Carbon fiber-reinforced Thermoplastic polymers

Subjects: Materials Science, Composites
Contributor: Basheer Alshammari

Carbon fiber-reinforced thermoplastic polymers are considered a promising composite for many industrial applications including in the automation, renewable energy, and aerospace industries. They exhibit exceptional properties such as a high strength-to-weight ratio and high wear resistance and stiffness, which give them an advantage over other conventional materials such as metals.

Keywords: carbon fibers ; polymer-matrix composites (PMCs) ; thermoplastic resin ; surface treatment

1. Introduction

In an ever-evolving world, developing new sustainable materials with excellent properties while ensuring they fall into the category of circular economy materials is essential to meet industrial demands and prevent environmental pollution. New materials must overcome existing challenges such as high cost, recyclability, reliability, and energy consumption. For example, such materials for high-performance products need to be lightweight and strong to take diverse loading conditions, such as turbine blades in wind energy applications. They also must not create new problems regarding safety, availability, and processability. One of the main challenges of developing a new product is reducing the weight and increasing load-bearing capability at the same time [1][2][3][4]. One of the promising lightweight materials is carbon fiber (CF), characterized by high-strength, high-temperature resistance, and good chemical resistance. CF is non-toxic, low-density, has high wear resistance, and is a non-corrosive, recyclable material with an outstanding strength-to-weight ratio. Overall, it has exceptional thermal, mechanical, and electrical properties. CF is made when source materials such as synthetic polymers (polyacrylonitrile, pitch resin, or rayan spun) are carbonized through oxidation and thermal treatments (hydrolysis) at high temperatures while applying tension with final CF products' appropriate controlled properties. It is well known that higher carbonization temperatures (up to 2500 °C) can achieve a high carbon content in CF. Today, CF-reinforced polymer matrix composite products are widely used in various applications due to their excellent mechanical, thermal, electrical, structural, and tribological properties. These applications include use in wind energy, aerospace, automobile, infrastructure, marine, and building and construction industries, as well as in sporting goods [4][5][6][7].

Carbon fiber reinforced polymers (CFRP) have been widely investigated. Many types of research have focused on using CF-reinforced thermosetting polymers such as epoxy and polyester resins. Many published reviews have explored state-of-the-art CF-reinforced thermosetting polymers. Moreover, manufactured thermoset composites are unrecyclable due to thermosetting polymers' characteristics. Hence, in large-scale production aspects, they exemplify environmental and economic issues [8]. A recent review by Hegde et al. [9], who reviewed CFRP materials and their mechanical performance, stated that such materials' prices considerably dropped in the 1990s. Subsequently, these materials were utilized in sports equipment. Additionally, between 1998 and 2006, the utilization of CFRP doubled in the world market. The compound annual growth rate for the utilization of CFRP in 2018 was predicted to be 12.5%.

On the other hand, another class of promising lightweight materials is thermoplastic polymers. They are also called thermosoftening plastics that become modulable at certain temperatures and solid upon cooling. Most thermoplastic polymers are recyclable and easily shaped to the desired requirements. Thermoplastic polymers can be combined with unidirectional CF, discontinuous (short and long CF), or CCF to achieve composite materials with improved mechanical, thermal, and electrical properties in one or multiple directions. Thermoplastic polymers can further be classified as the following: (1) commodity or general plastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and acrylonitrile butadiene styrene (ABS) resin. (2) High performance or engineering plastics including polyamide (PA), polyethylene terephthalate (PET), polycarbonate (PC), polyetheretherketone (PEEK), polyetherimide (PEI), polyethersulfone (PES), and polyphenylene sulfide (PPS) [1][4][7]. Therefore, thermoplastic polymers have received vital consideration as a matrix due to the lack of prerequisites in curing stages and less dangerous chemical compositions, and better recycling suitability and mass production capability compared to thermosetting polymers. These characteristics give thermoplastic polymers an advantage over thermosetting polymers. Furthermore, the final composite products have enhanced properties compared to the individual components, i.e., thermoplastic and CF. Carbon fiber-reinforced thermoplastic polymers (CFRTP) offer weight reductions of about 50% compared to steel and 20% compared to aluminum [5][10][11].

