FUTURE DIRECTIONS AND TRENDS OF THE CARBON FIBRE MARKET

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Abstract

Carbon fibre production and its postprocessing is a sub-sector of the chemical industry. With the beginning of carbon fibre production in 1971, the market for those fibres is rather young. Commercial production of carbon fibres began in Japan and was initiated by companies like Toray, Toho Rayon (nowadays: Toho Tenax) and Mitsubishi. These companies still are among the biggest producers in the world. During the mid-1980s, US and European companies (e.g. Zoltek, Cytec and Hexcel) also have begun the production of carbon fibres, and there is also one important established producer (Formosa Plastics) from Taiwan. Although the latest developments show that more and more enterprises from related branches, most notably from polyacrylonitrile fibre production, and other regions are aiming at entering the carbon fibre market. Today polyacrylonitrile based carbon fibre production is dominated by 8 large companies. These 8 companies have more than 88 % of the worldwide production capacity of carbon fibres. Seen from a historical perspective, the main development direction of carbon fibres was maximizing of strength and Young's modulus and not mainly on the properties, which are needed for a proper CFRP layout. Furthermore, the required fibre properties are even unidentified in some cases.

1. Introduction

The fact, that carbon fibres available on the market usually display similar properties, while not being standardised, presents two problems for component developers. Firstly, developers can only utilize fibres with a limited property range. Secondly, due to the lack of standards, each component must be adjusted to the properties of the respective fibre type. A load capable design is therefore difficult. In contrast, exact knowledge of the requirements of each fibre type is at times not available for component developers. Above all, a lack of experience in handling the respective materials is the reason. In this paper, an overview on the historical development of carbon fibres is provided. Subsequently, the market development of the last years is shown and the production capacities of selected manufacturers are presented. Finally, future requirements and target markets of carbon fibres are addressed.

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2. Carbon fibre histrorical development

Per definition, carbon fibres are fibrous materials with a carbon fraction of above 90 % [1]. Mechanical properties are therefore no initial part of the definition of carbon fibres. Carbon fibres were first discovered by Thomas Edison [2]. During the development of the light bulb, Edison applied a carbonised cellulose fibre as the glow filament. Edison did not make use of the mechanical properties of the fibre, instead he utilized the electrical conductivity of the fibre. Nowadays, cellulose based carbon fibres are not used for mass markets anymore, due to the low yield of around 30 % [3], [4].

The development of Polyacrylonitrile (PAN) based carbon fibres dates back to the 1950s: In the United States a stabilised fibre (precursor of a carbon fibre) was produced by Houtz. In Japan Asahi Kasai and other companies realised the commercial production of acrylic fibres in 1957 [5]. A process for the production of PAN based graphite fibres was patented by Shindo in 1959 [6]. The yield was around 50 % and by that considerably higher than the yield of cellulose based carbon fibres. In 1961, research and development of carbon fibre technologies was initiated by Toray. In 1964 an additional patent for the production of carbon fibres was filed for application by a group of researchers from the United Kingdom (U.K. Royal Research & Development Corporation (NRDC) [7]. The U.K. Royal Nuclear Power Corporation (AERA) began research and development of industrial carbon fibre production in 1965 [5]. Another mile stone was reached in 1967, when Rolls-Royce developed a commercial jet engine based on carbon fibres [5]. In 1969 Mitsubishi Rayon started researching precursor technologies and Toho Tenax started researching precursors as well as carbon fibres.

Due to the big edge in terms of experience and development, Toray commissioned the first major industrial production of the Toray carbon fibre “Torayca” in 1971. 4 years later Toho Tenax commission their first commercial production line in 1975. The first commercial production of pitch based carbon fibres was initiated in the same year by the Union Carbide Corporation (UCC) in the United States. However, cost as well as properties (approx. 2GPa tensile strength) were unfavourable compared to PAN based carbon fibres [9]. Today, with a market share of above 90 %, PAN is therefore the dominant base material for the production of carbon fibres [10]. The historic development of carbon fibres is displayed in Figure 1.

