Jovana Spasenović[1]
Ivan Blagojević[2]

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Composite materials in automotive industry – a review

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***Abstract**: Composite materials have found extensive use among many industries including automotive. Vehicles are supposed to be lightweight, have low emission and energy consumption to provide some environmental protection while having appropriate stiffness and strength to assure occupant protection. These requirements can be met with the use of composite materials. Although composites have been present in the industry for decades, their use in the automotive sector is moderately new, which requires development in design and manufacturing processes, testing, and recycling - this paper indicates the details by which the automotive industry differs from others. Principal recycling methods, related legislation, and where recycling products are used are described. Specific uses of composite materials that show a high level of innovativeness are indicated – hybrid and natural composites, structural batteries, and high-performance vehicles.*

***Keywords**: composite materials, automotive industry, recycling, motor vehicles*

Kompozitni materijali u automobilskoj industriji – pregledni rad

***Apstrakt**: Kompozitni materijali se primenjuju u mnogim granama industrije, uključujući i automobilsku. Vozila treba da budu laka, imaju nizak nivo izduvne emisije i potrošnje energije u cilju zaštite životne sredine, dok posedovanjem velike čvrstoće i jačine unapređuje bezbednost putnika. Ove zahteve moguće je ispuniti korišćenjem kompozitnih materijala. Premda se kompoziti koriste u industriji decenijama, u automobilskoj je njihova upotreba prilično nova, što*

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[1] University of Belgrade, Faculty of Mechanical Engineering, jspasenovic@mas.bg.ac.rs
[2] University of Belgrade, Faculty of Mechanical Engineering

zahteva razvoj drugačijeg procesa projektovanja i proizvodnje, ispitivanja i reciklaže. Ovaj rad navodi detalje po kojima se primena kompozita u autoindustriji razlikuje od primene u drugim granama industrije. Deo koji se odnosi na reciklažu opisuje osnovne metode reciklaže, povezane zakone i primenu produkata reciklaže. Takođe, radom se ističe specifična primena kompozita koja pokazuje visok nivo inovativnosti – hibridni i prirodni kompoziti, strukturne baterije i vozila visokih performansi.

Ključne reči: *kompozitni materijali, autoindustrija, reciklaža, motorna vozila*

1. Introduction

Composite materials are extensively used in many industries, including aerospace, automotive, marine, and wind energy industry (Krauklis et al., 2021). Being lightweight, durable, having high strength, good strength to weight ratio, corrosion resistance, high impact strength, design flexibility, and low thermal expansion, makes them a material of choice for numerous engineering applications (Ravishankar, Nayak & Kader, 2019). There are several reasons for the use of composite materials in the automotive industry. The development of electric vehicles brought with it the challenge of creating a lightweight but durable vehicle, as well as the possibility of changing the exterior of an automobile as we know it, which can be achieved by the application of composites. The use of glass fibre reinforced polymer can reduce weight by 20-35%, while carbon fibre reinforced polymer can reduce the weight by 40-65% (Balakrishnan & Seidlitz, 2018). Vehicle manufacturers are utilizing the properties of composites in their favor to achieve the limit of 95 g of CO_2 per kilometer for their fleet (Job et al., 2016), since 100 kg weight saving in each vehicle leads to a reduction in CO_2 emission of 20 g/km (Ishikawa et al., 2018). With the increase in use of composite materials comes the increase in scrap waste, as well as End-of-Life (EoL) waste.

2. Design and manufacturing process

Composite products in the automotive industry are usually made from polymer matrix (either thermoset or thermoplastic) reinforced with glass or carbon fibres. They can measure up to metal products in terms of stiffness, strength, and damping properties if designed properly. Material properties are adjustable by engineers. The purpose of composites is for engineers to be able to design a material to suit the desired function the product is to perform. When using anisotropic materials, oriented stiffness and strength properties are as much of a disadvantage as an advantage, due to those properties in a perpendicular direction to the direction of fibres being considerably lower.

