Chapter 6

Nanomaterials in the Automobile Sector

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Abstract

The automobile sector is continuously putting efforts into ensuring the safety and comfort of passengers, intelligent traffic guidance systems, pollution reduction, and successful recycling processes. The constructive and successful utilization of nanomaterials is an effective and potential scientific strategy that simplifies the technologies to develop lighter, more durable and economical, faster, and smart devices by consuming less raw materials and optimum energy. Emerging nanomaterials in the automobile sector explores how nanomaterials and nanotechnology are utilized to boost the performance of materials and devices required for automobile application by designing and developing nanocomposites, nanoalloys, nanocoatings, nanocatalysts, nanolubricants, and nanoadditives. In addition to these, this chapter will focus on the application of green polymer nanocomposites in automobile sector to address the issues associated with nanotoxicity.

Keywords

Automobile, Nanomaterials, Nanotechnology, Nanoalloys, Nanocoatings, Nanocatalysts, Nanolubricants, Nanoadditives, Green Polymer Nanocomposites, Nanotoxicity

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1. Introduction

Free movement is the basic need of people and the fundamental requirement for the development of modern society. Automobiles play an important role in this regard. The automobile sector ceaselessly works on passenger safety and comfort, smart traffic guidance systems, pollution reduction, animal and human health safety, eco-friendliness, and eventually successful recycling processes. Day by day, the conventional materials have been replaced by the smart nanomaterials such as nanocomposite gels [1-3], nanocomposite polymer films [4-6], structural colored nanomaterials [7-9], molecular machines [10], nanomaterial based biosensors [11], and so on. Considering all these factors, the utilization of nanomaterials is an effective and prospective scientific strategy that put forward the technologies to design and develop lighter, smaller, safer, economical, durable, faster, and intelligent devices through the consumption of less amount of raw materials and optimum energy. The productive, constructive, and functional applications of nanomaterials through the incorporation of operative technology are termed nanotechnology. Nanomaterials with the help of potential nanotechnology may offer stronger but lighter engine and body materials, fuel cells, self-healing and scratch-resistant coatings, self-cleaning windshields, improved tires, quality lubricants, better catalytic convertors, nanoporous filters, eco-friendly corrosion protection, smart sensors and vision system, durable tires, and so on [12].

Fuel economy regulation and customer expectations, battery-electric vehicle (BEV) technology, advanced driver assist systems (ADAS), mobility-as-a-service (MaaS), safety, innovative manufacturing technologies, and material cost are the major driving forces that influence the material change in automobile sectors [13]. The utilization of nanomaterials in a different format for automobile construction has been greatly dominated by seven fundamental reasons depicted in Fig. 1. Customers are expecting that their new vehicles would be more fuel-efficient than their previous one. Greenhouse gas (GHG) emission regulations, corporate average fuel economy (CAFE), and customers' expectations have pressured automobile producers to improve vehicle efficiency. In this context, manufacturing lightweight vehicles is the key to meet imposed regulations and consumer expectations. Involvement of nanotechnology, nanomaterials, and nanocomposites are capable of producing lightweight construction materials without compromising other desirable properties and features [14]. The next corresponding driving force for material
change is the prospective utilization of battery electric vehicle (BEV) technology. Batteries used in electric vehicles are substantially heavier than internal combustion engines (ICE) with comparable performance. In particular, the weight of Chevrolet Bolt (electric vehicle) 136 kg more than Volkswagen Golf of similar size [15]. Similarly, the new Mini EV (2020 model) of BMW is 130 kg heavier than a base Mini Cooper. For this reason, BEVs are coercing automakers to attempt to find novel and creative ways to reduce vehicles' weight. The third major driver is ADAS which includes infotainment, comfort, and productivity features for consumers. The thrust for automatic vehicles will lead to more sensors and additional supporting devices that lead to a heavier vehicle of 130-180 kg extra weight. The automakers plan to increase the consumers' safety and comfort by including more and more automatic features almost every model year [16]. This trend is likely to continue for personal vehicles and may become more prevalent for shared vehicles. ADAS and users' demand for smarter vehicles with more content will need lightweight construction materials. Vehicles used for ride-sharing are projected to run 5-7 times more miles per year than personal vehicles. As the components (suspension systems, doors, seats, and so on) of shared vehicles are used extensively, shared vehicles require improvements in robust joint design, structural durability, better thermal control, higher fatigue targets, and vehicle end-of-life cycle. These requisites demand high-performance materials that can achieve engineering targets under harsher conditions. Automobile producers are always trying to provide safer vehicles to a consumers where selecting effective material is crucial. It has been believed that the lighter vehicle is more vulnerable than a heavier one in a crash; however, it is not universally true. Developments in vehicle design, application of smart technologies, and selection and optimization of novel construction materials with a high strength-to-weight ratio can result in lightweight vehicles with expected safety. Manufacturing technology acts as both an obstacle as well a trigger to creating novel materials. Huge capital investments in present manufacturing procedures (injection and stamping molding) reduce the fast transformation to novel materials and innovative processes. However, the adaptation of Industry 4.0 catalyzes the creation of modern materials and groundbreaking manufacturing processes. Last but not the least driving force is the price of the material. The overall cost involved in processing and optimizing materials is a major variable in the automotive sector. In this highly competitive business, consumers are always looking for value for their money. As the world will face the scarcity of existing fuel very soon, the automakers are trying to introduce different technologies for producing fuel-efficient motor vehicles. The details of low fuel consumption technologies found by automakers have been summarized in Fig. 2.
Figure 1. The major driving forces that influence the material change in automotive sectors.