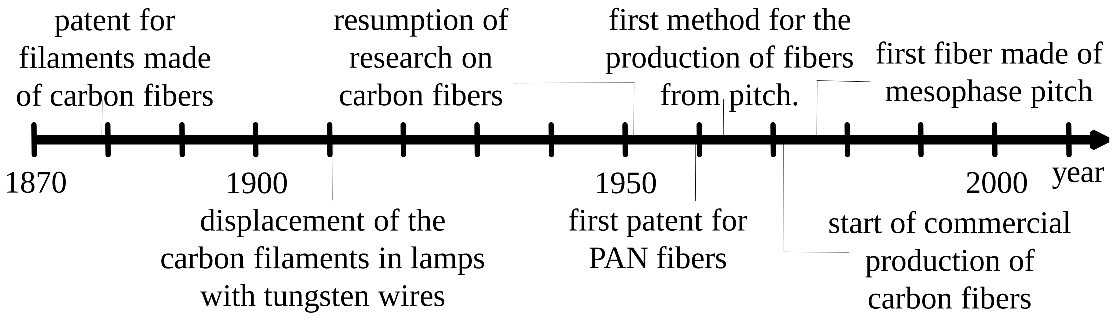

Figure 1. Historical carbon fibre development [10]

Recent research addresses the biopolymer lignin [11], [12], [13] and melt spun precursor [14], [15], [16]. The fact, that lignin is applicable for carbon fibre production was first shown in the 1970s [17], [18]. However, mechanical properties are not yet in line with market standard. Therefore, a commercial application did not take place yet.

The first commercially available carbon fibre was the Torayca T300 by Toray. Mechanical properties with a tensile strength of 2450 MPa were very low compared to today’s carbon fibres (up to 7 GPa tensile strength) [19]. In the beginning stages of market entry, carbon fibres were increasingly used in sports gear (golf club). Since the 1970s, carbon fibres were increasingly used in aerospace applications [8]. Especially the aviation sector demanded carbon fibres with maximised mechanical properties,

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which posed a major influence on the development during the 1980s. In Figure 2 the development of carbon fibre strength over time of selected PAN carbon fibres is displayed.

Due to this development, the mechanical properties of the Torayca T300 were continuously increased to 3530 MPa tensile strength, 230 GPa Young's modulus as well as an elongation at break of 1.5 %. In 1984 Toray introduced the T800H carbon fibre with a tensile strength of 5590 MPa, a Young's modulus of 294 GPa and an elongation at break of 1.9 %. The tensile strength of the T800H was more than doubled compared to the initial T300. Development of the mechanical properties peaked in 1986 with the Toray T1000 with a tensile strength of 7060 MPa and a Young's modulus of 295 GPa [19], [20].

