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Review

Nanomaterials for automotive outer panel components: a review

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Abstract The future of mobility focuses on multidimensional parameters critical to vehicle emissions, passenger safety, and intelligent systems. Conventional materials are generally able to match the demands as mentioned above identified by the industry. However, due to the requirement for automotive components to amalgamate efficiently with future intelligent systems, there is a necessity for implementing advanced materials. Nanomaterials emerge as an optimal contender for usage in automotive body panels. Owing to their particles existing on the nanoscale, these materials offer enhanced physical, chemical, and electrical properties compared to conventional materials. As a direct effect of the above, automotive components can be manufactured in a lighter, safer, and economical manner. Crucially, nanomaterials show potential for tribological, rheological, electrical, and optical applications in automobiles. It leads to optimizations within vehicle powertrain and exhaust, tires, vision systems, and surface coating, leading to reductions in vehicle weight, greenhouse gas production, and overall carbon footprint. This article implements a study on the characteristics, properties, potential applications, and manufacturing techniques for nanomaterials. Various nanomaterial composites with differing chemical compositions are explored to gauge possible variations and compromises related to desired properties. Through transitive methods of inference formation, the capability for nanomaterial usage in automotive body panels is comprehensively examined.

1 Introduction

The automobile industry has an essential role in developing countries' economies. Any automobile component should be manufactured at the lowest price possible without degrading the

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product quality, hampering the safety standards while maintaining carbon emissions within the guidelines as stated by the government. This goal has to be achieved through any means necessary to meet the increasing global demand for automobiles. Whenever we talk about the capital of production in the automotive sector, it is predominantly in context with lightweight components of which the body panels are the foremost [1]. Fuel-saving methodologies justify the requirement for lightweight vehicles. Customers buying cars want the maximum mileage output from their vehicles. All users want to save their money on fuel. However, we live in times where we should understand the future scarcity of fossil fuels. Reports estimate that humans will have depleted all their gasoline and crude oil sources within the coming years. It, however, does not imply the end of the automotive industry. It is possible to take specific measures to save fuel to make it last longer. Today, engineers are trying their best to improve the efficiency of their engines. They can extract the maximum work from the engines at minimal wastage, but the truth is that all the research and development has almost reached the verge of advancement [2]. Therefore, the only option left with IC engine designers and engineers is to shift to alternate source of energy to power their engines. The review of alternate fuels is not the purpose of this scientific review but to address the scientifically proven and probable application of nanotechnology in the automotive industry. But the next question that may arise is how we expect nanotechnology to solve fuel usage. We look into the research facts and scope of automobile fuel usage improvement after engines reach their maximum efficiency limit. In [3], researchers proved that reducing the weight of automobile components can lead to fuel efficiency. One can understand that once the overall loaded weight of the vehicle reduces, the specific dynamic resistance acting on the vehicle reduces. The knowledge of automotive engineering tells us about the three significant resistances a vehicle should overcome while in a dynamic state. Namely, aerodynamic drag, gradient resistance, and rolling resistance. If one carefully observes the dynamic force equation associated with all three, one may notice that all of these resistances are related directly to the vehicle's laden weight. Hence, here is the catch. If we can successfully reduce the weight of the vehicles significantly, the resistance acting on the vehicle would reduce, and hence operational energy required to move the vehicle would be less. Hence, the engine tends to operate in its maximum fuel efficiency range, i.e., in the region above its optimum air–fuel ratio of 14.7:1. This way, the mileage can be increased with the use of present engine technology. Now, this is the place where nanotechnology comes into action. Nanomaterials can make car body panels lighter than aluminum and any other previously employed composite material while also being more substantial than the general grade steel that has long been employed in the automotive industry to attain exceptional mechanical qualities. All of the discussion done till now was concerning limitations in IC engine technology. But work done by researchers in [4] provides the solution to the alternate source of energy. They showcase the critical fact that the conventional IC engines will be replaced by electric motors powered by electric battery packs sooner or later. Today we see that TESLA has become the market leader in terms of electric automobile production. Does this imply that there is no need to lighten the automotive body further? Again, literature review shows that though the vehicles are purely electric, they are still seeking lighter automotive body panels. Because present electric vehicles' mileage efficiency with current battery technology is nowhere near that, we needed to address this issue to increase the market share of electric vehicles. As a result, the need for lighter automotive body panels created using nanomaterials is essential even in the electric car business. Thus, material scientists and automotive design engineers need to figure out the fabrication process of nanomaterials with a less carbon footprint than the current manufacturing techniques. Understanding and manufacturing an adequate material for automotive application has been a task for most material scientists and automotive engineers today. Specifically, for the body of an electric car, which represents the automotive industry's future possibilities in the following decades, lightweight materials are critical to accepting the extra weight of batteries by reducing the curb weight and improving the maximum range of the electric car.