Figure 2. Details of low-fuel-consumption technologies. The figure has been reproduced with the permission from [17].
To date, steel is the primary material for constructing automotive structures. Recently, different high-strength steels (HSSs) have been developed and utilized to construct a lightweight automotive body. To attain more lightweight body, better HSSs are required. Nanostructured steels or ultrafine-grained (UFG) steels or nanosteels are highly promising to become one of the new HSSs for better performances. For example, high manganese-containing twinning induced plasticity (high-Mn TWIP) steels having austenite microstructures are classified as second generation advanced high strength steels (AHSSs) or Gen-2 steels which have of superior tensile strength and elongation. Next generation or third-generation AHSSs (Gen-3 steels) are steels containing less alloy elements than TWIP steels with moderate elongation between HSS and TWIP. Fig 3 shows the projection of utilization of the materials that are going to be decreased by 2040 while Fig 4 represents the projection of the utilization of materials that are going to be increased by 2040 in automobile sectors. The utilization of mild, HSS, AHSS, and hot formed steel (HF) is projected to be reduced in future automobile industries. On the contrary, the consumption of Gen-3 steel, aluminum alloys of different grades (Al alloy 5xxx and 7xxx grades), polymers, and polymer nanocomposites (PNCs) will increase for future production of automobiles. Al alloys of different grades are suitable for automotive doors, roof panels, lift gates, hoods, fenders, and body sides. PNCs find their potential applications in automobile construction due to their outstanding and novel physical and chemical properties. Present and future applications of nanomaterials in automobile construction are given in Table 1.

Figure 3. The projection of materials utilization that is going to be decreased by 2040 in automotive sectors [13].
Table 1. Present and future applications of nanomaterials in automobile construction. The future applications have been represented by italic letters.

<table>
<thead>
<tr>
<th>Application /Effect</th>
<th>Functionalities</th>
<th>External Components</th>
<th>Car body</th>
<th>Interior</th>
<th>Chassis and tires</th>
<th>Electronics</th>
<th>Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Hardness, friction, tribological features, breaking resistance</td>
<td>Nanocoating Polymer glazing</td>
<td>Nanosteel</td>
<td>Carbon black in tires Nanosteel</td>
<td>Low-friction aggregate components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric</td>
<td>Large surface-to-volume ratio, porosity</td>
<td>Gecko effect</td>
<td>Nano filler Gecko effect</td>
<td>Supercaps Fuel cells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Size dependent electromagnetic</td>
<td>Gluing on command</td>
<td>Switchable materials</td>
<td>GMR sensors Solar cells</td>
<td>Piezo injectors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Color, fluorescence, transparency</td>
<td>Electrochromatic layers</td>
<td>Antiglare coatings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Reactivity, selectivity, surface properties</td>
<td>Care and sealing systems</td>
<td>Corrosion resistance</td>
<td>Decontamination in the cabin</td>
<td>Catalysis Fuel additives</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Polymer nanocomposites (PNCs)

The PNCs, where the nanomaterials are utilized as a reinforcer, owing very large interfacial area per volume, and the gaps between the fillers and polymer matrix are significantly short. As a result, molecular interactions between the fillers and matrix will endow PNCs novel features that the conventional polymers or common macrocomposites do not have. The application of PNCs in automobile parts and systems is intended to escalate manufacturing speed, environmental sustainability, thermal stability, recycling, and reduce body weight. The successful and effective utilization of PNCs for structurally noncritical parts of automobiles such as body panels, front and rear fascia, valve/timing covers, cowl vent grills, interior, and truck beds could reduce several hundred millions kilograms of automobile body weight every year [18]. PNCs and nanofillers composed of automobile parts provide better thermal and dimensional stability, strength, noise reduction, improved modulus, corrosion resistance, cost versus performance ratio, and reliability than their counterparts. General Motors (GM), Montell USA, and Toyota have developed polypropylene (PP)/clay hybrid PNCs of better mechanical strength for automobile applications [19, 20]. The first commercial application of nanocomposites for automotive exterior components was accomplished by GM in 2002. They introduced a nanoclay/thermoplastic olefin nanocomposite running board to their GMC Safari and Chevrolet Astro vans [21]. Clay-based nanocomposites are applied to manufacture automobile's side doors, molding, cargo bed bridge, console, panels, engine cover, seat backs, and trim. Mercedes-Benz, Honda, Ford, Pontiac Bonneville, and Porsche have developed and utilized thermoplastic polyolefin resin based PNCs reinforced by silicon carbide (SiC) nanoparticles and PP for making their automobiles' interior and exterior components [22]. The appropriate application of PNCs in the automobile industry may reduce the amount of commonly used 900 kg of various metals to approximately 600 kg. Some of the commercially available PNCs developed by various companies, including Toyota, GM, InMat LLC, and Ube, have been summarized in Table 2. The application of PNCs for making automobile parts is shown in Fig. 5.