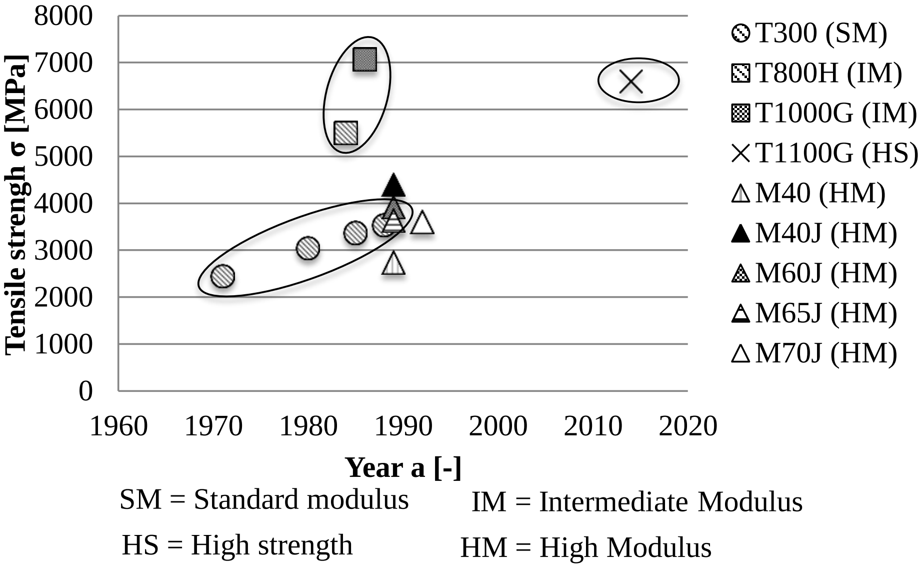

Figure 2. Tensile strength development of PAN based carbon fibres

However, due to the high price, the T1000 was only utilized in special application [19]. Today, tensile strength of a commercially available T1000 is 6370 MPa and the same E-modulus as before [21]. In conclusion, the main focus of the development of this fibre was an improvement of tensile strength with only a slight change of the Young's modulus.

Both the T800H and the T1000 carbon fibres are classified by Toray as "Intermediate Modulus" fibres. Both Young's moduli are only 30 % above that of the T300 (classified as "Standard Modulus"). However, a fibre type with a high Young's modulus and a high strength was demanded, especially by the aviation sector [19], [20]. In response, Toray developed the "High Modulus" fibre type during the 1980s. In Figure 3 the development of the Young's modulus over time is displayed.

High Modulus fibres were developed for a high Young's modulus in combination with a moderate strength. At 392 GPa, the M40 fibre shows a 70 % increase of Young's modulus in comparison to the T300 fibre. In contrast, strength is considerably below the T300 at 2740 MPa. The highest Young's modulus are shown by the M65J and M70J fibres with 640 GPa and 690 GPa. Tensile strength for both is 3600 MPa. Both fibre types are not commercially available anymore. Still available is the Toray M60J with a 588 GPa Young's modulus and a relatively high strength of 3920 MPa.

After the end of the Cold War in 1991 and the end of the first Gulf War, the aviation industry fell into a regression. World trade did not grow to the predicted extent and the demand of high strength and

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high modulus carbon fibres shrank. Further development of the mechanical properties of carbon fibres stagnated. Up until today, no fibre with a tensile strength way above 7 GPa is commercially available. Therefore, market demand of low cost carbon fibres grew [19], [22]. Carbon fibres were increasingly utilized in the construction sector (e.g. pressure tanks) and transportation sector. Cost efficient “Large Tow” carbon fibres with 24,000 and more filaments were developed. This development ultimately led to the industrial production of the BMW i3 and i8 passenger cabin, consisting exclusively of carbon fibres [23].

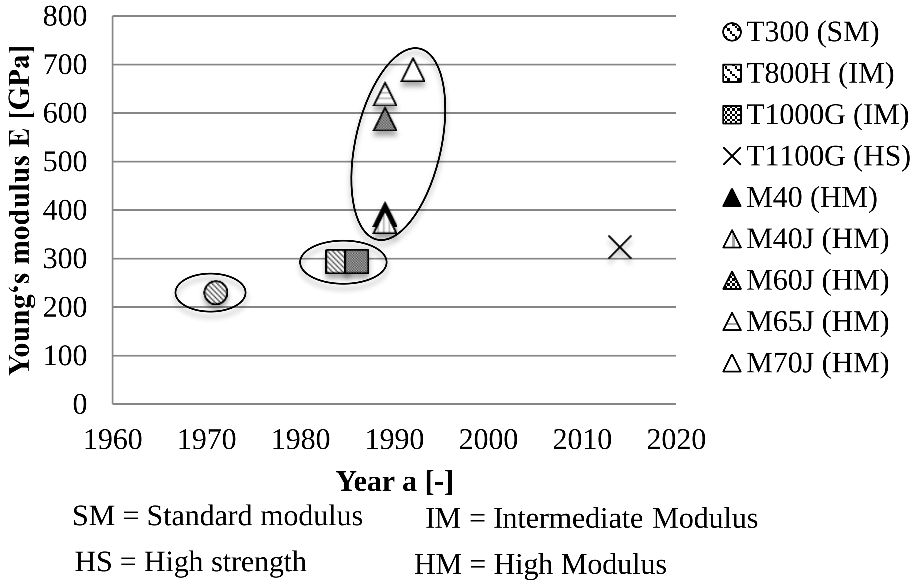

Figure 3. Young's modulus development of PAN based carbon fibres

3. Manufactures and production capacities

Caused by investments in new facilities, carbon fibre production capacities were strongly increased in recent years. Figure 4 depicts the development of installed capacities from 2002 to 2012 based on selected sources [28], [29], [30], [33], [34], [35].

