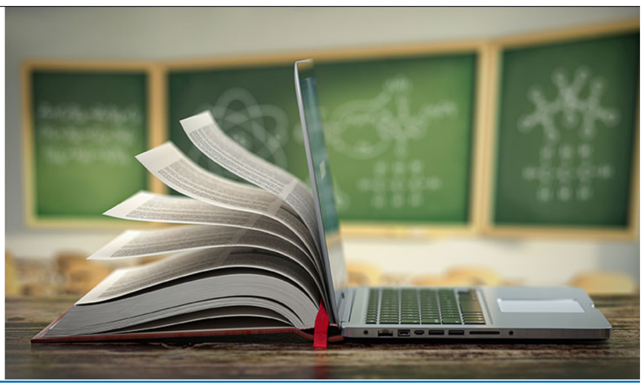
PAPER • OPEN ACCESS

A review of carbon fiber materials in automotive industry

To cite this article: H Ahmad *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **971** 032011



IOP Conf. Series: Materials Science and Engineering **971** (2020) 032011 doi:10.1088/1757-899X/971/3/032011

A review of carbon fiber materials in automotive industry

H Ahmad[1,*], A A Markina[2], M V Porotnikov[2] and F Ahmad[3]

[1]Department of Metallurgical and Rotary Machines,Ural Federal University, 19 Mira str., 620002, Yekaterinburg, Russia.
[2]Department of Lifting and Transporting machines, Ural Federal University, 19 Mira str., 620002, Yekaterinburg, Russia.
[3]Department of Mechanical and Aerospace Engineering, Air University Islamabad, Service Road E-9 / E-8, Islamabad, Islamabad Capital Territory 44000 Pakistan

*hussainahmad456@hotmail.com

Abstract. In present scenario, light weighting becomes a main issue for energy efficiency in automotive industry. The emission of gases and fuel efficiency of vehicles are two important issues. The best way to improve the fuel efficiency is to decrease the weight of vehicle parts. Research and development played an important role in lightweight materials for decreasing cost, increasing ability to be recycled, enabling their integration into vehicles, and maximizing their fuel economy efficacy. There arises a need for developing a novel generation of materials that will combine both weight reduction and safety issues. The application of carbon fibre reinforced plastic material offers the best lightweight potential to realize lightweight concepts. Carbon fibre reinforced plastic has outstanding specific stiffness, specific strength, and fatigue properties compared to commonly used metals. In automotive industry, the advantages of carbon fibre reinforced plastic are reduction in weight, part integration and reduction, crashworthiness, durability, toughness, and aesthetic appealing. Carbon fibre reinforced plastic is a composite material that has been used extensively in various applications such as aerospace industry, sports equipment, oil and gas industry, and automotive industry. Keeping in view the aforementioned advantages of carbon fibre reinforced plastic, the authors have presented a brief review on carbon fibre for automotive industrial applications.

1. Introduction

The world energy crisis has become more serious since the beginning of 21st century. The reduction of fuel consumption and emissions are some of the main problems of automotive industry that is needed to be solved. More than half of the total volume in production of a modern car consists of cast iron and steel parts, about 11 % – plastics, aluminium alloys (9 %); rubber 7% and 3% respectively. The share of non-ferrous alloys (magnesium, titanium, copper and zinc) is about 1%; other materials (varnishes, paints, electric wires, facing materials, etc.) make 13.5 % as shown in Fig. 1 [1].

