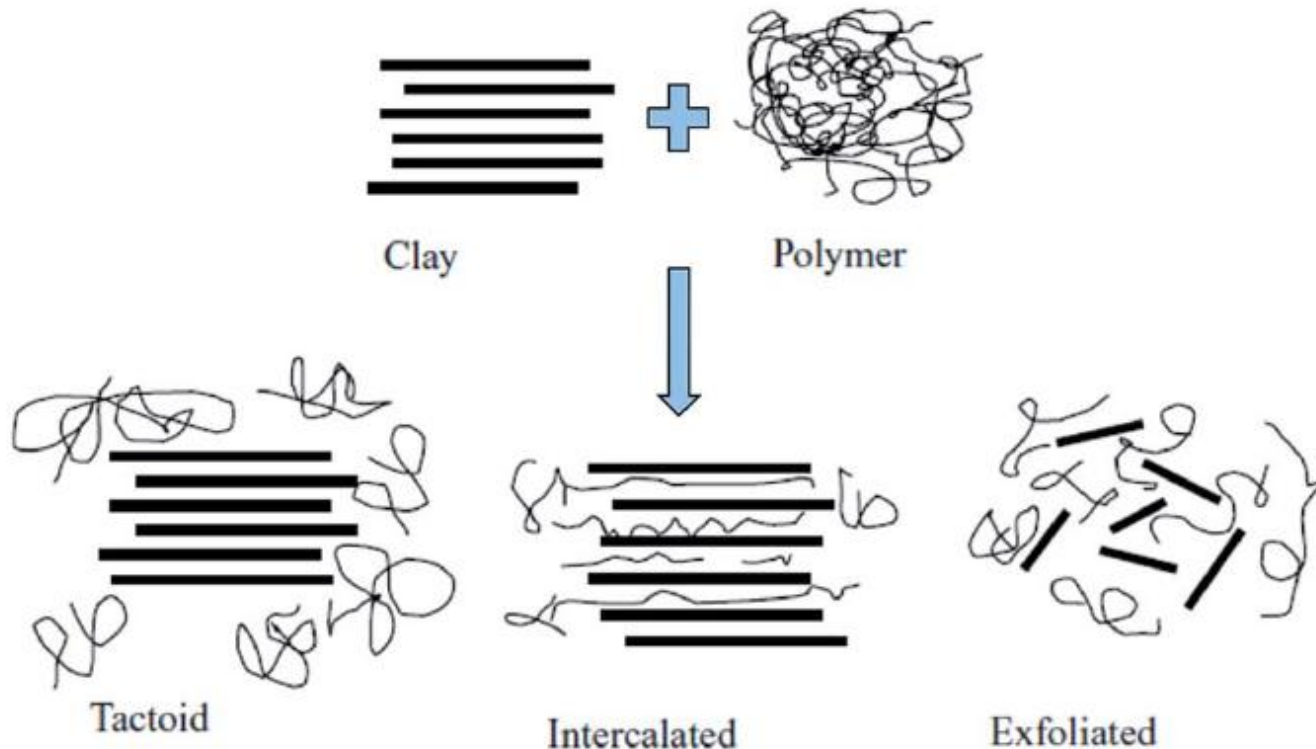
The Forecasted Market
Size for 2033 in USD:

\$1.81B

 **market.us**
ONE STOP SHOP FOR THE REPORTS

<https://market.us/report/intumescent-coatings-market/>

Clays as polymers fillers



Key challenge is to obtain an effective dispersion and exfoliation of the nanofillers in the polymer matrix to yield well aligned high aspect ratio particles for mechanical reinforcement and/or a **tortuous diffusion pathway for improved barrier properties**. Source of the figure: Gas barrier properties of polymer/clay nanocomposites, RSC Adv., 2015, 5, 63669–63690