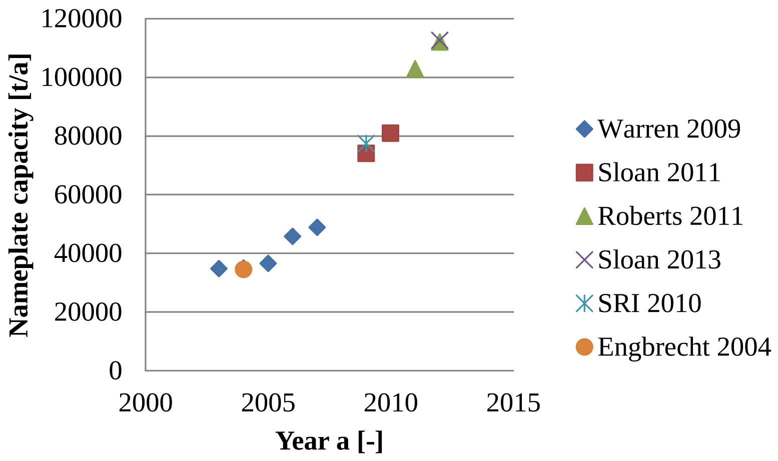

Figure 4. Development of nameplate capacity for carbon fibre manufacture [28], [29], [30], [33], [34], [35]

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Overall capacity more than tripled in that time frame, equalling an average capacity increase of approx. 14 % annually. Though incomplete, information from the selected sources are widely consistent. Today's overall capacity is assumed to be above 100.000 t annually [34].

The fact, that all of the above listed capacities are nameplate capacities must be noted. This does not include losses due to plant downtime [33]. Production of carbon fibres concentrates on the ”Standard Modulus” fibre segment. Such fibres own a market share of approx. 80 to 90 % and in most cases a large filament count in the 12 to 50 k range [33], [36]. The remaining 10 to 20 % consist of fibres from the “Intermediate” and “High Modulus” segment [33], [36]. In total, approx. 100 different PAN based carbon fibres are commercially available. Up to date, more than 90 % of worldwide production capacity is represented by less than ten manufacturers.

In accordance, the largest manufacturers in descending order and with their production site locations are [23, 29, 37].

- TORAY Industries Inc., Chuo, Japan (Japan, USA, France)
- ZOLTEK Companies Inc., St. Louis, USA (USA)
- SGL Group SE, Wiesbaden (Germany, USA)
- TOHO TENAX Co. Ltd., Chiyoda, Japan (Japan, Germany, USA)
- MITSUBISHI RAYON Co. Ltd., Chiyoda, Japan (Japan, USA)
- FORMOSA PLASTICS Corp., Taipei, Taiwan (Taiwan)
- HEXCEL Corp., Stamford, USA (USA, Spain)
- HYOSUNG Corp., Seoul, Republic of Korea (Republic of Korea)
- CYTEC Industries Inc., West Paterson, USA (USA)

Nowadays new entrants in the market emerge from China [37]. Since 2013 ZOLTEK Companies Inc., St. Louis, USA, is an affiliate of TORAY Industries Inc., Chuo, Japan [38].

4. Growth and barriers

The authors are therefore in disagreement in terms of growth prediction. Whereas SLOAN predicts an average growth of only approx. 10 % annually from 2012 to 2020, WALKER predicts a growth of approx. 19 % annually until 2015 34,42. All other author's predictions are distributed evenly between these two extremes.

