Carbon Fibre - Cost Overview

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Abstract

Carbon fibres are well known for their excellent mechanical property. It's used as a structural material due to its high specific strength in a fibre form supported by its low density compared to conventional metals. Carbon fibre was used in the 19th century & over 70 years of continuous research & development diversified carbon fibre applications from Defense and aerospace to Automobile, wind energy, industrial segments, sports, etc. Its wide usage is limited due to the cost of production. Carbon fibre needs to be cost-effective. For the same, its standard grade's price needs to be reduced from 20 – 25 \$/ Kg to 10 -12 \$/Kg. We herein attempt to provide a summary of a Factor affecting the cost of carbon fibre like Raw material, manufacturing methods, & cost of quality. Here we also discuss the recent cost-effective manufacturing technologies like Cut carbon fibre (CCF) for composite-based applications, Textile grade PAN & advanced processing techniques like plasma oxidation for low-cost Carbon fibre.

Keywords

Carbon fibre, Precursors - Polyacrylonitrile, Pitch, Renewable resources – Lignin, Textile grade PAN (T – PAN), Advance plasma oxidation techniques, Cut carbon fibre (CCF), Tow size, Cost of the quality, Cost reduction, Application.

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1.0 Introduction

Carbon fibre is a superior material known for its versatile properties like mechanical strength (tenacity 3-6 GPa, modulus of 300- 500 Gpa), low density (1.8-2.2g/cm2), and excellent formability into different composite products [1]. It is used in aerospace, high-performance cars, equipment for defence, and windmill application [2,4]. More than 96% of commercially available carbon fibre is based on Polyacrylonitrile (PAN) based chemistry, which gives the best product at a commercially viable price [3]. The standard grade carbon fibre, which has the most significant share of commercially produced fibre with average tenacity in the range of 3.5GPa, is sold approximately in the price range of USD 20-22\$ [5]. Some of the carbon fibres used for aerospace applications with higher modulus or tensile strength are sold even at a higher price than this. The cost of carbon fibre became the main hurdle in its growth.

Recent governmental, environmental, and industrial consortium efforts are pushing the automobile industry to reduce its carbon footprint [6, 8]. One way to reduce carbon emissions and increase the fuel efficiency of an automobile is to mitigate its weight [9, 10]. Here the low-density (~1.8 g/cc) carbon fibre with moderate tenacity of 1.75 GPa and modulus of 175GPa can become a solution [11, 12]. The industry desired the price of carbon fibre to be below US10\$/kg to make it commercially viable [13]. It led to a lot of research on low-cost carbon fibre. Research studies are coming up the different materials and improved processes to reduce the cost of carbon fibre [14-19]. Textile grade carbon fibre is gaining much attention in this regard; ORNL has developed a new method to process the textile grade carbon fibre and get the desired quality of carbon fibre with the targeted price [20, 21].

2.0 The inception of carbon fibre manufacturing:

To understand the current manufacturing scenario of carbon fibre, we need to understand the inception of carbon fibre manufacturing. Carbon fibre as a material has been well known since the late 19th century, as Mr. Joseph swan and later Mr. Thomas Edison developed them for electric bulb application from cellulose. But it was in 1958 Dr. Roger bacon at Union carbide's R&D that developed a graphite whisker. The short carbon fibre has a strength of 20 GPaandmodulus of 700 GPa, which created a new interest in carbon fibre manufacturing [22]. Union carbide later patented the longer carbon fibre manufacturing by graphitisation of rayon fibre [23].