Aerospace industry has been using composites for decades, so structure analysis methods have been developed. The aerospace industry utilizes laminated composites, that assure stiff structures, but slow manufacturing process. For the automotive industry, this process is not feasible, so short fibres that are more easily formed into a desired shape are used. Simulation methods developed for the aerospace industry cannot be used in the automotive industry, for which new, specific methods need to be developed. Nevertheless, the automotive industry can rely on the knowledge of aerospace in terms of understanding failure criteria and behavior of composites under different loading conditions (Yancey, 2016).

When manufacturing composite parts, it is important to also pay attention to tooling and mold design. With the development of new materials comes the need for modification of traditional processing methods. Autoclaves are expensive, so their use in the automotive industry is not preferred except in the case of high-performance vehicles, where there is a small series of vehicles, making this process financially feasible. Prepreg laminas are used when working with thermoplastics, while resin transfer molding is preferable for thermosets (Balakrishnan & Seidlitz, 2018). One must think about an effective and efficient low-cost repair process. Damage on composite products can be assessed by infrared thermography, ultrasonic testing, and digital shearography. Repair techniques used in automotive are scarfing repair (for wider and bigger parts; hard and soft patching is done) and injection repair (for narrow and smaller parts) (Balakrishnan & Seidlitz, 2018).

3. Testing of composite products

Testing of composite structures is rather expensive, so most of the time the engineers rely on component and subcomponent testing, and finite element analysis. Subcomponent testing implies testing of joints, complex geometry parts, and when there is a large difference in materials in contact, while component level testing is used for validation of design and manufacturing processes, as well as assessing the performance of structures in use. Although these tests can be used in all phases of product design, their cost and complexity rise with mentioned level. Therefore, testing on lower levels is done extensively to gather as much data as possible, and the pyramidal approach is used. The pyramidal approach consists of 4 stages: coupon, structural element, subcomponent, and component stage (Buragohain, 2017).

4. Crashworthiness

Safety requirements for vehicle structures are ensured by car safety assessment programs.

According to (Elmarakbi, 2013), there are several advantages of using composites to improve structure crashworthiness in vehicles:

- Specific energy absorption can be significantly higher, so composite structures may achieve the same level of crashworthiness as current steel structures, with a considerably lower weight.
- A vehicle that weighs less may have advantages during a rollover crash.
- Composites deform by brittle fracture, so the structure may disintegrate completely, whilst metal structures fold, having a limited foldable length.

Composite structures may contain "triggers" that ensure the deformation is initiated at the desired location. Triggers may be in the form of change in the cross-section, reducing the number of plies or changes in alignment (when deformation is to be initiated inside a structure and not at the joint) (Elmarakbi, 2013).

5. Hybrid composites and natural fibres

Hybrid composites, consisting of two or more solid materials in the mix, are widely used. A hybridization technique combines synthetic fibre reinforcement with natural fibres into a polymer matrix to form a hybrid composite. The combination of materials may result in advantageous material properties and a lower cost of the final part. Hybrid composites are classified according to the method of manufacturing and are classified as interply, intraply, intermingled, selective, and super hybrid composites. Apart from the following use, hybrid composites may be used in pistons, as brake friction material, anti-roll bars, etc. (Ravishankar, Nayak & Kader, 2019).

Hybrid composites are used in (Ravishankar, Nayak & Kader, 2019):

- AUDI A3, A4, A4 Avant, A6, A8, Roadster, Coupe – seat backs, side and back door panels, boot lining, hat rack, spare tyre lining
- BMW 3, 5, 7 series and others – door panels, headliner panel, boot lining, seat backs
- FORD Mondeo CD 162, Focus – door panels, B-pillar, boot liner

- DAIMLER/CHRYSLER A, C, D, S series – door panel, windshield, dashboard, business table, pillar cover panel
- OPEL Astra, Vectra, Zafira – headliner panel, pillar cover panel, door panel, instrument panel
- ROVER 2000 and others – insulation, rear storage shelf/panel
- SAAB – door panels
- SEAT – door panel, seat back
- VOLKSWAGEN Golf A4, Passat Variant, Bora – door panel, seat back, boot lid finish panel, boot liner.

