Nanostructured Material Engineering for Advanced Automotive Lightweight Upgrade

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Abstract. Driven by the dual imperatives of environmental protection and performance enhancement, the automotive industry has introduced new priorities for lightweight design in new energy vehicles. Automotive lightweight materials face the main challenges of uniform dispersion of the nanoparticles, scalable and economical manufacturing processes, dependable and lasting multi-material integration, and durability under service conditions. This review investigates the use of nanomaterials in lightweighting automotive applications by surveying the four main classes of carbon, ceramic, silicon, and polymer nanocomposites and evaluating their synthesis routes, interfacial engineering, and performance metrics. A mixed approach using literature review and specific case studies was applied to compare the mechanical properties, dispersion stability, and scale up difficulties of different nanofiller systems. Significant works on carbon nanotube and graphene reinforced carbon fibre composites, alumina nanocoated, high aspect ratio silicon carbide nanowires, and nano-clay enhanced polymers were studied to calculate mass loss, stiffness loss, and loss of durability in the body, chassis, and interior components. The obtained results revealed that the incorporation of nanomaterials enables component weight reductions of 10 to 60% while continuing to provide good structural strength, stiffness, and corrosion or wear resistance. Problems with nanoscale particle agglomeration, economic mass production, and safety standardization were noted. The review provided final remarks on optimizing dispersion techniques to minimize material and process expenditure, effectively accelerating the use of nanotechnology in automotive.

Keywords: Automotive lightweighting, nanomaterials, conventional lightweight materials, automotive applications.

1. Introduction

The automotive industry is in a period of rapid change, and many governments and consumers are demanding cleaner vehicles. New energy vehicles (NEVs), such as electric and hybrid cars, lead this transformation [1, 2]. Automakers have invested heavily in NEVs technologies with the goal of reducing carbon emissions and dependence on fossil fuels. With the rapid development of NEVs, it is also facing great challenges, that is, large battery packs and solid safety frames will significantly increase the weight [3]. This extra weight will reduce the mileage, which will also raise production costs and limit vehicle performance.

Engineers tackle this issue with lightweight designs, such as redesigning the vehicle structures from scratch [4], or replacing heavy metals like steel with lighter ones [5]. Aluminium alloys offer weight savings and corrosion resistance [5]. Magnesium alloys cut mass further but cost more [5]. Fibre-reinforced plastics were also adopted in semi-structural roles. Multi-material structures match each load location with the optimal material, which can yield significant mass savings. However, connecting different materials requires mechanical fasteners or advanced adhesives, which may affect durability, cost and recyclability. Crash simulation becomes more complicated in mixed material designs. It is necessary to verify the performance of each joint and interface, which will increase the time and cost of the development cycle. Structural optimisation is another path. Unnecessary materials are removed by topology optimisation [4], and lattice structures are applied in non-critical areas. These methods can reduce the weight by up to 20 %. The trade-off is often higher manufacturing complexity and cost [4].

Nanomaterials have attracted extensive attention because of the unique size effects, interface effects and controllable physicochemical properties [6, 7]. Carbon fibre, ceramic coatings (such as alumina and zirconia) and polymer-based nanocomposites exhibit lightweight, high strength and excellent environmental adaptability, providing a new technological approach to achieve lightweight automotive upgrading. Although some studies have verified its application prospects in the laboratory and some engineering prototypes, there are still technical gaps and challenges between theory and practice in the collaborative design, composite application and large-scale preparation of different nanomaterials.

This review aims to provide a solution for vehicle lightweighting through systematic research on nanomaterials and focuses on four key nanomaterial types for automotive lightweighting, including Carbon-Based Nanomaterials (especially carbon fibre-based nanocomposites), ceramic nanomaterials (such as alumina and zirconia), silicon-based nanomaterials and polymer nanocomposites. The processing routes and performance of these materials were discussed and compared. Moreover, the practical application cases of nanomaterials in automobile body materials were also described [8, 9]. This review will explain how nanoscale features affect bulk properties from a scientific point of view, and provide guidance on material selection and processing from an industrial point of view. These insights are expected to guide future research and support wider adoption of nanotechnology in automotive design.