<table>
<thead>
<tr>
<th>Polymer Matrix</th>
<th>Nanofiller</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide 6</td>
<td>Exfoliated clay</td>
<td>Timing belt cover</td>
</tr>
<tr>
<td>Thermoplastics olefin</td>
<td>Exfoliated clay</td>
<td>Exterior step assist</td>
</tr>
<tr>
<td>Polyisobutylene</td>
<td>Exfoliated clay</td>
<td>Tires</td>
</tr>
<tr>
<td>Polyamides nylon 6, 66, 12</td>
<td>Exfoliated clay</td>
<td>Auto fuel systems</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>Halloysite clay</td>
<td>Ultrafiltration membranes</td>
</tr>
<tr>
<td>Epoxy</td>
<td>Clay</td>
<td>Automobile body parts</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Clay</td>
<td>Automobile body parts</td>
</tr>
</tbody>
</table>

Green PNCs, produced from eco-friendly polymers reinforced with nanofillers, hold huge potential for constructing automobiles' body and engine parts without creating any harmful and hazardous impact on the environment and health [24]. Green PNCs are free from the risk of any health hazards and are expected to be environmentally friendly and
biodegradable. Green PNCs are fabricated by fortifying the eco-polymer matrices such as cellulose, natural rubber, polysaccharides, chitin, collagen, polyhydroxyalkanoate, poly(ethylene oxide), poly(vinyl alcohol), polyethylene glycol, polyamide, polycarbonate, polyanhydride, polycaprolactone, and polylactic acid through the incorporation of eco-friendly nanofillers such as cellulose nanomaterials (nanofibers, nanoparticles, nanocrystals, etc.), natural fibres (jute, bamboo, zein, etc.), silica, clay, starch nanocrystals, halloysite nanotubes, nanocarbon, and carbonaceous nanomaterials. Many automobile companies such as BMW, Mercedes, Proton, Audi, Volkswagen, Daimler, Ford, Opel, and Cambridge Industry utilize different natural fibers-based PNCs in automobile sectors [25]. The applications of natural fiber-reinforced polymer nanocomposites in automotive industry have been condensed in Table 3.