Figure 10 shows selected growth forecasts for the development of the carbon fibre market until 2020 in absolute numbers. It can be observed, that estimations display a wide range. For 2020 predictions range from approx. 100,000 t annually by SLOAN up to approx. 240,000 t annually by WALKER, while all other predictions are located below 150,000 t annually 34,42. Only few of the authors offer a separation into sub markets. Upon observation of the sub markets automobile, wind energy, aerospace as well as sport and leisure, the origin of these differences become clear. The biggest impacts on the transformation of the markets come from wind energy and automobile [24], which also causes a shift in growth from small tow to large tow [42].

For aerospace applications the authors show growth rates within a narrow corridor of 10 –12 % annually. Calculations for this market are possible due to precise predictions for future airplane production for different airplane types and due to widely known material compositions of the respective airplane types. Major growth driving force is a general growth of airplane production with a simultaneous shift of the model mix to high CFRP fraction airplanes.

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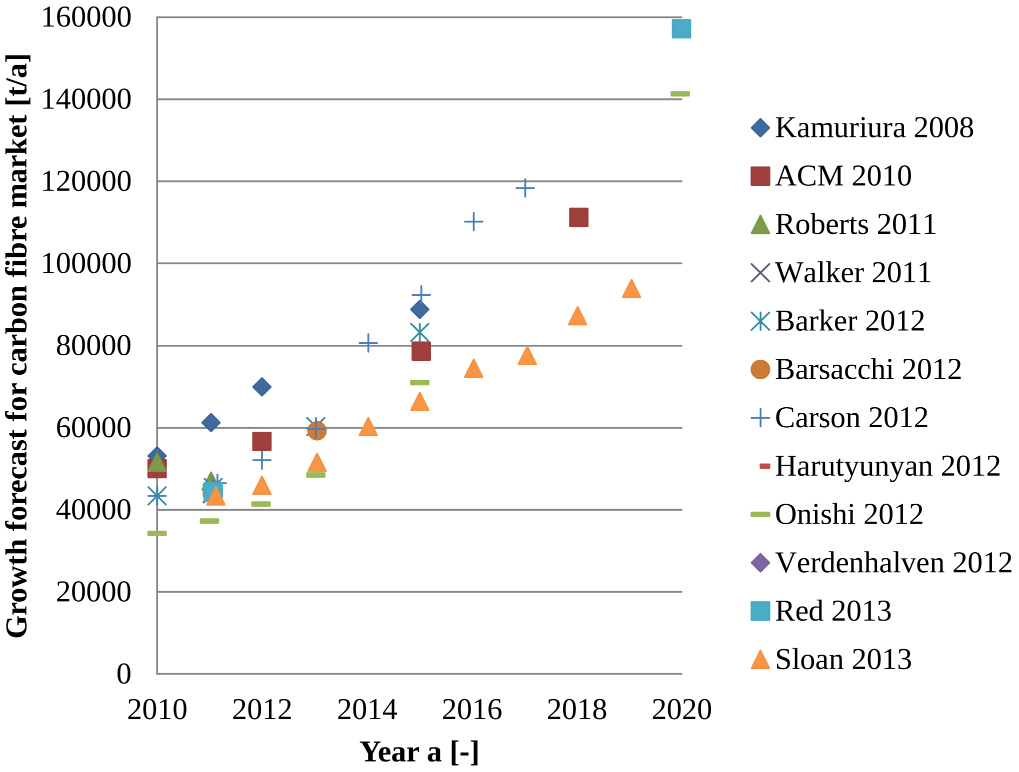

Figure 5. Growth forecast for carbon fibre market 2020 [24], [27], [29], [31], [34], [42], [43], [44], [45], [46], [47]

Sport and leisure applications only display a low growth rate. Predicted rates range from 2 to 5 % annually, far behind the other observed sub markets. Significant growth impacts are not expected in this market.

In the wind energy sector predictions range from 19 to 26 % annually for the application of carbon fibres. With the exception of WALKER's prediction, this will be the biggest area of carbon fibre application by 2020. The range of growth rate predictions is small compared to those for the automobile sector. Predictions are derived from the installed generation capacity and the amount of CFRP used in dependence of the rotor diameter.

