CARBON FIBER REINFORCED POLYMER - THE FABRIC OF THE FUTURE?

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Abstract. This Article is about chances for carbon fiber reinforced polymers, following shortened CFRP, concerning its efficient, powerful, ecosensitive, sustainably and new technical inventions in several areas. It discusses this innovative new material concerning previous history, its production, its pros and cons and new possibilities, as well as the recycling in all its perspectives. Also, biodegradable alternatives of CFRP, like green composites and biocomposites are discussed.

CFRP in nowadays

Due to its low weight and high mechanical properties, CFRP is increasingly found in the automotive industry, power engineering, high-performance sports, boatbuilding and aerospace industry. The highly frequently use of CFRP is based on its resource saving possibilities of lightweight construction and long-life cycle. This high-duty CFRP gives the chance for even bigger and solid constructions, for example used for wind power plants. Worldwide there are wind power plants with a performance of about 190GW. In 2010 a growth of 15%, about 30GW a year, was predicted. To accomplish this growth, CFRP is essential needed to design larger, durable and more efficient constructions of wind power plants.

Furthermore, the application of CFRP is essential in order to optimize the fuel consumption and hence resulting reduction of carbon dioxide emission of public transportation. Those public transports gain more and more importance in the United States of America, Europe and Asia as well. In the next years, approximately the aerospace industry and automotive industry will increase the demand of CFRP. (1) (2)

History

Carbon fiber have their beginning of history in the end of 19th century. In the Beginning the fibers were used as filaments for electrical incandescent bulbs. The production of those carbon fibers was protected by patents in 1878 through Swan und 1879/1892 through Edison. The development of composites began in the year 1935 with the production of fiberglass, which had non-satisfying mechanical properties. The further advancement arose a boric fiber, which was thickly vacuum-metallized, an in addition, heat-proof carbon fiber. In 1966 was polyamide initiated. In the 1950s the aerospace industry claimed a new material solid and light construction at the same time. In order to cope with the development required by aerospace industry, an example was taken of the nature, where many anisotropic structures are found. Caused by the advanced research on anisotropic structures, a great aperture was made in 1955. The British Royal Aircraft Establishment produced fibers, with directional crystal structures. (3) (4) (5)

The growing requirement especially in the latest years is shown in Figure 1. The ordinate shows the demand of CFRP in tons per year. The demand for CFRP has almost doubled over the last seven years.

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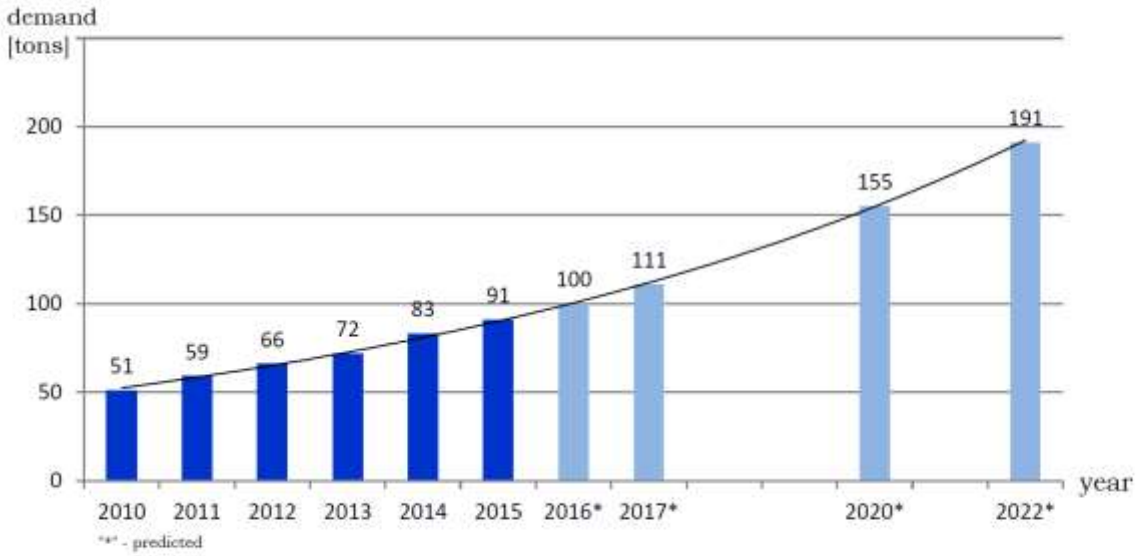

