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THE CARBON AGE – CHARACTERISTICS OF THE CARBON FIBERS

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ABSTRACT: *In the various areas, quantities of the materials and goods used by mankind show rapid growth, whereas its form, rate of use is significantly varying. Today requirements and expectations concerning the various materials are wide ranging, so the properties of these materials are developed in accordance to the demands. Presently the carbon fiber is being used more and more frequently in those areas which require special demands. This is explainable by its outstanding properties, namely high tenacity, stiffness, low heat dilation, conductivity etc. From composites, lightweight structures may be produced to meet higher level applications. Carbon fiber reinforced composites – in the areas demanding high mechanical usage, will be of determining importance in the future.*
KEYWORDS: *carbon fiber fabrication, properties, application*

INTRODUCTION

Presently Carbon Fiber is being used more and more frequently in those areas which require special demands. This is explainable by its outstanding properties, namely, (high tenacity, stiffness, low heat dilation, conductivity etc.). Carbon Fiber is rigid, brittle and because of this, its processing requires particular care, special handling. With the development of the manufacturing, and processing technologies and the decrease of its price, carbon fibers expectedly and in the future will play a key role in the field of high demanding composites.

DISCUSSIONS

In the various areas, quantities of the materials and goods used by mankind show rapid growth, whereas its form, rate of use is significantly varying (Figure 1). In the second half of the 20th Century, concerning the high ratio of metal usage, a change and shift towards polymers, composites and ceramics can be observed, and their usage is increasing significantly. Today requirements and expectations concerning the various materials are wide ranging, so the properties of these materials are developed in accordance to the demands.

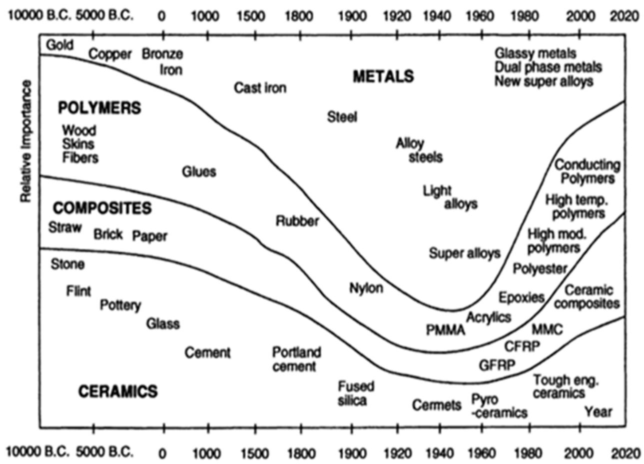

Figure 1. Relative importance of material development through history

In the development of new materials, a decisive role is played by Space Research and the Military Industry in which for developing special material properties, the sources for research are readily available. Demands are emerging in more and more areas for using the thusly developed materials and structures, and with the further development of processing technologies, along with mass production, their prices are decreasing making them available for use in a wide range.

In 1879, Edison made the first Carbon Fiber by carbonizing bamboo fiber to use it as incandescent filament in light bulbs. Carbon Fiber, because of its excellent properties and high price was first made in the 1960's from regenerated fibers, and then by carbonizing PAN fiber. It began to be applied in the Aerospace industry. This was followed by the expensive and valuable sport goods, and currently machinery parts (Figure 2).

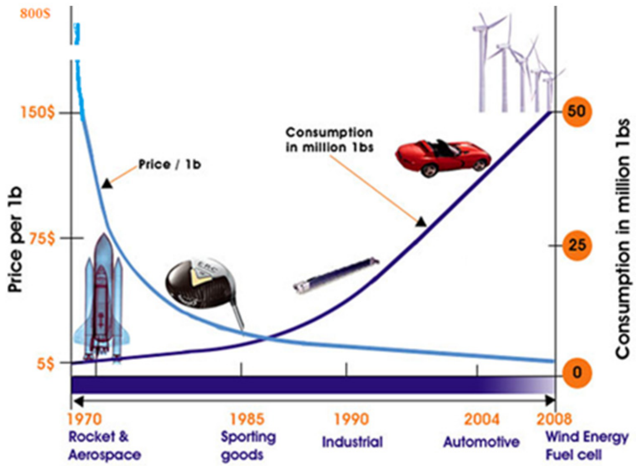

Figure 2. Trend and forecast in carbon fibres shipment

From composites, lightweight structures may be produced to meet higher level applications. The mechanical properties of fibers, textiles used for reinforcing composites, related to weight are characterized by high tenacity, low elongation and high elasticity modulus. Amongst the plastic-reinforcement fibrous materials, the properties of carbon fiber „Black Magic" are especially outstanding. Carbon fiber reinforced composites – in the areas demanding high mechanical usage, will be of determining importance in the future (Figure3).