They are also used in FIAT Punto, Bravo, Marea, ALFA ROMEO 146, 156, RENAULT Clio, PEUGEOT 406 (Ravishankar, Nayak & Kader, 2019).

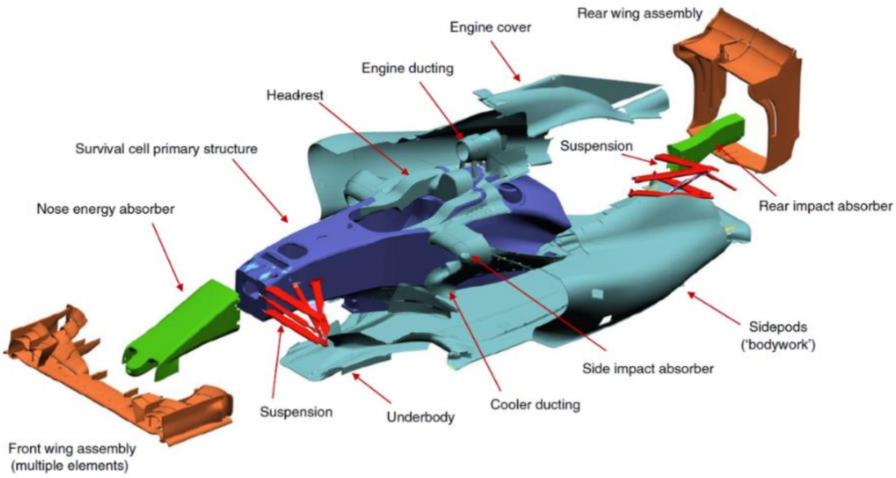
When it comes to cost reduction when using composites, natural fibres are a promising path to take. The addition of natural fillers to polymer matrix brings high strength and stiffness, biodegradability, and sustainability to composite products. They are a challenge to be used in the exterior of the vehicle since they are affected by weather conditions – temperature and humidity. Also, they have a shorter life cycle (Ferreira et al., 2019).
Natural fibres are used in (Ferreira et al., 2019):

- Mercedes-Benz E class – door panels
- Audi A2 – door trim panels
- Toyota RAUM 2003 – spare tyre covers
- BMW – lower door panel

6. Use of composites in high-performance vehicles

Considering racing cars, F1 cars in particular, viewed from the outside, every part on display except wheels, tyres, and braking system components, are made from composites (O'rourke, 2016). The first composite structure to be used in motorsport was carbon fibre monocoque chassis in McLaren MP4/1 in 1981 designed by John Barnard (de Camargo, Giacometti & Pavlovic, 2017). Composites make up parts with different required strengths – from medium strength bodywork to maximum strength survival cell. It is important to note that the racing car industry, where a small series of vehicles is made, is a great match for composites since the price of raw materials is high. Manufacturing processes used in the race car industry are prepreg material lamination, vacuum-bag and autoclave curing, machining, assembly, and bonding. There are also restrictions in materials to be used in F1 – for example, boron fibres, continuously reinforced thermoplastic- and metal-matrix composites, as well as carbon nanotubes, are banned (O'rourke, 2016). Solar cars utilize composite structures as well. They are often characterized by exquisite shapes, minimizing drag coefficient, that combined with lightweight structure from composite materials provides longer range and lower energy consumption. It was shown in (de Camargo, Giacometti & Pavlovic, 2017) that a front wheel hub made from composite materials in a solar car reduces the weight of the hub significantly (the use of carbon fibre reinforced polymer reduces the weight of the hub by 45%, while the use of basalt fibre reinforced polymer reduces the weight of a hub by 37%), ensuring energy savings.

