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CARBON FIBER, THE BLACK WONDER

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In recent decades to meet the growing demands of users the performance of machines and equipment has increased significantly due to the widespread use of electronic solutions and accurate manufacturing. However, this has also increased energy demand and the CO_2 emissions. There is virtually no alternative to lightweight constructions: the carbon fibres reinforced materials (FRP), that are superior to steel and aluminium in almost all respects when it comes to cutting the weight and a number of beneficial properties. And, in terms of specific stiffness and lightness, carbon fiber reinforced plastics is simply unbeatable.
The aerospace, automotive, high performance machine parts, the wind-power industries, the hydrogen storage vessels producers have been aware of this they are being used in rapidly increasing quantities in more and more areas. The presentation will to give provide an overview of the use of the CFRP.

Keywords: applications, carbon fiber, composites, lightness, stiffness, tension

INTRODUCTION

In the various ages, materials used by man changed significantly, in our time polymers, as competitors to metals are becoming more and more significant (Figure 1).

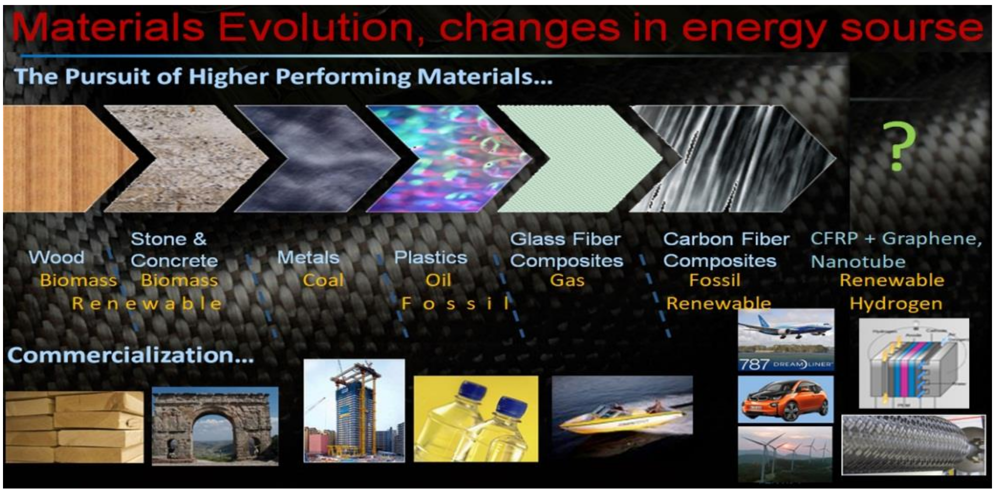


Figure 1. Evolution of used materials as a function of energy sources

Another great challenge of today is to ensure the ever increasing demands for energy, while reduction of carbon dioxide emissions harmful to the environment is a must. Coal and the carbon atoms, has previously made a decisive contribution to technological development (it has become an essential source of energy since the Industrial Revolution, and a key blending element for steel/cast iron structures). The ratio of the amount of structural materials is illustrated in the Figure 2.

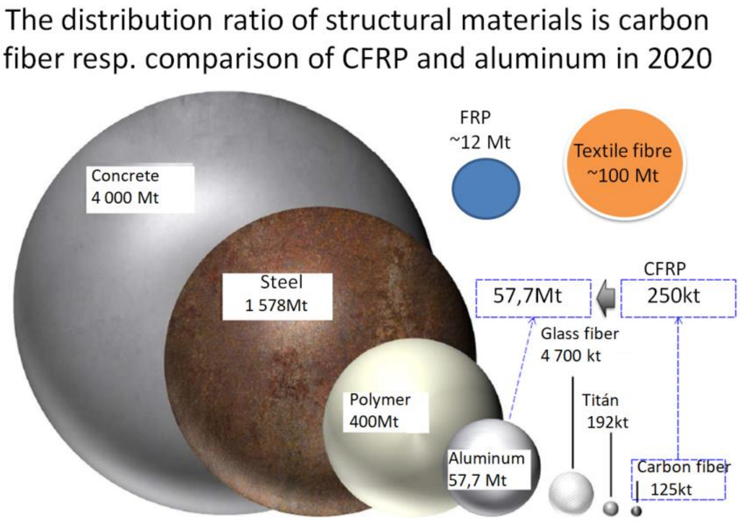


Figure 2. The distribution ratio of structural materials

Carbon fiber, which is largely used as a composite, makes up a small proportion but is growing rapidly due to its many excellent properties. Technical developments make it possible, even technical and economic requirements, to use new, high-performance materials. The final product was formed from the previously block-shaped section materials by cutting. Today, dynamically growing 3D printing shapes the end elements of the end product by superimposing thin planes, which has greatly facilitated the creation of lightweight structures. Facilitation of structures is essential to reduce the use of this energy and thus CO_2 emissions. Today, the knowledge and application of carbon atomic arrangement and compounds is crucial for high-tech developments. The specific surface area of small micro/nano-sized materials is large relative to the mass, and the surface can be treated to provide strong bonding between different materials (Figure 3).