CFRTPs are frequently manufactured using conventional molding approaches, such as injection, rotational, extrusion, vacuum, and compression moldings. Although CFRTP has attracted many researchers recently due to its excellent mechanical and thermal properties, recyclability, flexibility, less production time, and environment-friendly manufacturing, it is still in the development stages for some applications, and there are existing issues with high manufacturing costs to be overcome [1][7][8].

It is well known that synthesized CF materials have a smooth, natural surface with chemical inertness and are non-polar, while the polymer is generally polar. Due to this different polarity, the reinforcing process must be preceded by treating the CF's surface. The treatment is conducted by creating functional groups on the surface of CF to ensure good interfacial adhesion between the polymer (matrix) and the CF (reinforcement), which is required to achieve high-performance composite materials; this is essential to their practical application. Many researchers have noticed the importance of strong bonding between the reinforcement and the matrix for high-performance composites [11][12][13][14][15].

Moreover, during the manufacturing process, many aspects must be taken into account to ensure a high quality of the final product while maintaining an efficient manufacturing process. For instance, the manufactured CF must be wear resistant, handle loads without cracking, and function successfully in a wide range of conditions such as high temperatures and humidity. Additionally, during the manufacturing process, energy consumption, cost of equipment and labor, environmental sustainability, and large-scale production ease are essential factors that must also be taken into account [4][15][16][17]. To improve the composites' potential in the mentioned sectors and others, it is important to make a strategic road-mapping activity. Europe has a competitive composites industry. However, many challenges are still to be addressed. A roadmap for the challenges and the industrial uptake of CF and advanced high-performance composites' supply chain in Europe has been published recently by Koumoulos et al. [15].

2. Properties of CFRTP

Researchers and developers have shown a great deal of interest in CFRTP composite due to its tremendous and wide range of properties and the potential of utilizing it in many industrial applications. These properties can be altered or enhanced by determining which materials and methods to use. Every choice made during the process will affect the composite properties; hence, it will either limit or expand the possibility of utilizing the material in specific industries. Some of these properties are crucial in every thinkable application, such as the mechanical strength of CFRTP.

The interfacial property is a primary factor because when the bond is strong, the load is transferred successfully from the matrix to the CF without causing any damages to the product. The interfacial bond between the CF and the thermoplastic matrix is seemingly weak due to their unidentical polarities. Thermoplastics are mostly polar, while CF is not. Several CF surface treatment methods have been investigated to solve this issue, including both chemicals and physical treatment approaches [7][18][11][12][14][19][20][21][22][23][24][25][26][27][28]. It has been reported that the adsorption of some polymeric particles using the electrophoresis process could be used for controlling the interfacial properties and adhesion between carbon fibers and thermoplastic resins through the control surface adhesion between CF and polymer matrix [29].

Due to excellent mechanical properties, the use of CF has grown remarkably. The CF-reinforced thermoplastic composites enhanced mechanical properties of final composites, including tensile strength, tensile modulus, flexural modulus, flexural strength, creep resistance, wear resistance, and toughness alongside other properties such as thermal and electrical conductivity. In the automotive, aerospace, and many other manufacturing industries, the usage of CF-reinforced polymers has rapidly improved in the last ten years due to the features mentioned above. However, the CF-reinforced composites have low wettability with most polymers because of their nonpolar surface characteristics. The low-interfacial bonding strength between the fibers and polymer matrices results in inadequate mechanical performance in composites [9][26][30][31][32]. The apparent ILSS of the composite is usually used to characterize adhesion quality between the fiber and matrix [33][34][30]. Likewise, a transverse fiber bundle test technique has been proposed to assess the fiber/matrix interfacial adhesion without making composite materials [35][36].