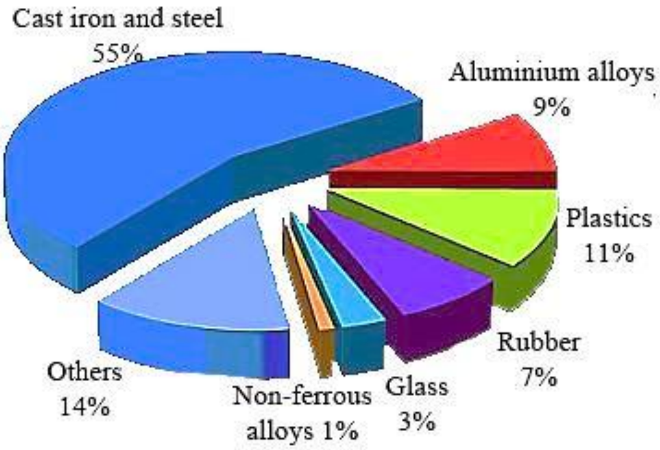


Figure 1. Various types of materials used for Manufacturing of car parts.

To overcome the problem of energy efficiency, various researchers suggested that different parts of vehicle could be replaced with different lightweight materials such as alloys and other traditional materials to reduce the weight of cars [2]. Every 10 kg of reduction of a vehicle reduces the fuel consumption and leads to drop in carbon emission of 1g/km. Carbon fibre compounds have low weight, high strength, high rigidity, good vibration resistance, fatigue resistance, corrosion resistance, and many other advantages [3]. In the past few decades china has developed carbon fibre and its composite materials research [4]. However, its application in the automotive industry is still behind aviation, aerospace, and other industrial fields. Researchers around the globe are trying to reduces the weight of car as well as to develop inexpensive manufacturing techniques for the manufacturing of lightweight materials such as carbon fibre reinforced plastic (CFRP). Isaiah [5] suggested that replacing steel with CFRP has the potential to significantly reduce vehicle weight by 60%. The specific energy absorption (SEA) of the chopped carbon fibre composite material calculated was a the highest as compared to that of all other composites analysed which shows the crashworthiness of this material. It was calculated that only 4.27 kg of Chopped carbon fibre would need to be placed at specific places in the car to ensure passenger safety in the event of a crash at 15.5 m/s (35 mph) [6].

Carbon fibres can be used in various parts of vehicle. The carbon fibre reinforced composites are used in bumpers due to its improvement in strength and appreciable reduction in weight and size of frame [7]. A study done by P Kumar [8] on automotive bumpers for three different designs such as basic bumper design with steel, with the attachment of foam, and with the attachment of honeycomb which shows a higher strength to weight ratio than steel. Beside Bumper's manufacturing, the composite materials also provide a wide range of other potential automotive applications such as body panels, suspension, steering, brakes and other accessories. Apart from body panels, other automotive application of composites include instrument panels, leaf springs, drive shafts, fuel tanks, cross wheel beam, intake manifold. Parts made with the carbon fibre SMC (Sheet Moulding Compound) can decrease the weight up to 55% as compared to those made of traditional SMC [9]. Bambach in his research suggested a new technique of strengthening vehicle roof structure by bonding carbon fibres to the steel surface. The bonding of carbon fibres to the vehicle roof structure of passenger car increases the strength to weight ratio by two times [10].

Meanwhile, the usage of carbon fibre in additive manufacturing (AM) can improve material properties and reduce the required manufacturing time [11]. The use of carbon fibre composites for dual purposes other than just being used to improve the crashworthiness of vehicles must be explored. For example, one could use the chopped carbon fiber composite material for reinforcements in the inside of a door in addition to its use as a crashworthy material. Its use will improve the structural integrity of door as well as acoustics in the car. However, it must also be realized that it is going to be

IOP Conf. Series: Materials Science and Engineering **971** (2020) 032011 doi:10.1088/1757-899X/971/3/032011

very difficult to replace the low-cost metals that are currently being used for parts that satisfy the functional needs in a car with a more costly carbon composite material [6]. Currently, a large amount of CFRP parts is used in high end sports vehicles which are produced approximately 500 units per year [12]. CFRP has the property to be formed in any shape including large and complex shape. Its amenability enables to provide more stylish look on the exterior [12]. Hyoung et.al found that the composite automotive lower arm had two times higher stiffness and buckling strength compared to conventional steel lower arm while having 50% less weight [13]. Carbon fibre especially for body coverings and structures composite materials can reduce car quality by more than 30% [4].