Figure 5. Prospective areas and components of an automobile for the appropriate utilization of green polymer nanocomposites for manufacturing parts. The figure has been reproduced and modified with permission from [23].
Table 3. The application of natural fiber composites in automotive industry.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audi</td>
<td>A2, A3, A4, A4 Avant, A6, A8, Roadstar, Coupe</td>
<td>Bootliner, hat rack, side and back door panel, spare tirelining, and seatbacks</td>
</tr>
<tr>
<td>BMW</td>
<td>3, 5, and 7 series and other</td>
<td>Seatback, molded footwell linings, headliner panel, bootlining, door panels, and noise insulation panels</td>
</tr>
<tr>
<td>Citroen</td>
<td>C5</td>
<td>Interior door paneling</td>
</tr>
<tr>
<td>Daimler</td>
<td>A, C, E, and S classes</td>
<td>Pillar cover panel, door panels, car</td>
</tr>
<tr>
<td>Chrysler</td>
<td>EvoBus (exterior)</td>
<td>Windshield/car dashboard, and a business table</td>
</tr>
<tr>
<td>Ford</td>
<td>Mondeo CD 162, Focus</td>
<td>Floor trays, B-pillar, bootliner, door inserts, and door panels</td>
</tr>
<tr>
<td>Fiat</td>
<td>Punto, Brava, Marea, Alfa Romeo 146, 156, 159</td>
<td>Door panel</td>
</tr>
<tr>
<td>GM</td>
<td>Cadillac De Ville, Chevrolet Trail Blazer</td>
<td>Seat backs, cargo area floor mat</td>
</tr>
<tr>
<td>Lotus</td>
<td>Eco Elise (July 2008)</td>
<td>Body panels, interior carpets, spoiler, and seats</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>C, S, E, and A classes</td>
<td>Glove box (cotton fibers/wood molded, flax/sisal), instrument panel support, insulation (cotton fiber), molding rod/apertures, seat backrest panel (cotton fiber), trunk panel (cotton with PP/PET fibers), door panels (flax/sisal/wood fibers with epoxy resin/UP matrix), and seat surface/backrest (coconut fiber/natural rubber)</td>
</tr>
<tr>
<td>Trucks</td>
<td></td>
<td>Internal engine cover, bumper, wheel box, engine insulation, sun visor, interior insulation, and roof cover</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td></td>
<td>Cargo area floor, instrumental panel, and door panels</td>
</tr>
<tr>
<td>Opel</td>
<td>Vectra, Astra, Zafira</td>
<td>Door panels, instrumental panel, headliner panel, and pillar cover panel</td>
</tr>
<tr>
<td>Peugeot</td>
<td>406</td>
<td>Seatbacks, parcel shelf front, and rear door panels, Rear parcel shelf</td>
</tr>
<tr>
<td>Renault</td>
<td>Clio, Twingo</td>
<td>Rear storage shelf/panel and insulations</td>
</tr>
<tr>
<td>Rover</td>
<td>2000 and others</td>
<td>Door panels</td>
</tr>
<tr>
<td>Saab</td>
<td>9S</td>
<td>Package trays and door panel</td>
</tr>
<tr>
<td>Saturn</td>
<td>L300</td>
<td></td>
</tr>
<tr>
<td>Toyota</td>
<td>Raum, Brevis, Harrier, Celsior,</td>
<td>Spare tire cover, door panels, floor mats, and seatbacks</td>
</tr>
<tr>
<td>VAUXHALL</td>
<td>Corsa, Astra, Vectra, Zafira</td>
<td>Interior door panels, pillar cover panel, headliner panel, and instrument</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>Passat Variant, Golf, A4, Bora</td>
<td>Door panel, boot-lid finish panel, seatback, and bootliner</td>
</tr>
<tr>
<td>Volvo</td>
<td>V70, C70</td>
<td>Natural foams, seat padding, and cargo floor tray</td>
</tr>
</tbody>
</table>

PNCs utilized in the automobile industry for making tires. Precipitated carbon black (70-500 nm) blended with amorphous silica has been used for decades as nanofillers for the rubber compound for automobile tire manufacturing [26]. Modern advancement in nanotechnology has enabled the application of carbon nanotubes, rubber nanoparticles, and nanoclay for enhancing durability, rolling resistance, and wet grip of automobile tires. Most
of automobile tires are made of rubber mixed with different nanomaterials as fillers. PNCs of nanosilica, carbonaceous nanomaterials, silicate, clay, nanocalcium carbonate, and others blended with diverse polymers such as styrene butadiene rubber (SBR), epoxidised natural rubber (NR), butyl rubber (BR), and so on. The major tire industries use epoxidised NR/organo-clay nanocomposite, SBR/clay nanocomposite, BR/clay nanocomposite, nanorubber, NR/BR/SBR-nanocalcium carbonate composite for manufacturing automobile tires.

Epoxy nanocomposites (ENCs) exhibit outstanding chemical, mechanical, thermal and electrical properties, high strength, and corrosion resistance, which are essential in automobile manufacturing. Numerous ENC\s such as epoxy-inorganic NCs, epoxy-carbon fiber NCs, epoxy-clay NCs, epoxy-carbon nanotube NCs (ECNTNCs), epoxy-graphene NCs, epoxy-titanium NCs (ETNCs), epoxy-glass fiber NCs are highly potential to be used in automobile manufacturing industries [27]. The automotive brake system functions by transforming kinetic energy into thermal energy. To construct a perfect braking system, combining brake pad and disc of different specifications is necessary. Potassium titanate based nanomaterials could be an effective and suitable replacement in this regard. However, a phenolic resin based braking pad gets decomposed at high energy braking conditions. Modified epoxy resin can be an excellent candidate to overcome this limitation [28]. ENC\s have been extensively used as coatings for automobile surfaces due to their excellent chemical, mechanical and thermal characteristics, corrosion resistance, and effective adhesion quality [29-31]. ETNC\s can be used to manufacture automotive headlights, windows, and mirrors with antifogging and anti scratch properties [32]. Effective employment of EPN\s can successfully protect automobile users from a severe accident occurred by fuel tank leakage by improving corrosion resistance properties, design variability, and safety at an optimum cost [33].

3. Nanoalloys

Nanostructured steels or nanosteels are considered as Gen-2 and Gen-3 steels. Grain purification towards nanometer grain sizes is one of the major microstructural controlling approaches that will result in Gen-3 steels. Usually, the parts in an automobile body are divided practically into two segments having different functions. Components of the forepart and back frame section deform heavily during any collision to absorb impact belonging to the one segment, while the parts of the passengers' cabin, which deform less to protect the occupants from injury during a collision. Gen-3 steels with tensile strength of over 1000 MPa are suitable for making up the passengers' cabin [34].