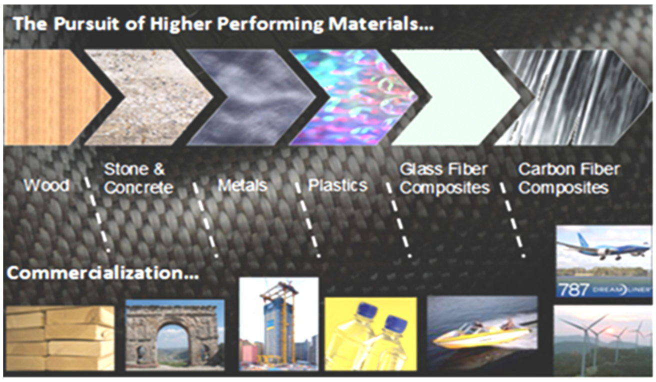

Figure 3. Materials evolution

The properties and price of carbon fibers also encompass a broad territory. With the price decreasing of the higher filament numbered (higher than 24K), carbon tows produced for commercial usage, the greater volume and the wider industrial usage came to prominence and this tendency, expectedly, will continue.

The Carbon Fiber is made mostly (approx; 95 %) from a synthetic fiber well known in the textile industry, namely PAN (Polyacrylonitrile), and it is so called precursor fiber (Figure 4), whereas the raw material of the remaining 5 % is either tar or regenerated fibers.

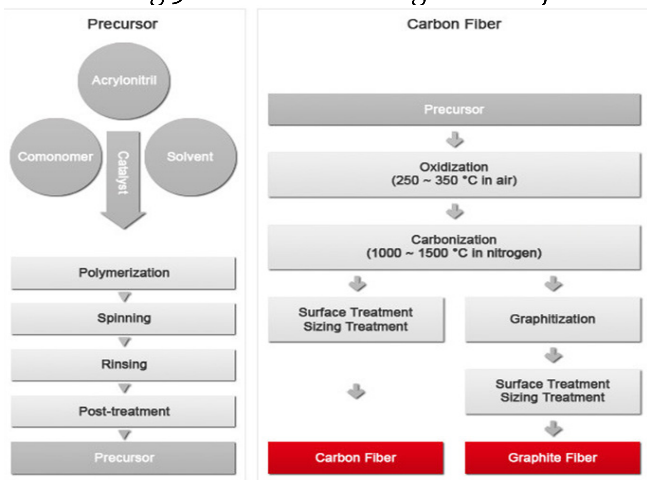

Figure 4. Manufacturing process of carbon fibers (PAN-based)

The PAN precursor based oxidized fiber (OPAN), carbon and graphite fiber production process is well depicted in Figure 5.

