CHALLENGES OF OBTAINING NANOCOMPOSITES FOR LIGHTWEIGHT ELECTRIC VEHICLES

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Abstract

Nowadays, the global automotive industry faces challenges in critical areas, reducing the vehicles' weight being one of them. The continuous development of new materials and the exponential increase of research articles on this subject highlight alternative ways to lighten electric vehicles and their subsystems. It is noteworthy that the optimization of the engineering and iteration processes are required to maximize the vehicle's weight reduction, combining the materials' properties and the manufacturing processes to meet the final product specifications. The development of new materials, such as high-resistance steels, aluminum alloys, and polymers reinforced with carbon fiber, became important advances in the automotive industry as they present lightness, corrosion resistance, specific resistance, excellent electrical properties, and are easy to process. Polymer nanocomposites are a great ally in the present and in future automotive industry, creating new possibilities for increasing the vehicles' performance. Graphene has raised much interest recently due to its mechanical, electrical, and thermal properties. Combining it with polymeric materials makes it possible to create nanocomposites that combine the excellent properties of graphene and lightweight. The present work shows the context in which graphene nanocomposites reduce the weight of electric vehicles, showcasing their benefits and manufacturing challenges.

Background

Electric vehicles (EV) were introduced in 2012 due to the necessity of reducing gas emissions of the traditional internal combustion cars and the depletion of oil reserves.[1] The worldwide use of EVs increased from 130 thousand to 4.8 million between 2012 and 2019, way lower than the amount of total vehicles, estimated in 1.89 billion by 2030.[2]

Reducing the vehicles’ weight is one of the most significant challenges of the automotive industry, being evidenced as there is a transition to the use of EVs, which are heavy due to their powerful batteries.[3] The weight reduction represents a better fuel consumption efficiency during vehicle use, increasing air quality due to a drastic decrease in toxic gas emissions, and enhancing sound quality because of silent electric motors.[2], [4] One of the possibilities that can be used to reduce a vehicle’s weight is substituting the heavy conventional materials, such as metals, with lighter reinforced polymeric composites or even polymers reinforced with nanomaterials.[5]

The composite materials are constituted of at least two components, the matrix, and the reinforcement. In this context, recent research has been carried out with the aiming to enhance the materials that are commonly used in the automotive industry, such as polyolefins (polyethylene – PE – and polypropylene - PP). They have low density and high mechanical properties and the possibility of an environmentally friendly bias when hybridized with recycled materials of biological origin.[6], [7] Another polymer of interest for the automotive industry is acrylonitrile butadiene styrene (ABS), which combines good mechanical structure with insulating capabilities, maintaining a bright surface.[8]

In this context, the addition of different fillers in the polymers mentioned above has been studied to provide better properties for the final polymeric composite product. Among the materials used as reinforcements for a polymer composite, long glass fiber, carbon fiber, and calcium carbonate can be highlighted as good choices to form new high-performance materials. The nanomaterials, such as carbon nanotubes, graphene, and natural fibers, can also be used as new reinforcements’ alternatives, providing favorable properties, and reducing the vehicle's weight due to their lightweight.[3], [9]

The addition of inorganic and organic reinforcements is the most common method to obtain high-performance polymer composites, as they can improve the mechanical properties, abrasion resistance, and heat resistance of the polymer matrix.[10] Polymer matrix composites can be used to obtain lightweight car parts, reducing energy consumption and greenhouse gas emissions, due to the possibility of modifying the raw material [11] and optimizing the forming process [12].

Therefore, polymer composites have substituted traditional materials throughout the years, motivated by the necessity of lighter materials. Polymers contribute to numerous innovations in security, performance, and fuel efficiency. Pradeep et al.[13] estimated that a vehicle consumes 6 % to 8 % less fuel as its weight is reduced by 10 %. Therefore, each kilogram reduced from the car's weight could potentially prevent 20 kg of CO_2 emissions.