Titanium (Ti) is an alluring metal for transportation equipment in automotive industries because of its high specific strength, heat, and corrosion resistance compared with other lightweight materials, such as Al, Mg alloys, and carbon fiber-reinforced polymer composites. Ti and its alloys have been utilized in the automobile sector to curtail the vehicles' weight [35]. Over the last few years, Ti nanoalloys, Ti-6Al-4V and Ti-Al-Fe, have been used for making engine valves, exhaust systems, and connecting rods of sports
motor vehicles. In addition, many Ti-alloys of Cu, Al, Si, and Nb have been developed to enhance mechanical strength, deformation characteristics, corrosion, and oxidation resistance at higher temperatures. At present, Ti-alloys have found more applications in the automobile sector. Fuel tanks, fracture-split connecting rods, and fuel cells for automotive are constructed from Ti nanoalloys [36]. Nissan and Toyota have used different Ti nanoalloys commercially to make their automobiles exhaust systems. For example, Ti-1Cu was used for NISSAN GTR Spec-V in 2009 and for NISSAN GT-R in 2016, and Toyota used Ti-0.5Al-0.45Si-0.2Nb for TOYOTA LEXUS LFA in 2009. Many fuel cell-driven vehicles use polymer electrolyte fuel cells (PEFCs), where a separator is considered one of the essential components. Ti foils are used to construct separators employed in the fuel cell-driven vehicle "MIRAI" produced by Toyota Motor Corporation in 2014.

Fig. 6 depicts the chronological development of Ti nanoalloys automotive parts since 1990. Honda Motor Company introduced a connecting rod made of Ti-3Al-2V RE (Rare earth) in their sports automobile. In1998, Toyota released ALTEZZA, the first mass-produced automobile with Ti nanoalloy-based intake and exhaust valves. Volkswagen AG introduced the LUPO with Ti-6.8Mo-4.5Fe-1.5Al (or low-cost beta, LCB) alloys-based coil springs in 2000. The CORVETTE Z06 from Chevrolet, manufactured by GM, USA, was manufactured with Ti alloy based (Cp-TiGr.2) exhaust system in 2001 to improve the performance of vehicles by reducing body weight. To become the third most versatile automotive construction material after Fe and Al, Ti and its alloy must defeat the limitation of the present average cost of mass-produced parts. It is essential to practice new smelting methods to reduce the production cost. Moreover, remarkable improvement in performance can extend the utilization of low automotive parts of Ti nanoalloys through the replacement of iron parts. It is necessary to recognize the potentialities and find parts and structures that can effectively and successfully utilize Ti nanoalloy's performance from environmental conditions around the automobile industry.

Low cost fuel cell-driven vehicles require cheap and durable cathode catalyst for oxygen reduction reaction (ORR). Previously, Pt nanoparticles were modified with another metal support fuel cell with lower operation cost. In this context, a limited electrochemical dissolution Cu nanoparticles produces Pt-Cu nanoalloy based catalysts capable of maintaining activity even under the harsh automobile drive-cycles to be applied in fuel cells driven motor vehicles [37]. Pt-Cu core-shell nanocatalyst is a significant development for making cathode catalysts suitable for proton-exchange membrane fuel cells (PEMFCs). It is highly potential to be used in the automobile sector to support motor vehicle activity under usual driving conditions at continuous circuit voltage (Fig. 7).
Figure 6. Chronological development of typical practical Ti parts in the automobile industry. The figure has been reproduced with permission from [17].

Figure 7. Profiles of consecutive steps for the preparation of three different systems Pt-Cu bulk alloy, skeleton and core–shell. The figure has been reproduced with the permission from [37].
Alloy nanoparticles composed of Cu and Zn can improve automobile engine performance and emission characteristics when mixed with fuels [38]. Cu-Zn nanoalloy particles are highly promising to be used as fuel additive for diesel engines. Nanoscale ceramics are used in automobile motors and transmissions to provide higher heat and wear resistance features. For instance, nanostructured ceramics based zirconium (Zr) and alumina nanoalloys have been selected for making cylinder of an engine. Nanoalloy composed of silicon carbide and nitride nanocrystals is used for manufacturing valve springs and ball bearings.

