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Application of Nanocomposites in Automotive Lightweighting

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Abstract. In the development of the global automotive industry, electrification has become a trend, and lightweight vehicles have attracted the attention of all sectors of society, which is the key to improving structural performance and saving energy.The use of fiber composites or metal materials can not achieve the unity of performance and weight, which is not conducive to the development of the industry. The advantages of nanocomposites are reflected in the low content of fillers, which can play the role of multifunctional integration, attract the attention of more and more people in the automotive industry, and promote the development of automotive materials. This paper systematically introduces the characteristics of nanofillers and composites, reviews the mainstream manufacturing process, analyzes the impact of factors such as cost, agglomeration and adaptability, and forecasts the development trend of technology.

Keywords: Nanocomposites, Automotive Lightweighting, Nanofillers, Interface Modification, Electrically Controlled Components

1. Introduction

At present, the world's automotive industry has developed in the direction of electric vehicles, and the lightweight of vehicles has become an inevitable trend. If the weight of the vehicle can be reduced, the energy consumption will decrease, and the driving range will increase. Too much dependence on traditional metal materials will cause certain limitations. Steel, aluminum alloys and other materials are relatively heavy, and the content of fibers in ordinary fiber composites is relatively high, which means that the weight of the vehicle will increase and the difficulty of production will increase. The biggest problem with natural plant fiber materials is that they have a high water content, the interface between matrix and fiber is weak, and the water absorption rate is relatively high. The biggest advantage of nanocomposites is that they can bring 0D, 1D, 2D and other nanomaterials to the matrix, and can improve impact resistance, tensile strength and so on with low additive content. Lightweight and good mechanical properties are the main research directions of the automotive industry. To reduce the heavy battery weight and improve driving range, composite materials are widely considered for many key parts of electric vehicles, as shown in Figure 1 [1].

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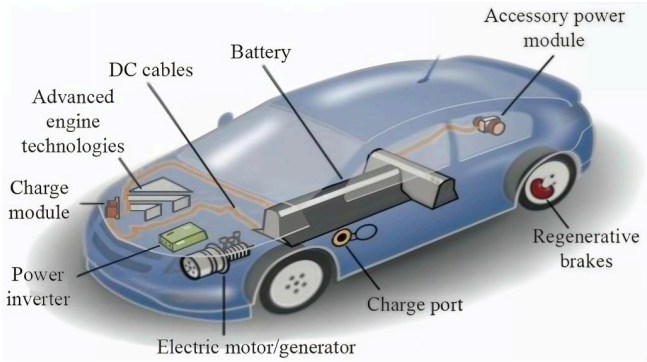


Figure 1. Schematic diagram of compositebased lightweight components for electric vehicles [1]

This paper focuses on nanocomposites used in automotive components, including the body, chassis, interior, transmission, and electronic cooling parts. The matrix is primarily polymer-based, including thermosetting matrices such as unsaturated polyester and epoxy resins, as well as thermoplastic matrices such as polypropylene (PP) and polyamide (PA). A small portion uses aluminum-based metal matrices for non-battery electronic components requiring high thermal conductivity. Nanofillers include 0-dimensional nanoparticles (nano-SiO_2, Al_2O_3, TiO_2), 1-dimensional nanofillers (carbon nanotubes, nanocellulose), and 2-dimensional lamellar fillers (graphene, montmorillonite, MXene). Macroscale natural/synthetic fibers can be hybridized with nanofillers to form hybrid nano-bio composites, with agricultural waste fibers such as pineapple leaf fiber (PALF) and jute serving as macroscale reinforcement.

The main automotive applications can be categorized into four types: body components and protective nanocoatings, chassis and transmission system structural/semi-structural components, non-load-bearing interior components, and heat dissipation and housing components for electric motors and power electronic devices in new energy vehicles. The purpose of this study is to sort out and analyze the types of nanomaterials in the automotive field, and to make a reasonable comparison between nanofillers of different dimensions, so as to predict the development trend of this field in the next stage.