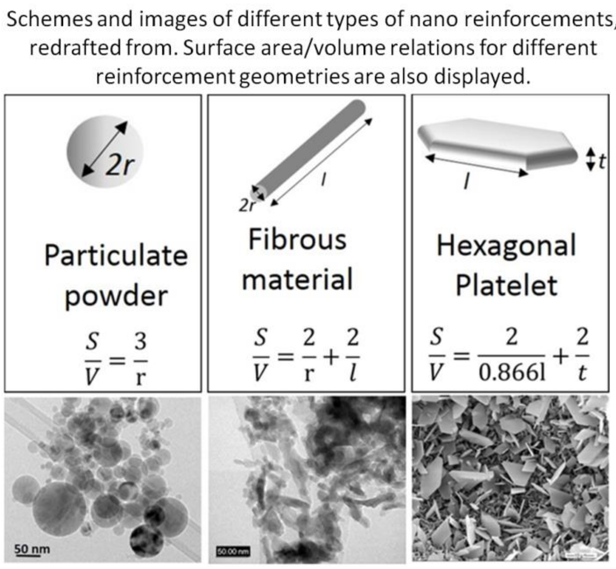


Figure 3. Schemes and images of different types of nano reinforcements

For example the little solid material's embedded into a matrix, well-dispersed little parts (graphene nanotubes) create a 3D reinforced and conductive network that provides a new set of properties and has minimal compact on the other key properties of final product (Figure 4).

Figure 4. Particle size distribution in a given volume

Carbon atom connection structures

The structure of the **carbon atom** is illustrated in the figure. The four electrons of the outer electron orbit create a huge number of possibilities for connection with other atoms as well as between carbon atoms (Figure 5).

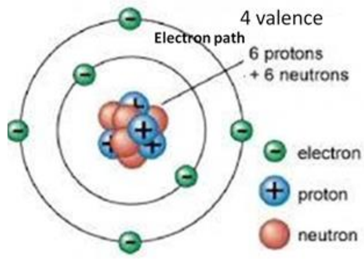
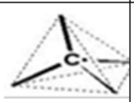
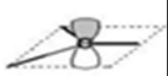
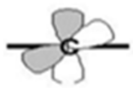


Figure 5. The carbon atom

Earlier for example the carbon in two basic, but startlingly different forms (allotropes) was known, namely graphite (the soft, black stuff in pencil "leads") and diamond (the super-hard, sparkly crystals in jewelry). The amazing thing is that both these radically different materials are made of identical carbon atoms. The atoms inside the two materials are arranged in different ways, and this is what gives the two allotropes their completely different properties (Table 1):

- **graphite** is black, dull, and relatively soft (soft and hard pencils mix graphite with other materials to make darker or fainter lines);
- **diamond** is transparent and the hardest natural material so far discovered.

Table 1. Connection of a carbon atom

Number of one carbon atom attached to a carbon atoms	4	3	2
Fragmentation of connected atoms			
Incidence	Diamond 3D	Graphene Sheet	Polyamide chain Linear
Possible number of electron p-bonds	0	1	2

In the last century, **polymers** have been artificially formed chain molecules by the linear coupling of carbon atoms. Polymer chain molecules can be used to make high strength (especially aromatic) fibers during fiber drawing (Figure 6).

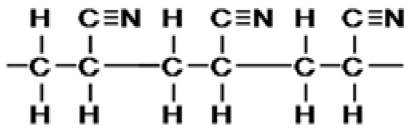


Figure 6. Polyacrylonitrile (PAN) chain molecule

The last few years, scientists have discovered various other carbon allotropes with even more interesting properties. There are present in Figure 7.

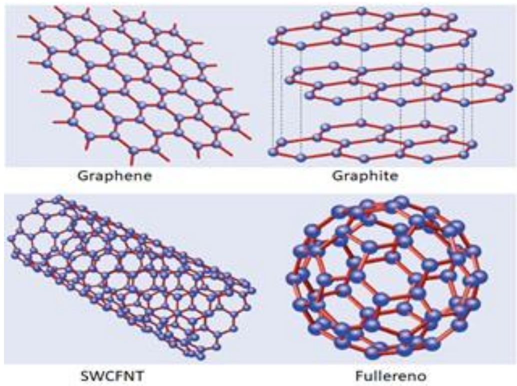


Figure 7. Honeycomb sheets of carbon just one atom thick

- **Fullerenes** (discovered in 1985) hollow cages of carbon, including the so-called Buckyball, made from a kind of football-shaped cage of 60 carbon atoms).
- **Nanotubes** (discovered in 1991; flat sheets of carbon atoms curled into amazingly thin, hollow tubes one nanometer in diameter)—and (drum roll). Single Walled Carbon Nano Tube (SWCNT) have an excellent properties; in mechanical (100 times stronger than steel), in thermal (thermal stability up 1600°C in vacuum), in electronic (5 times lighter then copper) and chemically inert, compatible with almost all materiel (Figure 8).