Figure 1 **CFRP requirement (2)**

Carbon Fiber Reinforced Plastic

CFRP is a combination of carbon fiber (short fiber, long fiber or continuous fiber) and a matrix. The material of the Matrix is distinguished between duroplast, thermoplastics and elastomer, that have different structures. (see Figure 2)

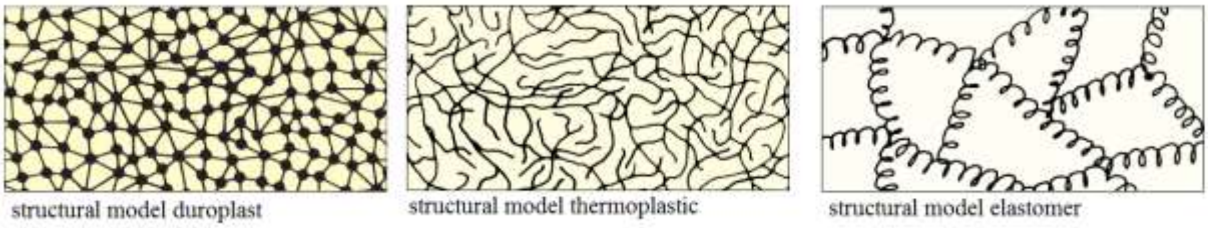

Figure 2: **Structural models (6)**

Laminate layers are made of the carbon fiber and matrix. These laminate layers are compressed together in unidirectional or multi-directional laminates (sheets) and hardened. For parts with critical high stress locations there are laminates with thickness changes in the sheets, in order to accomplish the high mechanical requirements but to save material and weight at the same time. (3) (6)

The technical process of CFRP is not developed as good as it is in metal processing, because there are a lot less experiences with it. Therefore, engineers are asked to develop ideas to produce faster, more precisely and, above all, more material-saving parts made of CFRP. Moreover, it is important to find an alternative for the high-power demand, that occurs due the production of CFRP in order to establish new, more efficient production methods. One option could be heat supply by microwave plasma. (7)

Production of CFRP

The anisotropic polyacrylonitrile fiber, following shortened PAN-fiber, is stabilized through oxidation in a quasi-continuous, high power demanded process at a temperature of 200°C - 300°C in order to produce an infusible fiber. The stabilized PAN-fiber will be carbonized at 1400°C afterwards. In this process, the fibers react to "molecular bands" that has a graphite like structure. Finally, the fiber surface is treated and a preparation is applied to wound into a spool. The fibers have a diameter of 5 - 7 μm. There are other fiber types that differ in their modules.

For the matrix is a duroplast or thermoplastic used. Polypropylene is used for thermoplastic CFRP. Duroplast matrices are epoxy or polyester resins. The Duroplast matrix-materials are very good, because they adhere very well to the fibers.

The Fibers are embedded in the matrix so that a laminate single layer is formed. These single layers are laid into unidirectional or multidirectional laminates. They are consolidated under pressure and heat. The curing process takes place in autoclaves at 130°C - 180°C. The pressure inside the autoclave is between 1bar to 10bar pressure.

CFRP has anisotropic behavior due the use of the fibers, which is utilized to produce a fabric which is mechanically, in a definable direction, highly resistant against stress. This characteristic leads to material savings but at the same time the required properties can be adjusted. Anisotropy means that material is very strong in one direction. For CFRP, as an example, it is the longitudinal direction of the PAN fibers. There are components in which the anisotropic property is used to realize an even lighter construction. But if this property is not desired, however, the sheets can be laid unidirectionally, so a quasi-isotropic laminate is produced. (7) (8)

Production of CFRP Components

Components made of duroplast, preimpregnated CFRP are cured at a temperature of 180°C for several hours in an autoclave. These preimpregnated sheets are called prepregs. This process is combined with a high-energy input, because some components, especially for the aerospace industry, have great dimensions and therefore the whole space in the autoclave has to be heated. (4)

In addition, there are thermoplastic pre-product sheets, that can be formed under heat and pressure to produce components. Components produced of thermoplastic CFRP have a lower resistance against high temperatures, in comparison to duroplast CFRP components, but the forming need a lot less power. (7)

In contrast to the CFRP's with duroplast or thermoplastic matrices, there are also other composites which can be processed differently and consist of other fibers. One example of this is the production of carbon fibers from renewable raw materials, e.g. lignin or a reinforcement of the polypropylene with hemp fibers. (9)

Development Trend

As a result of the increasing experience with CFRP, the pre-products and components become more and more efficient. The increase in performance will be more and more precisely adapted to the application area in the components and for example, components can be realized with different thicknesses or various fiber orientations, depending on the highest stress direction. Also, research is being carried out on the hybrid constructions in which CFRP and titanium is mated not cutting. These improvements van be calculated very well by the finite element method.