2 Understanding the process

2.1 Automotive component manufacturing

At the nanoscale, materials exhibit a diverse range of chemical, physical, and biological properties of the material change that contrast from the properties of their atoms, molecules, or bulk materials. The cause of this effect is spatial confinement that leads to a large surface area to volume ratio composing high surface energy and decreased flaws. Pseudo-elastic behavior at high temperatures leads to higher fracture stress and resistance to failure. These are considered critical physical properties that automotive body panels should possess. These properties are a result of reduced grain structure as deformation is not possible at the nanoscale. It results in extended wear resistance, improved lubrication, reduced weight due to lighter materials, etc. Nanomaterials influence the necessary advancements extensively in the automotive sector through the production and development of innovative materials and methods. The literature survey shows that most research and developments based on materials for body panels are in the automobile sector. It is the most dependent and regularly used means of transportation compared to any other means of transportation. [1]. In automobile body parts, nanomaterials are employed for paint coatings, lightweight components, self-cleaning nanopolymers, and scratch-resistant nanopolymers. In vehicles, the usage and durability of body parts, long-lasting paint coatings, engine performance, tire life, and compartments are enhanced by integrating various nanomaterials like carbon nanotubes, aluminum trioxide, titanium dioxide, carbon black. The toughness, lightweight, fire impeding, and ultra-violet resistance are significant properties for the automotive industry, increased by using nanoclay and nanoparticles such as titanium dioxide and silicon dioxide graphene and carbon nanotubes. The difficulty related to typical paints is that they provide low efficiency when transferring characteristics of the paint, low fire-retardancy ability, reduced surface quality, and an increased tendency for dust particles and water to adhere to the surface. The nanoadditive overcomes these drawbacks in coatings; they improve abrasion resistance, and remarkably, nanomaterials with a base element of titanium or zinc oxide can increase ultraviolet resistance made possible through reflecting and absorbing harmful UV rays [5]. Weight reduction of vehicles is the most critical aspect in the automobile industry today. By reducing the weight, we can increase the fuel efficiency that reduces CO_2 emissions, which is very important for every automobile manufacturer to meet the stringent government guidelines for decreasing the pollution, production cost, and carbon footprint of the automobile industry. It is estimated that by reducing the weight of an automobile by 10%, there will be an increase in fuel economy by 7% [2]. To test the sustainability and suitability of the material for automotive application, specific forces that act on the vehicle body through the suspension system and transmitted from the ground include the study of dynamic forces, free, forced, and damping vibrations and their transmissibility, damping frequency, and other properties, etc. [6]. In this context, [7] deals with all those mentioned above vibrational and damping characteristics of multi-walled carbon nanotubes. Considering the dynamic behavior of automobiles, control of body vibration and harshness can be accomplished by minimizing vibrations caused by the engine, tires, chassis, and aerodynamic drag. In this context, the car body material should be resistant to such harmonic loadings and creep. All these properties should be present in the nanomaterial used to manufacture the body panel. Today, the customer demands a high level of comfort from their vehicle due to the benchmark set up by the leading luxurious vehicle manufacturers. An engineer wishes to balance the economic and sustainability factors while designing the automotive body panel, which can be achieved using nanomaterials [9]. In recent years, engineers have tried to replace the body made out of fiberglass with reinforced plastic composites made of natural plant fibers [9, 10]. According to the text study, materials experts predict that a composite car body panel might be 40–60 percent lighter than a present steel body and 40–55 percent lighter than aluminum, with a maximum mass reduction of 25–30 percent for an optimum steel body. Remarkably, the number of vehicles worldwide is expected to increase to up to 2 billion by 2035. Hence, it has become a dire challenge to fabricate a new variety of elastomeric nanocomposites. Interestingly, this new nanomaterial application could be extended from automotive body panels to the development of tires with reduced losses, thus decreasing overall fuel consumption [11]. Viscoelastic properties of polymer grafted spherical nanoparticles can be tuned by controlling the composition of nanoparticles. Hence, the viscoelastic PNCs prove to have a possible application in automotive body components prone to high temperatures; such an example is the dampers of the automotive suspension system used to reduce vibrational and acoustic effects of maneuvering vehicles. These properties make nanomaterials reliable and suitable candidates to substitute metals for automobile body panels, as seen in Table 1. Usage in terms of both cost factor and performance criterion is a rigorous requirement for polymeric nanocomposites in the automotive sector. Challenges for nanomaterial to be used as automotive body part: processing, high cost and lead time, oxidative/thermal instability of nanoclays. [12, 13] To meet these expectations, the application of high-strength and lightweight materials is regarded as the most promising possibility. Applying new high-strength materials besides high strength steels like DP1000, TRIP780 has been a task of researchers in their work, and all these are a part of sheet metal forming operations [14]. Aluminum body panels have been estimated to show 50% weight saving in body-in-white (BIW) applications, leading to a 30–40% overall weight reduction ratio [14, 15]. But through the application of nanomaterials, these figures can further be increased. Even carbon nanotubes used as reinforcement in aluminum matrix composites can prove to be a viable solution. From safety aspects, specifically the durability of the vehicles (automobile, aerospace, and marines), nanomaterials can improve vehicle safety owing to their characteristic properties. [15, 16]. Material scientists and engineers have explored the miraculous phenomenon at the nanoscale once nanotechnology is applied due to the unique material physics and chemistry of its products, all of which make significant contributions to the materials industries around the world [17]. Nanotechnology so far shares the development of tools, instruments, and structures by the controlled manipulation of shape and size at the nanoscale [18]. This serves as a convenient tool to preserve automotive body panels from corrosion and imparts abrasion resistance. Nanotechnology can be extended to other automotive components such as paint, batteries, fuel cells, tires, mirrors, and windows [19]. The establishment of nanotechnologies improves the execution of existing technologies for the automotive industry. This is because, at the nanoscale, the electrostatic forces and quantum effects overcome gravity forces, which leads to enhanced material properties. Recent advancements in nanomaterials have been widely implemented in the automotive industry to bring new and unique services and enhance vehicle performance. Table 2 highlights the various advantages of common nanomaterials.