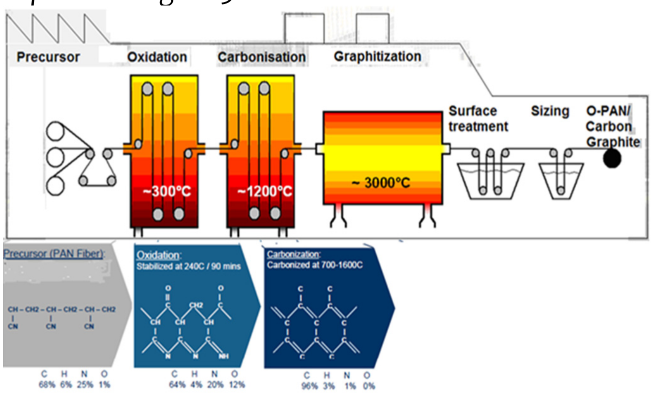

Figure 5. The oxidation, carbonization and graphitisation process

The OPAN fiber is produced by oxidizing the moderately stretched PAN fiber at 220-250 ºC. In the process of the oxidation, taking several hours, most of the burnable gases and toxic materials are exhausted from the fiber, while its chemical structure changes. The OPAN fiber (approximate with 62% of carbon content) formed after oxidation, becomes a textile material having excellent heat, flame and fire resistant properties, which after various textile industry operations (Stretch - Breaking, Carding, Spinning, Weaving, Knitting, or in Tow / Staple fiber form using non-woven methods) may be further processed. Products' made from OPAN do not melt, have a high LOI value (40-60), its heat resistance is above (300 ºC), and because of this, they are mainly used in areas where heat, fire resistance, heat insulation (welding blankets, protective clothing, etc.) is required. During the oxidation process, a crust forms on the surface of the OPAN fiber, and because of this, its loop tenacity is low (8-15% of the tensile strength), thusly the fiber is brittle. By increasing of the temperature and processing time, the density of OPAN fiber (ρ=1.35-1.42 g/cm^3) can also be increased, and with this, heat resistance of the material can be augmented, but the fiber will be more rigid. Although OPAN and carbon fibers are both black, their other properties are basically different (Figure 6.).

Properties	OPAN	Carbon fiber
C contain (%)	62	>95
Thermo resistant	Good thermo-Insulator	Good thermo-Conductor
Electric	Electric Protective	Electric Conductivity
Tensile strength (MPa)	260	4000
Modulus (GPa)	8,5	242
Elongation (%)	20-25	1,5

Figure 6. Properties of OPAN and carbon fibers

OPAN products processed by textile industry methods and then carbonized can be used in a variety of unique applications.

In the hydrogen driven electrical transformer, the carbon membrane allows the protons to pass through while by separating the electrons, electric current is generated.

In the case of sodium-sulphur electrical energy storing, the sulphur is stored in the carbonized OPAN membrane sponge.

In the C-C composite technology, the thick felt made from OPAN is carbonized at high temperature and the C is diffused into the material. From the thusly created, compact structured CandC composite material, high temperature 1000 ºC bearing, aircraft and racing car brake discs and brake pads are made.

In the manufacturing of carbon fiber, by leading the pre-tensioned fibers exiting from the oxidation oven into high temperature (800-1500 ºC) nitrogen gas blanketed ovens, the structure of the carbon fiber is formed (Figure 7).

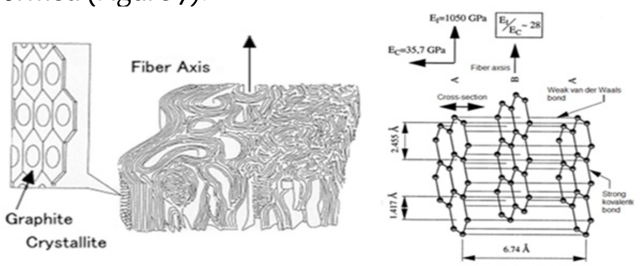

Figure 7. Structure of carbon fiber

To forward chemical bonding with the matrix material of the composite, after exiting from the ovens, the surface of the fibers is activated and sizing is also carried on to their surface.

In the course of graphite production the pre-tensioned fibers are further led through high temperature (2000-3000 ºC) nitrogen gas blanketed ovens. The raw material, production technology parameters (tensioning zones, stressing level, temperatures, surface treatment etc.) all have deciding effect on the properties of the fiber (by increasing the temperature, rigidity of the fiber also increases), thusly tenacity and stiffness properties of the carbon fibers encompass a wide range.

The carbon fiber, without twisting is wound onto 5-12 kg- spools. To avoid twisting, the tow is unwound tangentially from the rotating spool. The diameter of the carbon fiber is around 5-7 μm (approx. 0.4 – 0.7 dtex). The thickness of the carbon tow is defined by the number of single filaments it contains, where (K=1000) (1K, 2K, 6K, 12K, 24K, 50K, 60K, 300K, etc.).

The tows may also be used in the following forms:

- Milled powder (less than one mm long) form, or compacted into chips / pellet form.
- Chopped (3-10 mm),
- As tow, by direct extruding.
- Laid, spreaded tow, wound or,
- Using various textile technical methods, variously structured sheet forms (UD, BD, MD or 3D may be attained). Impregnated (pre-pregs) or using the dry infusion process, embedded in matrix material, they can be used as composite reinforcement (Figure 8).

Figure 8. Product forms of carbon fibers

From further processing point of the carbon fiber, it is important that the filaments in the tow be oriented and parallel. It is expedient to guide the carbon fiber – similarly to the Kevlar – on orange peel formed tow guiding elements.