2. Fundamentals and reinforcement mechanisms of nanocomposites

In the process of preparing nanocomposites, it is necessary to prepare a matrix, interface, nanoscale reinforcement phase and so on. Although they are similar to traditional macroscopic fiber composites, they are different in many ways. The biggest difference is that the reinforcement effect of the former is higher than that of the latter, and the filler content is relatively low. This is because nanoscale fillers have a higher specific surface area, which can change the stress transfer and crack propagation in the matrix when the content is low, and can adjust the barrier, thermal, mechanical and other properties of the material.This paper briefly analyzes the matrix and nanofillers in the automotive system, focuses on how to adjust the interface, and lays the theoretical foundation for the subsequent use of nanocomposites in lightweight design.

2.1. Matrix materials

The matrix is the continuous phase of the composite, which can protect the filler and transfer the load. It can be said that the matrix can determine the service life and molding process of the composite. Polymer matrix is widely used in automotive nanocomposites, which can be divided into

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thermoplastic and thermosetting types. Unsaturated polyester and epoxy are typical thermosetting resins. After curing, they can form a network, have strong strength and high heat resistance, and can be used to make semi-structural parts with high performance. However, once they are formed, they can not be processed or melted again, and it is difficult to recycle them. Aluminum-based metal matrix is used in a few high thermal conductivity components, which can enhance the thermal conductivity and strength of the material by means of nanoscale phase. The matrix has a significant impact on the filler dispersion. Polyamide and epoxy are typical polar matrices, which can produce strong interfacial interaction with nanofillers. Polypropylene is a non-polar matrix, which has weak interfacial compatibility, and the filler needs to be modified.

2.2. Nanofillers of different dimensions and their reinforcement mechanisms

According to geometric dimensions, automotive nanofillers can be divided into three categories: 0-dimensional nanoparticles, 1-dimensional nanofibers, and 2-dimensional layered fillers. The modification mechanisms of fillers with different dimensions differ significantly and are the core of performance regulation in automotive nanocomposites.

2.3. Reinforcement mechanism of 0-dimensional nanoparticles

0-dimensional nanoparticles include ceramic particles such as nano SiO_2, Al_2O_3, and TiO_2, with all three dimensions at the nanoscale. Their reinforcement mechanisms mainly include defect filling, crack pinning, and stress transfer. Nanoparticles can fill micropores and defects inside the matrix, reducing stress concentration within the matrix; when cracks reach the nanoparticle location, crack blunting and deflection occur, consuming fracture energy and inhibiting further crack propagation. Arumugam et al. introduced 2 wt% alkali-modified nano SiO_2 into a pineapple leaf fiber/unsaturated polyester system and found that the composite's water absorption decreased from 51.19% to 5.5%, and flexural strength increased by 36%. Nanoparticles filled the pores on the fiber surface, improving the fiber-resin interface adhesion while enhancing the material's water resistance [2]. However, such ceramic particles provide limited improvement in impact toughness. Excessive filler content can cause agglomeration, forming defects inside the matrix and reducing mechanical performance. These fillers are mostly used in automotive interior parts and protective coatings. However, such ceramic particles provide limited improvement in impact toughness. Excessive filler content can cause agglomeration, forming defects inside the matrix and reducing mechanical performance. These fillers are mostly used in automotive interior parts and protective coatings. Nyiranzeyimana et al. investigated hybrid biocomposites reinforced by nano-Al_2O_3/TiO_2 and jute fiber, confirming that 0D ceramic nanofillers could effectively improve surface performance for automotive exterior biocomposite components [3].

2.3.1. Reinforcement mechanism of 1-dimensional nanofillers

One-dimensional fillers are represented by carbon nanotubes and nanocellulose, having a high aspect ratio. Carbon nanotubes can construct a continuous stress transfer network within the matrix, improving tensile strength and fatigue resistance while providing thermal conductivity to the material. Mahmood et al. studied PA6/multi-walled carbon nanotube composites and found that with only 0.5 wt% nanotube filler, a continuous thermal conduction path formed inside the matrix, the in-plane thermal conductivity of the material nearly doubled, and the tensile modulus increased by about 22%. Such thermal enhancement at low filler content meets the integrated lightweighting and

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heat dissipation requirements of electric control housings in new energy vehicles [4]. The main challenges of 1-dimensional nanofillers are that nanotubes easily entangle, making uniform dispersion in the matrix difficult, and the raw material cost is relatively high. Biomass nanocellulose can be used to prepare low-carbon and environmentally friendly automotive interior parts. First occurrence: The Internet of Things (IoT) is a network of interconnected devices that communicate and share data.