2. Literature Review

Ghassemieh [2] provided a comprehensive details of materials used in manufacturing of vehicles. She discussed the properties of all materials to be accepted in automotive production. In her article she give a brief review on different materials like steel, magnesium, alloys and composites. The potential application of these materials in different parts of vehicle is identified by the author. Other class of materials considered is composites and plastics with synthetic or natural fibre as reinforcement. Whereas the synthetic fibres are more traditional composites used, and is gaining popularity in automotive industry because of its environmental concerns. With regards to composites, the cost is one of the main barriers in the use of these materials. Therefore, a cost analysis is also presented in this article. A review of production and manufacturing of different automotive parts is also presented by the author.

According to John et.al [7] Carbon Fiber Reinforced Epoxy and Carbon Fiber Reinforced plastic (CFRP) are extremely strong and light fiber reinforced polymer which contains carbon fibers. Since CFRP consists of two distinct elements (carbon fibre and epoxy) and the material properties depend on these two elements. The reinforcement will give the CFRP, its rigidity and strength. Unlike isotropic materials like steel, CFRP has directional strength properties. The properties of CFRP depends upon the layout of carbon fiber and proportion of carbon fiber. Because of a large number of favorable properties like low coefficient of thermal expansion, good fatigue resistance and easiness for the production of complex shapes along with high tensile and compressive strength, CFRP have become alternatives for conventional materials like steel and iron in many applications. The CFRP are used in bumpers due to it high strength and appreciable reduction in weight and size of frame. Nowadays the use of CFRP has been decreased because of its expense, however; its reduced weight and higher strength still give this composite an edge over other materials.

Wang et.al [14] investigated carbon fibre-reinforced(CFRP) composite sandwich structures cured at high temperatures with aluminium honeycomb structures as the core material. The effects of core material thickness and density on material properties of composite sandwich honeycomb structures were studied. Both the material bending strength and stiffness were analysed by three-point bending tests, whereas the panel peeling strength was analysed by panel board peeling tests. The material strength could be improved by increasing the density or thickness (figure 2), while optimum middle density or thickness values maximized the bending stiffness. In addition, the stiffness changed to a higher degree with a change in density or thickness than the strength. Experimental samples with a density of 101 kg/m3 and a thickness of 20 mm for the aluminium honeycomb core exhibited high strength, stiffness while decreasing weight. Improving interfacial properties between the panel board and core material can increase the panel peeling force.

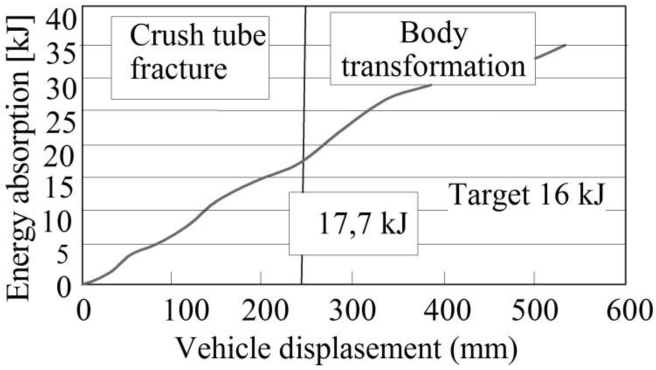


Figure 2. Energy absorption of CFRP during collision test [15]

2.1. Properties of Carbon fiber

2.1.1. Crashworthiness. According to the comments of Jacob et.al [6], the energy absorption capability of a composite material is important in developing improved human safety in an automotive crash. In passenger vehicles, the ability to absorb impact energy and be survivable for the occupant is called crashworthiness of structure. The crashworthiness in terms of specific energy absorption (SEA) of a chopped carbon fiber (CCF) composite material system was compared with that of other fiber resin systems. The quantity of these material systems needed to ensure passenger safety in a midsize car traveling at different velocities was calculated and compared. The SEA of the chopped carbon fiber composite material was the highest as compared to that of all the other composites probed. It was calculated that only 4.27 kg of it would need to be placed at specific places in the car to ensure passenger safety in the event of a crash at 15.5 m/s (35 mph). The CCF composite tested at 5 mm/min crushing speed met both the criteria that needed to be satisfied before a material is considered highly crashworthy. The high SEA recorded for the less costly CCF composite material, shows how successful one might be in analyzing different grades and combinations of carbon fiber and resins for use in automotive applications. Some of the Embodied energies of different materials were shown by Othman et.al [12] as given in Table 1.