4. Nanolubricants

The objectives of using a lubricant is to reduce the friction, wear, and tear of automobile engines when two facets of engine components come in contact with each other. An appropriate and sufficient amount of lubricant supports the components of engines or other system to run fluently and incessantly. In addition, the lubricant prevents unexpected pressure or vibrations at bearings, minimize corrosion, provide sealing, and transport contaminants to filter for cleaning purpose. Inadequate and inappropriate utilization of lubricant reduces the engine life and may cause engine damage, fire, local welding, and overall engine failure. The application of lubricants is referred as lubrication which might be classified as boundary lubrication, mixed lubrication, hydrodynamic lubrication, and elastohydrodynamic lubrication [39]. Lubricants are commonly composed of base oil such as esters, hydrogenated polyolefins, silicones, fluorocarbons, etc. (90%) and additives (10%). Dry graphite, graphene, carbon nanomaterials, tungsten disulfide, and molybdenum disulfide are some examples of commonly used non-liquid powder lubricants. Nanomaterials are used as lubricant additives to enhance the tribological properties of lubricants. Addition of nanomaterials decreases the friction of two contacting surfaces and increases the thermal conductivity of lubricants. The concentration and size of nanomaterilas are major factors that determine the tribological features of lubricants. The friction and wear of the worn surfaces is a principal cause of energy dissipation in automobile engines. Nanomaterials are highly promising for utilizing as lubricants, which are called nanolubricants, in automobile sectors since nanolubricants are capable of creating superlubricity [40-43]. In the automobile lubrication system, the boundary lubrication region is a highly concerned area to be taken care of due to the high friction coefficient. The boundary friction coefficient is higher in piston and camshaft regions. If the lubricant film is not thick enough to meet the requirement, grooves, microcracks, and valleys will be appeared on the rubbing surfaces due to the adhesive and abrasive wear. This undesirable situation can be handled by applying nanolubricants, which will help from nanoscale dimension by making the tribopair surfaces smooth and improving antifriction features in automotive engines. The nanolubrication mechanisms of carbon nanotube and graphene have been shown in Fig. 8 and Fig. 9, respectively [44].
Figure 8. Nanolubricant mechanism of carbon nanotube in automobile engines. The figure has been reproduced with the permission from [44].

Figure 9. Nanolubricant mechanism of graphene in automobile engines. The figure has been reproduced with the permission from [44].

Graphene-based nanolubricants with anti wear and antifriction features can minimize exhaust emissions and save energy by improving the tribological behavior of automobile engines [45]. The loss of power during engine operation is due to the friction and wear that
result in higher fuel consumption and emissions. Lubricant, loaded with graphene nanoadditive, contributes to saving the energy of automobile engines through the self-healing mechanism of the worn surfaces of an engine. Application of graphene based nanolubricant enhances the antifriction feature by 29-35% and anti-wear feature by 22-29%. In addition, the engine performance is improved by 7-10% while the fuel consumption and emission (CO₂, HC, and NOx) are decreased by 17% and 5.42%, respectively. The combination of copper and graphene (Cu/Gr) nanomaterials also improves the properties of automobile lubricants [46]. The addition of Cu/Gr nanolubricants lowers the friction coefficient by 26.5-32.6% and wear rate by 25-30%. A homogeneous mixture of silica and graphene (SiO₂/Gr) can enhance water-based lubricant's rolling properties and tribological performances [47]. The addition of SiO₂/Gr nanoadditive brings down the friction coefficient by 48.5% and wear rate by 79%.

5. Nanocatalyst and nanoadditives

A catalytic converter, installed in an automobile vehicle, is an emission control device employed to reduce the toxic emissions from an ICE. The noble metal catalysts are generally used as catalytic converters in an automobile. Among platinum group metals, palladium (Pd) blended with suitable metal and composite oxides is an effective catalyst for the oxidation of carbon monoxide (CO) at low temperature. Pd metal nanocatalyst is the best possible catalyst for automobile applications [48]. Small particle size and greater dispersibility make the Pd nanocatalyst highly active. Other metals belonging to platinum group such as rhodium is utilized as a reduction nanocatalyst and Pt is utilized as reduction-oxidation nanocatalyst in catalytic converter. Structural formation after calcination, chemisorptions of CO, and the regeneration of PdO nanocatalysts have been represented graphically in Fig. 10, Fig. 11, and Fig. 12, respectively.
Biofuels are receiving extensive attention to be used as fuel for automobile engines. The effect of the addition of nanomaterials such as the oxides of Al, Ce, Cu, Fe, Mg, Mn, Ni, Pd, Pt, Si, Ti, Zn, Zr, and graphene nanoparticles, carbon nanotube, and many more in biofuel has a great impact on the performance of automotive engines [49]. The biofuels are mixed with titanium dioxide (TiO₂) at different concentrations and examined for the performance and emission properties of automobile engines. The addition of TiO₂ with biofuel improves the performance of automobile engines such as power, torque, exhaust gas temperature (EGT), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). In addition, fuel nanoadditives minimize the emission of GHGs and particulate matters and curtail the specific fuel consumption (SFC) [50]. Al oxide nanoadditives significantly reduce the ignition delay (ID) and combustion time (CD), while enhance the peak pressure and heat release rate (HRR) at the highest load and cylinder pressure. The nanoadditive is capable of minimizing hydrocarbon and CO emissions by 26.72% and 48.43%, respectively [51]. Addition of carbon nanotube to automobile fuel at 30, 60, and 90 ppm proportions enhances the power, BTE, and BSFC of diesel engines by 3.67%, 8.12%, and 7.12%, respectively [52]. Graphene oxide (GO) nanoadditive at different concentrations can improve automobile engine performance remarkably [53]. Cerium oxide (CeO₂) nanoparticle addition to fuel enhances the performance and emission characteristics of automotive engines [54-56]. Moreover, the addition of nanoadditives can extend the fuel droplet life during fuel injection and combustion process (Fig. 13 and Fig.
The delay in the evaporation process may reduce the loss of fuel and improve fuel efficiency significantly.