2.3.2. Reinforcement mechanism of 2-dimensional layered nanofillers

Graphene, montmorillonite, and MXene are 2-dimensional layered nanofillers that extend the diffusion path of water vapor and corrosive media, improving the material's barrier and corrosion resistance while enabling mechanical reinforcement. Attar et al. investigated nylon-6/graphene nanoplatelet nanocomposites prepared by twin-screw melt-blending. At 3 wt% graphene nanoplatelet loading, the elastic modulus of composites could increase up to 29.7 % compared with neat PA6, benefiting from the stiffening effect of GnPs and effective stress transfer at the nanoscale interfaces. Nevertheless, the addition of GnPs led to a reduction in impact strength, which was related to filler agglomeration and weak interfacial interaction between graphene nanoplatelets and polymer matrix [4]. The layered GnP structure is capable of blunting crack tips and altering crack propagation paths within the matrix. In the early stage of the development of automotive nanocomposites, the polypropylene system was modified with montmorillonite. The layered barrier effect of the system could resist aging and improve the performance of materials. Two-dimensional nanomaterials have a certain shielding effect on electromagnetic, which can play a protective role in electronic control components.

Nevertheless, the addition of GNPs led to a reduction in impact strength, which was related to filler agglomeration and weak interfacial interaction between graphene nanoplatelets and polymer matrix [5]. The typical fracture morphology reflecting such interfacial characteristics is displayed in Figure 2.

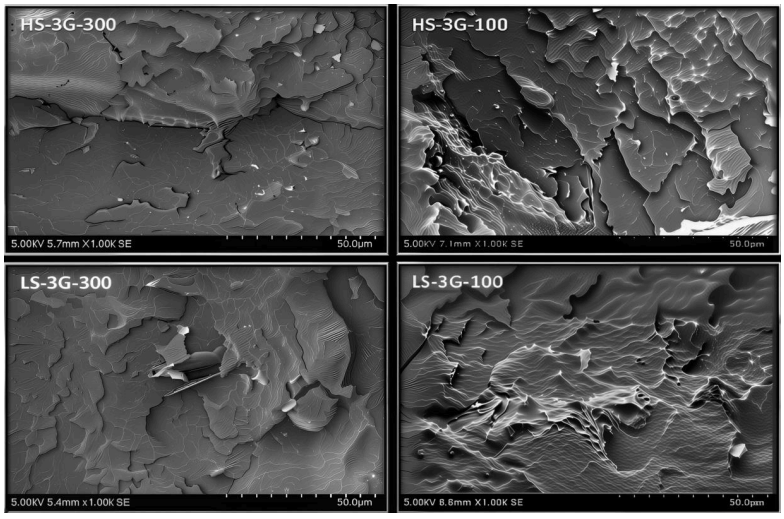


Figure 2. Fracture SEM morphologies of PA6/GNP nanocomposites under different twinscrew processing conditions [5]

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2.4. Interface structure and interface regulation mechanism

Nanocomposites have interfaces, which are nanoscale transition zones that exist between the matrix and nanofillers. Whether the interface is bonded effectively will have a direct impact on the efficiency of load transfer, and the success of nanomodification depends on it. There are many types of interface interactions, which can be roughly divided into physical and chemical bonds. Physical bonding means that the matrix can be anchored to the surface of nanofillers, but the strength of this bonding is relatively low; Chemical bonding is the most ideal, because there are many active groups on the surface of nanofillers, which can form covalent bonds with the matrix, so as to enhance the stability of the interface, improve the load transfer efficiency, and form a covalent bond interface network. It should be noted that silane coupling agents should be used in the preparation process, and active groups should be introduced into the surface of nanofillers. It is necessary to form covalent bonds between polar matrices and oxygen-containing nanofillers. When external forces are applied, hydrogen bonds can be broken and reformed, so as to improve the toughness of materials and absorb fracture energy.