Aesthetics are also an important parameter when it comes to the sale of cars [21]. Additionally, attention must be paid to the development of automotive nanocomposite clear coatings,

Table 1 General nanomaterials and their enhancing characteristics

Type of nanomaterial	Application	Enhancement	Refs.
Nanobase	Tire cap	Improved gripping power/strength and handling properties Reduced heat effect in tires and reduce rolling friction	[20]
Nano-Pro-Tech	Nanocoating for the tire tread	Reduces heat generation, longer tire life	[20]
Nanoclay containing BIMSM	General, Automotive body panel application	High specific strength, Low coefficient, thermal expansion, and high thermal resistance, good damping capacities, superior wear resistance, High specific Stiffness, Satisfactory level of corrosion resistance	[20]
Nanoreinforced composites	Replacement for the old reinforcement materials	Surpasses the limit of old composites providing superior characteristics	[20]

Table 2 Various nanomaterials and their functions

Nanomaterial	Function	Advantage	Refs.
Nickel (Ni)	Conductive tracing for printed circuit boards (PCBs)	Can conduct electron lithography	[27]
Silver (Ag)		High conductivity reduces precious metal usage	
Tungsten (W)			
Aluminium titanate (Al_2TiO_5)	Ceramics for structural applications	Reduced cost of production	[27]
Aluminum oxide (Al_2O_3)	Ceramics for structural applications	Reduced cost of operation with improved mechanical properties	[27]
Tungsten carbide (WC)	Surface coating	Thinner surface coatings with reduced material usage	[27]
Cerium oxide (CeO_2)	Catalyst	Reduced particle size, reduced material usage, and improved wear properties	[27]
Titanium oxide (TiO_2)	Catalyst	Reduced particle size, improve reaction kinetics	[27]

as all on-road vehicles cannot be upgraded with new automotive body panels. The mechanical properties of the body material can’t be enhanced like impact resistance, higher elastic modulus, enhanced dynamic force vibration resistance. However, specific characteristics related to aesthetics like more scratch and wear resistance, higher load-bearing capacity, better electrical and thermal conductivity have a scope of improvement. Before bringing nanomaterials into the application, it is necessary to understand the general concept of automotive body structures [22]. Then, feasibility tests are to determine the scope of replacing current material used at a specific location in the automotive body/frame structure. We have different types

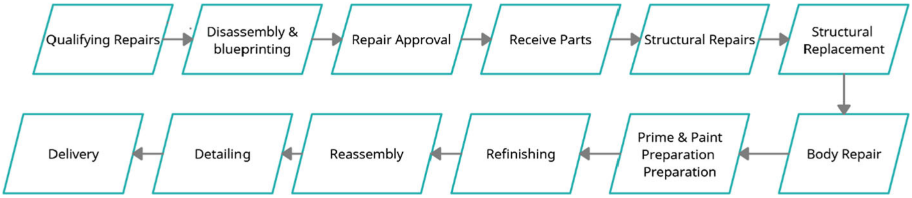

Fig. 1 An automotive body shop process flow diagram

of chassis frames solely developed for a specific application/task to fulfil. Thus, it is essential to understand the nature of forces that a specific vehicle structure or body has to bear. Accordingly, the nanomaterial base body has to be developed, and an appropriate technique has to be chosen for the production of the body panel. A cost-effective and safe vehicle body panel/structure is expected to flex in certain regions to absorb a significant portion of the high strain energy impact forces [23, 24], reducing the rate of velocity drop, ensuring that passengers experience minimal vibrations and receive the least amount of impact energy, and so furthermore, the knowledge of nanotechnology can be extended further for the production of antifog coatings for the headlamps, fog lights, rear view cameras, and other LED base sensors whose performance can be tampered with due to the deposition of fog [25, 26].