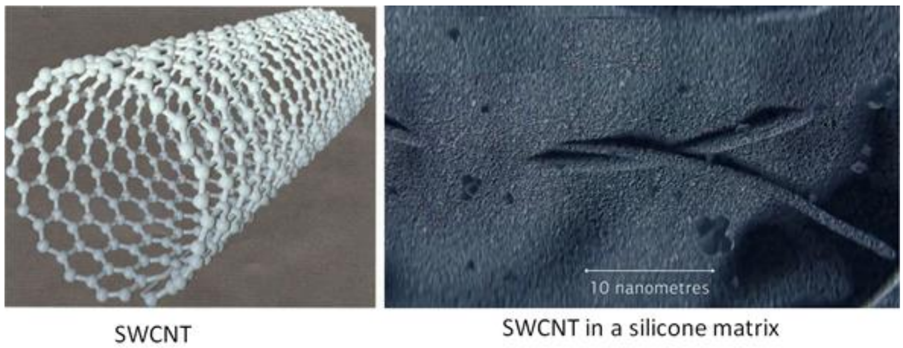


Figure 8. Nanotubes

Embedded into composites it is used as a directional structured reinforcing, bracing material. If the 20th century was the age of plastics, the 21st century seems set to become the age of **grapheme** (discovered in 2004) - a recently discovered material made from honeycomb sheets of carbon just one atom thick (0.345nm). It's just about the lightest, strongest, thinnest, best heat- and electricity-conducting material ever discovered. And if we're to believe the hype, it promises to revolutionize everything from computing to car tires and solar cells to smoke detectors (Figure 9).

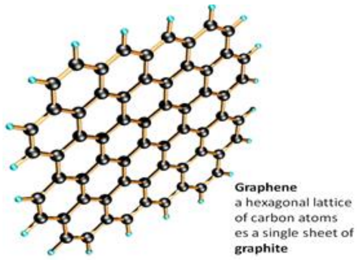


Figure 9. Grapheme is a honeycomb lattice

Nanofibres is very fine fibres (d<500 nm), produced with electrostatic spinning technology. It's possible to make very fine nonwoven structure for filtration (Figure 10).

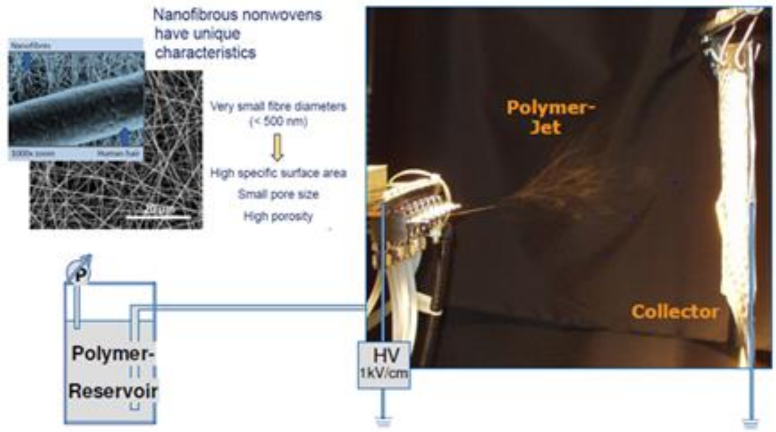


Figure 10. Electrostatic spinning of nanofibres

Carbon, OPAN and Graphite fibers to produce using identical raw material (PAN Precursor) and in the first phase of production, also using identical (Oxidation) processes, produces three types of black fibrous material, namely; oxidized (OPAN), carbonized and graphite fibers, it's properties, processing and field of application is significantly different (Figure 11).

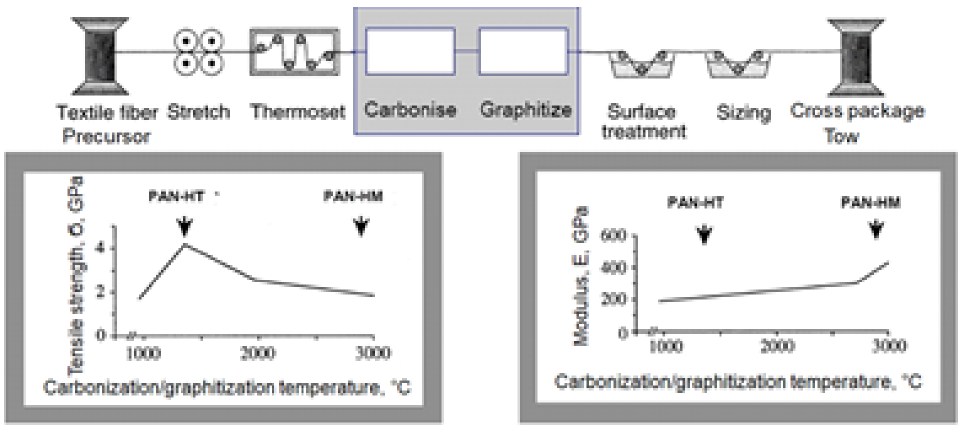


Figure 11. Production of carbon fibers from PAN precursor

The **oxidized fiber** - the so called **O**xidized **P**oly**a**crylo**n**itril fiber (OPAN, OPF) - (having high LOI (**L**imited Oxygen Index) value and excellent heat resisting, heat – sound insulating properties) can be processed into technical products or for e.g. protective clothing's using the well-known textile technology processes.