Besides the great mechanical properties of CF, it can be used for other tasks based on its multifunctional properties, including electrical conductivity and electromagnetic interference shielding. These properties of CF used as reinforcement in composite structures are the basis for several multifunctional applications. The significance of carbon is the extremely stable hexagonal plane grid and the planes' delocalized electron cloud. The deformation and separation of the hexagonal carbon rings require high energy, which provides the CF's strength at the macro level. The free electrons in the electron cloud make it an excellent electrical conductor. The electrical resistance of CFRTP depends mostly on the type of material used (precursors), the manufacturing conditions, the crystalline structure of polymer matrices, and treatments [2][3].

The primary thermal properties of CFRTP are thermal stability, thermal conductivity, melting temperature (T_m), and glass transition temperature (T_g). Researchers have investigated these properties extensively in an attempt to enhance them. The T_g of polymer composites normally depends on several factors such as the chemical structure and conformation of the polymers, degree of crystallinity, fiber dispersion, and interactions between the fiber and the polymer. Several studies have confirmed that the addition of fillers affects the T_g and the breadth of the transition due to changes in the mobility of the polymeric chains in the host matrix. By improving thermal properties, CFRTP becomes more suitable for fulfilling the already existing demands in various high-temperature sectors such as the aerospace, oil, and gas industries.

3. Future Prospects

Overall, CFRTP composite materials have become a progressively used class of lightweight materials. The research and development activities carried out to investigate the relationships between processing, structure, and properties of CFRTP have resulted in a better fundamental understanding of these materials and led to an enhancement of their properties, offering more flexibility in the design for several possibilities applications. Therefore, CFRTP is a promising candidate in a variety of industrial applications. The properties of CFRTP composite materials such as high strength, low weight, and good thermal and electrical properties make it a preferred composite material compared to neat polymers, CFRPs, and even other metallic materials. However, the polymer matrix and the treatment method of CF prior to the manufacturing process is crucial and will affect the composite properties; hence, it will also affect the applications of the composite material. Thus, the large-volume market applications of CFRTP are still to be discovered. Nevertheless, with the huge demand of emerging industries, the opportunities for improvements, and the support of developing standardizations for testing and using CFRTP composite, more high-efficiency CFRTP products will be developed.

4. Conclusions

The outstanding properties exhibited by CFRTP are the primary motivation for further research and development. For example, these properties improved significantly with the addition of carbon fiber (CF) as a reinforcement compared to the neat polymer properties, which paves the way for CFRTP products in many industrial sectors. Furthermore, the modification of the CF's surface is essential to improve the interfacial bond between the CF and the thermoplastic matrices. Either a chemical or physical modification technique will increase the oxygen concentration on the CF's surface. Increasing oxygen makes the surface of CF more similar to the thermoplastic matrix in terms of polarity. Moreover, modifications have improved the filler/matrix bond and have had excellent positive effects on the mechanical properties of the composite compared to the untreated thermoplastic polymer/CF composites.

In general, the properties of various thermoplastic composites improved significantly with the addition of CF as a reinforcement compared to the neat thermoplastic properties. However, there is a variety in such improvements. This could be attributed to several factors, including manufacturing technique, processing parameters, thermoplastic type, CF type and orientation, loading, dimension, and surface treatment techniques, leading to interfacial adhesion and dispersion statues. All such aspects are essential to attain the anticipated properties, particularly mechanical properties, and to understand the relationships of the modification methods and mechanical properties of the final CFRTP composites.

References

1. Park, S.-J.; Heo, G.-Y. Precursors and Manufacturing of Carbon Fibers. In Superconductivity; Springer Series in Materi als Science and Business Media; Springer: Dordrecht, The Netherlands, 2014; Volume 210, pp. 31–66.
2. Qin, X.; Lu, Y.; Xiao, H.; Wen, Y.; Yu, T. A comparison of the effect of graphitization on microstructures and properties of polyacrylonitrile and mesophase pitch-based carbon fibers. Carbon 2012, 50, 4459–4469.
3. Forintos, N.; Czigany, T. Multifunctional application of carbon fiber reinforced polymer composites: Electrical properties of the reinforcing carbon fibers—A short review. Compos. Part B Eng. 2019, 162, 331–343.
4. Rajak, D.K.; Pagar, D.D.; Menezes, P.L.; Linul, E. Fiber-Reinforced Polymer Composites: Manufacturing, Properties, an d Applications. Polymers 2019, 11, 1667.
5. Ishikawa, T.; Amaoka, K.; Masubuchi, Y.; Yamamoto, T.; Yamanaka, A.; Arai, M.; Takahashi, J. Overview of automotive s tructural composites technology developments in Japan. Compos. Sci. Technol. 2018, 155, 221–246.