One of the benefits of sheet metal (malleable) is its capacity to be shaped to the greatest extent possible, critical within the car manufacturing process. As a result, the most critical factor in the vehicle shell-forming process is surface quality in terms of smoothness and the prevention of pollutants leaking into the system, which can cause undesirable noise and water seepage. Over to this, the stamping dies must be approved and enhanced, which is the maximum highly priced and time-eating task at some point of a brand-new automobile layout and launch. The die approval system can take approximately a long time before the Start of Production to attain the very last authentication of the measurements. The stamping process may be described as the system converting a metallic sheet workpiece into a beneficial form through stretching until it enters the yielding phase. Stamping is done using a shaping cavity (die) and a hydraulically or mechanically actuated press that forms the sheets into the desired shape. This cold working process is an overall shaping system adopted in every vehicle manufacturing firm, body repair shop (Fig. 1 represents a typical process flow in the body repair shop). However, this type of stamping manufacturing scheme is now no longer restricted to production engineering; indeed, this now incorporates the improvement of the desired tooling (i.e., shaping process). Such operations consist of die manufacturing similar to that of furnishings and mechatronics equipment, including the switch machines typically prepared with grippers that can hold the metal component through electromagnetic force or plates with suction cups. Stamping engineering is the first step in the die manufacturing process that begins by analyzing the preferred body panel forms supplied as a CAD file by the body design department. Then, the engineers select the appropriate material, i.e., choosing the metal grade, dimensions for the forging process, and the extent, quality, type of heat-treatment method through the information guide that is generally supplied through the metal mill. Feasibility analyses comply with every decided-on material, which results in a system plan, including the failure or repair analysis.

Formability may also be described as a quantity a metallic sheet workpiece may be worked or labored to a particular form by preventing any kind of failure, fracture, and forming defects that are different unwanted surface features. Formability is not a physical parameter or a system nature; however, it's a system attribute that relies on intrinsic and extrinsic

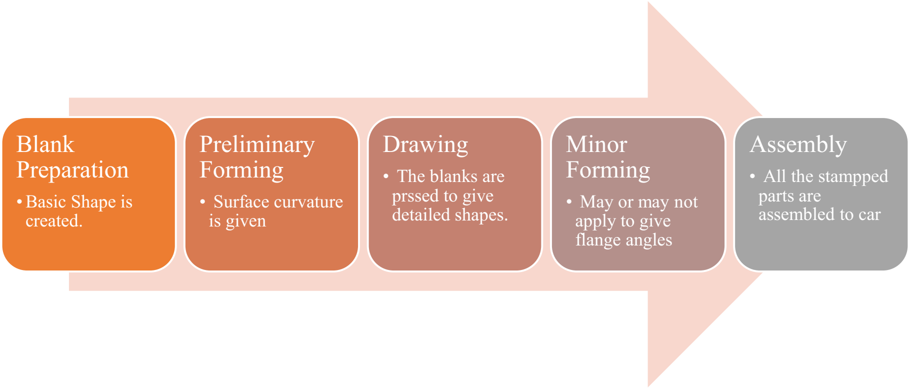

Fig. 2 Process flow in the stamping process

sheet metallic properties similar to the system conditions [8]. A standard process flow in the stamping process is shown in Fig. 2.

1. *Blank preparation* It involves a trimming movement approximately a closed-form. This is a piece, i.e., saved for shaping at a later stage. The blank form consists of any range of directly and curved-line segments. An exact glance at blanks indicates that the slitting and shearing operation had been used on them next. Slitting reduces linear dimensions (typically coils) of sheet metallic workpieces into shorter lengths through more than one extra pair of circular cutting tools. This process is regularly preceded by surface trimming of blanks and is applied in particular dies with appropriate widths. Shearing is achieved through a sharp knife working in a direct line via a quick return mechanism. The workpieces of metal rolled in the form of sheets are located among a desk-bound sharp cutting tool beneath. A linearly constrained higher blade constrained to moving along only in the direction is sheared by bringing the cutting knives close to the workpiece.
2. *Preliminary forming operations* The intention is to give the blank its shape, i.e., a semi-evolved blank, which is in the preliminary form. Primary forming operations encompass reshaping by providing bends and flanges via both reduced flanging. The span of the flange decreases as it attains its shape or stretches flanging in which the fabric is yielded by applying sheer force as flanging happens.
3. *Drawing operations* In the automobile forming shop, hydraulic presses are used. All dies are referred to as draw dies because the metal can be re-shaped in the die enclosure. But, the maximum number of times the reshaping results as deformation modes is dependent totally on the biaxial stresses that are generated when the press bends and flattens the flange structure. From time to time, drawing has been referred to as radial drawing, cup drawing, deep drawing, etc. This process has a unique group of parameters that distinguish between different processes. The precise characteristic of deep drawing is the deformation phase of the flange. The blank is pushed into the machine, where its circumference needs to be decreased. Because the blank is extruded withinside the reversed direction, this results in a radial reduction of the circular geometry, which is responsible for generating compressive residual stresses in the material, ultimately resulting in straining withinside the tangential direction of the material blanks. Instead of expected radial reduction, this ensures radial extension.
4. *Minor forming operations* Majorly, automobile panels demand a collection of steps and procedures throughout the forming process because reshaping the flange angle is not