The biggest uncertainties in the comparison of different market predictions come from the application in automobile manufacturing. While ROBERTS predicts an average growth of 15 % annually from 2012 to 2020, WALKER predicts an average growth of approx. 47 % annually from 2010 to 2020. The huge range displays, how significant uncertainties in the assumptions, serving as basis for the predictions, exist. Even though volumes of automobile production and the division in car segments offer good models from various manufacturers, the extent of CFRP application in the respective car segments remain unclear.

Particularly in the automobile industry, a trade-off between performance and cost of the utilized carbon fibres ensues [34]. While carbon fibres in the aerospace industry in the future must continue to fulfil highest requirements in terms of tensile strength and Young's modulus, the automobile industry pursues reduced property requirements, but more aggressive target costs [34].

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5. Future and todays carbon fibre requirements

Carbon fibres are used in a very wide variety of applications. Reasons for application are numerous and are not limited to lightweight materials [34], [49]. Many more application segments exist in addition to the aerospace industry [26]. Main focus is placed the application of fibre reinforced plastics, which can be utilized in various applications from industries such as automobile, wind energy, medical engineering and sport and leisure. In addition, carbon fibres are used in combination with other matrix materials such as metals and concrete. For carbon-carbon composite materials, break and clutch discs or discharge nozzles of rocket jets can be named as examples [26], [41]. For the reinforcement of ceramics as mirrors for high energetic lasers carbon fibres can be employed [26].

Aside from composite materials, carbon fibres can also be used directly as textiles. Applications include electrical resistance heating elements, micro electrodes or cathode and anode material in fuel cells [26]. Further use is the application as sealing material for pipe connections in high temperature applications by GARLOCK GmbH, Neuss, Germany and KLINGER GmbH, Idstein, Germany [26]. As unprocessed fibres, carbon fibres are successfully utilized as artificial Achilles tendons due to their good bio compatibility [50]. Many of these applications are of course niche products, for which application-oriented optimized solution are not feasible for established carbon fibre manufacturers. High costs for the user and high risks for the manufacturers can be named as the reasons for that. Instead, wind energy and automobile industry represent bigger markets, where establishment of standardised fibres is profitable. In addition, the application of carbon fibres in fuel cells must not be disregarded. Due to the steady growth of electromobility this could become another big market for specially designed carbon fibre in the near future.

The application of CFRP as structure components of rotor blades in wind energy plants is necessary, particularly due to the requirement of high flexural rigidity and low weight for the large rotor diameters. Approx. 1 t of carbon fibres per installed capacity of 1 MW is used, which could increase caused by a shift to even bigger plants [28]. Due to the high predicted growth of up to 26 % annually, specially designed carbon fibres to the characteristics of the rotor blade requirements could be a reasonable approach [42]. In Figure 7 the predicted growth according to SLOAN, ROBERTS and WALKER for the wind energy sector with reference to the overall carbon fibre demand is displayed.

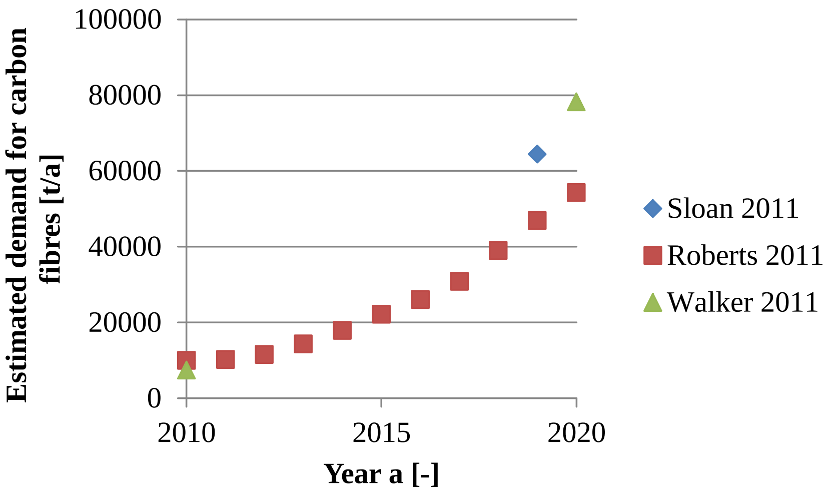

Figure 6. Estimated carbon fibre demand for wind turbine industry [29], [33], [42]