2.5. Interface failure forms and regulation principles

There are many forms of interface failure in the process of preparing nanocomposites, including interface debonding, filler pull-out, interface cracks and so on. If the interface bonding strength is too low, the load can not be transferred, and the strength of the material can not meet the requirements; if the interface bonding is too strong, the filler can not be pulled out, energy can not be dissipated, and the material will be brittle fracture.Therefore, it is necessary to adjust the interface to make it strong and tough, not only to transfer the load, but also to have a certain energy absorption capacity, and to increase the toughness of the material. Matrix functionalization, filler surface modification and other ways can make the thickness and strength of the interface meet the requirements, and the performance of the composite materials will be significantly improved.

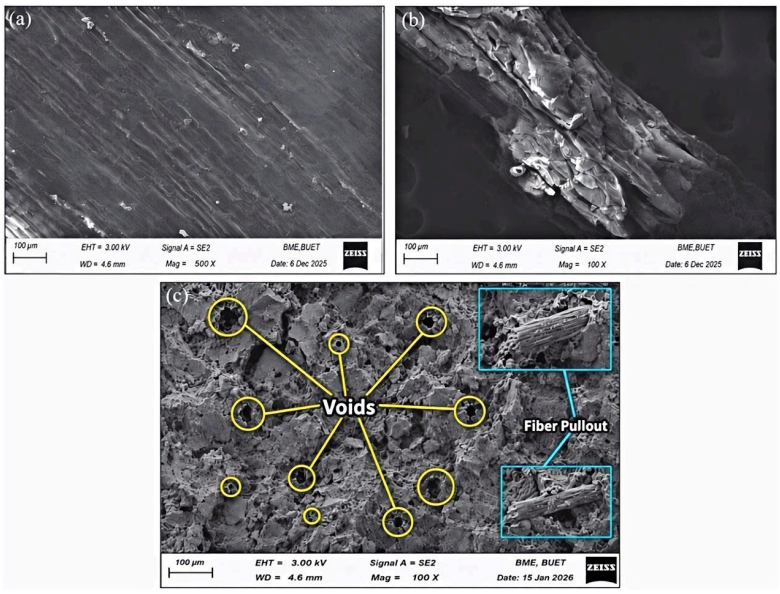


Figure 3. Fracture morphology showing typical interfacial failure features of hybrid fiber-reinforced epoxy composites: (a) matrix cracking, (b) fiber breakage, (c) voids and fiber pull-out [6]

DOI: 10.54254/2755-2721/2027.AD39307

These typical failure phenomena, including matrix cracking (Figure 3a), fiber breakage (Figure 3b), and voids and fiber pull-out (Figure 3c), can be widely observed in fiber- and particle-reinforced composite systems under external load [6].

3. Research on the application of nanocomposites in automotive lightweighting

Because the content of nanofillers is relatively low, but the reinforcement is relatively high, nanofillers are used in polymer composites, which can be processed with the help of injection molding technology, and can also use traditional aluminum and steel materials, which can achieve the goal of weight reduction. At present, both domestic and foreign scholars have focused on the following four aspects: metal substrate protective coating, new energy vehicle control component, car body structure, interior and exterior decoration parts. This is a new material system, which can be used in the process of automobile lightweighting, and the application potential of this material system has been recognized by many scholars.

4. 0D ceramic particle-reinforced composites and automotive applications

0-dimensional nanoceramic particles are widely investigated for polypropylene and polyamide systems, among which nano-TiO_2 and nano-SiO_2 are the most representative. Nanoceramic particles can effectively enhance the scratch resistance and stiffness of polymer matrices and greatly improve dimensional stability, which helps suppress warpage for injection-molded components such as bumper frames and automotive door parts. Besides mechanical reinforcement, nano-titanium dioxide exhibits photocatalytic characteristics and can endow automotive exterior protective coatings with self-cleaning performance. This material system benefits from low-cost raw nanofillers and good compatibility with large-scale automotive injection-molding production. Nevertheless, uniform dispersion of nanoparticles remains a major challenge; nanoparticles are prone to agglomerate at relatively high loadings, which restricts further improvement in impact toughness.