Polymers and their application in the automotive industry

In general, polymeric materials can be divided into three groups: common-use polymers (commodities), specific-use polymers (engineering polymers), and high-performance polymers (specialties). Commodity polymers are the ones that are produced on a large scale with added value, such as polyethylene (PE) and polypropylene (PP). Engineering polymers are also produced on a large scale, such as acrylonitrile butadiene styrene (ABS) and polycarbonate (PC). However, they present better properties and performances, making them suitable for specific applications. High-performance polymers present well-defined and unique properties with high added value.[14] A third of the car components are constituted by these materials, which have excellent impact resistance to meet modern security requirements. [8] Figure 1 shows the use of different polymers in car parts.

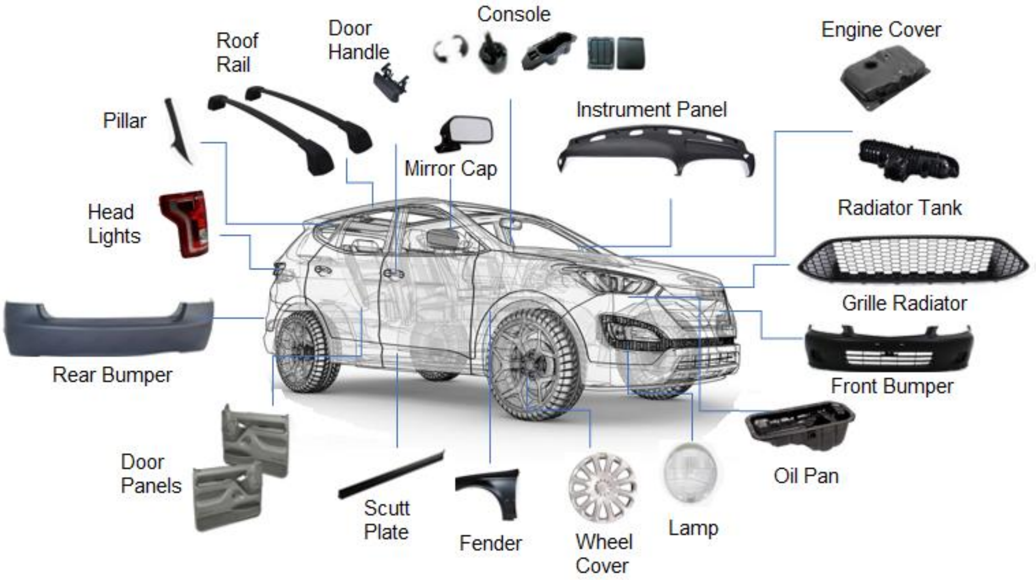

Figure 1: Different applications of polymers in vehicles' parts.

PC is known to be transparent thermoplastics with an amorphous structure. Its molecular structure has strong rigidity, good thermal resistance, resistance to impact, high viscosity during material processing, and is lightweight. On the other hand, it also is susceptible to damage from chemical products and scratches. Nevertheless, its easy processing makes it a good choice for use in numerous applications, such as car bumpers, car lamps, airplane panels, and helmets. [15], [16]

Another important thermoplastic is PP, widely used in the automotive industry, as it is also easy to process. [17] It presents good mechanical and thermal properties at room temperature. Moreover, it is lightweight, low-cost, and recyclable, which makes it a suitable option for different automotive applications, such as upholstery and interior trim. [17]–[19] By adding filler materials in the polymer matrix, the PP matrix's mechanical properties can be increased, and thus may be used also in structural car parts as well. [20]

The PE has good chemical resistance, produced in different densities, mainly low-density polyethylene (LDPE) and high-density polyethylene (HDPE). It also presents good mechanical properties, is lightweight, easily reparable, being an attractive choice due to its different colors and design possibilities. Its applications include oil tanks, brake fluid tanks, car bumpers, and car seats, which are also used in protective layers and fixing bolts due to their high rigidity and mechanical resistance.[15], [21]

ABS is a copolymer of acrylonitrile and styrene in the presence of polybutadiene, also having wide applications. The styrene gives the plastic a shiny look and water resistance, whereas butadiene gives resistance at low temperatures. It is applied to diverse car parts, panels, wheel covers, and coatings, with the possibility of using customized colors. [8]

The versatility of the materials previously mentioned allows for more complex, innovative, and efficient designs, with easy processing, and lower cost. However, there are limitations as the mechanical characteristics of the polymers are not yet comparable to the metallic ones. Therefore, more research is needed to find solutions to enhance the polymer's properties.