A significant part of the textile products made from OPAN is carbonized, from C&C composites airplane brake discs or brake linings are made. Another large part of the products, the sheet nonwoven fabrics after carbonization, constitute a functional element in fuel cells. The thusly resulting paper like 99% carbon content material is used for fuel cell in hydrogen driven electric motors or electrical energy storage. The **carbon fiber** following oxidation is produced by passing it through (under tension) high temperature nitrogen gas, thusly carbonizing it. The chemical structure of the graphite lattice plane formed in the direction of the fiber axis ensures high rigidity and strength.
The from the initial so-called PAN precursor fiber produce carbon fiber and graphite fiber continuously, depending on the carbonization temperature. At the end of the carbon fiber production line, the surface of the fiber is activated; a sizing material corresponding to the composite matrix is applied and then wound on a spool (Figure 12).

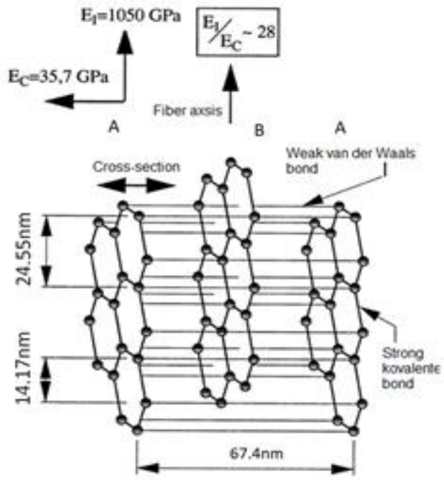


Figure 12. Lattice structure of a single carbon crystal

Carbon fiber is brittle and a good conductor of electricity, therefore in its processing special care is required. Carbon fiber has an Ø of 7 µm (approx; 0.7 dtex fineness), its tow contain a high number of parallel fibers (2, 4, 12. 24, 50 k (k→kilo, 1000 filament) (Figure 13). The specific mechanical properties of fibers far exceed those of conventional metallic structural materials (Figure 13).

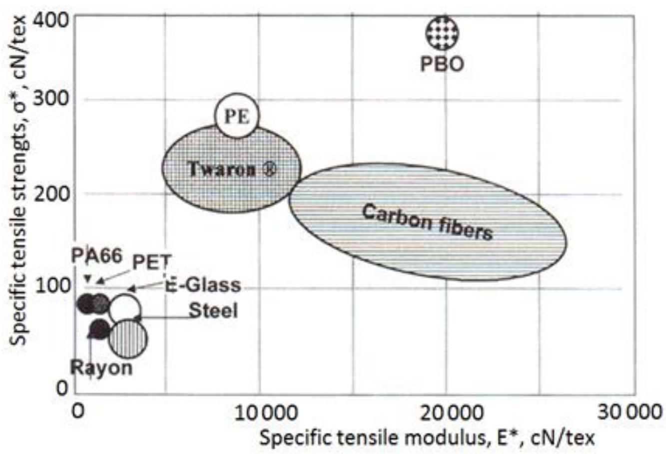


Figure 13. Performance comparison

Table 2 shows mechanical properties of some materials.

Table 2. Connection of a carbon atom

Materials	RSM[1]	Modulus GPa	RSTS[2]	Tensile strength GPa	Density ρ, g/m³	Diameter
Graphene	**~20**	~1000	**~750**	100-400	1,8-2,2	plate
SWCNT	**~32**	~1000	**~350**	100-200	~0,7-1,7	1-20 nm
Carbon nanofibers	**~9**	~500	**~15**	3-7	~1,8-2,2	20-200 nm
Carbon fibers	**~5**	230	**~12**	3,5	~1,8	7 μm
CFRP UD	**~3**	~120	**~6**	~1,8	~1,4	-
Aramid fibers	**~2**	60	**~15**	3,6	1,44	5-10 μm
Glass fibers	**~1**	75	**~5**	2,2	2,6	5-10 μm
High Tensile Steel	**1**	210	**1**	1,3	7.8	-

RSM[1] - Relative Specific Modulus (X material specific modulus/steel specific modulus)
RSTS[2] - Relative Specific Tensile Strength (X material specific Tensile Strength /steel specific Tensile Strength)

Textile structures, features

The carbon fiber is very fragile due to its low elongation (ε = 1-1.5%), which makes the textile processing of the cable very difficult. The surface of the cable throwing elements has a special design, the so-called orange peel-like.