possible to be finished in one go. Such processes generally have a hammering step performed as soon as the workpiece has been expanded across a vast radial punch (that keeps it away from splitting). The folds generated from machine hammering are unfolded, and the metal is reshaped into its preferred form with no extra work within the stamping line. The following standard process is redrawing. This is also a type of farming operation. We impose diameter limits on a cold drawn workpiece acquired following a drawing operation that can be instantly molded into a bowl-like structure with the required diameter. First, the bowl is redrawn into a single or additional level to accomplish final dimensional validation in bowl height and radius.

5. *Assembling activities* This encompasses specialized cells for combining panels to form the body in white through additives, including becoming a door interior and exterior panel member. Also, the remaining automotive body components that are stamped are assembled in one go. These final steps result in forming an automotive body in white ready for polishing and paint jobs.

2.2 Nanomaterials suitable for automotive applications

2.2.1 Automotive electrical applications

Supercapacitors show great potential for the storage of electric energy in HEVs and EVs. Although they have high specific power, their specific energy is relatively low compared to conventional Lithium-based energy storage systems. Additionally, supercapacitors also face issues with low energy density and high costs. A supercapacitor's energy storage capacity is proportional to the surface area of the embedded electrode. Nanomaterials are being incorporated into the electrode fabrication process for supercapacitors to overcome the technology's limitations. Carbon-based nanomaterials allow for a high surface to volume and weight ratio and provide viable solutions for the production of large surface area electrodes. The internal resistance of the supercapacitor is a factor that affects its longevity, and this parameter can be improved via the use of carbon-based nanotubes. Carbon-based nanomaterials are best manufactured for large-scale production via Chemical Vapor Deposition (CVD). A catalyst reacts with a synthetic gas mixture and, upon heating, forms nanotubes on the catalyst's surface. Because this technique is costly and energy-intensive, the overall environmental benefit from the nano-embedded supercapacitor must offset the losses to provide an environmentally sustainable operation [28]. While most ceramic nanocomposites containing precious metal nanoparticles are made by precipitation, their electrical characteristics and application variety stay the very same [29]. Solar cells are often used atop car roofs to generate electricity to power auxiliary systems such as interior ventilation. Nanocomposites with semiconductor dots embedded into them show potential for increasing absorption rates of solar radiation efficiently. Due to the variable arrangement of nanodot layers within the matrix, the concentration, sizing, layer distance, etc., can be manipulated based on process conditions to achieve properties desirable for solar power generation [30]. These materials conduct electricity well, are heat resistant, and behave as superconductors at lower temperatures. Nanotubes also display piezoelectric properties when a comparatively low voltage is applied to them [31]. Nylon-CNT hybrids used in blends show resistance to static electricity build-up when used in automotive fuel systems due to the capacity to vary electrical properties as desired [32]. In the domain of batteries, nanomaterials significantly reduce the path length and hence time for the transfer of electrons/ions, inducing enhanced power rates. For Li-ion batteries, nanomaterials provide an increased surface area of electrode/electrolyte for contact with Li+ ions, enhancing the overall ion transfer rate. Due to quantum effects existing within nanoparticles, increases in electrical resistivity can be achieved [33]. Therefore, the collaboration of many of those mentioned above enhanced electrical properties demonstrates the potential for automotive body panels that implement intelligent systems within them.

2.2.2 Automotive electronics application

Due to their superior energy capacity, lithium batteries that can be recharged have revolutionized. Cell devices, camcorders, computers, and other electronic devices rely on batteries as their primary source of electricity [34].