Metallic car parts and polymer composites substitutions

The weight removal influences not only the assembly line, by using lighter and cheaper materials, but also the car's performance, as lighter vehicles save more fuel than the heavier ones.[22] The main car parts are built using metallic materials such as steel and different polymeric materials, which are lighter than the metal alloys but cannot withstand the same stress. Table 1 shows the simulated deformation values of a wheel with different materials obtained in the work of Gadwalla and Babu G [23]. The authors simulated the wheel rim's deformation behavior considering different materials. They reported that the pure polymeric materials (ABS and PETG) display more than twenty times more deformations than aluminum and carbon fiber. Therefore, simply replacing the materials is not a feasible solution as the mechanical properties of the polymeric materials are not in the same range as the metallic ones.[22], [24]–[26]

Table 1: Deformation values of static and dynamic simulations of a wheel rim considering different materials.[23]

Material	Static deformation (mm)	Dynamic deformation (mm)
Carbon fiber	0.248	0.18
Aluminum alloy	0.255	0.23
ABS	8.49	5.26
Polyethylene terephthalate glycol (PETG)	4.76	3.75

Its thickness can be increased to enhance the mechanical capabilities of a polymeric material. However, this approach increases the amount of material used to create the car part, leading to heavier parts. Another way to improve the mechanical performance of polymers is to add other materials to the matrix, creating a composite. Some authors reported that adding different graphene positively impacted not only the yielded composite's mechanical but electrical and thermal properties. [27], [28]

Table 2 shows the effect of adding different types of graphene loading on the tensile strength of the composite. Graphene in the composition increases the mechanical capabilities compared to the neat polymer. In the case of polypropylene, the tensile strength increased between 20 % and 30 %. However, the continuous addition of filler materials does not always represent an enhancement of the composite. For instance, PP with 3.0 wt.% of graphene nanoplatelets (GNP) performs better than the polymer with 1.0 wt.% of graphene.

Table 2: Tensile strength of different polymeric composites with various fillers materials and contents.

Matrix	Filler	Filler content (wt.%)	Tensile Strength (MPa)	Reference
ABS	-	0.0	33.6 ± 0.4	[29]
	GNP	2.0	39.9 ± 2.3	
		4.0	39.3 ± 1.2	
		6.0	41.5 ± 0.8	
		8.0	41.4 ± 1.0	
		12.0	42.4 ± 1.7	
		16.0	41.6 ± 1.1	
		20.0	42.9 ± 1.6	
		30.0	44.3 ± 1.9	
PP	-	0.0	30.2 ± 0.4	[30]
	GNP	1.0	36.3 ± 1.1	
		3.0	35.1 ± 0.7	
	Reduced graphene oxide	1.0	36.4 ± 0.4	
		3.0	36.2 ± 0.6	
	Partially reduced graphene oxide	1.0	35.3 ± 0.6	
		3.0	35.3 ± 0.5	
	-	0.0	16.1 ± 0.4	[31]
	GNP	1.0	18.9 ± 0.6	
		2.0	19.4 ± 0.7	
		3.0	19.7 ± 1.1	
		4.0	20.1 ± 0.6	
		5.0	20.2 ± 0.3	
PE	-	0.0	22.7 ± 0.9	[32]
	GNP	2.0	26.0 ± 1.3	
		4.0	25.7 ± 0.4	
	-	0.0	15.0 ± 0.3	[33]
	Reduced graphene oxide	0.1	15.7 ± 0.4	
		0.5	15.6 ± 0.6	
		1.0	16.2 ± 0.6	
		3.0	16.1 ± 0.2	
		5.0	16.4 ± 0.6	

Moreover, even in cases where the material's mechanical characteristics are enhanced with the addition of filler material, there is a trend of stabilization when the content is increased. This behavior is observed in all cases but is better seen in the ABS composites. In this case, the composite with 30.0 wt.% of GNP in its composition performs close to the composite with 6.0 wt.% of GNP. Therefore, even though there is an apparent increase in the physical properties of the yielded composites, only adding graphene is not enough to meet the required specifications for substituting the metal parts with polymer composites.[20]

Another possible approach is to use several fillers in the polymer matrix to achieve better results. Ashenai Ghasemi et al. [17] evaluated the impact of using short glass fibers and exfoliated GNP on the mechanical and thermal properties of PP composites. The authors reported that in samples with 10 wt.% glass fibers, the addition of graphene positively affected its mechanical capabilities, increasing Young's Modulus by 21 % by adding 2 wt.% of GNP. Papageorgiou et al. [34] observed a similar result, evaluating that the reinforcement with only glass fibers improves slightly higher than the reinforcement with only GNP. Nevertheless, the best results are achieved when both fillers are used. The authors reported that a composite composed of 16 % of fiberglass and 20 % of GNP presented a Young's Modulus three times higher than the pure polymer.