Clays as polymers fillers

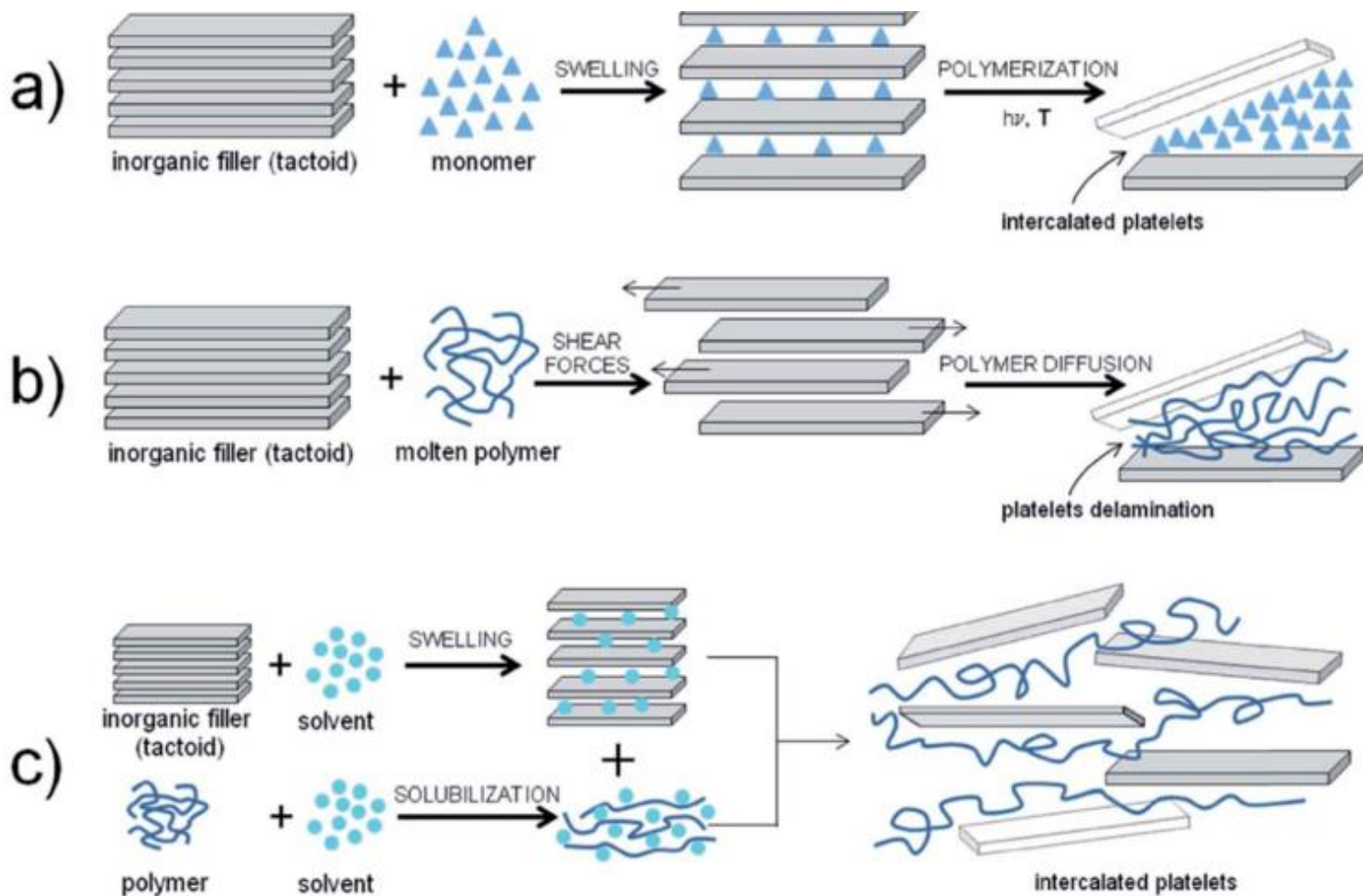
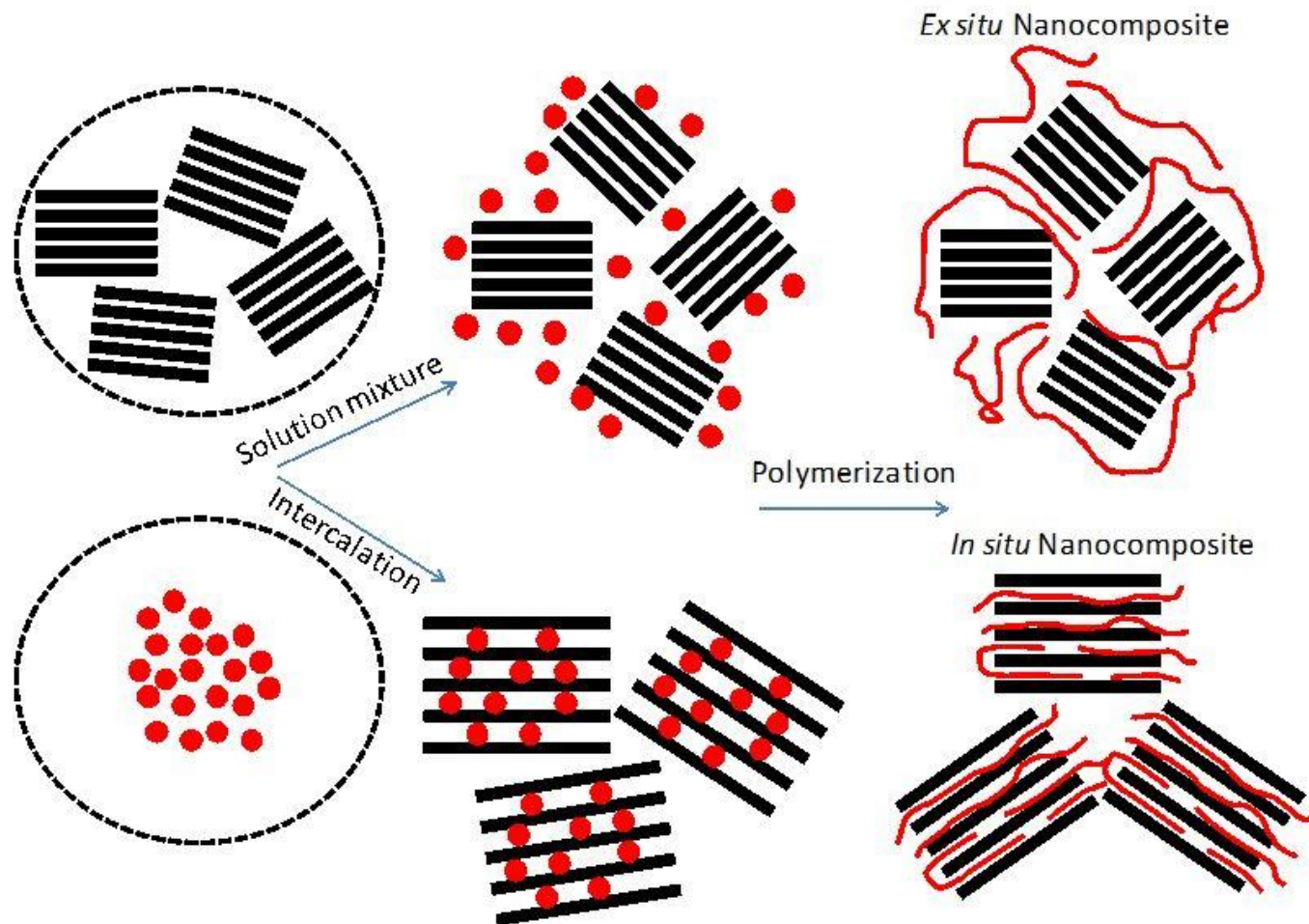