At unwinding of the tows, tow forces should be identical, minimal and independent from changes in the diameter of the spool, in short, it must be constant. At the unwinding creel, when positioning the tow spools at the lateral guiding of the tows, one must strive to minimize any breaks and that tows arrive parallel to the positioning reed. During the guiding, contact between the tows must be reduced to the minimum, overlapping of the tows is not allowed.

In the 50K, 6-10 mm wide tow, there are 35-60 filament layers on top of each other. During sheet formation, it is important that the tow filaments be spread homogenously, without gaps in the plane of the fabric. Namely, uniform penetration of the matrix into the thick filament layers is not ensured and because of this, the tows, by spreading them, are widened and thinned out. An important aim, is the formation of homogenous, gap free, thin, low area density (80-120 g/m²) filaments, which make it possible to form light, selective and valuable composite structures (Figure 9).

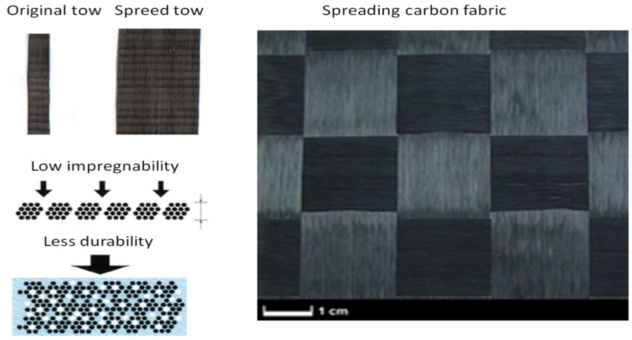

Figure 9. Spreading carbon tow and fabric

Table 1. The mechanical properties of metals

	C – HT High Tenacity	C – IM Intermediate Modulus	C – HM High Modulus	C – HMS High Modulus Strength	E - Glass	Aluminum	Steel
Dichte ρ g/cc	1.74	1.80	1.83	1.85	2.55	2.70	7.85
Elongation at break %	1.50	1.93	0.57	0.63	2.5		1.8
Tensile strength, σ MPa	3600	5600	2300	3600	2470	70-700	2880
Specific tensile strength σ* cN/tex (km)	206	301	125	194	95		36
Tensile modulus E GPa	240	290	400	550	70	70	200
Specific tensile modulus E* cN/tex (km)	13800	16100	21850	29730	2700		2500
Long time heat resistance ºC	500	500	500	500			
Coefficient of Liner Thermal Expansion, α 10⁻⁶/ ºC	-0.91	-0.91	-0.91	-0.91	4-9	22.2	13
Fiber diameter, d, μm	7	5	6.5	5	7-13		
Melting / Sublimation ºC	3600	3600	3600	3600	840	660	1500

Spreading of the tow can be intensified by eliminating twists, reducing sizing, ensuring long free guiding, heating, vibrating and by blowing air on it.

Carbon fiber is a high tenacity, high modulus brittle material, and because of this, in its processing, special handling is required. Since the density of carbon fiber ($\rho \approx 1.8$ g/cm³) and fiber reinforced composites ($\rho \approx 1.4$ g/cm³) is small, their tenacity, in relation to the weight of the material ($\sigma^* = \sigma/\rho g$) and their elasticity modulus ($E^* = E/\rho g$) values considerably surpass the mechanical properties of metals (Table 1).

Tensile strength of the various materials, in general engineering practice is expressed to cross section

(GPa) and weight used in the textile industry (cN/tex, km) as shown in Figure 10.

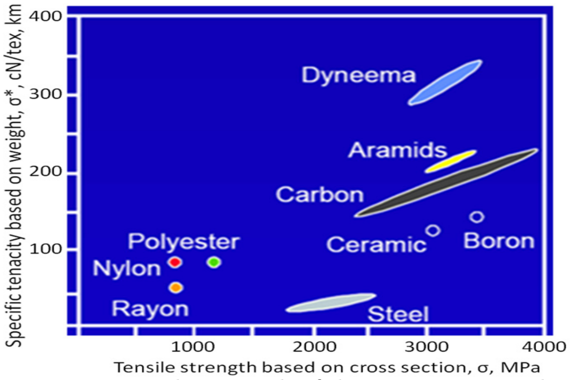

Figure 10. Tensile strength of the various materials, expressed to engineering (cross section) and weight use system