A further complicating condition is that the small broken fibers float in the air, and due to the good electrical conductivity of the carbon fiber, the control electronic equipment of the machines must be protected to prevent short circuits and the destruction of the electronic panels. For this reason, the processing of carbon cables requires great professional experience and expensive equipment (Figure 14).

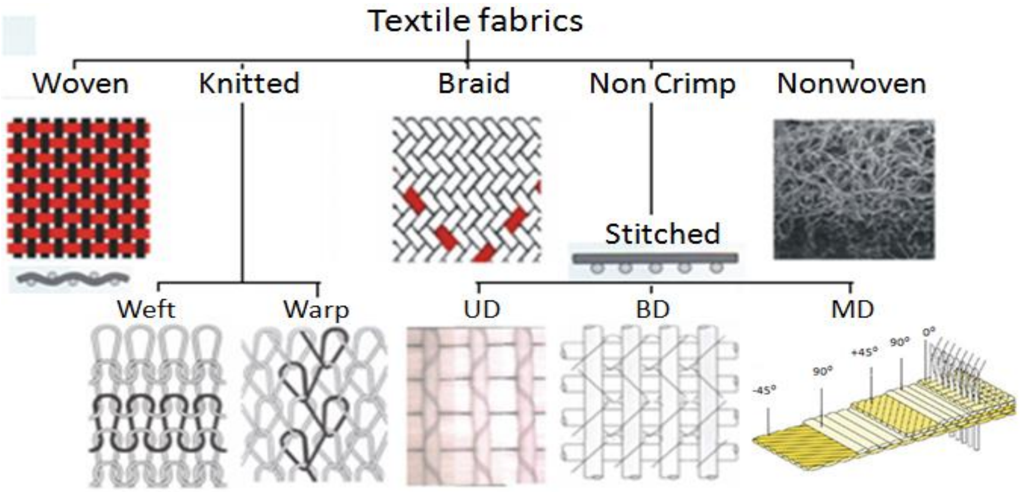


Figure 14. Types of textile fabrics

The orientation of the cables in the direction of the loads allows the production of anisotropic, high-performance composites (Figure 15).

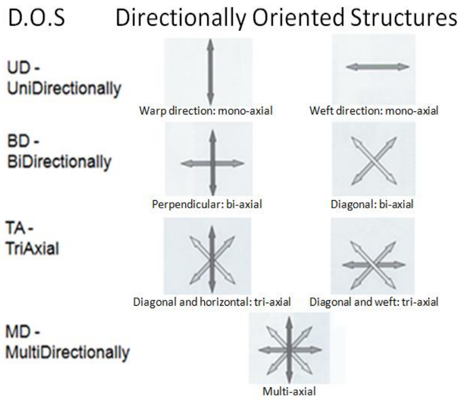


Figure 15. The orientation of the cables

In many cases, high rigidity is an important requirement for CFRP. For this reason, and also due to the high modulus of the carbon fiber, the design of the textile construction its straight position of the fibres is achieved by laying the cables (Figure 16).

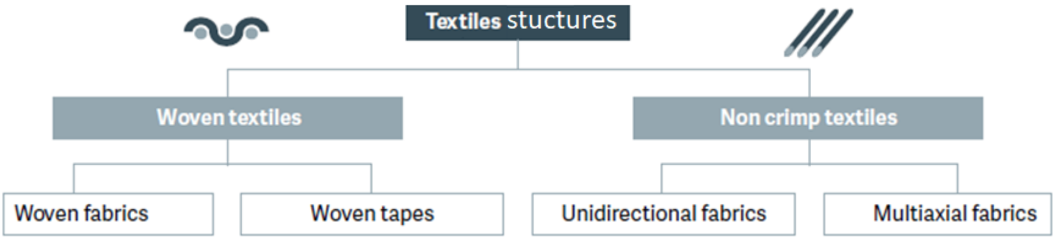


Figure 16. Textile structures

The fibers should be evenly distributed in the matrix. When placed in the form of a tow, the space in the cable gaps is filled only by the matrix, which is disadvantageous in terms of mechanical properties. By spreading the cable, this error can be eliminated and the liquid matrix evenly fills the space between the fibers (Figure 17).