Figure 13. Regeneration of PdO nanocatalysts. The figure has been reproduced with the permission from [55].

Figure 14. Step-by-step process of micro-explosion when cerium oxide (CeO$_2$) nanoparticle is blended with diesel. The figure has been reproduced with the permission from [54].
Nanomaterials to be used as nanoadditives should have essential properties such as greater surface area to volume ratio, micro-explosion, oxygen buffer, enhanced thermal conductivity, antiwear, corrosion inhibition, and catalytic activity (Fig. 15). Oxygen buffer properties ensure the availability of oxygen for complete combustion and curtail the amount of unburnt emission. Higher surface area to volume ratio enhances the catalytic performance by providing greater surface area for fuel particles to interact. Nanoaddtive should be capable of supporting micro-explosion of the automotive fuel at the nozzle, ensuring better atomization by mixing air and fuel properly. Antiwear and corrosion inhibition characteristics of nanoadditives will keep the fuel tank and delivery system clean and corrosion free. Nanoaddvitives having better thermal conductivity act as heat sink and minimize the engine temperature and emissions. Improved catalytic performance of nanoadditive increase the fuel combustion rate and lower engine emissions. Since late 1990, CNTs blended with nylon can also be found in the automobile fuel system to avoid static charge build-up.

![Figure 15. Nanoparticles with desirable properties in CI engines to enhance performance and emissions simultaneously. The figure has been reproduced with the permission from [54.].](image)

6. **Nanocoating**

Nanocoating is the formation of nanolayer thickness on the surfaces of materials to be protected from adverse conditions such as wearing, chemicals, corrosion, heat, radiation, friction, dirt, and fire. Nanotechnology continuously attempts to improve its outcomes by applying nanomaterials to meet the ever-increasing expectations on modern advanced nanocoatings. Carbon nanotube based composite provides automobile exterior body panels that supports the application of electrostatic paint lines [57]. Ceramic nanoparticles are added to auto-paints to improve their scratch resistance ability and protect their initial gloss for an extended period of time. Self-cleaning nanocoatings employed on the exterior and interior body parts provide antifogging windshield and mirror. Polymer coatings have been
extensively used in the automobile industry to inhibit the corrosion of metallic surfaces. The corrosion protection sometimes fails due to the repeated exposure of the coated surfaces to harsh chemicals or strong electrolytes. To improve the defensive mechanism of surface coatings, 2-aminothiazole (AT) modified TiO\textsubscript{2}-ZrO\textsubscript{2} nanoparticles are incorporated to polyurethane (PU). The PU-AT/TiO\textsubscript{2}-ZrO\textsubscript{2} PNC coated surface shows excellent corrosion inhibition during seawater exposure [58]. The synthesized PNC coating, PU-AT/TiO\textsubscript{2}-ZrO\textsubscript{2}, can provide outstanding hydrophobic, mechanical, and barrier attributes that reduce the degradation and extend the life of the coated surfaces. A self-cleaning hydrophobic nanocoating (SCHN) is highly prospective in the automobile sector [59]. Ni-SiC nanocoatings are suitable for using on the surface of automobile cylinder liners [60]. Fire and flame retardant nanocoatings can be used to coat automobile surfaces to protect from fire and to make fire alarms [61-64]. Flame retardant nanocoating composed of carbon black (CB), polyvinyl alcohol (PVA), and carbon nanotube can be used as a smart coating, which is capable of creating short time alarm at 350 \degree C and in the case of fire [61]. The experimental results show that the flame retardant nanocoating can be used as a fire-warning sensor. There are varieties of nanocoatings prepared from metal, ceramic, and PNCs capable of protecting the metal surfaces from corrosion [65-68].