Table 1. Embodied energies of common composite constituent materials [12]

Material	Embodied energy (MJ/kg)
Carbon fibre	183 to 286
Glass fibre	13 to 32
Polyester resin	63 to 78
Epoxy resin	76 to 80
Aluminium alloys	196 to 257
Stainless steel	110 to 210

The work presented by Lukaszewicz [16] is an introductory approach to manage the complexity of composite development including both geometrical and microstructural design. Composite materials such as CFRP gives an edge over conventional materials in energy absorbing structures of automobiles and hence reduce weight of body-in-eight (BIW). To design effective energy absorbing composite structures, both geometric and microstructural features need to be understood. Two sets of studies are introduced in this work where the geometry, such as aspect ratio was changed and in other microstructural features, such as braiding angle, fibre type and UD fraction were varied to study their impact on specific energy absorption. From the tests on glass and carbon/glass specimens SEA values from 20 to 60kJ/kg could be obtained which indicates the importance of informed decisions regarding the geometry as well as microstructure of composite energy absorbers.

2.1.2. Weight reduction. According to the comments of Hovorun et.al [1] research and development into lightweight materials is essential for lowering their cost, increasing their ability to be recycled, enabling their integration into vehicles, and maximizing their fuel economy benefits. Light weighting without loss of strength and speed properties is the present, and the future, of the automotive manufacturing industry. The body of the new electric car BMW i3 is largely made of carbon fibre. The body is made of synthetic material reinforced with carbon fibre. In the terminology of BMW, a new material is named carbon fibre reinforced Plastic (CFRP). It is very durable and light but expensive composite material with fiberglass reinforced plastic. The car body of this material is 50 % lighter than steel and 30 % lighter than aluminium.

Petersson et.al. [17] reveals different new ways of making carbon composite materials available for designing automotive industry production equipment by initiating a design and material concept that combines flexibility, with relatively low cost and high functionality reducing the weight up to 60%. Carbon composite materials are one such alternative that has excellent material properties. In his research he has shown that it is possible by changing material to achieve both lighter automotive industry production equipment and enhanced performance at the same time, which in the end can result in enhanced productivity.

Masilamani et.al [18] discussed in detail the benefits of usage of CFRP in each parts of car. The key driver is weight saved and the increase in specific strength and stiffness that carbon composite offer. The key enabler in using carbon fibre is low cost – high cost generally it makes carbon fibre components prohibitive unless additional revenue can be made. Much research is required to be done in order to reduce the curing time of CFRP and make it suitable for mass production. Every 10 kg of reduction of a vehicle improves the fuel consumption efficiency of automobiles and leads to a drop in carbon emission of 1g/km. Table 2 provides comparison of weight of steel and CFRP.

Table 2. Comparison of weight reduction in car roof by replacing CPRF with steel.

Description	Weight
Steel roof	11.2 kg
Composite roof (CFRP)	5 to 5.5 kg
Weight reduction	6 to 6.6 kg

Kim et.al [14] designed an automotive composite lower arm using carbon-epoxy composite materials. He found out that the composite lower arm he designed had two times higher stiffness and buckling strength compared to the conventional steel lower arm while having 50% less weight. For the composite lower arm, the failure load and stiffness were found to be 2.2 times greater and 2 times higher (3383 kgf and 70.9 kgf/mm) than those of the steel lower arm (1500 kgf and 32.75 kgf/mm), respectively, while meeting the target weight reduction of 50% (2.15 kg to 1.12 kg).