In micro-batteries, 3D configurations can be advantageous, mainly as microelectronics demands a high power supply from minimal space on the required chip. To improve capacitance and power delivery, high-surface-area nanostructured carbon electrodes are being developed. Aerogels, nano-templated carbon, and carbon nanotubes are among these materials. Nanomaterials can be used as catalysts in vehicle catalytic converters and power generation equipment to deal with such toxic substances, and poisonous like carbon monoxide and nitrogen oxide are examples of such gases, eliminating emissions from gasoline and coal combustion. The limited measurements change the scattered electronic structure in metals and semiconductors. As a result, physical characteristics such as energy excitation and fluorescence behavior may change. Thermally conductive products are commonly used in automobiles to heat and attach digital equipment to energy sink thermal energy extraction [35]. Graphene has been widely used to develop electrodes, detectors, power storage systems, solar batteries, and other applications.

2.2.3 Tribological applications

When used for powertrain, tribology-based applications such as hard/low friction coatings for components with high revolution rates, nanocomposites containing SiC, C, BN3, etc., can significantly reduce mechanical losses. This effect is visualized through the Hall–Petch equation, which relates improvement in strength to sizing reduction from micro to nanoparticles. The reduction in mechanical losses attributes to minimized component wear, thinner coating requirements, and reduced need for lubricant quantity. One study focuses on the production of nanolubricants combined with derivatives of multi-layer graphene and their positive effect on tribology-based properties, keeping conventional engine oil for baseline comparison. Reductions of up to 43% and 63% for friction coefficient and wear were found concerning engine oil. Engine oils use various additives such as anti-oxidants and viscosity modifies to derive desired properties. However, these conventional additives can break down at temperatures greater than 200 degrees Celsius and at pressures greater than 5000 psi. Additives that can tolerate these conditions do exist, although they are costly and harmful to the environment. Additionally, these additives function in a limited manner and are often corrosive under high temperature and pressure conditions. Metal-based nanoparticles embedded in lubricating oils have been found to have anti-wear properties at high temperatures and pressure while staying non-corrosive and non-degrading. Furthermore, due to the minuscule scale of particles present in nanomaterials, clogging of lubrication systems is avoided. In the field of friction and wear reduction, carbon-based nanoparticles such as graphene, CNTs, and fullerenes show the most promise. The friction reduction properties shown by derivatives of multi-layer graphene (MLG) are attributed to nano-sheets being layered on one another where wear has occurred to protect sliding contact surfaces thereby. Due to this layered structure and constant exfoliation between them, MLG can reduce friction by allowing for smoother surface sliding. The experimentation wherein reduced friction coefficient was obtained was conducted at 100 degrees Celsius, proving that nanomaterials are suitable fillers for additives in engine oil. The minor wear for plain engine oil is found to be 1.28 mm^3 and was found to reduce up to 0.84 mm^3 when combined with MLG. The mechanism that explains this reduction in wear is the tribosinterization of nanoparticles on the surface of wear. Due to particles being in the nanoscale, sinterization occurs instantly at room temperature, thereby forming boundary coatings with desirable mechanical properties. When a copper derivative of MLG is used, it is found that the inclusion of this element causes a ‘ball-bearing effect which is found to minimize surface wear. After around three months, MLG derivatives within the engine oil did not show any sedimentation effects, thereby proving the stability of such an additive [36]. Friction between tribological surfaces in engines accounts for significant energy losses and shortens the components’ overall lifetime. Automotive lubricants generally undergo Hydrodynamics (HD), Elasto-Hydrodynamics (EHD), Mixed and Boundary layer mode of lubrication. Research for Mixed and Boundary layer lubrication shows promise when nanomaterials such as Al_2O_3, graphene, and ZnO, are implemented. These are namely tribofilm formation, renewal/repairing effect, ball bearing, and surface smoothening mechanisms. When a small amount of Single-Walled Carbon Nano-Horn (SWCNH) type nanomaterial is dispersed, the dispersion method impacts tribological parameters, such as a 12 percent reduction in coefficient of friction. A nanolubricant suspension can also exhibit elastic tribological qualities while preserving essentially the same rheological qualities. In the rolling phenomenon for anti-friction/wear properties, spherical nanomaterials aid in the rolling along the surface of wear and transform pure sliding motion to a combination of sliding-rolling motion. The lack of understanding of chemical reaction mechanisms for nanolubricants and their properties is the most significant roadblock for research at this time [37]. A lubricant suspension including TiO_2 was found to increase the capacity to bear loads up to 35% compared to the base lubricant. Additionally, up to 81% reduction of surface roughness, 15% reduction in COF, and 11% reduction in wear scars for a derivative of this suspension was also found. To ensure efficient dispersion and solubility of Al_2O_3 and TiO_2 nanoparticles within the suspension, Oleic acid was used. The nanolubricants are found to be stable at room temperature for up to 14 days, after which aggregation occurs. With a 0.25 wt. % concentration of the above nanomaterials, the COF was found to be reduced by up to 50%. The kinematic viscosity of the suspension was also found to reduce with an increase in temperature, which aids in minimizing viscous friction. The overall viscosity index was found to increase by approximately 1.85% compared to the base lubricant, potentially leading to enhanced fuel economy. The nanolubricants were found to reduce COF most effectively under boundary/mixed lubrication conditions, i.e., at TDC and BDC, with reductions of frictional power loss of up to 50% for the TiO_2 suspension. This can be attributed to the nanolubricant converting sliding friction into more rolling friction along with tribofilm formation on such surfaces. The wear rate for the piston ring was found to be reduced by up to 29% for the Al_2O_3 suspension [38]. Lubrication mechanisms are generally categorized into direct and indirect forms of lubrication. The former consists of ball-bearing and tribological film mechanisms, and the latter consists of mending and polishing mechanisms. In the ball-bearing mechanism, nanoparticles are approximately spherical, allowing them to roll between contact surfaces, allowing this mechanism to be generally more suitable for nominal loading conditions. In the tribological film mechanism, an amorphous layer of nanoparticles forms on surfaces undergoing friction, thereby reducing the actual area of contact during surface mating. This induces a reduced COF and increases resistance to wear. In the polishing mechanism, nanoparticles smoothen surfaces under rubbing contact by inserting themselves into the gaps produced due to harsh surface contact, thereby reducing COF. The mending mechanism consists of nanoparticles collecting and depositing themselves within grooves formed at rough mating surfaces, reducing abrasion while also causing a self-repairing effect [39].