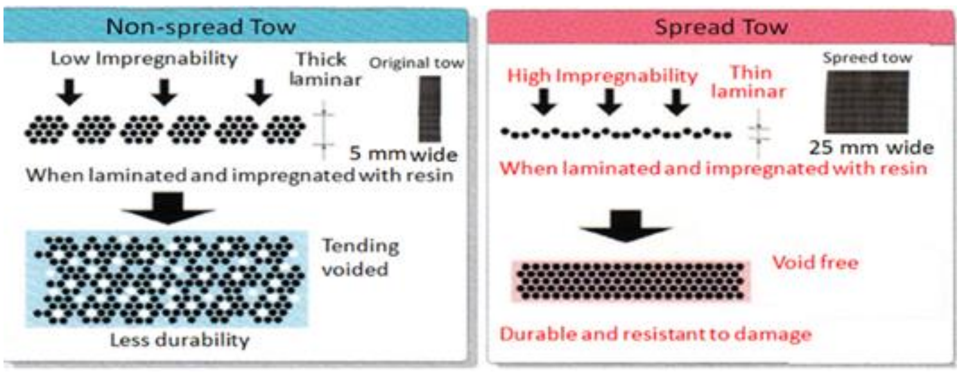


Figure 17. Fibres arrangement for non-spread and spread tow

Composite productions, properties

A composite is a material that is composed of several components, so that each of the individual components can be clearly differentiated physically from the other. The individual components then interact with each other so that the new material has new, improved properties that could not have been achieved with any of the individual components alone. A composite material consists of one or more than one reinforcement and one matrix (Figure 18).

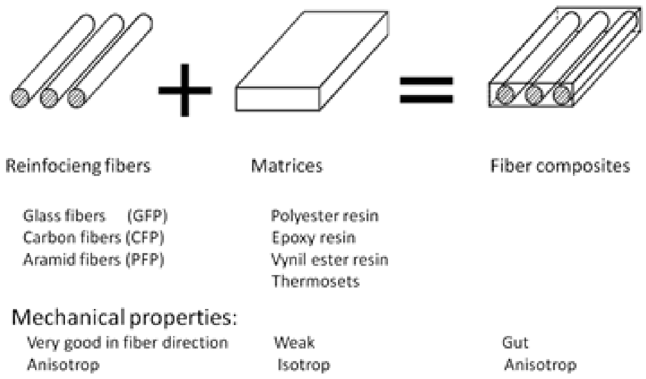


Figure 18. Structure of fibres composites

The matrix is the embedding material for the reinforcement. It serves the cohesion of the reinforcing material, protects the reinforcement from environmental influences and is mainly responsible for the uniform application of force for reinforcement. The matrix may be made of plastic (PMC), metal (MMC) or ceramic (CMC).

Similarly, there are various types of amplification. These are often categorized according to their form. Thus one differentiates e.g. between fiber-reinforced, particle-reinforced composites. The reinforcement serves to carry the load and thus increases the mechanical properties of the matrix in the composite.

Plastics, often referred to as polymer, are macromolecular chains of covalent bonds that are synthetically produced. Depending on the type of plastic, the properties can vary from elastic to brittle, or transparent to completely opaque. Mechanical properties, thermoforming or chemical resistance depend heavily on the choice of macromolecules, the manufacturing process and the addition of additives.

Plastics are divided into 3 categories: thermoplastics, thermosets and elastomers.

Thermoplastics consist of linear or branched macromolecules and can be plastically deformed after heating and also melt at elevated temperatures.

For **thermosets**, however, the macromolecules are spatially closely networked. This has the consequence that thermosets do not plastically deform and do not melt.

Elastomers are colloquially often referred to as rubber. These consist of wide-meshed macromolecules, which allow deformation under load, but retract elastically once the load is released. The cross-linking also makes it impossible to melt an elastomer (Figure 19).

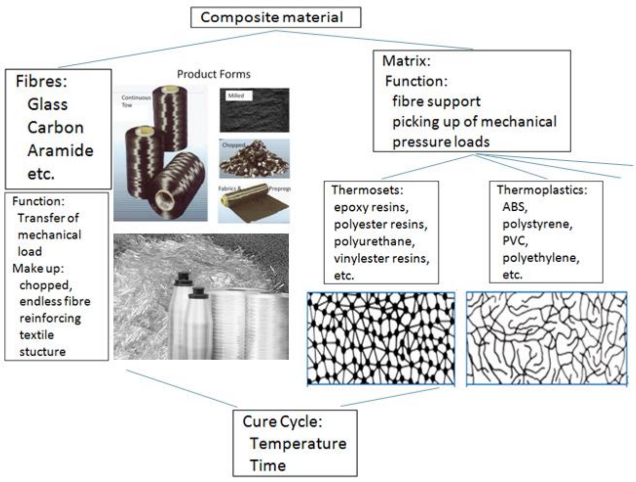


Figure 19. Types of composite materials

Fiber Reinforced Polymers (FRP) in which fibers or textile structures are embedded in a plastic (Figure 20).