4.1. 1D nanofiber/carbon nanotube reinforced composites and automotive applications

One-dimensional nanofillers represented by carbon nanotubes and nanocellulose possess high aspect ratios, which makes them promising for semi-structural components demanding good mechanical strength, fatigue tolerance and thermal conductivity. Carbon-nanotube-filled polyamide composites can realize weight reduction via thin-wall design and are potential candidates for vehicle-body mounting brackets. As reported by Mahmood et al., low-loading carbon nanotubes can construct continuous thermal conduction pathways within PA6 matrix and improve tensile modulus, which satisfies the combined lightweight and heat-dissipation demands for electric-control housing components of new-energy vehicles [2]. As a biomass-derived filler, nanocellulose can be compounded with polypropylene to manufacture interior parts including door panels and dashboard linings. Such materials are biodegradable, low-carbon and eco-friendly, matching the development trend of green automobile manufacturing. Major bottlenecks restricting practical application include the high raw-material cost of carbon nanotubes, expensive processing for homogeneous nanofiller dispersion, and challenges for large-scale industrial implementation.

4.2. 2D laminated nanocomposites and automotive applications

Graphene and montmorillonite two-dimensional laminates not only enhance mechanically but also offer excellent barrier, corrosion resistance, and electromagnetic shielding properties.

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Montmorillonite modified polypropylene is one of the earliest industrially researched automotive nanocomposites. Montmorillonite laminates can extend the water vapor penetration path, improve aging resistance, and are used in interior panels of car doors and A-pillars. Graphene composite coatings applied to chassis metal substrates can improve chassis corrosion and wear resistance. Under the premise of meeting corrosion protection standards, chassis steel plate thickness is reduced, indirectly achieving overall vehicle weight reduction. Related studies have sprayed graphene composite coatings on low-carbon steel chassis samples. Salt spray test results show the coating can increase the corrosion resistance life of the substrate by more than three times [7]. Two-dimensional nanomaterials also have potential for electromagnetic shielding of electronic control components. MXene nanosheet-modified polymer materials achieve electromagnetic shielding under lightweight premise, protecting electronic control components from electromagnetic interference. Two-dimensional nanomaterials also have potential for electromagnetic shielding of electronic control components. MXene nanosheet-modified polymer materials achieve electromagnetic shielding under lightweight premise, protecting electronic control components from electromagnetic interference. Zhao et al. reported an industrial-oriented study on graphene-modified polypropylene nanocomposite foams, realizing lightweight and noise-reduction performance for automotive exterior parts and pointing out critical processing obstacles for large-scale foam injection molding [8].

4.3. Bottlenecks in the industrialization of automotive nanocomposites

Despite many positive laboratory results, large-scale installation and application of nanocomposites still face many challenges.

Nano-fillers have high surface energy and are difficult to stabilize and disperse during large-scale production, making agglomeration easy and causing instability in mechanical properties of components; High-end nano-fillers (carbon nanotubes, graphene) have high raw material costs, limiting large-scale mass production; Under high and low temperature cycling and UV aging environments, the bonding strength between the filler-matrix interface weakens, and long-term reliability of materials requires more vehicle-level aging validation; After nano-composite plastics are scrapped, fillers are difficult to separate and recycle, reclaimed material performance degrades, and recycling systems suitable for the automotive industry are still imperfect.

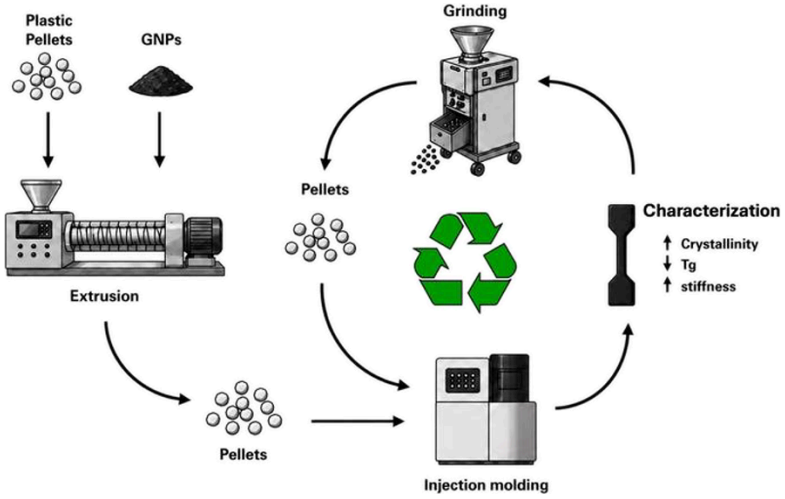


Figure 4. Schematic of repeated thermomechanical reprocessing cycle for PA6/GNP nanocomposites [9]

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Even for thermoplastic-based nanocomposites, repeated thermomechanical cycles during recycling may alter crystallinity and filler dispersion state, bringing performance fluctuations to recycled parts [9]. The whole thermomechanical cycle is illustrated in Figure 4.