6. Zhang, J.; Chevali, V.S.; Wang, H.; Wang, C.-H. Current status of carbon fibre and carbon fibre composites recycling. Compos. Part B Eng. 2020, 193, 108053.
7. Yao, S.-S.; Jin, F.-L.; Rhee, K.Y.; Hui, D.; Park, S.-J. Recent advances in carbon-fiber-reinforced thermoplastic composites: A review. Compos. Part B Eng. 2018, 142, 241–250.
8. Jin, F.-L.; Lee, S.-Y.; Park, S.-J. Polymer matrices for carbon fiber-reinforced polymer composites. Carbon Lett. 2013, 14, 76–88.
9. Hegde, S.; Shenoy, S.; Chethan, K. Review on carbon fiber reinforced polymer (CFRP) and their mechanical performance. Mater. Today Proc. 2019, 19, 658–662.
10. Othman, R.; Ismail, N.I.; Pahmi, M.A.A.H.; Basri, M.H.M.; Sharudin, H. Hemdi Application of carbon fiber reinforced plastics in automotive industry: A review. J. Mech. Manuf. 2018, 1, 144–154.
11. Kishi, H.; Nakao, N.; Kuwashiro, S.; Matsuda, S. Carbon fiber reinforced thermoplastic composites from acrylic polymer matrices: Interfacial adhesion and physical properties. Express Polym. Lett. 2017, 11, 334–342.
12. Park, S.-J.; Seo, M.-K. Carbon Fiber-Reinforced Polymer Composites: Preparation, Properties, and Applications. Polym. Compos. 2012, 135, 135–183.
13. Xie, S.; Liu, S.; Cheng, F.; Lu, X. Recent Advances toward Achieving High-Performance Carbon-Fiber Materials for Supercapacitors. ChemElectroChem 2018, 5, 571–582.
14. Shin, H.K.; Park, M.; Kim, H.-Y.; Park, S.-J. An overview of new oxidation methods for polyacrylonitrile-based carbon fibers. Carbon Lett. 2015, 16, 11–18.
15. Koumoulos, E.P.; Trompeta, A.-F.; Santos, R.-M.; Martins, M.; Dos Santos, C.M.; Iglesias, V.; Böhm, R.; Gong, G.; Chiminelli, A.; Verpoest, I.; et al. Research and Development in Carbon Fibers and Advanced High-Performance Composites Supply Chain in Europe: A Roadmap for Challenges and the Industrial Uptake. J. Compos. Sci. 2019, 3, 86.
16. Huang, X. Fabrication and Properties of Carbon Fibers. Materials 2009, 2, 2369–2403.
17. Baker, D.A.; Rials, T.G. Recent advances in low-cost carbon fiber manufacture from lignin. J. Appl. Polym. Sci. 2013, 130, 713–728.
18. Alarifi, I.; Alharbi, A.; Khan, W.S.; Rahman, A.; Asmatulu, R. Mechanical and Thermal Properties of Carbonized PAN Nanofibers Cohesively Attached to Surface of Carbon Fiber Reinforced Composites. Macromol. Symp. 2016, 365, 140–150.
19. Wong, K.; Mohammed, D.S.; Pickering, S.; Brooks, R. Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite. Compos. Sci. Technol. 2012, 72, 835–844.
20. Hung, P.-Y.; Lau, K.-T.; Fox, B.; Hameed, N.; Lee, J.H.; Hui, D. Surface modification of carbon fibre using graphene-related materials for multifunctional composites. Compos. Part B Eng. 2018, 133, 240–257.
21. Jin, F.-L.; Park, S.-J. Preparation and characterization of carbon fiber-reinforced thermosetting composites: A review. Carbon Lett. 2015, 16, 67–77.
22. Zhang, G.; Sun, S.; Yang, D.; Dodelet, J.-P.; Sacher, E. The surface analytical characterization of carbon fibers functionalized by H2SO4/HNO3 treatment. Carbon 2008, 46, 196–205.
23. Park, S.-J.; Donnet, J.-B. Anodic Surface Treatment on Carbon Fibers: Determination of Acid-Base Interaction Parameter between Two Unidentical Solid Surfaces in a Composite System. J. Colloid Interface Sci. 1998, 206, 29–32.
24. Ofoegbu, S.U.; Ferreira, M.G.; Zheludkevich, M.L. Galvanically Stimulated Degradation of Carbon-Fiber Reinforced Polymer Composites: A Critical Review. Materials 2019, 12, 651.
25. Lee, H.S.; Kim, S.-Y.; Noh, Y.J.; Kim, S.Y. Design of microwave plasma and enhanced mechanical properties of thermoplastic composites reinforced with microwave plasma-treated carbon fiber fabric. Compos. Part B Eng. 2014, 60, 621–626.
26. Unterweger, C.; Duchoslav, J.; Stifter, D.; Fuerst, C. Characterization of carbon fiber surfaces and their impact on the mechanical properties of short carbon fiber reinforced polypropylene composites. Compos. Sci. Technol. 2015, 108, 41–47.
27. Agrawal, M. Effect of fiber sizing on Mechanical properties of carbon reinforced composites: A Review. Org. Polym. Mater. Res. 2020, 1.
28. Park, S.-J.; Seo, M.-K.; Lee, Y.-S. Surface characteristics of fluorine-modified PAN-based carbon fibers. Carbon 2003, 41, 723–730.
29. Yamamoto, T.; Uematsu, K.; Irisawa, T.; Tanabe, Y. Controlling of the interfacial shear strength between thermoplastic resin and carbon fiber by adsorbing polymer particles on carbon fiber using electrophoresis. Compos. Part A Appl. Sci.