Characteristics of carbon fiber:

- Excellent specific strength and excellent specific modulus
- Low density (ρ=1.7-1.8 gcc)
- High dimensional stability
- High toughness
- Fatigue resistance
- Good vibration damping
- Self lubrication
- Low coefficient of thermal expansion
- Conductivity and thermal stability
- Electrical conductivity
- X-ray permeability
- Electromagnetic protection
- Biological inertness
- Chemical inertness
- Imperviousness to corrosion (high resistance to alkalis, acid and organic solutions).

The light (up to 24K) and heavy (above 24K) carbon fiber producers, and their development capacities are shown in Table 2.

TABLE 2	Manufacturer Nameplate Capacity, metric tonnes PAN-based Small-Tow (up to 24K) Carbon Fiber,						
	2008	2009	2010	2011	2012	2013	2014
Toray	17,600	17,900	18,900	18,900	18,900	18,900	18,900
Toho	10,500	12,200	12,900	12,900	12,900	12,900	12,900
Mitsubishi	7,900	10,850	10,850	10,850	10,850	10,850	10,850
Hexcel	3,550	4,850	4,850	7,300	7,300	7,300	7,300
Cytec	1,800	2,400	4,000	4,000	4,000	4,000	4,000
Formosa	2,850	2,850	3,000	3,850	4,000	5,000	6,000
Others	0	2,150	2,150	2,650	4,650	5,400	7,400
Total	44,200	53,200	56,650	60,450	62,600	64,350	65,350
	PAN-based Large-Tow (more than 24K) Carbon Fiber,						
Zoltek	10,950	13,450	14,050	16,750	17,250	18,250	18,500
SGL	5,000	6,000	7,500	8,500	9,500	11,000	12,000
Toho	1,300	1,300	1,300	1,300	1,300	1,300	1,300
PR China	400	400	800	2,800	3,800	5,000	7,000
Toray	300	300	300	300	300	300	300
Others	100	100	100	1,600	3,100	4,100	4,100
Total	18,050	21,550	24,050	31,250	35,250	39,950	43,200

For the main areas of applications of the carbon fiber demands are shown in Table 3.

TABLE 3	Total Global Carbon Fiber Demand, metric tonnes				
	2009	2010	2011	2015	2019
Aerospace	5,800	6,410	7,010	13,090	18,100
Consumer	6,420	7,000	7,660	9,410	11,120
Energy and industrial	21,210	25,870	29,620	66,760	105,060
Total carbon fiber demand	33,430	39,280	44,290	89,260	134,280

It can be seen that the greatest increase of carbon fiber usage is expected to be in industrial applications. According to the latest forecasts, by 2020, the yearly carbon fiber demand is estimated to be 340 000 tons.

CONCLUSIONS

Light tows are used in the aircraft industry, for sporting goods and for fine machinery components, whereas the coarse, heavier (above 24K) tows are used for bracing large wind blades (blade length above 40 m), automobiles, high pressure tanks, pipelines, offshore drilling, mooring lines, ship hulls, buildings reinforcement (Figure 11).

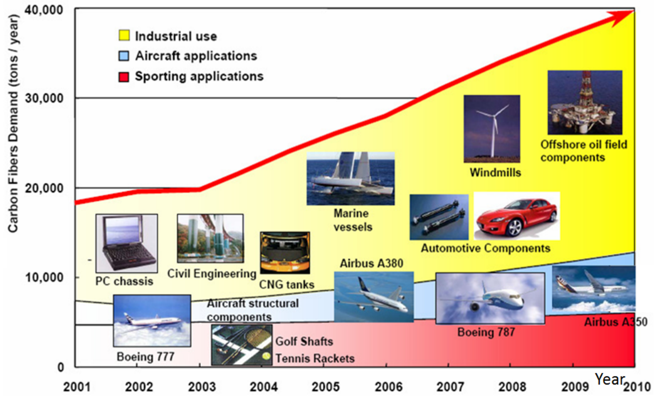

Figure 11. The main application areas of carbon fiber and trends

Carbon fiber – especially in cases where great mechanical requirements need to be met – is a composite reinforcer of key importance. The usage of the carbon fibers will expectedly have wider perspectives in the future.

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