Rayon is regenerated cellulose and carbon fibre produced from this process, giving a low process yield (less than 30%). Meanwhile, around the same time, Polyacrylonitrile as acrylic fibre for textile application was also developed at the commercial level at Dupont and sold under the brand name Orlon. After world war-II at Government funded institute GIRIO in Japan, Dr. Akio Shindo developed a process for producing the carbon fibre from Polyacrylonitrile using an

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intermediate slow oxidation process which gave a material yield of 50-60% [22]. Toray Industries developed this process further and since then led as the biggest manufacturer of the carbon fibre industry. In England, during a similar time, Courtauld developed a special acrylic fibre (SAF) with itaconic acid as a co-monomer for acrylic fibre dye-uptake.SAF had the drawback that it was getting yellow during the processing stage. Later they used this SAF for a faster oxidation process in the carbon fibre process. Even though PAN-based carbon fibre gives very high tensile strength, the overall process yield (~50%) and multiple manufacturing stages kept the cost of the product very high. Another material used as a carbon fibre precursor was Pitch. Pitch is an anisotropic composition of aromatic hydrocarbon. In 1970, Union carbide also developed mesophase pitch-based carbon fibres. The mesophase pitch has a good process product yield of ~80% and gives less load on the abatement process. The carbon fibre produced has a tensile modulus of ~900GPa. But the tenacity is less compared to PAN-based carbon fibre.

Earlier applications of carbon fibres were primarily related to defence applications like shells for missiles or as aeroplane components. Later, in 1972 the American golfer Jim flood won the golf tournament using a carbon fibre shaft-based golf club. It started the use of carbon fibre in sports gear applications. Post-cold war, the Demand for military applications was suddenly reduced, which led to a change in the focus of research on the utility of carbon fibre. With constant research and incremental development in the carbon fibre industry over 70 years, its usage diversified in different fields like wind energy, aerospace, automobile, and industrial segment.

Besides the technical challenges to manufacturing carbon fibre, its manufacturing cost becomes its biggest hindrance. Compared to a standard grade low carbon steel (1.1$/kg) or aerospace-grade aluminium(2.5$/kg),a carbon fibre cost is several times higher (range of 20 to 25$/kg). Despite its superior mechanical property, low density, and corrosion resistance.; its usage and production are limited. So current research work is mainly focused on producing low-cost carbon fibre.

Recently published [24] information about carbon fibre manufacturing and its demands in composite applications indicates the healthy growth in the carbon fibre market. In the year 2019, 161200 tonnes of carbon fibre were produced. The Japanese company "Toray" is aggressively pursuing growth, and they have produced 57000 tonnes of carbon fibre which is almost 35% of the world's total production. They recently took over leading composite manufacturer "Tencate", showing their commitment and ensuring the market for their produced fibre. After Japan, which has 43% of total world manufacturing capacity, country-wise, the United States ranks second with 25% of world production, mainly contributed by Hexcel and Mitsubishi Corporation. Chinese, Taiwanese, and SouthKorean are also trying to increase their manufacturing capacity. Chinese top five manufacturers having less than 10000 tonnes capacity per year contribute almost 13% of the global carbon fibre production. Kangdexin (in Changing, china) is said to have an aggressive plan to expand its manufacturing capacity to 70K tonnes per year.

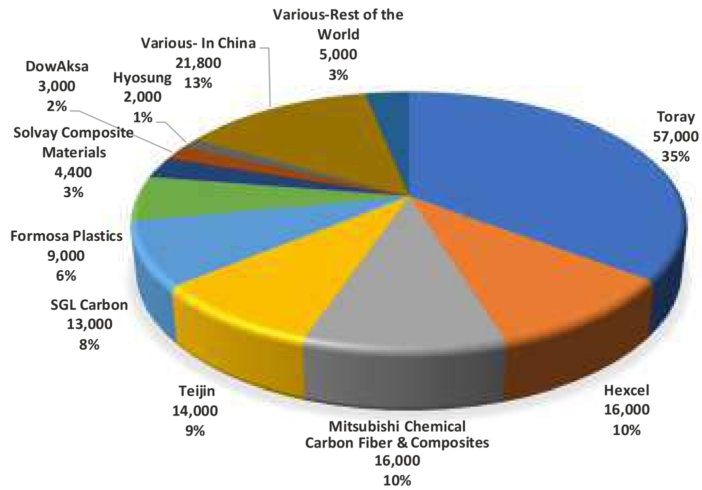

Figure 1 - Carbon fibre manufacturing capacity - year 2019

The carbon fibre industry has product varieties according to their end-use. They can be classified as per their mechanical strength or their tow size, which is the number of filaments in a bunch. Tow sizes are designed as per the requirement of the end application and the manufacturing processes of composite products. But broadly, we can classify them as per the end application like Aerospace, Industrial, and sports/leisure, which are broadly defined by the different strength grades of carbon fibre.