Illustration of (a) in situ polymerization, (b) melt intercalation, (c) solution intercalation

Source of the figure: Gas barrier properties of polymer/clay nanocomposites, RSC Adv., 2015, 5, 63669–63690

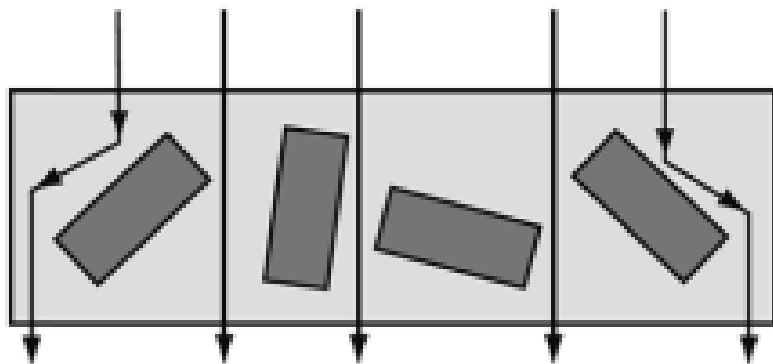
Polymer-clays composite materials



Source of the picture: Nascimento, G. M. D. . Structure of Clays and Polymer–Clay Composites Studied by X-ray Absorption Spectroscopies. In: Nascimento, G. M. d. , editor. Clays, Clay Minerals and Ceramic Materials Based on Clay Minerals [Internet]. London: IntechOpen; 2016

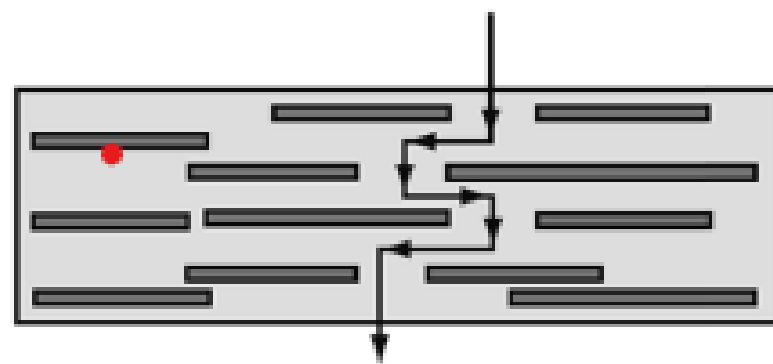
Clays as polymers fillers

Conventional composites



(a)

“Tortuous path” in polymer/clay nanocomposites



(b)

“Tortuous diffusion path” in polymer/clay nanocomposite. The nanoplatelets do not allow diffusion of small gases through them and are able to produce a tortuous path which works as a barrier structure for gases

Source of the figure: Gas barrier properties of polymer/clay nanocomposites, RSC Adv., 2015, 5, 63669–63690

Table 1 Gas permeability of polymer/clay nanocomposites

Polymer	Types of clay	Filler loading	Processing ^a	Permeant	Permeability (m ² s ⁻¹ Pa ⁻¹)	Reduction
SBR ¹⁸	O-MMT, CF	16 phr	Melt	O ₂	2.75×10^{-17}	46%
PLA ¹²⁰	O-MMT	7.9 wt%	Melt	O ₂	2.85×10^{-18}	24%
				He	6.79×10^{-17}	23%
PLA, PLA/PCL ¹²¹	O-MMT	3 wt%	Melt	O ₂	6.39×10^{-19}	26%
PA ¹²²	MMT	3 wt%	Melt	O ₂	3.37×10^{-19}	14%
				CO ₂	1.33×10^{-18}	13%
PET ¹²³	O-MMT	5 wt%	Melt	O ₂	1.69×10^{-19}	55%
PET ¹²⁴	O-MMT	5 wt%	Melt	O ₂	2.74×10^{-19}	69%
PET ¹²⁵	O-MMT	1 wt%	Melt	O ₂	1.42×10^{-17}	45%
PS ¹²⁶	O-MMT	2 wt%	Melt	O ₂	N/A	66%
PP ¹²⁷	O-MMT	4 vol%	Melt	O ₂	4.18×10^{-18}	46%
PP ¹²⁸	O-MMT	7.5 wt%	Melt	O ₂	2.59×10^{-15}	56%
PP ¹²⁹	MMT, O-MMT	5 wt%	Melt	O ₂	$\sim 6.00 \times 10^{-18}$	77%
				He	$\sim 2.25 \times 10^{-17}$	39%
				N ₂	$\sim 2.25 \times 10^{-18}$	89%

- permeability is a critical performance issue in many areas such as, packaging, construction, water, gas transportation, electronics, aerospace, etc.
- a limiting property of polymeric materials in food packaging is their **inherent permeability to gases and vapors**, including oxygen, carbon dioxide, and organic vapors.
- the penetration of gas into polymer films has a critical effect on their service performance.
- barrier polymers** have become more and more important in many packaging and protective applications, such as food industry, pharmaceuticals and electronic devices (e.g., flexible displays).