2. Characteristics and Challenges of Conventional Lightweight Materials

Modern cars depend on a variety of body materials. Each material balances weight, cost, and performance. Steel remains the most common choice [4]. It provides high strength and proven crash performance. Advanced high-strength steels (AHSS) allow thinner sections without loss of safety. AHSS thus deliver modest weight savings in mass-market vehicles. Steel's main advantages are cost and reliability [4]. Its high density, however, adds significant mass to the vehicle. Even with AHSS, weight reduction tops out around 10-20 % compared to mild steel.

Aluminium alloy is the second most used material [5]. They weigh about one third of that of steel. They also resist corrosion and are easily recycled. Premium and lightweight models usually use aluminium for hoods, doors, and body panels. Aluminium's lower fatigue strength compared to steel demands careful design and reinforcement. Table 1 shows the current usage status of aluminium alloys in certain vehicles [10]. Aluminium offers up to 40 % weight savings [5]. Its drawbacks include lower fatigue strength and higher joining complexity. Welding aluminium to steel can cause galvanic corrosion and weak joints.

Table 1. The application status of aluminium alloys in vehicles [10]

System name	Aluminium alloy parts
Engine system	Pistons, cylinder blocks, intake pipes, oil sump, as well as various brackets, bases, shields, etc
Transmission and walking system	Transmission housing, clutch housing, chassis swing arm, steering housing, steering knuckles, brake pump housing, brake callipers, etc
Cooling system	Evaporators, condensers, and pipelines of water tanks and air conditioners

Magnesium alloys provide even greater weight savings [5], and are used in steering wheels, seat frames, and engine blocks. However, the cost and corrosion issues of magnesium limit its broader application. Special coatings or heat treatments are required to protect magnesium components. The combination of excellent specific strength and specific stiffness has driven magnesium and its alloys to become automotive materials with great potential for weight reduction (Fig. 1) [11]. Magnesium cuts weight further. It is about 75 % lighter than steel [5]. Yet its high reactivity and flammability require careful handling. Protection is a must for a long life.

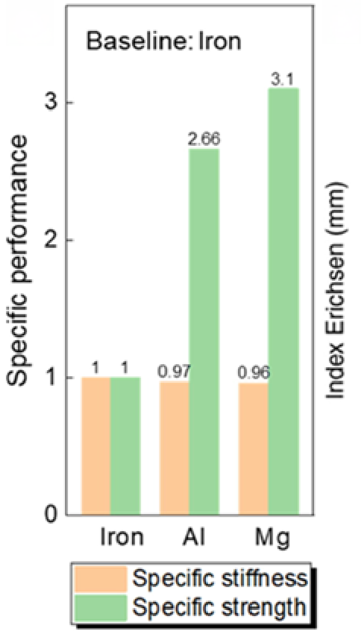

Figure 1. Comparison of the specific performance of iron, aluminium and magnesium [11]

Plastics and polymer composites appear in bumpers, dashboards, and interior panels [10], enabling complex shapes and reducing part counts. These materials are light and corrosion-free. Yet their low stiffness and strength restrict them to non-structural roles. Polymers excel in formability and cost. They are ideal for non-load-bearing parts. Their low stiffness and thermal stability, however, hinder use in primary structures [10]. Table 2 summarizes the strongpoints and challenges of traditional lightweight materials [12].

Table 2. Strongpoints and future challenges of conventional lightweight materials [12]

Lightweight materials	Strongpoints	Future challenges
Advanced high-strength steels	exceptional toughness; affordable anti-intrusion performance; high specific strength	springback during forming; wrinkle and fracture defects; strength-ductility balance issues
Aluminium alloys	superior corrosion resistance; excellent strength-to-weight ratio; high electrical and thermal conductivity; versatile surface treatment and processing	high raw-material costs; energy-intensive manufacturing; elevated operating expenses
Magnesium alloys	lowest density among structural metals; remarkable specific strength and stiffness	poor room-temperature formability; low creep resistance and durability; reliance on rare-earth elements; immature fabrication technologies; high material and processing costs
Synthetic polymer composites	outstanding corrosion resistance; high specific stiffness and strength; design flexibility; excellent vibration damping and fatigue resistance; superior impact tolerance	high cost of polymers and reinforcements; lack of scalable and cost-effective production methods; difficulty optimizing performance vs. expense