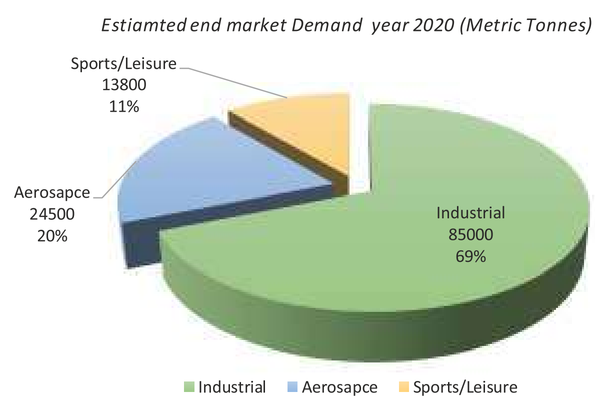

Figure 2 - Demand for carbon fibre as per application sector - year 2019

The overall yearly demand for carbon fibres as per the estimation until 2025 will reach the value of 191350 MT compared to today's 123300 MT. Steady growth in the industrial sector where Demand will reach for wind energy (27,300 MT), transportation (22,750 MT), infrastructure (20,800 MT), and pressure vessels (19,500 MT). The aerospace sector will require 30000MT, of which 15500MT will be used in commercial aeroplanes. The sports and leisure market will also show growth and Demand of19000MT.

The following table gives an idea about carbon fibre's classification based on the end application, its required mechanical strength, and the Tow size used. Based on Tow size (i.e. number of filaments/bunch), they can be classified as a Small tow(≥24000 or 24k filaments) which will be sharing 70% of the overall carbon fibre demand compared to large tow (≤24000 filaments like 40k or 50k) (Das et al. 2016). High modulus fibres(more than ~500GPa) are primarily used in aerospace and defence applications, where their cost is affordable in terms of end-use. Standard modulus grade fibre has almost 80% market share today. The standard modulus or general-purpose grade is sold approximately at 20$/kg.

Type	Modulus (GPa)	Strength [MPa]	Tow Size (K)	Application
Standard Modulus	230	3,500	12–50	Automotive, Aerospace
Intermediate Modulus	400	5,000	3–24	Pressure Vessels, Wind Turbine Blades, Aerospace
High Modulus	500	3,500	1–12	Aerospace

Table 1 - Grades of carbon fibre as per application sector(Das et.al)

But in the current situation of the COVID-19 pandemic, [25], these projections will be changed or delayed in the years to come. Post-pandemic, the world order will be changed. The way we were doing the business will change. Hostilities within countries will change trade relations. With economic recessions, the industry will be under tremendous pressure to sustain manufacturing and maintain the product cost. The aviation industry is severely affected by the current situation, and it will take a longer time to revive and get back into the business. Naturally, which will put a hold on aeroplane manufacturing and, subsequently, demand aerospace-grade carbon fibre, one of the costliest grades in carbon fibres.

Another factor that is ignored most of the time is the cost of quality. It's nothing but a loss in profit due to poor product quality [26]. It is known that the carbon fibre industry runs or control all the process step with tight tolerance. Ideally, the process tolerance coefficient of variation on percentage yield is targeted below 1.0%. But it is observed in real life that for small tow (1Kto 24K), it is in the range of 3%, and in the case of large tow (more than 24k), the tolerance limit is in the range of 15%. Based on the tolerance limits on product quality, there will be a production of sub-standard products and production waste, which will increase the cost of manufacturing or reduce the profits. Due to the secretive nature of the carbon fibre production process, it is challenging to get the actual data on carbon fibre's cost and the impact of various process controls on the product quality. The cost of the quality and the size of fibre production are also interlinked. The increase in two sizes in the same production facility increases the overall production capacity.