Automation in the area of CFRP is also significantly lower than in the metal sector. An assembly line production, as it is found in the automotive industry, can't yet be realized in the production of CFRP. However, if further steps are made in this area, the resource CFRP becomes more and more profitable so that it can be used not only for high-performance products, but in low cost segments as well.

Benefits and Drawbacks of CFRP

The main advantage of CFRP polymer is its outstanding strength to weight ratio in comparison to other materials. The ultimate tensile strength of carbon fiber alone can be more than 4000 MPa, which is about five times the ultimate strength of stainless steel. CFRP is lighter than aluminum, stronger than steel, and equipped with higher elasticity than titanium. (10)

Further advantages are the high rigidity and high elasticity combined with a low corrosion tendency and resistance to alkali. Not only for its relative low weight are there many applications of CFRP in aerospace industry, but also CFRP's high resistance to strain and abrasion is very useful for aircraft components, which are exposed to high stress during start, flight and landing. Components made of carbon fiber have an exceptional durability under the stress of constant use. (10)

Also, carbon fibers have low heat expansion ratio and high dimensional stability. CFRP being exposed to high temperature sustains its excellent mechanical performances. Another benefit is the high electric conductivity of CFRP and at the same time the excellent electromagnetic shielding property. (10)

On the downside CFRP has a low resistance to plastic deformation and would break when bending. This is because, the material shows a strong anisotropic behavior, meaning their properties depend on their orientation. The carbon fiber can only reach its good properties, when the load is applied in longitudinal direction along the orientation of the fiber in the matrix. A transverse load applied at 90° to the fiber axis leads to rapid material failure. (10)

A big issue is also the fire behavior of CFRP. Research shows that the ash of the carbon fiber reinforced composite released the fiber. Those released fibers, breathed in, are hazardous to health and generate an impact comparable to asbestos. Normally carbon fibers cannot be inhaled, but if, they reach temperatures of more than 650° Celsius, the fibers change and reach a critical size that can penetrate deep into the lungs. (10) (11)

Another problem is that carbon fiber is extremely high in manufacturing cost, which causes higher material cost for the composite. This is the main reason CFRP does not succeed in the mass market, as it is simply too expensive. (10)

In the beginning of producing CFRP, operating costs were not critical design parameters and neither were the environmental effects of production. So, that the energy demands of this heat intensive process are enormous and also greenhouse gases such as carbon monoxide and nitrogen oxide are released in the manufacturing process. Additionally, the waste produced by CFRP is environmentally unfriendly, because it is difficult to recycle. Now, most of the waste is burned or shredded into smaller parts. The polymer in the composite needs decades to fully break down. (12)

Biocomposites – A biodegradable alternative composite to CFRP

Most of all composite including CFRP are difficult to recycle or to reuse, so that about 94% of composites end up in landfills. More than 30 million tons of plastic waste was produced in the US alone in 2007. But CFRP is not only difficult to recycle, also most of its components is based on crude oil. The raw material polyacrylonitrile for the carbon fiber as well as the plastic for the matrix are based on this limited resource. Studies by the "World Wide Fund for Nature" have shown, that humanity is currently consuming natural resources at a pace 20% faster than Earth can produce them. Thus, there is a growing demand for biodegradable composites. (13)

And biocomposites are intended to fill this gap. A biocomposite is a composite material formed by a matrix and a reinforcement of natural fibers. Natural fibers are subdivided based on their origins, coming from plants, animals or minerals. All plant fibers are composed of cellulose while animal fiber consist of proteins e.g. hair, silk, and wool. For examples plant fibers are produced from the leaves of date palm or sisal, the stem of flax, hemp or jute, bamboo grass or the typical seed of cotton. These are only some examples of sources of natural fiber, but the most used natural-organic fillers are wood flour and fibers. Wood flour can easily be obtained from sawmill wastes and it is usually sieved before using it. The matrix of biocomposite are normally also made from petroleum-based polymer. (14)