2.2.4 Mechanical applications

The increasing demand for unique solid material properties while reducing weight has fueled significant work efforts in recent years with a primary goal of furthering the production of Al-based composite materials. Nanotechnology would allow for light-weighting, compacting, and high sensitivity for sensors and other related devices while also being eligible to meet emissions and safety regulations. Since multiple nanoparticle characteristics, including scale, govern the performance of the nanocomposite, equivalent diameter, actual surface area, percentage of volume used, and grid performance, a 30% improvement in vehicle performance measures such as aerodynamic drag, rolling resistance, and overall weight can result in a 28% reduction Different properties can be strengthened in packaging using nanocomposites for the gas shield, anti-bacterial activity, and other purposes. Components science and engineering decide the vital connection between atomic framework and material mechanical characteristics to develop an innovative product with enhanced characteristics. Cool axial loads Die cementation is an easy and cost-effective process of centralizing powdered substances into the vast majority of items and then sintered metal in a controlled environment [40]. As a consequence of smaller grain size, these enhanced properties exhibited by nanomaterials reduce the potential for deformation within the grain itself. Nanomaterials can contribute in the coming future to reducing vehicle gaseous and particulate-based emissions. Furthermore, due to the enhanced properties of nanomaterials, the rate of manufacturing, thermal and mechanical stability of the production process is expected to improve. This means that automobiles experience reduced wear, require fewer lubrication/paint coating instances, require less frequent servicing, and are lighter overall. Such vehicle bodies can maintain their level of stiffness and resistance to impact while also reducing fuel consumption. Coatings for body panels can potentially use nanofillers inorganic or organic (silicates, oxides, etc.). It is imperative to consider that the properties of any coating are inversely dependent on the size of the filler particles. Nanomaterials also find potential in self-repairing coatings wherein the material layer can retain its original form and shape under external temperature. Furthermore, nanomaterials provide aesthetic properties such as surface smoothness and glossy finishing. Compared to typically utilized more extensive filler material, silicate-based nanoparticle fillers such as nanoclay have a vast surface area of roughly 750 m^2 per gramme with aspect ratios often exceeding 200. To improve efficiency when employing a modest weight percentage of nanoclay, a high degree of exfoliation is desirable to improve the density of the material [41]. For a nanocomposite consisting of nanoclay embedded in a polypropylene matrix, the nanoclay is arranged in a lattice of a maximum of 25 layers. Enlargement of these clay layers during ion exchange allows for exfoliation. Compared to micro-composite variants of polypropylene, the nanoclay composite offered up to a factor of 1.3 increase in tensile strength [42]. Scratches are generally categorized as plastic type and fracture type, with the former exhibiting a comparatively polished surface than the latter, which exhibits jagged edges. Nanofillers used to increase the hardness of a surface coating are frequently incorporated with organosilanes to induce hydrophobia and improve the material's dispersion. This increase in hardness is attributed to a higher Young's modulus of elasticity. As the grain size of particles decreases from micro to nanoscale, hardness properties peak in the nanorange. SiO2-based nanoparticles, if consistently distributed within a polymer matrix, improve scratch and abrasion resistance. The widespread use of nanomaterials in an automobile in areas such as engine housing and body frame can reduce the vehicle's weight by a factor of three.