7. Major challenges and possible solutions

The adoption and utilization of nanomaterials in automobile sectors can be affected by numerous factors, including the risk of parts failure, demand and supply chain, recycling at the end of a product life cycle, environmental issues, cost-performance and risk-benefit ratio, and consumers' expectations. There is a huge chance of failure when newly developed materials are utilized commercially for the first time. There is the risk of vehicles recall from the automobile sector due to the failure of components made of newly developed materials. Many automakers have set up their own R&D sections to examine the novel materials and conduct feasibility surveys for effective and successful utilization to avoid such a scenario. These processes are expensive, time-consuming, and create obstacles to using innovative nanomaterials. Usually, newly developed materials are tested in the appropriate place at a low-volume vehicles. For example, BMW has used carbon fiber reinforced polymers (CFRPs) extensively in its "i-series" vehicles. Irregularity in demand and supply chain is another factor affecting the usage of nanomaterials in automobile sectors. Due to unpredictable conditions, the suppliers may not be able to maintain the supply chain for providing the required amount of nanomaterials with desirable qualities ceaselessly. This unexpected interruption can result in a delay in vehicle production. To avoid these undesirable circumstances, automakers rely on multiple suppliers rather than a single one and ensure that the required materials have a strong supply chain globally before initiating the use of nanomaterials in massive production. Manufactures deploy their investments globally to ensure continuous production by maintaining a quality supply chain of materials and developing infrastructure to drive innovation. Considering the health and environmental impact of nanotechnology products, it is essential to implement a life-cycle-based method associated with risk assessment for identifying potential problems and
adopting safer manufacturing processes that are harmless to health and environmental components. Nanomaterial based products are synthesized by either top-down or bottom-up methods which generate a great deal of wastage. The manufacturing of nanotechnology products requires the highest clarity, which is involved with post-processing or reprocessing stages, low yield, usage of toxic acidic or basic chemicals and organic solvents, a requirement of extreme operation conditions, the consumption of utilities, and the generation of GHGs that eventually produce waste materials. The excessive use of resources and energy ultimately creates severe and long-term impacts on the environment and human health due to the accidental or unintentional exposure of nanomaterials. So, ensuring the recyclability of nanomaterials is a principal factor in material qualification for achieving a greater risk-benefit ratio. Although the incorporation of nanomaterial can enhance the functionalities of bulk material, the production and processing cost may leave-behind the benefits. For instance, the price of carbon fiber is approximately ten times more than a similar amount of steel. The automobile sector is very competitive in terms of manufacturing cost, since the customers have many options, and several fragments of the automotive market are price-sensitive. Therefore, the selection, optimization, and manufacturing technologies of nanomaterials should be conducted very carefully to attain a maximum cost-performance ratio. Among multiple market forces prevailing in automobile sector, customers responsiveness always plays an important role in material selection, specifically for materials used for interior construction. For example, if leather seats are preferred by the customers, an automobile manufacturer may be reluctant to go for new material even though the new one is better but cheaper than the conventional one. The automakers can address this type of issue by optimizing the appearances and qualities of newly developed materials by adopting nanotechnologies that are state of the art. The utilization of artificial intelligence and innovative manufacturing approaches such as thin-wall casting, additive manufacturing, and resin transfer molding will create the opportunities for nanomaterial-based construction materials for automobile industries.

8. Future prospects

The automobile sector demands the rapid and practical development of nanotechnology, which can greatly impacting the expectations of consumers to improve their vehicles. Applying appropriate nanomaterials through effective nanotechnologies will generate smart automobile sectors and trends. Electronic control of automobile components is one of the quick-changing aspects of advanced and future automobiles. The electronically regulated antilock braking system, fuel injection, headlamp brightness control, exhaust emission, automated air conditioning, sensor-based driver’s seat adjustment, and automatic steering control are some of the instances where the application of nanomaterials could be the best solution. Nanotechnology implementation may enable artificial intelligence for safe driving by reducing personal failures. Nanomaterials can be utilized to develop and fabricate all automotive components and subsystems. Advanced nanoparticles can be used as nanofillers for smart nanocomposites, nanodevices, nanocoatings, nanoelectronics, nanobatteries, nanofuelcells, nanosensors, and so on for cutting-edge automobiles.
Conclusion

Nanomaterials have greatly influenced the advancement of the automobile industry since the physical and chemical properties of the bulk material can be modified and controlled at the nanoscale level. The chapter has focused on some of the crucial and significant applications of nanomaterials in the automobile sector. Many of the nanotechnology applications for automobile purposes are limited to the research level because of the lack of successful initiatives for commercialization. Nanomaterial selection, processing, optimization, fabrication, modification, manufacturing cost, recycling, and hazards are some of the limitations that hamper the commercial nanotechnology applications in automobile sector like other nanotechnology based sectors. The utilization of nanomaterials through nanotechnology is yet an incompletely developed process in any of the industries, but it is strongly believed that the nanotechnology is going to rule the automobile sector to a substantial range and will create products with novel characteristics which are unimaginable today.

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