Figure 1. Exploded view of F1 vehicle



Source: O'rourke, 2016

Figure 2. Aptera solar vehicle

Source: Aptera, 2021

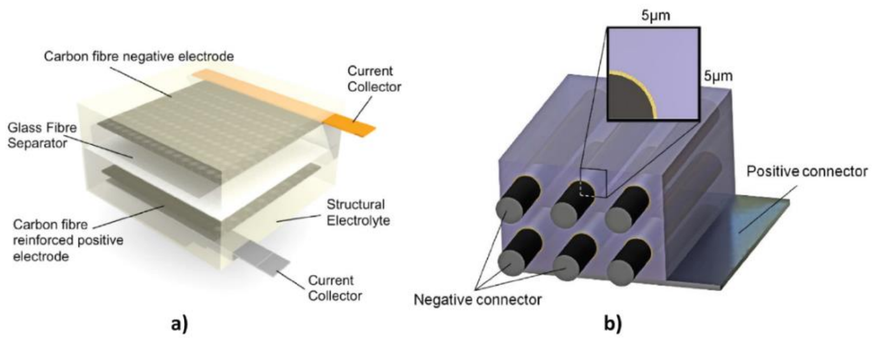
7. Structural batteries

Current battery systems take up a large portion of total vehicle mass and do not provide any structural support. For the development of electric vehicles in terms of a larger range, the total vehicle weight must not increase, while energy storage has to. Composites found use in yet another state-of-the-art topic – structural batteries – that provide mass-less energy storage for electrically powered structural systems (Asp et al., 2019). Structural power composites can be structural capacitors, supercapacitors, and batteries. There are two ways to incorporate batteries into structures – making a multifunctional material (using carbon fibres with electrolytic matrix) and embedding battery foils into laminates (Asp et al., 2019).

There has been limited research on this topic up until now, with the first research starting in 2007 by the US Army Research Laboratory (ARL) (Asp et al., 2021). According to (Asp et al., 2021), existing research showed that developed structural battery composites show either good electrochemical or mechanical performance; stiffness and strength were not investigated in the direction perpendicular to the direction of fibres; the research does not fully exploit multifunctional material constituents. The use of structural battery composites is expected to surpass automotive applications.

Structural battery composites can be used in door and roof panels, as well as bonnets, where they carry loads apart from providing energy storage. This technology has problems (concerning ion-conductivity, mechanical properties of combined electrolyte and matrix, separator layer thickness, manufacturing and validation of structural battery composites, manufacturing and validation (Asp et al., 2019)) that need to be solved before large-scale implementation. The advantage of the use of structural battery composites is in energy storage space – space formerly used for batteries can be used for something else since batteries are confined in roof and door panels or bonnets. For solving some of the aforementioned problems, new structural battery electrolytes have been developed (Asp et al., 2019).

Figure 3. (a) Laminated and (b) 3D-fibre structural battery designs



Source: Asp et al., 2019

8. Recycling of composite materials

Even though composite parts and structures have a long life cycle, the first generation of such parts (e.g. wind turbine blades) is coming to the EoL (Van Oudheusden, 2019). That raises the question of recyclability of composites as a problem that needs to be widely researched and even partially solved. It is expected that the use of composites is to increase in the future, consequently, their recyclability question is to be resolved until numerous products come to the EoL. Considering the strength, durability, and inhomogeneity of composites, they are challenging to recycle (Job et al., 2016).

One of the reasons for solving the recyclability problem of composites is the EU directive considering landfills (99/31/EC) and incineration (2000/76/EC). The legislation tends to increase manufacturer responsibility, recycling rate and decrease the availability of landfills (Job et al., 2016). Another directive (2005/64/EC) states that 85% of a vehicle is required to be recyclable. Known sources of waste include end-of-life components, manufacturing cut-offs, out-of-date prepregs, production tools, as well as test samples (Borjan, Knez & Knez, 2021). There is a large amount of dry fibre waste, from offcuts, converters making fabrics and veils, and from fibre manufacturers (Job et al., 2016).