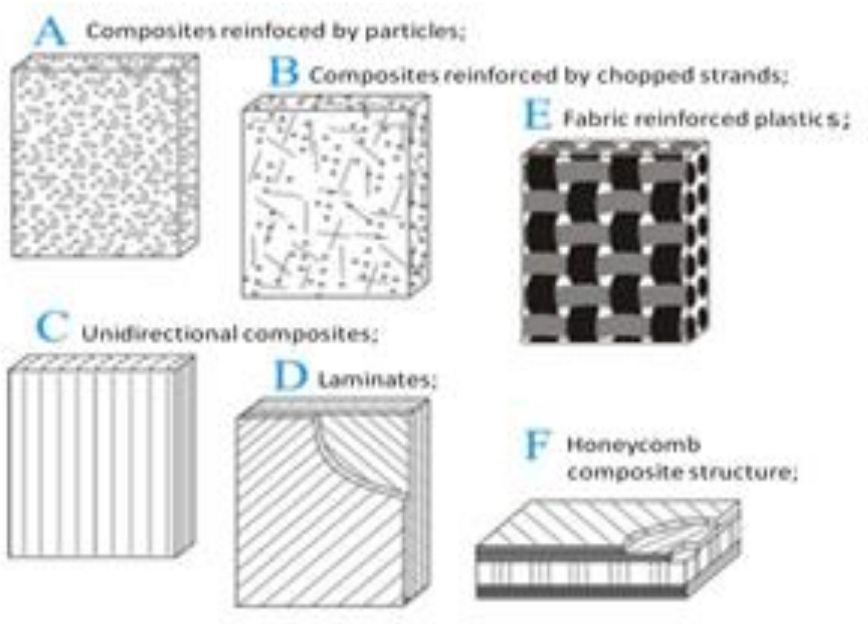


Figure 20. Structure of composite

Composite can be divided into:

- Low Performance Composites; typically with chopped and milled glass and carbon fibres
  No textile process inwolved. Fibers are injected into the moulding process or directly sold as glass or carbon fibre mats (see A and B pictures).
- High Performance Composites; typically with filaments or long strached of carbon, p-aramid, glass
  Textile processes are involved: Non crimped fabrics (UD, MD), weaving (spreaded, 3D structures), braiding, embroidery, laminates, etc. structures (see C, D, E, F structures).

Carbon Fiber Reinforced Polymer (CFRP) the ideal material for lightweight construction:

- Light weight,
- High specific strength,
- High specific stiffness,
- High bending stiffness,
- Excellent fatigue strength,
- Good vibration damping,
- X-ray transparency,
- High chemical resistance,
- Low thermal expansion,
- Corrosion resistance

Application of composites

Composite materials are increasingly used for primary structures in aerospace, transportation, marine, renewable energy production and storage, industrial, commercial and recreational structures.

Lightweight construction is short for lightweight, and implies a design technique that aims to maximize weight savings. Reasons for this include the targeted cost or raw material savings, as well as the increase of payloads or the simplification of assembly and handling. The way in which lightweight construction can be achieved varies. Thus, integratively constructive material and production engineering means can be used in an overall structure (Figure 21).

Figure 21. Small tow versus large tow segmentation

Reasons for a desired lightweight construction can be different. Often a weight saving, especially in the automotive or aviation sector, can reduce energy consumption and thus costs and raw materials during use. Frequently accelerating or decelerating loads (e.g., road or rail vehicles, elevators, robotic parts) can increase payload and reduce operating costs. Lightweight construction continues to offer a flexible alternative for installations or in building construction (Figure 22).

Figure 22. Applications of composites

In general, materials with low density and high mechanical properties are used in particular. This can be either a monolithic material or a composite material. Lightweight metallic materials are e.g. Aluminium, magnesium and titanium. In addition, fiber composites are nowadays regarded as a frequently used material category. In addition to space travel and aviation, a radical change is expected in the field of vehicles to reduce pollution, both for propulsion fuels and for new structures (Figure 23).