5. Existing challenges and future outlook

5.1. Existing technological and industrial challenges

First, the barrier of raw material costs is prominent. High-grade nanofillers such as carbon nanotubes and graphene are expensive. For example, the cost of graphene prepared by chemical vapor deposition can reach 100–1000 USD per gram, accounting for more than 60% of the total material cost, which limits its promotion and application in ordinary passenger vehicles; only zero-dimensional nanosilica and montmorillonite show relatively favorable cost advantages.

Second, we should deepen the understanding of hybrid composites, especially to analyze the characteristics of natural fiber composites, to carry out more in-depth research on the pretreatment technology of fiber chemicals, to make full use of agricultural waste fibers, to apply them to semi-structural parts and interior components, and to improve the sustainability of materials from the whole life cycle.

Third, a variety of composite materials are developed to give play to the advantages of self-healing function, shielding, thermal conductivity and load bearing, and can meet the needs of motor housing, which is conducive to the integration of functions.

Fourth, the advantages of artificial intelligence and machine learning should be brought into play to optimize the process and formulate reasonable plans.Computational materials science and topological optimization can help in the screening of new materials and avoid repeated experiments.

Fifth, to continuously promote the upgrading of thermoplastic nanocomposites, to continuously enhance the performance of materials, to improve the performance of joining dissimilar materials, to develop reasonable evaluation standards, and to promote the rapid development of laboratory achievements.

5.2. Future technological development directions

First, develop low-cost, scalable nanofiller preparation technologies, promote masterbatch processes, alleviate dispersion and agglomeration challenges of fillers, enhance the mass production adaptability of materials, and reduce the production costs of high-end fillers such as carbon nanotubes and graphene.

Second, continuously advance the research and development of bio-based nano-natural fiber hybrid composites, optimize fiber chemical pretreatment processes, fully explore the application potential of agricultural waste fibers, expand their applications in automotive interior components and semi-structural parts, and improve the material's sustainability throughout its entire lifecycle.

Third, develop multifunctional integrated nanocomposites that combine mechanical load-bearing, thermal conductivity, electromagnetic shielding, and self-healing functions, targeting the needs of electric vehicle motors and electronic control housings, and promote functional integration of components.

Fourth, combine artificial intelligence and machine learning to assist in formulation design and process optimization, and integrate topology optimization and computational materials science methods to accelerate new material screening, reduce repetitive experiments, and shorten the R&D cycle.Moreover, hybrid nanocomposites designed for new-energy-vehicle battery housings should

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receive more attention. Balancing mechanical bearing capacity, thermal management and recyclability is critical for the practical deployment of lightweight composite enclosures [10].

Fifth, focus on advancing thermoplastic nanocomposites to improve material recycling performance; enhance technologies for joining dissimilar materials, establish in-vehicle aging evaluation standards, and promote the translation of laboratory research achievements into practical automotive components.

6. Conclusion

Nanocomposites, relying on unique nanoscale effects, can enhance multiple properties of polymer matrices such as mechanical strength, heat resistance, and barrier performance even with an extremely low filler content, providing an important technological pathway for automotive lightweighting. Current studies indicate that 0D, 1D, and 2D nanofillers exhibit promising application potential in vehicle structural components, interior and exterior fittings, new energy vehicle electronic control parts, and metal protective coatings. The main bottlenecks limiting large-scale automotive application are the stable dispersion of nanofillers at scale, long-term aging reliability of materials, and production costs. With continuous breakthroughs in interface modification and scalable preparation technologies, nanocomposites are expected to play a greater role in automotive lightweighting, particularly in the lightweighting of new energy vehicles.

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