Permeability is **the rate at which gases can pass through a material**

Gas transmission rate (GTR) through a polymer material can be described as follows:

$$J = \frac{-D \cdot S(p_1 - p_2)}{t}$$

where:

J is gas transmission rate, in other words, the flux through the sample

D is the diffusion coefficient

S is the solubility of the gas in the material

t is the thickness of the sample

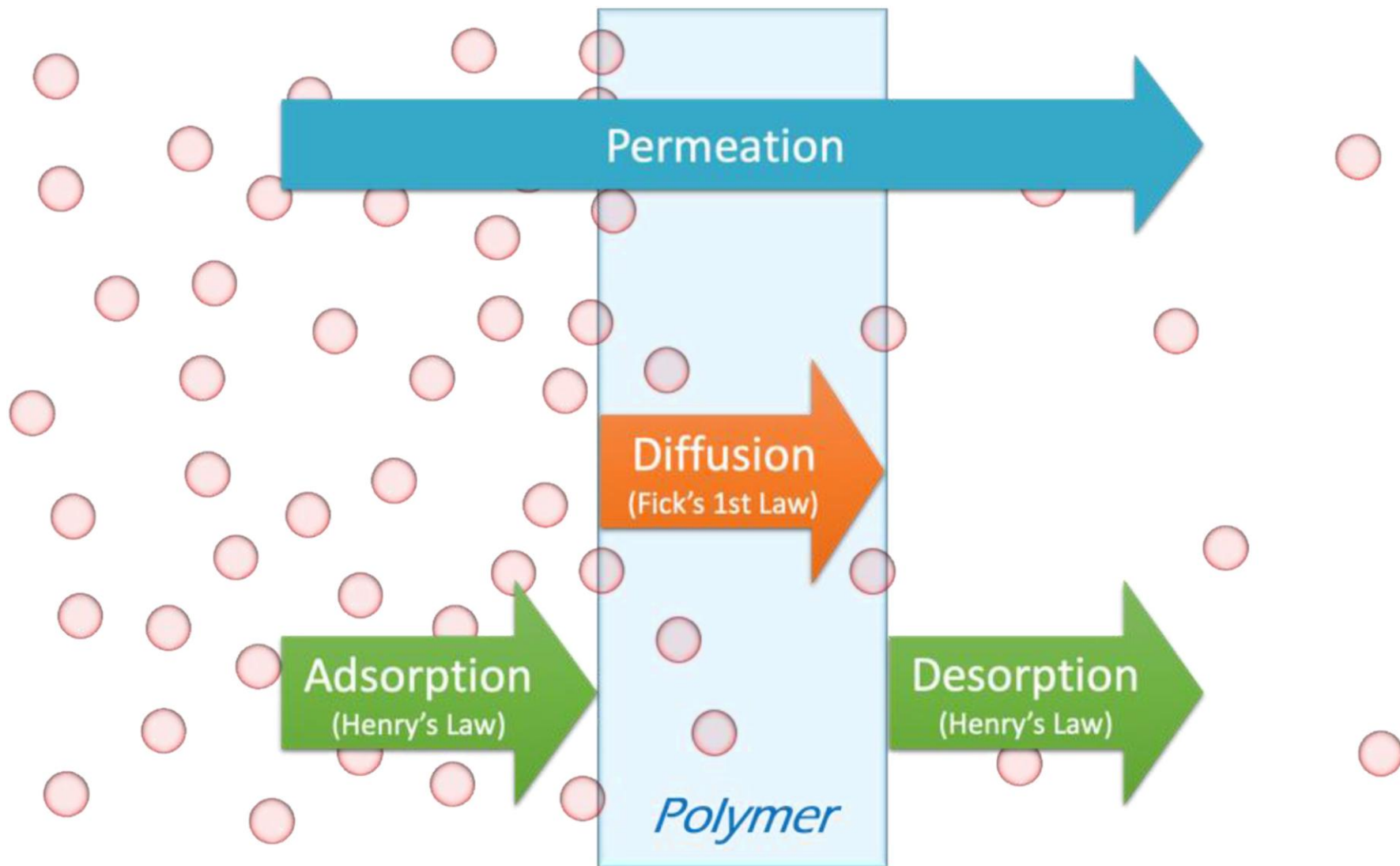
p_1 and p_2 are the pressure or concentration of gas or liquid on each side of the membrane.

When we flow nitrogen continuously over one side of the membrane, the concentration on this side is equal to zero.

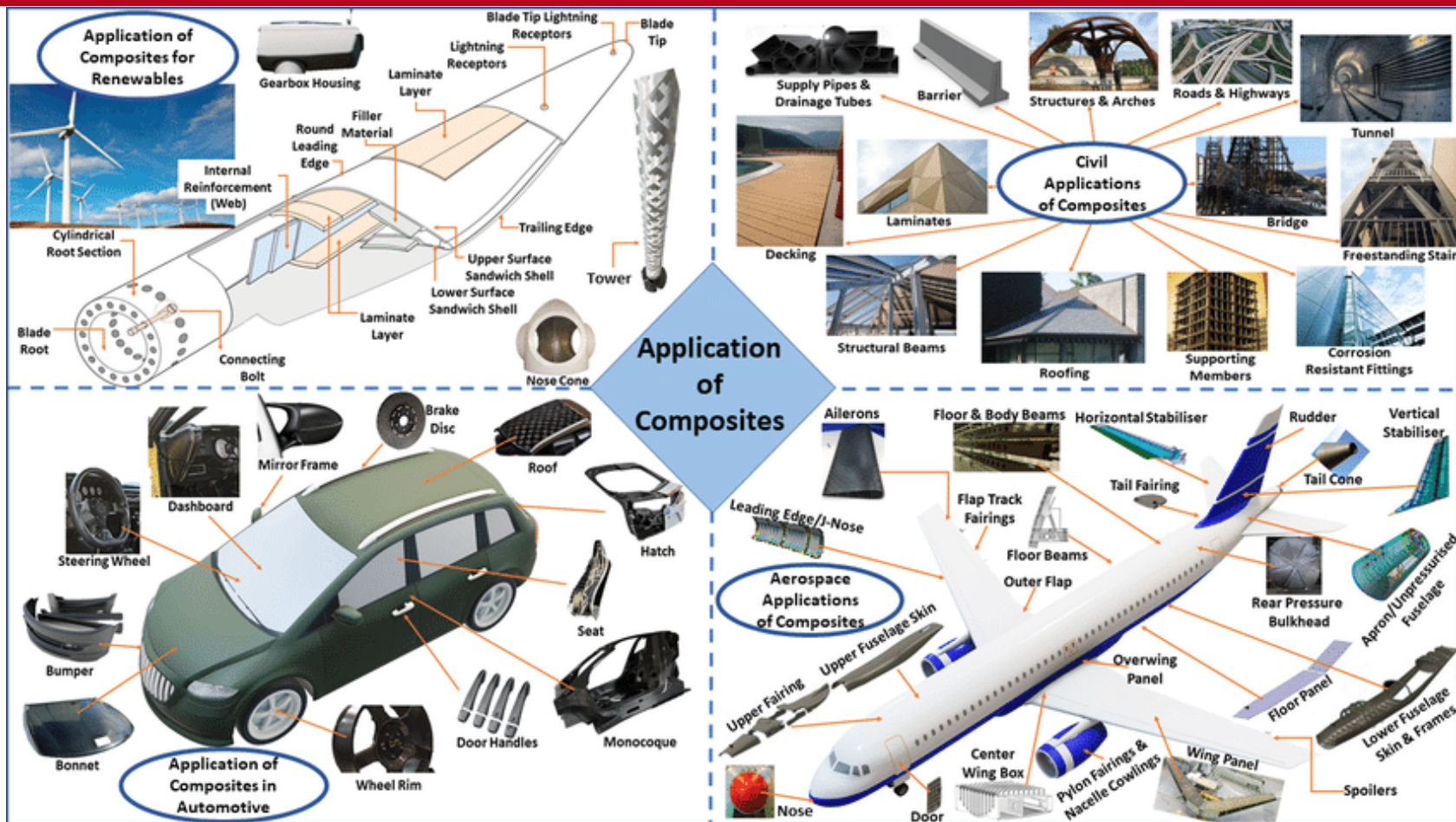
Moreover, the diffusion coefficient depends on the temperature:

$$D = D_0 \bar{e}^{E_A/RT}$$

In-depth: permeability



Applications of composite materials



Application of composites in the areas of renewables, civil infrastructures, aerospace, and automotive (clockwise from top left).

Source of the picture: Gupta, R. et al. (2021). A Review of Sensing Technologies for Non-Destructive Evaluation of Structural Composite Materials. Journal of Composites Science. 2. 319. 10.3390/jcs5120319.

Applications of composite materials



Compound annual growth rate
(CAGR)

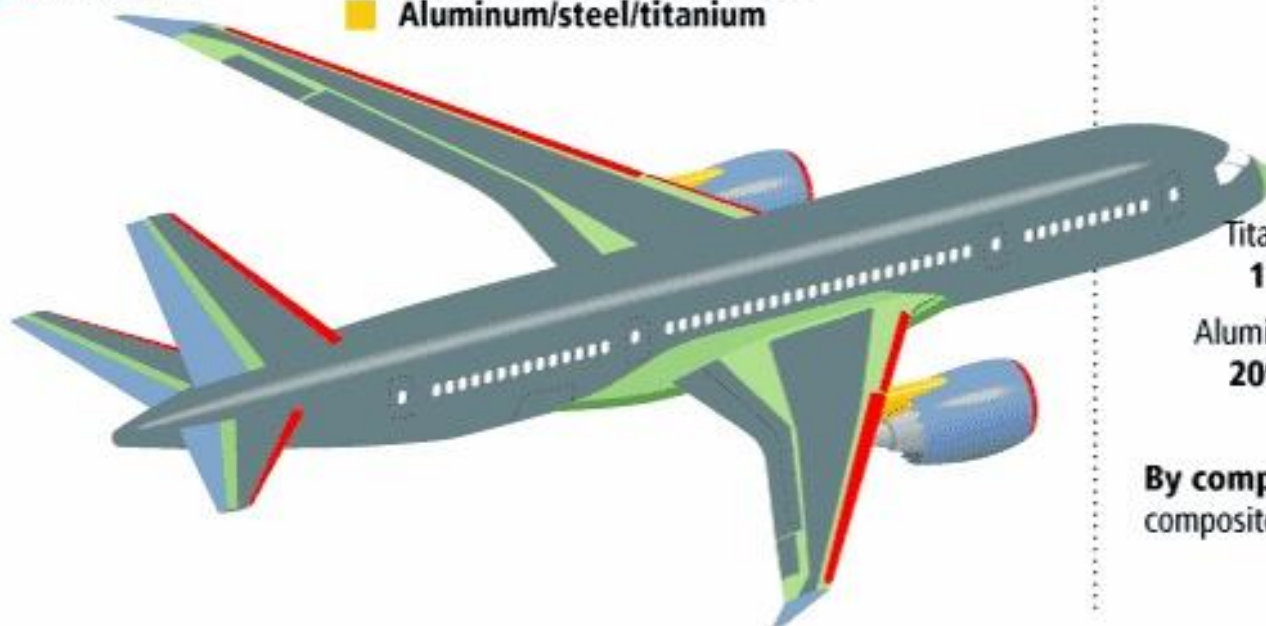


Source of the picture: <https://www.gminsights.com/industry-analysis/construction-composites-market>

Use of composite materials

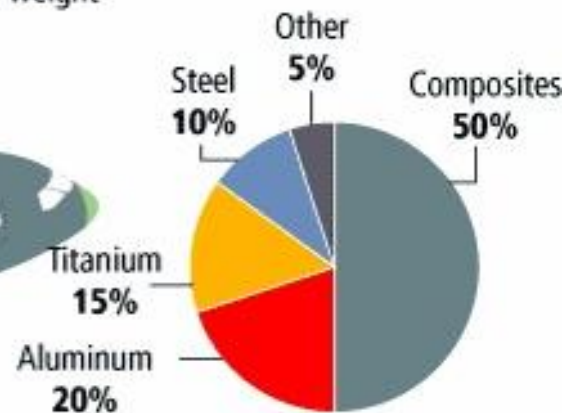
Materials used in 787 body

- Fiberglass
- Aluminum
- Carbon laminate composite
- Carbon sandwich composite
- Aluminum/steel/titanium



Total materials used

By weight



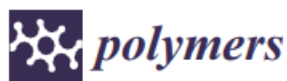
By comparison, the 777 uses 12 percent composites and 50 percent aluminum.