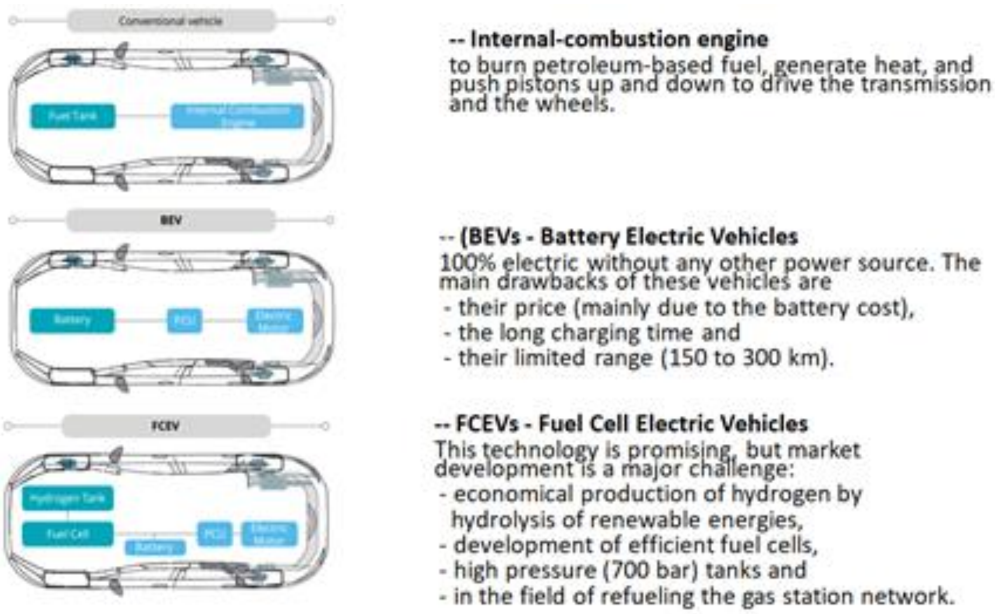


Figure 23. Propulsion system of vehicles

In addition to space travel and aviation, a radical change is expected in the field of vehicles to reduce pollution, both for propulsion fuels and for new structures. The rapid spread of electric vehicles is expected in the coming years, for which the development of lithium-ion batteries is essential. Within a few decades, with the increase in the share of renewable energy, energy storage will also become crucial. Renewable energy, which is also of great importance for the environment, is expected to be widely used in the storage of hydrogen obtained from the decomposition of water and for the electric propulsion of vehicles.

Technology for storing hydrogen in high pressure CFRT tanks and fuel cell propulsion has been developed, however, in the current situation; economy is not yet cost effective. In addition to space travel and aviation, a radical change is expected in the field of vehicles to reduce pollution, both for propulsion fuels and for new structures. The rapid spread of electric vehicles is expected in the coming years, for which the development of lithium-ion batteries is essential. Within a few decades, with the increase in the share of renewable energy, energy storage will also become crucial. Renewable energy, which is also of great importance for the environment, is expected to be widely used in the storage of hydrogen obtained from the decomposition of water and for the electric propulsion of vehicles.

Technology for storing hydrogen in high pressure CFRT tanks and fuel cell propulsion has been developed, however, in the current situation; economy is not yet cost effective (Figure 24). As the share of renewable energy sources increases, energy storage will become necessary for the continuous supply of energy, with the hydrogen economy promising. With the hydrogen produced by decomposing water in the overproduction phase of renewable energies, the electric drive from the high-pressure tanks of vehicles with the fuel cell is technologically developed and solved. Hydrogen has a high specific energy content (E=40 000 Wh/kg), but even at 700 bar its density (ρ=40 kg/m^3) is low. Reducing the weight of the hydrogen tank can only be achieved with a composite tank reinforced with carbon fiber winding, which will project a huge demand for carbon fiber in the near future. Technology for storing hydrogen in high pressure CFRT tanks and fuel cell propulsion has been developed, however, in the current situation; economy is not yet cost effective (Figure 24).

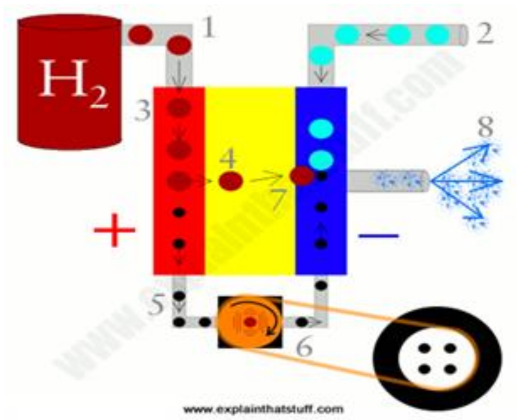


Figure 24. Schematic illustration of hydrogen drive

The use of composite in national economies is an indicator of development similar to electronics (Figure 25).

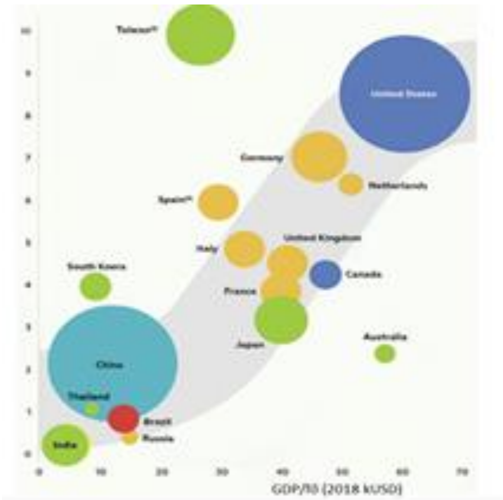


Figure 25. Comparison of countries by GDP and per capita composite production (kg/capita), 12.4 Mt in 2018s

CONCLUSIONS AND RECOMMENDATIONS

Thanks to the many outstanding properties of composites and intensive technological developments, they can be expected to be widely used in many key areas in the future. The use of CFRP materials to reduce the weight of high-efficiency, large-sized wind blades and high-pressure vessels can be expected for a bright future. Hydrogen propulsion technology is well developed, development is unbroken, economy is not yet competitive, but its future is indisputable, which is also desirable in terms of reducing environmental pollution and CO_2 emissions (a big step forward).

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