This commercial carbon fibre precursor material, i.e. PAN, Pitch, and Rayon, has advantages and drawbacks in terms of fibre properties and processability. Overall the carbon fibre with desired physical properties is costlier.

3.0 Carbon fibre its end application in composites:

At the initial stage of development, the Demand for carbon fibre was limited. They were mainly used for defence applications. In 1960, American golfers demonstrated the superiority of carbon fibre-based golf-club compared to conventional construction materials. It opened a new area in sports goods. Japan's Toray took the lead in this area and significantly developed the carbon fibre variety for sports applications.

Carbon fibre growth is always going hand-hand with growth and development in composite manufacturing. The cost of the Composite product defines the Demand for carbon fibre. Composite manufacturing defines the required properties of carbon fibre like tensile properties, surface treatment, and tow size. E.g. For aerospace applications, high modulus (500GPa) and high strength(more than 3.5Gpa) carbon fibre with a tow size of lesser than 12k filaments are preferred. Large tows (24k to 50k) having standard (230Gpa) or intermediate(400Gpa) modulus; are used in automotive parts or windmill application [3].

The automotive market is very price sensitive. As per Auto-industry, for successful commercial utilisation of carbon fibre, its cost should be 10-12$/kg range, Which is driving the development of low-cost raw materials for carbon fibre manufacturing. A low-cost renewable resource like lignin is one of the candidates in the development process.

Composite manufacturing processes like filament winding, autoclave moulding, compression, and resin transfer moulding; have their issue. Like longer manufacturing time, resin curing time, energy-intensive autoclave for curing, labour intensive prepreg layup process which adds up to the final cost of the product [27]. New development in Cut Carbon fibre (CCF) from large tow carbon fibre is promising for the automotive application [28]. CCF is compatible with most composite-making processes like stir and slip casting, compression moulding, and automated spray deposition. It overcomes the disadvantages of long carbon fibre processing, where it requires unique processing like filament winding, co-curing, and tow spreading, which significantly increases its processing cost. So, it is evident that the demand for carbon fibre in industrial application development in low-cost composite manufacturing is essential [29].

4.0 Carbon fibre manufacturing in terms of its raw material and end product cost:

Carbon fibre production was first started with rayon based process, but due to lower product yield (33%) and low mechanical strength, it is losing its competition with PAN-based processes. The use of Polyacrylonitrile as the prime material for manufacturing carbon fibre compared to other raw materials is the ease of production with acceptable quality fibres and high product yield. Nowadays, there is a strong drive towards using cheap renewable resources like lignin as raw material, but it's still in the research and development stage.

Carbon fibre cost depends upon the raw material and production process. We can classify carbon fibre manufacturing in broadly three steps. Raw material preparation for precursor, precursor spinning, and precursor thermal treatment. A precursor is a raw material in the fibre form that will be converted into carbon fibre by thermal treatment.

Following are the various raw materials available and used to manufacture carbon fibre. The base raw materials are petroleum-based products like Polyacrylonitrile, Pitch, or natural sources like regenerated cellulose rayon. Precursor formation involves two steps that are raw material preparation and fibre formation by spinning process. Precursor thermal treatment is divided broadly into two stages, i.e. stabilisation (oxidation) and carbonisation. There is significant material loss during thermal treatment due to pyrolysis, which gives a negative product yield. Product yield has a direct and major impact on the cost of final carbon fibre.

Precursor	Cost ($/kg)	% yield	Cost of carbon fibre ($/kg)
PAN	3.0-6.0	50-55	20-25
Pitch	1.0-2.0	80-90	~60.0
Rayon	~2.2	10-30	NA
Melt spun PAN	3.15	=50	13.0-17.0
Lignin	~1.52	30-55	4.0-6.27
Polyethylene	1.57-2.36	70	NA
Textile grade PAN	2.2-2.5	~50	11-12

NA-not available

Table 2 - Costs of carbon fibre based on precursor yield

Table 1 indicates the cost of precursors produced from different raw material sources. The cost of the carbon fibre was derived based on the %carbon yield and the approximate precursor thermal processing cost. The values indicated lags the detailed costing as per the Tow size and processing conditions; it is given as a general idea to understand the product yield and cost. PAN chemistry-based precursors which are produced by the wet spinning method, are available at the price of 3.0-6.0$/kg. Considering 50% carbon yield, it turns out to be a costlier precursor. Large tow size carbon fibres produced from PAN chemistry like SGL's sigrafil C (24k-50K tow size) and Zoltek's Panex-33(48K tow size) are sold at the cost range of 15.4-24.2$/kg.