Source of the picture: Metallurgist

Use of composite materials

Table 1. Properties and applications of metal matrix composites in aircraft.

Matrix Material	Reinforcement Material	Properties	Application	References
Titanium	SiC	-High-impact energy -Weight reduction (32%)	Landing gear	[57]
Al	Cu-Nb,	-Improved high-temperature strength	Engines	[58]
Al alloy (LM25)	SiC	-Light-weight -Optimum performance -Reduces fuel costs	Aircraft wing	[59]
Al alloy	SiC	-Low density -High elastic modulus -High thermal conductivity -Preventability of resonance vibration	Fuel tank (door part) and fans (F-16 fighter aircraft)	[30]
Al alloy (AA6061)	Activated carbon	-Good thermal resistance	Engines	[60]
Cu	Nb3Sn	-Creep resistance -Stiffness	Engines	[61]



Review

Scientific Advancements in Composite Materials for Aircraft Applications: A Review

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Source of the table:

Use of composite materials

Table 3. Carbon fiber-reinforced carbon composites for aircraft applications.

Composites	Properties	Application	Reference
Carbon/Carbon composites	-Lightweight (40%) -Good thermal shock resistance -Good tribological properties -High heat capacity (2.5 steel) -High strength (2 steel)	Boeing 767-300 -Aircraft brakes (brake disc)	[87]
Carbon/Carbon composites	-Lightweight as compared to phenolic nozzle	Rocket nozzles (throat and exit cones)	[88]
C/C-SiC (SiC infiltrated C/C composites)	-Smaller size brake systems -High coefficients of friction -Higher transmitted braking power -Low wear rates (at temperatures above 1000 °C)	-Emergency brake systems	[89]
C/C-SiC (SiC infiltrated C/C composites)	-Microporous -High thermal shock resistance -Corrosion resistance -Good sealing agent for the pressurized pipes -Oxidation resistance at high temperatures	-Coated pipes	[90,91]

Source of the picture: Metallurgist

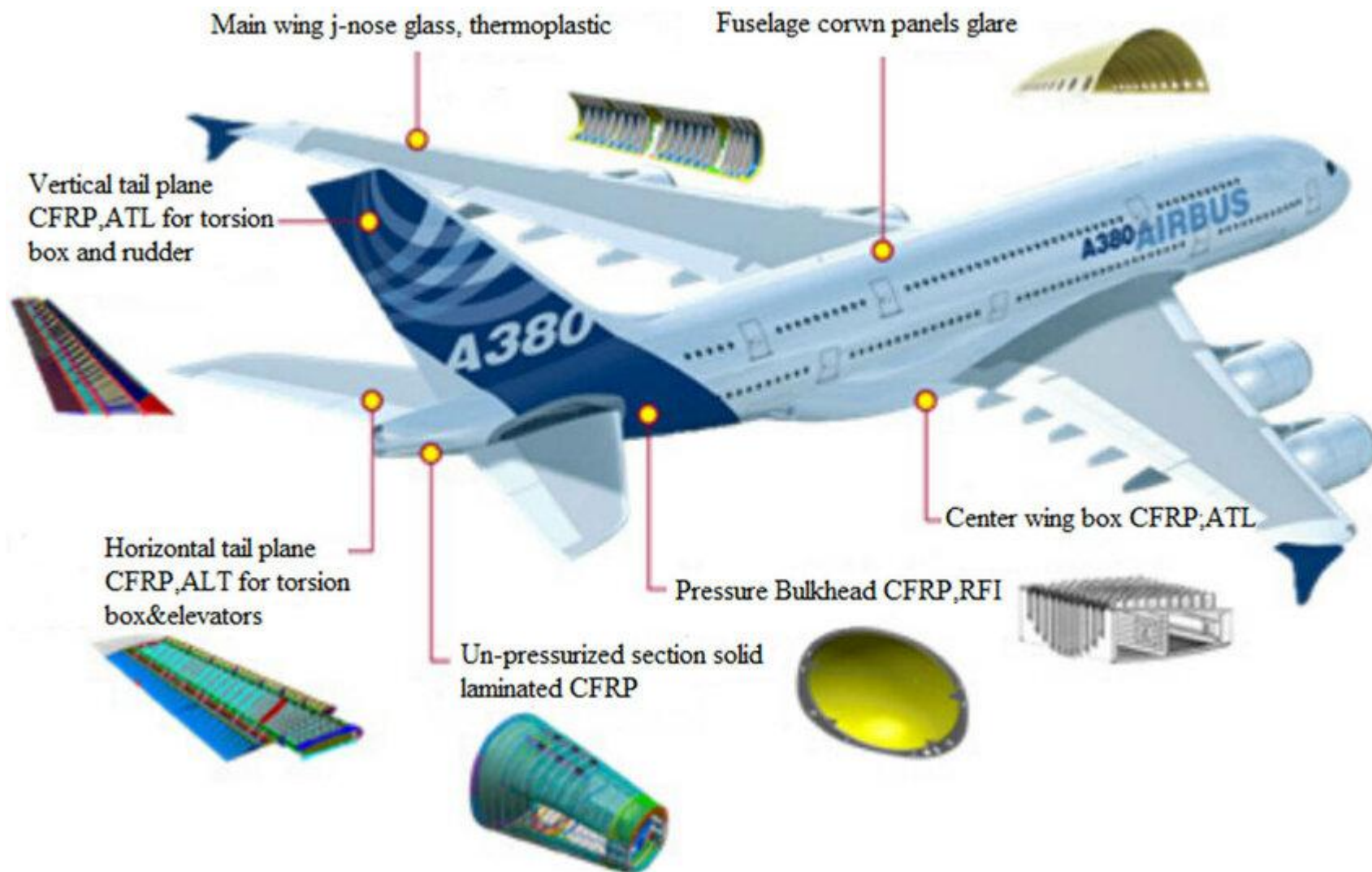
Use of composite materials

Table 4. Polymer matrix composites and their reinforcements in various aircraft applications.