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The current demand of carbon fibres for the production of rotor blades of approx. 9,000 t annually is already sufficient for the full utilization to capacity of a carbon fibre production line [23]. For example, carbon fibres with a larger filament diameter would be accompanied by a higher flexural rigidity. Unfortunately, no such correlation between a diameter and weight or strength exists. The weight would increase quadratic and the strength would decrease with an increasing diameter. Hollow fibres pose an alternative, because the flexural rigidity could be utilized more efficiently while only displaying low weight increase and strength loss. Another approach is the use of hybrid fibres. Thick filaments could be mixed with thin filaments in the same component. The advantages of both fibres could be used in one component, which means the mechanical properties can be adapted exactly to the application. Another aspect of this approach is, that the high weight of the thick filaments is compensated by thin filaments.

Target costs for a mass application in the automobile industry are provided by various authors, as depicted in Figure 8. The different data range from 3 to 7 USD/lb. carbon fibre [35], [42], [51], [52], [53]. In addition to target costs, minimum requirements to the mechanical performance are defined. In 2009 WARREN defined mechanical low performance target properties for carbon fibre application in the automobile industry. According to WARREN a strength only ≥ 1.7 GPa, a rigidity of ≥ 172 GPa and a residual elongation of ≥ 1 % present the target performance [35]. The target properties therefore are significantly below the properties of commercially available fibres. The opportunity of producing low cost fibres by reducing mechanical properties therefore exists. In conclusion, the high growth of approx. 15 % annually to a current demand of above 5,000 t annually in the automobile industry justifies the introduction of tailor-made fibres [23].

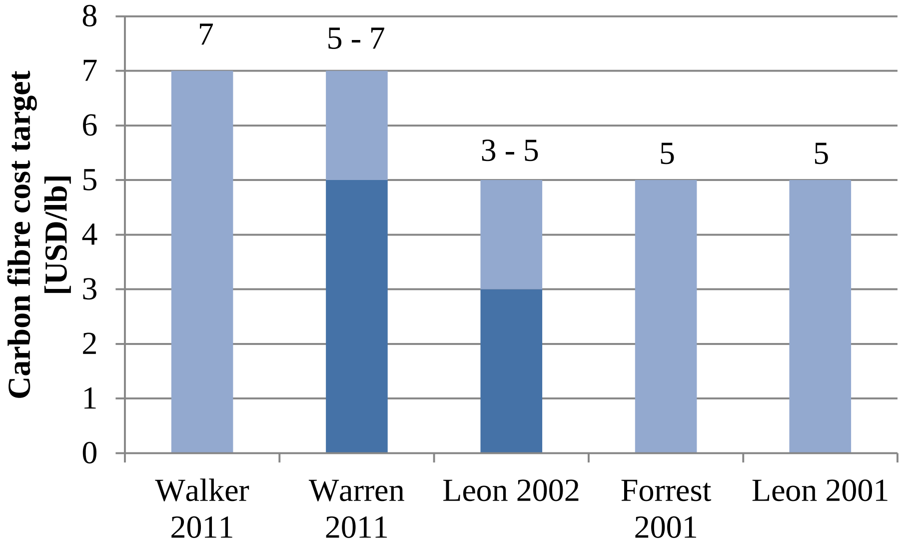

Figure 7. Carbon fibre cost targets for automotive application [35], [42], [51], [52], [53]

6. Conclusions and recommendations

What does the future hold for carbon fibres? Will the trend develop to standard fibres or tailor-made fibres? We say both will be the case, because the difference between standard and tailor-made fibres only exists in the difference of market size of the application and demand of the fibres. As soon as the demand surpasses an overall carbon fibre line production capacity of 1,500 t annually, supply of such a fibre to the market becomes profitable for established carbon fibre manufacturers. Low demands however, will have difficulties to reach market establishment. Those fibres will most certainly also not represent low cost solutions.

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