2.2. Use of Carbon fiber in automobiles

2.2.1. Chassis. Masilamani et.al [18] A chassis being the frame of the vehicle has to be stiff or strong to absorb and stop movements and vibrations from engine, suspension and axes. It should be light as well, so as to improve the vehicles performances and fuel efficiency. CFRP is suitable because it is approximately twice stronger but much lighter than steel or aluminum. Carbon fiber body is inflexible. For instance, metals can be melted or welded whereas carbon fiber chassis will not bend, and when it faces enough force it breaks and cannot be joined together. With acceleration defined as change in velocity it can be said that decrease in the weight of vehicle results in the same force greater acceleration. This means that a race car with less weight has the capability to increase speed more rapidly and change directions more quickly. A chassis is usually used in super cars where the strong and light weight property of carbon fiber takes preferences over high cost.

2.2.2. Bumper. Kumar et al. [19] carried out his work on the automotive bumper by using carbon fibre, honeycomb structure and foam. The bumper beam analysed for the steel and composite material with the basic bumper design in the first phase, and then front part is modelled with the honeycomb and foam type in the second phase to compare the deformation and energy absorbed during the impact. The study of automotive bumper was done for three designs namely, basic bumper design with steel, with the attachment of foam and with the attachment of honeycomb. In his research he has shown that the carbon fibre gives the high strength to weight ratio in comparison with the steel and dissipates energy. The basic design with front part as a foam absorbs the energy and ensures the pedestrian safety. The honeycomb structure having strength to absorb more energy hence decreases the chest and thereby ensures passenger's safety.

Do-Hyoung Kim et.al [20] studied various designs of glass/carbon mat thermoplastic (GCMT) and calculated various mechanical properties. Then, the GCMT bumper beam was optimally designed for each material case by using the μGA algorithm with the impact simulation. In accordance with the weight, amount of carbon fibre and impact performance an optimum design was selected. Then, the real bumper beam was manufactured by using the final design and its impact performances were measured. It was found out that the optimally designed GCMT bumper beam had 33% less weight compared to the conventional bumper beam while having a better impact performance as shown in Table 3.

Table 3. Final design results obtained from impact simulation and real test

	Weight (kg)	Instrusion (mm)	Deflection (mm)
Simulated	2.49	130	82
Tested	2.61	123	89
Conventional	3.9	136	93

2.2.3. Engine Cradle. Fonseca et.al [21] demonstrates the feasibility of considering polymer-metal hybrid (PMH) engine cradles for weight reduction and improving structural performance by integrating a recycled carbon fibre (rCF) material and PMH technologies that allow reducing processing time of CFRP components. The initial conceptual design consists of creating C-type/hollow-type inserts and modifying the plastic components by considering the dimensions and thickness of insert and inclusion of plastic ribs as the design parameters. The PMH engine cradles are then evaluated by performance criteria, including weight reduction, stiffness, natural frequency and strength. The integration of rCF with injection-moulding over metal inserts causes weight reduction. The hollow-type and C-type PMH engine cradles achieved the weight reduction of 19% and 16% compared to the reference steel engine cradle and meet the evaluation criteria. The results contribute to the advancement of lightweight engine cradles with improved structural performance, fabricated with low-cost carbon fibre and fast manufacturing processes.

2.2.4 Roof Panel. Bambach [10] presented a novel approach of strengthening vehicle's roof structure components by bonding carbon fibres to the steel surface. The strengthening potential is checked with a numerical study of two different passenger vehicles subjected to various roof crush test protocols. Numerical models of fibre composite strengthening systems are confirmed against experiments, then applied to numerical models of the vehicles. It is shown that fibre composite strengthening of vehicle roof structures has the potential to contribute to higher roof strengths and light-weighing in future vehicle fleets. His study has demonstrated the considerable potential for vehicle roof strengthening by fibre-epoxy strengthening systems. The bonding of carbon fibres to the vehicle roof structure components can improve the roof strength, and similarly the vehicles' roof strength to weight ratio, by nearly two times. A 37–68% mass saving resulted with using fibre composite in place of added steel for equivalent roof strengthening. In Fig 3. the setup used by Bambach for roof crush test is shown.