Alternative filler materials in polymer composites reinforcements

As already mentioned, adding a filler material in the polymer matrix is the most common method to increase the composite's performance. Glass fibers are usually used to provide reinforcement to polymers, in a higher concentration it provides an increase in the tensile strength of the composite material. There are alternatives that have proved to be interesting for the industry, in this replacement or use in a hybrid form. Carbon fiber, for example, emerged as an alternative to fiberglass due to the weight reduction of materials, resulting in lower fuel consumption.[3], [35], [36]

In addition, with the industry trend to develop sustainable materials, composites with natural fibers are important opportunities, aiming through them, also to reduce weight. Among them, we highlight the nanoparticles obtained from cellulose (nanocellulose), low density renewable fiber and excellent mechanical properties. [37] Nanocellulose (NC) when inserted into PE and PP, demonstrates to composites a combination of lightness with favorable mechanical properties, which could reduce the weight of the automotive component by at least 25%.[38]

Other nanoparticles have also been studied and compared to the results of, such as nano-$CaCO_3$, in which NC shows some improvements even in this comparison, such as lower density, higher strength and higher elastic modulus value. [39] When compared to K-49 aramid fiber and AS4 carbon fiber, it appears to be a material that can replace these more sophisticated materials.[40], [41] Figure 2 shows some of the possible materials that can be used to reduce the electric vehicle's weight.

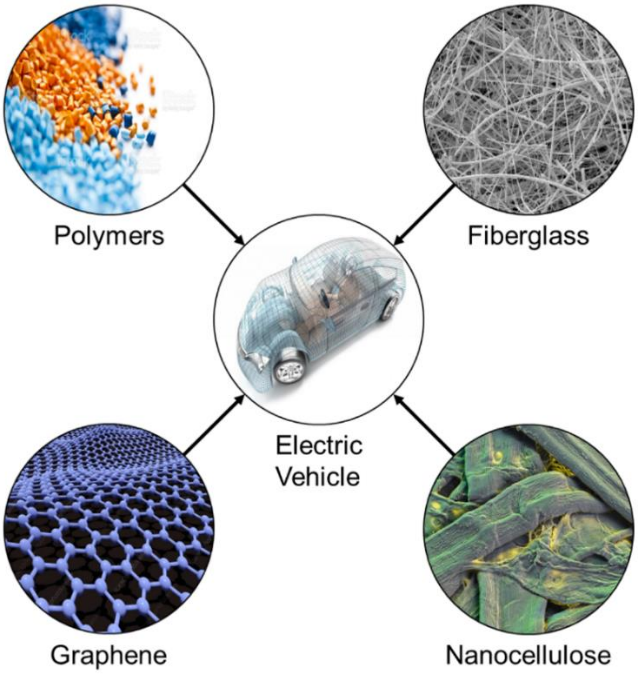

Figure 2: Different materials that can be used in electric vehicles to reduce its weight.

Aside from the natural fibers, graphene can also be used as a possible reinforcement filler. The different types of graphene make it capable of being used in a wide variety of materials, enabling the development of materials for other areas, such as composites, energy generation and storage, and sensors. However, one of the main problems of using graphene is its dispersion in the polymer matrix. [42]

Challenges of graphene dispersion and scalability

Poor dispersion between graphene nanofiller and polymer matrix would limit the development and application of polymeric composites. Dispersion and cost are the significant factors restricting the development of graphene polymer composites. [42]The composite production method is a key to better properties of composites as it would help achieve a uniform dispersion and distribution of filler in the polymer matrix. Furthermore, the development of better interfacial bonding between the filler and polymer matrix not only depends on the effectiveness of the coupling agent but also depends on good dispersion and distribution of the filler, which themselves rely on the processing techniques.[43]

The dispersion and distribution of charges in polymers can be mechanical mixing in the mixing in solvents with ultrasound tip assistance, in-situ polymerization, and molten state. The particulate's surface activity strongly depends on the form of the mixture to be used and its interaction with the polymer matrix [44].