Green composites

A composite made from only eco-sustainable material is called green composite. Green composites have the synthetics matrix replaced with a biodegradable one. Those natural-derived polymers are made from starch, gelatins, polyesters, lignin, lipids, natural rubber. One example is a composite based on starch and bamboo fibers or another one based on soy proteins in combination with pineapple and jute fibers. Those green composites do not achieve the same properties as biocomposite, or even CFRP. Green composites are mainly produced by American, German, Japanese, British and Italian firms (14) (15)

The structure of natural fibers

The main components of natural fibers are cellulose, lignin, pectin, and waxes. The cellulose fibrils are aligned parallel along the length of the fiber, which provides maximum flexural strength and tensile strengths. Lignin is the compound that gives rigidity to the plants. At the moment, there has been no method established by which it is possible to isolate lignin in its native state from the fiber, so that the fiber can only be produced naturally. Pectin give plants flexibility and waxes ensure the cohesion of the fiber. The inner structure of the fiber, the microfibrillar angle, cell dimensions, defects, and the chemical composition of fibers in the matrix are the most important variables that determine the overall properties of them. For example, more parallel to the fiber axis orientated microfibrils, lead to rigid, inflexible fibers, but for high tensile strength. The reason for the reinforcing efficiency of natural fiber lays on the nature of cellulose and its crystallinity. Generally, tensile strength and Young's modulus of fibers increases with increasing cellulose content and the microfibrillar angle determines the stiffness of the fibers. (14)

Application of Biocomposites

Industrial applications of green composites are in general those applications which do not require very high mechanical resistance but, instead, low purchasing and maintenance costs. Some examples of applications are window frames, furniture, railroad sleepers, gardening items, or shelves. Also, the automotive industry played an important role in the field of biocomposites. Already in the late 1990s Mercedes-Benz was the first carmaker to use reinforced polymers with jute fibers in their door panels. After this many other main carmakers followed this example, and natural composites were also used for door panels, roof upholstery, headrests, parcel shelves. The use of biocomposite improved the car companies image regarding the environment, but also the weight, elastic modulus and costs helped to raise awareness of this new material. (15)

Benefits and Drawbacks of Biocomposites

Research makes good progress in investigating the exploitation of natural fibers as load bearing constituents in composite materials. The use of natural fibers in composites has increased due to their relative cheapness in comparison with other fibers like carbon, their ability to recycle and that they can compete well in terms of strength per weight of material. Biocomposites have a low specific weight, which results in a high specific strength and stiffness. They also present safer handling and working conditions compared to synthetic reinforcements. The main benefit of natural fibers is their positive environmental impact. Biocomposites, which raw material is available worldwide and based on a renewable resource, are with production requiring little energy. In fact, they are carbon dioxide neutral which means they do not return excess carbon dioxide into the atmosphere when, composted or combusted. Further, Biofibers possess high electrical resistance and thermal recycling is possible. (14)

On the other hand, the choice of matrix material is restricted, due to the processing temperature of natural composites is limited to 200°C as green fibers undergo degradation at higher temperatures. Another issue is the high moisture absorption of natural fibers leading to swelling and presence of voids at the interface, which results in poor mechanical properties and reduces dimensional stability of composites. Another restriction to the successful exploitation of biofibers for durable composite application is low microbial resistance and susceptibility to rotting. Now, the major disadvantage of natural fiber reinforced composites is, that the inherent polar and hydrophilic nature of lignocellulosic fibers and the non-polar characteristics of most thermoplastics results in compounding difficulties lead to irregular distribution of fibers within the matrix which impairs the strength of the composite, so that most Biocomposites have a tensile strength in-between 345 to 1035 MPa. So, when very high strength is needed, but the environmental impact of the composite is also important, it is worth to have a closer look at recycling of CFRP. (10) (13) (14)

Recycling

Components produced from CFRP have a lighter weight and thus save resources during use. Nevertheless, the fuel economy for aircraft and vehicles are relatively low. Not to be neglected is the very energy-intensive and cost-intensive production of CFRP. So what happens with the complexly produced CFRP components after their use and the resulting production waste like blends.

Every year, many tons of CFRP waste is generated in Europe, most of which is incinerated, i.e. converted into thermal energy. Even if CFRP has very good thermal data during combustion, it is not economically and ecologically recommended. Demand for CFRP is increasing, but capacity is limited.