3. Lightweight nanomaterials

3.1. Carbon-Fiber-Based Nanocomposites

Carbon fibre reinforced polymer (CFRP) composite materials have characteristics of high specific stiffness, specific strength, light weight, and chemical stability. The unreactive surface of carbon fibre (CF) results in low interfacial adhesion with the polymer matrix, and thus several interfacial flaws and voids are formed in the manufactured CFRP composite materials [13]. CFRP composites modified with various nanomaterials such as carbon-based nanoparticles, silicon-based nanomaterials, and metal nanomaterials have enhanced the mechanical properties, impact resistance, and interfacial adhesion between fibres and matrix. Prepreg lay-up with autoclave curing remains the benchmark for large structural parts. Resin transfer moulding and compression moulding of fibre-reinforced sheets are used for medium-volume production [9]. Automated tape-laying and out-of-autoclave techniques have reduced cycle times and costs [9].

In industrial manufacturing, by integrating carbon nanotube composite materials into the body panels, the weight of the car has been significantly reduced by 30 % compared to traditional materials in the BMW i3 (as shown in Fig. 2) [7]. In addition, CFRP lower control arms have been adopted by premium automakers. Replacing aluminium arms with carbon-epoxy units yielded a 50 % weight reduction and a 120 % increase in stiffness [9]. Composite hoods and fenders now appear on flagship models, delivering 40-60 % mass savings relative to stamped steel [6].

Figure 2. BMW was the first mass-produced light vehicle, and the main parts of its body structure were made of carbon fibre reinforced composite materials [7]

Audi’s R8 spaceframe uses a nanoparticle-toughened epoxy matrix in its CFRP monocoque. Compared with a comparable aluminium frame, this design reduces body-in-white mass by ~40 % while meeting Euro NCAP crash requirements [3].

3.2. Alumina (Al_2O_3) Nanocoating

Alumina coatings take advantage of the high hardness and chemical stability of Al_2O_3 to protect metal substrates from wear, corrosion, and heat. Three methods are commonly used to prepare alumina nanocoating. In plasma electrolytic oxidation (PEO), an oxide layer grows directly on aluminium, forming a dense adhesion film [5]. Moreover, Al_2O_3 nanoparticles (<50 nm) were dispersed in a liquid precursor by sol-gel methods and cured into a transparent coating without cracks. In addition, atmospheric plasma spraying (APS) is used for thick and high temperature applications [14]. For painted or decorative body panels, sol-gel Al_2O_3 coatings offer the best balance of thinness, transparency, and scratch resistance. For load-bearing aluminium parts, PEO provides superior adhesion and wear protection. APS is typically reserved for high-temperature under-the-hood applications rather than visible bodywork.

Automotive applications include PEO-treated aluminium wheels that exhibited five-fold wear resistance over conventional anodic oxidation [5]. In headlamp lens, sol-gel Al_2O_3 coatings improved scratch resistance by 30 % without degrading optical transparency [14]. On exhaust manifolds, thin Al_2O_3 layers reduced substrate temperatures by up to 50 ℃, extending component life and enabling tighter thermal management [14]. Clearcoat systems on body panels have incorporated Al_2O_3 nanoparticles to improve the ultraviolet resistance and abrasion performance [5]. Nanocoating can enhance the strength and wear resistance of substrates, allowing car manufacturers to use thinner and lighter materials without sacrificing durability. Traditional coatings are composed of binders and crosslinking agents, while nano-coatings are made up of highly elastic organic binders and highly strong inorganic nanoparticles. Separate parcels of nanomaterials are tightly packed together to increase the hardness of the paint, making it more scratch resistant. The diagrams of the structures of traditional and nano-coatings are shown in Fig. 3 [15].