Recycling of fibre-reinforced composites can be done with or without fibre and matrix separation. If done without separation, the material can be chopped and reused as a filler, while the other option can yield recycling products used in new directionally reinforced parts or structures (Krauklis et al., 2021).

According to (Van Oudheusden, 2019), composites recycling methods can be divided into three groups: mechanical, thermal, and chemical recycling.

Mechanical milling and fragmentation degrade parts into smaller fragments. The product is a mixture of resin, fibres, and filler. Resin-rich powders can be used as a filler, but this is rarely the case due to the low price of new fillers. The fibres can also be reused, bearing in mind that the mechanical properties of composites manufactured with this kind of fibres are notably worse, due to the difficulties in bonding recycled fibres and new resin. These difficulties can be overcome with certain processes. Without the use of recycling products, the whole recycling process can be unjustified or even unsustainable (Van Oudheusden, 2019).

High voltage pulse fragmentation is an electromechanical process that utilizes electricity to separate matrix and fibres. One of the disadvantages is the energy needed for this process (Van Oudheusden, 2019). Reducing the energy demand of recycling processes is important for improving sustainability or for reducing the collateral damage caused by excessive energy input (Job et al., 2016).

Thermal recycling methods are often combined to achieve better results, meaning pyrolysis is often combined with gasification or combustion to achieve cleaner fibres. The differentiation between thermal recycling processes is in the amount of oxygen available during the process: if there is no oxygen – pyrolysis is occurring; if there is limited oxygen – gasification; excess oxygen represents combustion or incineration (Van Oudheusden, 2019). Pyrolysis is the most common method (Krauklis et al., 2021).

Products from resins can be recovered from fibre/matrix separation processes such as pyrolysis and solvolysis (Job et al., 2016).

Chemical recycling, also called solvolysis, uses the chemical depolymerisation of the matrix by using heated solvents or solvent mixtures (Van Oudheusden, 2019). There is a range of solvents, temperatures, pressures, and catalysts to choose from when performing this process. This type of recycling is not used for glass fibres (even though it can be used for both carbon and glass fibres), due to their low cost and great degradation in properties after the process. Due to the smaller cost of glass-reinforced polymers, the best recycling route for them is mechanical, with further use of recycling products as cement filler. Products of solvolysis are fibres, fillers, and depolymerized matrix in form of monomers or petrochemicals (Van Oudheusden, 2019). Solvolysis has no commercial applications yet (Krauklis et al., 2021). The utilization of sub- and supercritical fluids may replace many environmentally harmful solvents currently used in industry, such as organic solvents (Borjan, Knez & Knez, 2021).

One of the alternatives to recycling would be the reuse of existing composite structures as a part of new structures. For example, that would be the use of wind turbine blades in bridge constructions (Van Oudheusden, 2019). It is to be kept in mind that the number of parts that are near the end of their life cycle is limited, and they will eventually be at the EoL of the new structure, which will in turn need to be recycled. Since there are many composite types, by means of material type, structure type, and use, there is no unique way to recycle all composite products, but the processes are to be modified for particular structures.

9. Conclusion

The rise in use of composite materials is dictated by an urge to have lighter but strong vehicles, with low emission and energy consumption. Composites provide the possibility to adapt product properties to the desired function of the product. Composite products need adjusted manufacturing and testing methods, that are constantly under development. Hybrid and natural composites are expected to be used widely due to their low cost. It is expected that the composite recycling technology will improve over time. Products of recycling need to be of better quality for the process to be feasible. One of the main initiators for the development of recycling methods is the EU legislation, that obliges composite manufacturers and users to look at the bigger picture and think of EoL of both constituent materials and final structures.