The method of dispersion in solution stands out for being a technique favorable to the dispersion of nanometric particles, which involves dispersion of the charges in a suitable solvent, mixing, dispersion in the solution, and orientation within the composite [45]. This nanofiller dispersion step of the process is a fundamental part of obtaining a final material with promising properties. Initially, magnetic agitation is used and/or, depending on the type of load to be dispersed, mechanical agitation [46]. Magnetic stirring helps break larger agglomerates, but it does not have excellent efficiency and capacity for breaking and separating nanometric particles. For this reason, the sonication technique is widely used in liquid media to separate the fine fraction from the particle [47].

Ultrasonic dispersion generates the breaking of agglomerates by the effect of cavitation, the phenomenon of formation and destruction of air bubbles caused by ultrasonic waves. can be divided into three stages: nucleation (formation of air bubbles), growth, and implosion of the bubbles, where the last step can promote the separation of particles [48].

Colloidal graphene suspensions may be advantageous because they could be used for a wide range of applications, moreover, by mixing them with polymers, graphene-based polymer composites can be prepared. In these production methods, the key challenge involves exfoliating graphitic materials in a liquid that can stably disperse graphene sheets.

In-situ polymerization presents a unique opportunity to prepare well-dispersed polyolefin nanocomposites. This is done by first dispersing nanoparticles in a polymerization solvent, followed by homogeneous polymerization within the dispersion through the addition of catalyst and monomer.[49]

An industrially important technique for the dispersion of fillers in thermoplastics is melt blending or melt mixing. In the melt mixing, the polymer is melted and combined with the desired amount of the filler materials by using twin screw extruders [50]. After mixing fillers, the filler/thermoplastic blends can be injection molded to fabricate the desired product. Unlike solution mixing, melt mixing is environmentally friendly, but the dispersion of filler by melt mixing is somewhat compromised and largely dependent upon the extruder's sophistication and advancement extruder [51]. A comparison of properties of graphene-filled polymer composites reported in the literature is presented in Table 3.

Table 3: Comparison of different graphene filler types and concentrations in ABS, PE, and PP polymer composites.

Matrix	Filler (wt.%)	Method	Mechanical properties	Reference
ABS	GNP (3%)	Melt Mixing	30% increase in tensile strength	[52]
	Few layered graphenes (0.24%)	Solution mixing	43% increase in tensile strength	[53]
	GO (2%)	Melt mixing	28% increase in tensile strength	[54]
PE	GNP (1%)	Melt Mixing	24% increase in tensile strength	[55]
		Solution Mixing	20% increase in tensile strength	
	Graphene (1%)	Melt Mixing	21% increase in tensile strength	[56]
PP	GNP (4.6%)	Solution Mixing	15% increase in tensile strength	[57]
	GNP (9.3%)	Solution Mixing	12% decrease in tensile strength	[58]
	GNP (3%)	Melt Mixing	60% increase in tensile strength	[59]
	Graphene nanosheets (17.4%)	Polymerization in-situ	25% increase in tensile strength	[60]

Summary and Next Steps

The present work showcased some of the possibilities of using alternative materials for reducing the vehicles' weight. Polymeric composites are already used in the automotive in many applications. However, by adding new materials, such as natural fibers and graphene, the range of their applications can get much wider. The literature studies showed that by adding graphene and its derivatives fillers (graphene oxide, graphene nanoplatelets), the mechanical properties of the polymeric composites are enhanced in such way that creates the possibility of substituting heavy duty materials, such as metal alloys, for the new composite materials. The main issue on using graphene relies on the processability and scalability of this technology. The dispersion of graphene in the polymer matrix is still an issue that is far from being completely solved, with various research branches trying to come up with the best solution. Nevertheless, the use of graphene as a filler in the polymeric matrix is an interesting and exciting, opening new possibilities for new electric car's design with enhanced performance aimed for better quality and less waste.

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