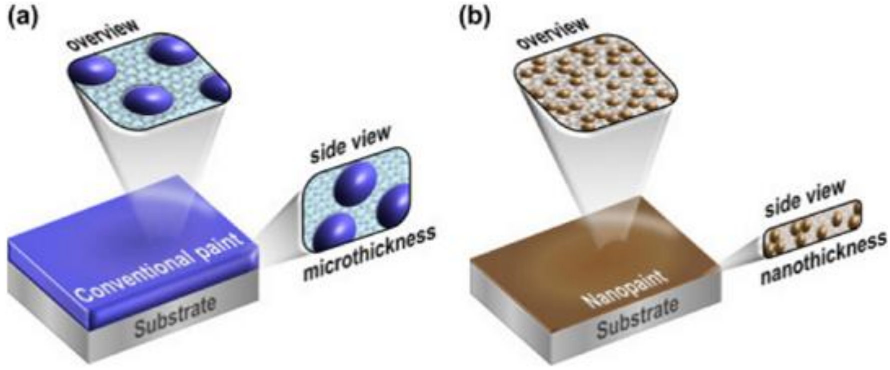

Figure 3. The differences in structure and polish in conventional versus nano paint and the thickness of layers that form after the paint is applied [15]

Volvo Trucks applies PEO Al_2O_3 coatings to aluminium suspension control arms. Field data show that the abrasion and corrosion resistance are improved by five times after 80 000 km of mixed-terrain operation [5].

3.3. Silicon-Based Nanomaterials

High aspect ratio silicon carbide nanowires (SiC NWs) and spherical nanosilica (SiO_2) particles have been integrated into carbon-fibre/epoxy resin composites to improve the ability to resist crack propagation and thermal deformation. SiC NWs bridge microcracks within resin-rich interlayers, dissipating fracture energy and increasing interlaminar shear strength by up to 18 % after 1 000 thermal cycles at 120 ℃ [13]. Nanosilica particles (< 50 nm), surface-treated with silane coupling agents, restrict polymer chain mobility and form hydrogen bonds at the filler-matrix interface, raising the glass-transition temperature of composites by 25 % and reducing cure-induced warpage by 20 % [12]. Composite prepregs are produced by dispersing 1-3 wt% of these nanofillers into epoxy resin via high-shear mixing and ultrasonication, followed by vacuum degassing and curing at 120-150 ℃ under pressure. In under-hood engine covers, the addition of 1 wt% SiC NWs yielded a 0.5 mm reduction in wall thickness—equating to a 12 % mass saving—without sacrificing bending stiffness, while nanosilica-reinforced chassis cross-members demonstrated improved dimensional stability under service temperatures. These developments illustrate how silicon-based nanomaterials can be employed to achieve both lightweighting and enhanced performance in automotive composite components.

3.4. Polymer Nanocomposites

Polymer nanocomposites combine light matrix with nanoscale fillers (clay, carbon nanotubes, graphene) to achieve superior mechanical and barrier properties under a load of less than 5 wt% by weight [3]. Fillers with high aspect ratio form percolated networks to enhance stiffness, strength, flame retardancy, and thermal stability. Uniform dispersion via melt compounding, ultrasonication, or in-situ polymerization is critical to avoid agglomeration and voids [16].

In automotive components, nylon-6 with 3 wt% nano-clay is used for engine covers, delivering 50 % higher tensile strength and improved chemical resistance under oil and coolant exposure [16]. Volkswagen Group fitted its MQB-platform Golf with nano clay-reinforced nylon-6 intake manifolds. The weight of these parts is 15 % lighter than that of the glass-filled variants, and they meet long-term oil-mist permeation standards in hot-soak testing [7]. Ethylene-vinyl acetate nanocomposites are used as underbody shields, reducing noise and vibration while cutting part mass by 15 % versus conventional filled plastics [17]. Ethylene-vinyl alcohol nanocomposite fuel tanks have achieved 10 % mass reduction through superior hydrocarbon barrier performance. Interior trim panels made from polypropylene-graphene blends provide higher stiffness and a premium finish on standard injection-moulding lines [17]. These examples highlight how polymer nanocomposites enable mass savings of 10-25 % without compromising durability or manufacturability. In the past decade, the US automotive composite materials market has experienced stable revenue growth (Fig. 4 (a)) [18]. Polymers dominate this group which includes polymer composites where polymer resins matrix materials are reinforced with a slew of inorganic, organic or metal fibres or particles and followed by ceramic or metal composites It can be seen globally that about 65 % of polymer composite materials are utilized for external and internal parts of automobiles, while the rest is utilized for structural and powertrain systems (Fig. 4 (b)) [19].