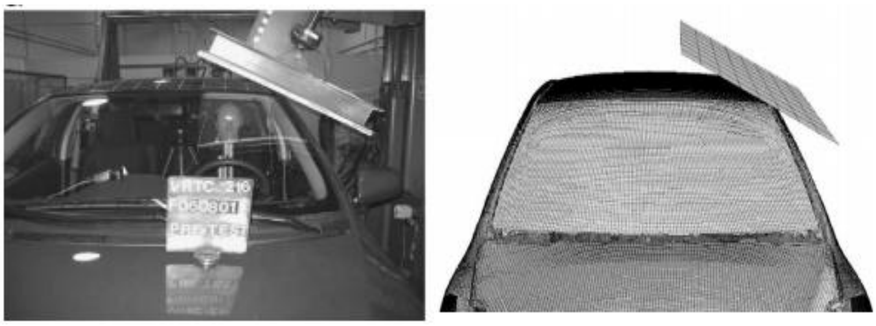


Figure 3. Test setup for the FMVSS 216 roof crush test protocol.

Jain [22] BMW M3 CSL car model utilises CFRP for a production of roof structure. The mass of CFRP roof structure is 6 kg (50%) lighter than the conventional roof.

2.2.5. Tailgate. According Masilamani et.al [18] the stiffness and reduced density of CPRF made it possible to remove the two tailgate stabilizers which can reduce further weight. Due to CPRF it is now possible to remove interior trims components which can be painted directly. Due to the integration property of carbon fibre there is reduction in the number of parts that have to be assembled. It will provide easy assembly and ability to provide complex shapes. The combination of plastic with carbon fibre can reduce the weight of tailgate by 7kg (35%) but it is still not considered good for mass production because of the time it takes during manufacturing.

2.2.6. Hood. Hathcock et.al [23] In this study investigated the potential of graphene additives in carbon fibre body panels through manufacturing of a proof of concept hood for the 2016 Chevrolet Camaro. In order to develop the novel hood, which uses an advanced graphene infused carbon fibre, different amounts of graphene additives were investigated to determine the optimum performance. A new lightweight graphene (0.1%) enhanced carbon fibre composite has been proven as an effective material for concept automotive hood for the 2016 model year Chevy Camaro as it reduces weight of the hood body by 50%, improving structural performance whereas, increasing the cost.

2.2.7. Ribs Construction. Gundolf et. al [24] used circular carbon fibre reinforced plastic (CFRP) in rib construction at the position of the b–pillar that creates a light, safe passenger compartment to assure the safety of the passengers as well as the components of an alternative drive train in case of a side crash as shown in figure 4. Another example is a new light front-end structure which resembles current configurations in the package, but simultaneously reveals a clearly improved structural performance.

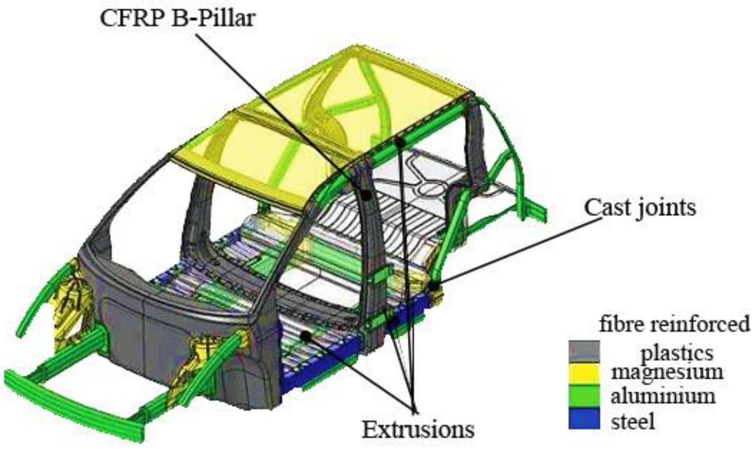


Figure 4. Rib and Space Frame Model.