Matrix	Reinforcements	Properties	Applications	Ref
Polymer	Hybrid kenaf/glass fiber	-High specific strength -Rain erosion resistance	-Aircraft brakes	[157]
Polypropylene	Hybrid bamboo/glass fiber	-Improved tensile strength -Increased fatigue life	-Aircraft structures	[158]
Polymer	Ramie fiber	-Reduction in weight (12–14%)	-Aircraft wing boxes	[159]
Polymer	Carbon fiber	-Design flexibility -High stiffness -Reduced scrap -Resistance to flames and heat -Fatigue resistance -Corrosion resistance -High strength -Damage and impact tolerance -Vibration-damping properties -Fracture resistance	-Aircraft brakes -Fuselage -Window frames -Aircraft wing -Rotors -Brackets -Boxes -Bulkheads -Fittings -Airframe -Blades -Vertical fins -Tail assemblies -Food tray arms	[160]
Poly(lactic acid) (PLA)	Glass fiber	-Improved flexural properties -Improved tensile properties	-Engine access door -Acoustic liners -Vanes	[161]
Epoxy resin	Fiber	-Flame retardant -Good mechanical performance -Resistance to irradiation	-Aircraft structures	[162]
Epoxy resin	Carbon black	-Improved mechanical strength -Resistant to oxidation -Flame retardant	-Controlling static electricity in the avionics system	[163]
Epoxy resin	Epoxy resin Carbon fiber/S2-Glass fiber	-High OHT (open hole tension) strength -High deformation before fracture	-Aircraft structural framework	[164]
Silicone	Nano-carbon (graphene, carbon nanotube, and carbon black)	-Excellent performance at different temperature ranges -Resistant to chemicals, and aging, -Unique electrical insulation properties -Excellent resistance to oxidation	-Aircraft structure	[165]

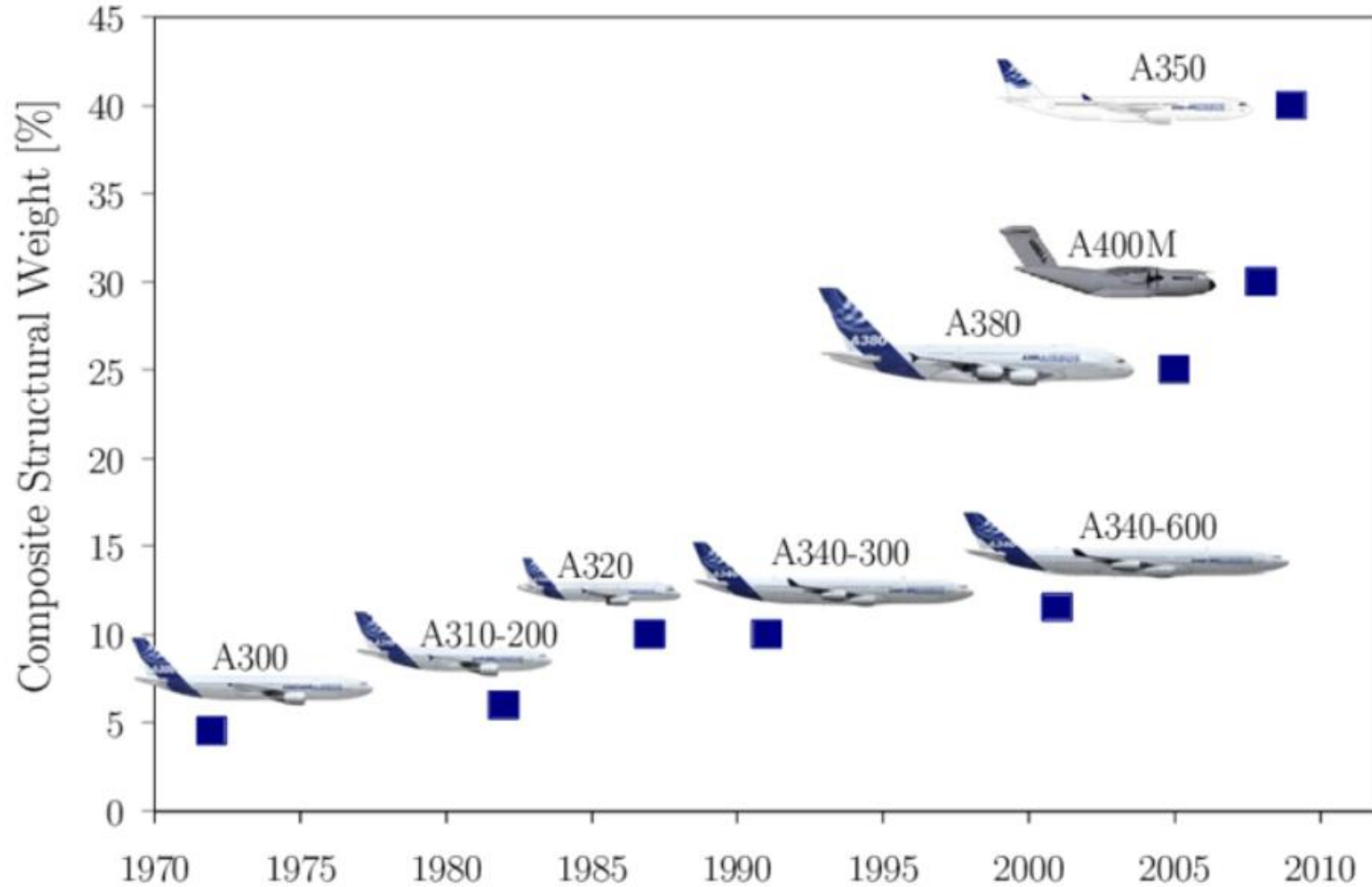
Source of the picture: Metallurgist

Use of composite materials



<https://www.airbus.com/en/newsroom/news/2017-08-composites-airbus-continues-to-shape-the-future>