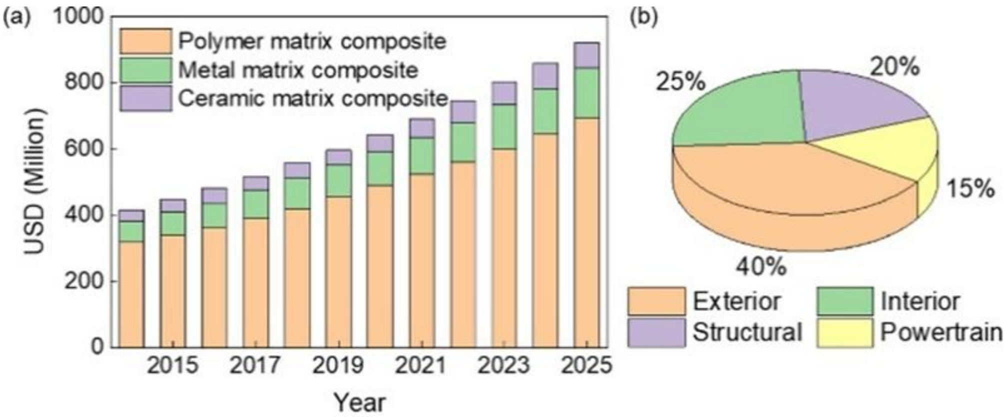

Figure 4. (a) Polymer composite market revenue for the automotive industry in the United States from 2014 to 2025 [18]; (b) World application distribution of polymer composites by different parts of the automobile industry [19]

4. The relationship between traditional materials and nanomaterials

Nanomaterials add new options for lightweighting [1, 6, 7]. They work at dimensions below 100 nanometres. Their high surface-to-volume ratio alters mechanical and thermal behaviours. Despite their promise, nanomaterials face hurdles. Uniform dispersion in the host matrix is a major challenge. Agglomeration can create weak zones. High-volume production remains costly. Processing often requires specialised equipment and controlled environments. Health and safety concerns around nanoparticle handling also demand strict protocols.

Nanomaterials do not aim to replace conventional materials completely, but to enhance and complement them. Steel and aluminium parts gain extended service life from nano coatings. Polymers gain strength and heat resistance from nanofillers [7]. CFRPs gain improved damage tolerance and fatigue life [12]. Hybrid structures can use steel shells with nano-coated aluminium reinforcements. They can embed polymer nanocomposites in key areas. These designs balance strength, weight, and cost. They also reduce corrosion and fatigue issues.

Scalable production methods are one of the focuses of future research. It must also refine joining techniques for mixed materials. Standards for nanoparticle use and safety protocols must mature. Success in these areas could redefine vehicle construction and accelerate the adoption of lightweight, high-performance materials.

5. Conclusion

The review states that nanomaterials will replace advanced techniques that mechanize how cars are made because it can reduce weight while maintaining structural strength. Carbon-based nanocomposites reinforced with carbon nanotube or graphene resulted in 50-60 % weight reduction for structural components when compared to traditional metals. In addition, alumina nanocoating resulted in up to 40 % mass reduction due to improved wear and corrosion resistance. The latter enabled a 12-20 % weight reduction in engine covers and chassis members. Furthermore, silicon carbide nanowires in addition to nanosilica fillers and polymer nanocomposites with low filler concentration (< 5 wt%) recorded 10-25% mass reduction in the intake manifold and interior panels. Alongside these, other passive barriers demonstrated greater efficacy.

Low and high nanofiller loading polymers not only improve performance but also reduce energy consumption as well as rolling resistance and powertrain load. These enable a reduction in CO_2 emissions over the vehicle's lifecycle. Developments in scalable processing, including out-of-autoclave curing, sol-gel coatings, and continuous dispersion techniques, are becoming more economically advantageous for mass production.

To make the most of these advantages, future work should develop new surface treatments and powerful mixing methods. It will also be important to create continuous, energy-saving production techniques to reduce material costs. At the same time, the industry needs clear health, safety, and environmental rules to ensure nanoparticles are handled safely in the manufacturing and recycling process. On top of that, better ways to join different materials together and advanced simulation tools will speed up design and testing under real-world conditions. By overcoming these hurdles, automakers can adopt nanotechnology at scale, leading to lighter, greener, and higher-performing vehicles.

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