2.3. Mass Production

Work done by Jacobs A [25] on megacity vehicle of BMW also features a new vehicle architecture and extensive use of lightweight carbon fiber composites. BMW believes it is the only car maker with the manufacturing experience necessary to use carbon fiber in mass production. Amanda Jacob reviews the project details released so far. BMW is confident that with its 10 years of in-house expertise and experience it has achieved its long-term goal: the mass production of CFRP components. In a target to achieve and develop processing capabilities the company has invested heavily in this field.

Visal et.al [26] says that carbon fiber reinforced polymers (CFRPs) are one of the stiffest and lightest composite materials. they are much convincing than other conventional materials in many fields and applications such as higher price and lower formability. Moreover, the nanoparticles increase mechanical properties of these composites. As these composites are costly materials, Non-destructive testing (NDT) such as Eddy current pulsed thermography (ECPT) is used for studying properties against impact loading. Modifying composite papers with Hot Melting Fibers (HMF) shows increase in mechanical properties without considerable reduction in electrical properties. From various experimentation done by research team it is clear that addition of CNT or Nano clay which in this case is montmorillonite Nano clay properties of CFRP are showing promising increase and enhancement. As well as for NDT testing the early stage of heating phase is suitable for carbon fiber mapping and that both latter heating phase and cooling phase can be used for impact characterization. Both results under reflection mode and transmission mode illustrate that the detection of impact is mainly based on the carbon structure broken and conductivity change but not the thickness change using eddy current pulsed thermography.

3. Conclusion

The aim of the review is to report the advancements made in carbon fibre material in automotive industry technology and its wide variety of applications. However, some of the latest efforts and developments are discussed in more detail. Meanwhile, this technology has become state-of-the-art knowledge among the involved researchers. Moreover, this technology has researched wider audience along the worldwide. Despite, continued research in terms of mass production, manufacturing cost, joining technologies, developments and additional research on automotive industry overcoming some of present challenges and limitations that are needed in industrial applications.