Pitch-based carbon fibres are costlier even though Pitch is a cheaper petroleum by-product. Standard grade carbon fibre from Pitch needs to be converted into mesophase Pitch for manufacturing. This conversion process of the isotropic Pitch to mesophase is costly. It requires careful chemical processing to get the desired level of high molecular weight polyaromatic structures like asphaltenes.

The melt spinning method reduces the cost of spinning due to higher spinning speed (3 times the wet spinning), and it also avoids the usage of hazardous solvents [30,31]. To make it melt process-able, PAN polymer can be co-polymerised with higher co-monomer content (10% methyl acrylate), which negatively affects the overall carbon yield of the final carbon fibre [32]. Alternatively, plasticizers (like water) are also used to ease melt processing. However, it requires a specially designed melt processing system to handle the high water pressure [33, 34]. The carbon fibres produced also have micro-voids (act as weak spots), which leads to lower tensile strengths (~2.5GPa). Overall, this method is still in the concept stage, and the properties of resultant carbon fibres are inferior to wet spun PAN-based carbon fibres. Pitch is a cheaper petroleum side product [35]. The cost of purification of Pitch and converting it into mesophase (required for high-strength fibre) escalates the cost of pitch precursor higher than the PAN precursor [36]. Rayon is not the preferred precursor as the %carbon yield is very low [37].

To lower the cost of precursor polymer, various precursor chemistries like lignin and polyethene were explored. Lignin precursor is one of the cheapest precursors available at the cost of ~1.5$/kg [14, 39, 39]. Lignin goes through complex chemical reactions during stabilisation. It gives a lower material yield (10-28%) with low strength carbon fibre (tensile strength 1.2-2.5GPa). Sulphonatedpolyethene is considered for melt spinning application which gives carbon fibre with better carbon yield of (>60%) and medium tensile strength in the range of 2.5GPa [40, 41]. Commercially this process is not viable due to the handling of corrosive sulphonation reaction. Efforts were made to use textile-grade PAN as a precursor for cost-effective carbon fibre. However, the absence of essential carboxyl functional co-monomer, low polymer molecular weight (≤105Da), higher precursor fibre denier, low molecular orientation, and low tensile strength of precursor fibre resulted in low tensile strength carbon fibre [42, 43].

Another approach for reducing the cost of the precursor is blending PAN with low-cost lignin. Carbon fibres produced by blending had a micro-void issue on the fibre surface and had a low tensile strength of 1.2GPa. Compared to other precursors' chemistry, PAN-based precursors are the costlier but superior option in manufacturing and have better tensile properties [44].

The lower cost of textile grade PAN compared to PAN precursor may be attributed to the scale of manufacturing, i.e. producing 100K filament size tow compared to less than 50k filament size tow [29]. Textile grade PAN is processed using an advanced plasma oxidation technique that has been demonstrated at a laboratory scale. SGL/FISIPe, in collaboration with ORNL, has developed carbon fibre from textile grade PAN-based copolymer of vinyl acetate and methyl-acrylate. At the experimental level, they demonstrated carbon fibres with desired tenacity. They expect the cost of carbon fibre produced using textile grade PAN and advanced processing techniques like plasma oxidation will be at~11-12$/kg [20, 21].

Looking at available raw material options, textile grade PAN seems to be a viable option to produce in the existing manufacturing setup. At this point, we want to understand the key differentiators between the Commercial PAN precursor and textile grade PAN (T-PAN) fibre in terms of its physical and chemical properties and need to highlight the process and hardware changes required to use T-PAN as a carbon fibre precursor

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