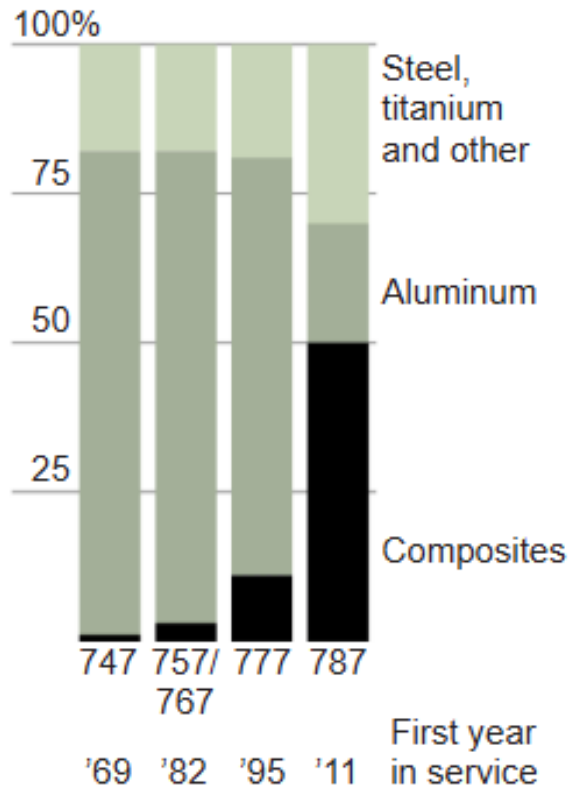
Use of composite materials



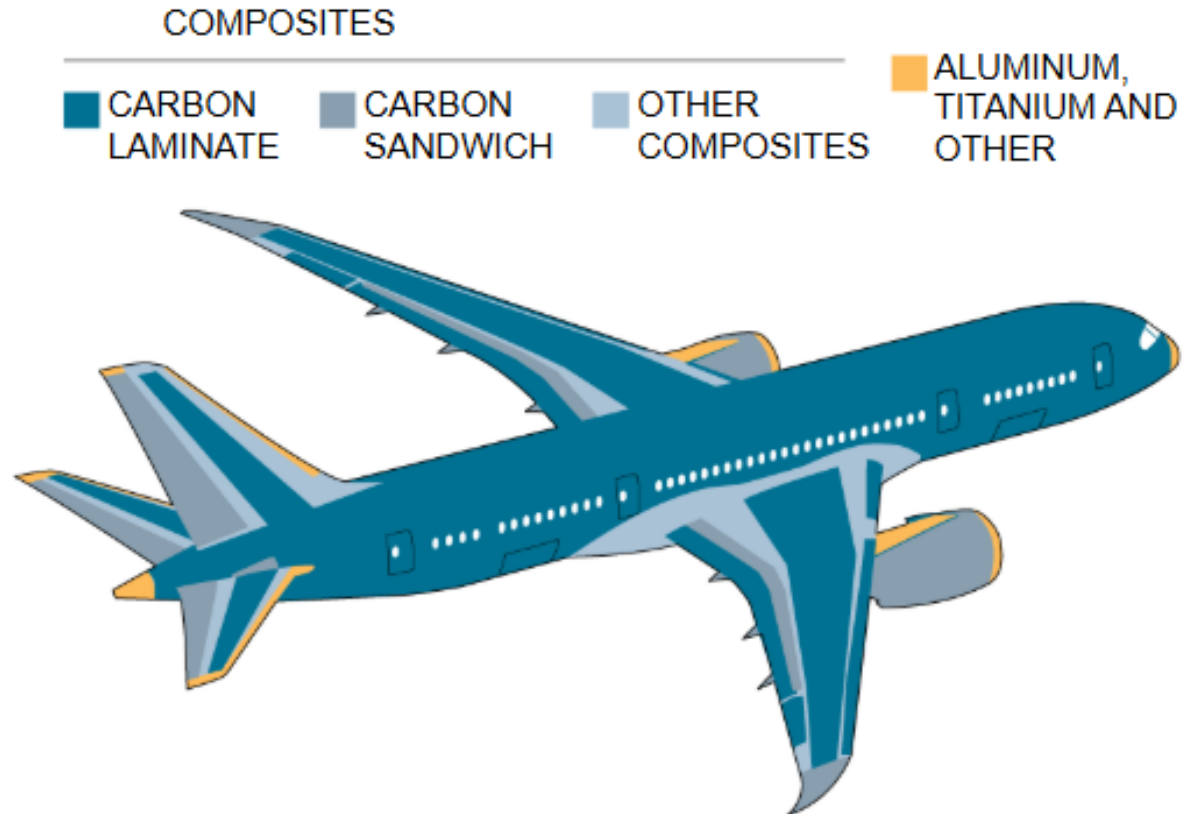
Portion of composite materials in Airbus aircrafts
(by courtesy of H. Assler, Airbus Deutschland GmbH)

Use of composite materials

Materials used in Boeing planes



Boeing 787 Dreamliner skin structure



<https://archive.nytimes.com/www.nytimes.com/interactive/2013/07/29/business/The-Jump-to-a-Composite-Plane.html>