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References

Aptera Motors. (2021). *Aptera*. Retrieved from https://www.aptera.us/

Asp, L. E., Bouton, K., Carlstedt, D., Duan, S., Harnden, R., Johannisson, W., ... & Zenkert, D. (2021). A structural battery and its multifunctional performance. Advanced Energy and Sustainability Research, 2(3), 2000093. doi: 10.1002/aesr.202000093

Asp, L. E., Johansson, M., Lindbergh, G., Xu, J., & Zenkert, D. (2019). Structural battery composites: a review. *Functional Composites and Structures*, *1*(4). doi: 10.1088/2631-6331/ab5571

Balakrishnan, V. S., & Seidlitz, H. (2018). Potential repair techniques for automotive composites: A review. *Composites Part B: Engineering*, *145*, 28-38. doi: 10.1016/j.compositesb.2018.03.016

Borjan, D., Knez, Ž., & Knez, M. (2021). Recycling of Carbon Fiber-Reinforced Composites—Difficulties and Future Perspectives. *Materials*, *14*(15), 4191. doi: 10.3390/ma14154191

Buragohain, M. K. (2017). *Composite structures: design, mechanics, analysis, manufacturing, and testing*. Boca Raton, USA: CRC press.

De Camargo, F. V., Giacometti, M., & Pavlovic, A. (2017, April). Increasing the energy efficiency in solar vehicles by using composite materials in the front suspension. In *International Conference on Sustainable Design and Manufacturing* (pp. 801-811). Springer, Cham. doi: 10.1007/978-3-319-57078-5_75

Elmarakbi, A. (2013). *Advanced composite materials for automotive applications: Structural integrity and crashworthiness*. Chichester, United Kingdom: John Wiley & Sons.

Ferreira, F. V., Pinheiro, I. F., De Souza, S. F., Mei, L. H., & Lona, L. M. (2019). Polymer composites reinforced with natural fibers and nanocellulose in the automotive industry: a short review. *Journal of Composites Science, 3*(2), 51. doi: 10.3390/jcs3020051

Ishikawa, T., Amaoka, K., Masubuchi, Y., Yamamoto, T., Yamanaka, A., Arai, M., & Takahashi, J. (2018). Overview of automotive structural composites technology developments in Japan. *Composites Science and Technology, 155*, 221-246. doi: 10.1016/j.compscitech.2017.09.015

Job, S., Leeke, G., Mativenga, P., Oliveux, G., Pickering, S., & Shuaib, N. (2016). Composites Recycling–Where are we now? Retrieved from https://compositesuk.co.uk/system/files/documents/Recycling%20Report%202016%20-%20Light%20Background.pdf

Krauklis, A. E., Karl, C. W., Gagani, A. I., & Jørgensen, J. K. (2021). Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. *Journal of Composites Science, 5*(1), 28. doi: 10.3390/jcs5010028

O'Rourke, B. P. (2016). *Formula 1 Applications of Composite Materials*. Reference Module in Materials Science and Materials Engineering. doi:10.1016/b978-0-12-803581-8.03964-3

Ravishankar, B., Nayak, S. K., & Kader, M. A. (2019). Hybrid composites for automotive applications–A review. *Journal of Reinforced Plastics and Composites, 38*(18), 835-845. doi:10.1177/0731684419849708

Van Oudheusden, A. (2019). *Recycling of composite materials* (Student report, Delft University of Technology, Delft, Netherlands). Retrieved from http://resolver.tudelft.nl/uuid:0749ed5c-7aeb-4275-abee-0f904a08ea4d

Yancey, R. N. (2016). Challenges, opportunities, and perspectives on lightweight composite structures: aerospace versus automotive. In Njuguna, J. (Ed.), *Lightweight composite structures in transport* (pp. 35-52). Woodhead Publishing.