References

[1] Hovorun T P, Berladir K V, Pererva V, Rudenko S and Martynov A 2017 Modern materials for automotive industry *Journal of engineering sciences* **4** 8-18
[2] Ghassemieh E J 2011 Materials in automotive application, state of the art and prospects *New Trends and Developments in Automotive Industry* (Edited by Marcello Chiaberge, Published by InTech) pp 365-94
[3] Bhatt P and Goe A 2017 Carbon Fibres: Production, properties and potential use *Material Science Research India* **14** 52-7
[4] Yanrong Z, Ping H, Jicai L 2015 Application of Carbon Fiber Composites in the Automotive industry *China Synthetic Resin and Plastics* **32** 95-8
[5] Isaiah D 2016 Carbon fibre: the fabric of the future *Automotive World Megatrends Magazine* **1**
[6] Jacob G C, Fellers J F, Starbuck J M and Simunovic S J 2004 Crashworthiness of automotive composite material systems *Journal of Applied Polymer Science* **92** 3218-25
[7] John A, Alex S and Baselios M 2014 A review on the composite materials used for automotive bumper in passenger vehicles *International Journal of Engineering and Management Research* **4 (4)** 98-101
[8] Rahimi-Gorji M, Pourmehran O, Hatami M and Ganji D 2015 Statistical optimization of microchannel heat sink (MCHS) geometry cooled by different nanofluids using RSM analysis *Eur. Phys. J. Plus* **130** 22
[9] 2003 Carbon fibre SMC halves weight of automotive parts *Reinforced Plastics* **47 (7)** 16
[10] Bambach M 2014 Fibre composite strengthening of thin steel passenger vehicle roof structures *Thin-Walled Structures* **74** 1-11
[11] Van de Werken N, Tekinalp H, Khanbolouki P, Ozcan S, Williams A and Tehrani M 2020 Additively Manufactured Carbon Fiber-Reinforced Composites: State of the Art and Perspective *Additive Manufacturing* **31** 100962
[12] Othman R, Ismail N I, Pahmi A H, Basri H M, Sharudin H and Hemdi A R 2018 Application Of Carbon Fiber Reinforced Plastics In Automotive Industry: A Review *Journal of Mechanical Manufacturing* **1** 144-54
[13] Kim D H, Choi D H and Kim H S 2014 Design optimization of a carbon fiber reinforced composite automotive lower arm *Composites Part B: Engineering* **58** 400-7
[14] Wang J, Shi C, Yang N, Sun H, Liu Y and Song B 2018 Strength, stiffness, and panel peeling strength of carbon fiber-reinforced composite sandwich structures with aluminum honeycomb cores for vehicle body *Composite Structures* **184** 1189-96
[15] Taketa I, Yamaguchi K, Wadahara E, Yamasaki M, Sekido T and Kitano A 2006 The CFRP automobile body project in Japan. In: *Proceedings of 12th US-Japan Conference Computational Materials,* pp 411-21
[16] Lukaszewicz D 2013 Design drivers for enhanced crash performance of automotive CFRP structures. In: *23rd International Technical Conference on the Enhanced Safety of Vehicles,*
[17] Petersson H, Motte D and Bjärnemo R 2013 Carbon Fiber Composite Materials in Modern Day Automotive Production Lines: A Case Study *In: ASME 2013 International Mechanical Engineering Congress and Exposition* **2A** pp. V02AT02A037
[18] Masilamani R, Dhandapani N, Kumar K, Mani K 2017 A review on usage of carbon fiber reinforced plastics in automobiles nternational *Journal of Pure and Applied Mathematics* **117 (20)** 537-44
[19] Praveen K A, Sameer B, Bhaskar Comparative Study of Automotive Bumper with Different Materials for Passenger and Pedestrian Safety *Journal of Mechanical and Civil Engineering* **11 (4)** 60-4
[20] Kim D H, Kim H G and Kim H S 2015 Design optimization and manufacture of hybrid glass/carbon fiber reinforced composite bumper beam for automobile vehicle *Composite Structures* **131** 742-52

IOP Conf. Series: Materials Science and Engineering **971** (2020) 032011 doi:10.1088/1757-899X/971/3/032011

[21] Fonseca J H, Han G, Quagliato L, Kim Y, Choi J, Keum T, Kim S, Kim N and Lee H J 2019 Design and numerical evaluation of recycled-carbon-fiber-reinforced polymer/metal hybrid engine cradle concepts *International Journal of Mechanical Sciences* **163** 105-15

[22] Jain A, Verpoest I, Hack M, Lomov S V, Adam L and Van Paepegem W 2012 Fatigue Life Simulation on fiber reinforced composites –overview and methods of analysis for the automotive industry *SAE International Journal of Materials and Manufacturing* **5(1)** 205-14

[23] Hathcock M, Davies N, De Pau A, Horton J, Reasoner Z, Scalf R, White B, Jordon J, Kumar A and Frazier R 2017 Opportunities to improve carbon fiber composites for vehicle lightweighting using graphene additives *In conf. SPE Automotive Composites Conference and Exhibition* p 10

[24] Kopp G, Beeh E, Schšll R, Kobilke A, Stra P, Krieschera M 2012 New lightweight structures for advanced automotive vehicles–safe and modular *Procedia - Social and Behavioral Sciences* 4**8** 350-62

[25] Jacob A 2010 BMW counts on carbon fibre for its Megacity Vehicle *Reinforced Plastics* **54** 38-41

[26] Visal S, Deokar S 2016 A Review Paper on Properties of Carbon Fiber Reinforced Polymers *International Journal for Innovative Research in Science & Technology* **2** 238-43