The CFRP material circuit must be closed. Thus, CFRP would have considerable advantages in the carbon dioxide balance compared to other composites, would save waste, relieve the environment and reduce costs, since reused or recycled CFRPs are significantly cheaper. (7)

Types of waste

Three groups of waste can be distinguished. Fundamentally, a recovery of the carbon fibers is possible and desirable. Further categories of the classification can be divided into carbon fiber types and matrix types, such as the fiber arrangement.

1. Wastes arising during the manufacture of carbon fibers or semi-finished fiber products: These are pure carbon fibers, which have not been impregnated with resin and are easily recyclable. Other wastes are e.g. in weaving mills in the production of fiber semi-finished products. The sewing causes edge residues and requires the separation of the polyester threads from the carbon fibers. Through various steps, such as grinding, cutting and textile processes, the fibers can be reprocessed into semi-finished products.
2. Production waste resulting from the processing of CFRP semi-finished products: In the processing of semi-finished products, e.g. prepregs can contain up to 35% waste residues. The dimensions of the remains depend on the component and range from a few centimeters to half a meter. Partially, complete Prepreg rolls are disposed of after quality or product inspection. The reason for this are fluctuations in the fiber volume, deviations from the matrix system as well as weaving errors or overlaps. Wastes are also produced during further production processes. The advantage of these materials is the possible re-use for other productions (for certification reasons not in the aviation industry) or tools. Since the fibers have already been

impregnated with a plastic matrix, recycling can only be done by particle recycling or a separation of fiber and matrix, called pyrolysis.

3. Patterned or used parts without further use. The carbon fibers are embedded in a cured matrix. In addition, these wastes are often contaminated with sealants, paint layers, inserts or sandwich cores, which must be removed by methods such as magnetic separation of metallic components. To make matters worse, recycling by pyrolysis is not easily possible.

Recycling of Group 2 and 3 is somewhat more difficult. It is possible by particle recycling or pyrolysis, since the carbon fibers have to be separated from the composite matrix. Furthermore, the problem on contamination should be given more attention. (16)

Waste problem

Some companies only produce very small amounts of CFRP waste and dispose of these as commercial waste instead of collecting and recycling them. Therefore, Recycling has to be generally more profitable, companies must benefit from the closed material cycle and promote it. Laws should not only take account of components, but also, in particular, of production waste. To act sustainable belongs to the quality standard as well.

Recycling types

Currently, methods of recycling are being researched and developed. The challenge is to separate the carbon fibers in their entire length without damage to the composite matrix. It is also desirable to retain the composite matrix. So far only approaches for the recycling and the re-use of CFRP are available, since the products are only crushed and thus also the fibers. The recycling thus results in relatively short fiber, which can be no longer processed into fiber mats for high-quality CFRP components, but are suitable for numerous other applications, e.g. reinforcing components in plastic parts, injection molding of lightweight components, interior lining and vehicle electronics. If, for example, the short fibers obtained from recycling are used for further components, where the fiber lengths are sufficient, the weight of the product and the amount of waste will be reduced further. Moreover, recycled CFRP is significantly cheaper than newly produced CFRP. (16)

Without separation of carbon fibers and matrix

The composite material is melted and formed into a new component. The problem is that not all thermoplastics can be connected, the plastics are subject to wear and teer and thus the quality decreases. (12)

Separation of carbon fibers and matrix

The matrix bursts off the fiber by a hammer blow, the fiber is shortened by this and can be embedded in other plastics as reinforcement. The matrix is thermally processed and reused. Thus, both substances can be reused. (12)

Thermal separation – pyrolysis

The thermal decomposition temperature of carbon fibers is 3600 ° C and is thus higher than that of the matrix (max. 400 ° C.). If the composite is heated, the matrix decomposes and the carbon fiber is retained. A disadvantage of this method is the enormous energy expenditure. (16)

Conclusion

CFRP is definitely the composite of the future. However, as with all other resources sustainable management is required. We must reuse, recycle or recycle products. A simple disposal is neither ecologically and economically justifiable. The plants need to be more efficient and sustainable, for example through the use of residual heat and renewable energies. Recycling methods must be further developed. Natural fibers are also conceivable in the future, but research must continue in this area.

CFRP should be used deliberately for long-lasting, high-quality products and then reused. It is quite useful to use CFRP in aircraft and vehicle construction as well as in many other areas.

Recycled fibers should increasingly be used in areas of reinforcements or non-structural components.

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