Manuf. 2016, 88, 75–78.

30. Chunzheng, P. Improved interfacial properties of carbon fiber/UHMWPE composites through surface coating on carbon fiber surface. Surf. Interface Anal. 2018, 50, 558–563.
31. Fu, X.; Lu, W.; Chung, D. Ozone treatment of carbon fiber for reinforcing cement. Carbon 1998, 36, 1337–1345.
32. Altay, L.; Bozaci, E.; Atagur, M.; Sever, K.; Tantug, G.S.; Sarikanat, M.; Seki, Y. The effect of atmospheric plasma treat ment of recycled carbon fiber at different plasma powers on recycled carbon fiber and its polypropylene composites. J. Appl. Polym. Sci. 2019, 136.
33. Han, S.H.; Oh, H.J.; Kim, S.S. Evaluation of fiber surface treatment on the interfacial behavior of carbon fiber-reinforce d polypropylene composites. Compos. Part B Eng. 2014, 60, 98–105.
34. Wenbo, L.; Shu, Z.; Lifeng, H.; Weicheng, J.; Fan, Y.; Xiaofei, L.; Rongguo, W. Interfacial shear strength in carbon fiber-reinforced poly(phthalazinone ether ketone) composites. Polym. Compos. 2013, 34, 1921–1926.
35. Ozkan, C.; Karsli, N.G.; Aytac, A.; Deniz, V. Short carbon fiber reinforced polycarbonate composites: Effects of different sizing materials. Compos. Part B Eng. 2014, 62, 230–235.
36. Li, H.; Wang, Y.; Zhang, C.; Zhang, B. Effects of thermal histories on interfacial properties of carbon fiber/polyamide 6 c omposites: Thickness, modulus, adhesion and shear strength. Compos. Part A Appl. Sci. Manuf. 2016, 85, 31–39.