2.2.5 Rheological applications

Nanomaterials in automotive fluids have improved their thermal performance via increased heat transfer coefficients for fluids such as coolants. This allows for increased engine cooling rates and a higher level of simplicity for thermal management systems. For parts used within automobiles, reduced thermal expansion is ideal to ensure tolerable dimensional stability. Nano-based fluids such as CNT and silica significantly enhance heat transfer rate when embedded in conventional engine coolants. Variable viscosity magneto-rheological (MR) fluids with embedded nanoparticles are conceivable.

The rheological properties of nanomaterial-based lubricants, such as viscosity, density, and thermal conductivity, critically depend on the dispersion pattern of nanoparticles within the base lubricant. Depending on the dispersion method, up to a 37% increase in viscosity is recorded in some cases. Additionally, a nanolubricant suspension can have elastic tribological properties while roughly maintaining its rheological properties [1]. Iron carbide crystals in the nanoscale have been found to provide hard surfaces but low COF when sprayed/coated onto cylinder walls.

2.2.6 Surface coating, optical and adhesive applications

Nano-based coatings for implementation on glass fittings used in vehicles provide a hydrophobic property, ensuring that water does not collect on the glass, thereby improving visibility standards. The use of such coatings improves the scratch resistance of the glass, and due to the polishing mechanism, water contacting the glass collects as water beads that roll off the surface. Convectional surface coatings are found to chemically and mechanically degrade due to changes in environmental conditions. Dispersion of nanoparticles into these coatings stabilizes them further from the harsh effects of the surrounding environment. Nanomaterials-based coatings are currently used for vehicle reflectors, windshield glazing, and defogging. The electrical properties of nanomaterials are used when implemented in automatically dimming rear view mirrors that are achievable through a reversible chemical reaction. Surfaces that require anti-reflection properties often incorporate bumps/dimples at the nanoscale and are seen in applications such as vehicle dashboard displays. Hydrophilic forms of nanolayers exhibit the potential for self-cleaning surfaces when exposed to water. Adhesive bonding properties that can be varied based on electromagnetic field fluctuation make use of nanomaterial properties. Due to the large surface area to volume ratio of nanomaterials, the heat transfer rate to the corresponding adhesive is suitable. The effect of bonding can be activated or reversed based on the nature of the electromagnetic field. Therefore, bonding can be added/removed in a manner that does not damage any surfaces or components. This allows for quicker and more controlled adhesive bonding, lowering cycle times during the processing of automotive components [43]. Hydrophilic sol–gel-based nanotechnology is used in anti-fogging coatings for automotive headlamp housings. This is attributed to the ability of the mixture to reduce the surface tension of water while maintaining its surface tension above water [44]. For nanovarnish coatings, nanoparticles are distributed arbitrarily within the paint matrix. Still, during curing and hardening, these particles create a structured network within the matrix that increases the scratch resistance by a factor of almost three. Electrochromic mirrors work by identifying regions of glare within the mirror's frame via appropriate sensors and conducting optical dulling of the region in question until such a time that the original glare does not exist. Nanomaterials can also enhance industrial glueing processes due to their large surface area to volume ratio, which allows for manipulation and control over the desired absorption frequency. Therefore, providing uniformity and selectivity when heating of glue layers is conducted. In addition, the energy required for this process is significantly less than when compared to conventional glueing methods [45]. According to the desired optical application, the nanoparticle's size can be altered to achieve an output wavelength of the specified region. Due to the high surface area to volume ratio of nanomaterials, many atoms are defined on the surface compared to the majority of the material, therefore relatively enhancing surface properties. Such materials can prevent reflection off surfaces, i.e., be implemented in anti-reflective coatings due to their lower wavelength than visible light. Typical automotive surface paint coatings have low flame resistance, poor surface finish, and a high affinity for dust/water. Silicon-based nanocoatings, although currently expensive, offer a very high degree of flame resistance and enhanced levels of most other required properties. UV resistance can be improved by the usage of Ti/ZnO-based nanoparticles. Nanocomposites and nanolayers are used in the photoactive membranes, protective layers, and the solar array substrate to increase the diversity and performance of solar panels in an array of solar energy. So, this is a potential application for researchers working on solar vehicles. The body panel itself may be used as a solar panel.

2.2.7 Tire applications

A material used in automobiles must generally have maximum strength to weight ratio to improve safety, engine performance, and fuel economy. Nanomaterial reinforced composites can effectively replace conventional materials in this industry due to their variable parameters, allowing for improving material properties and regions where conventional materials cannot be fitted [27].

Vehicle tires contain carbon black, CNT, nanoclay, etc., as fillers and Nano-based additives while surrounded by rubber matrix to reinforce the tire and provide pigmentation applications. Carbon black and rubber form a powerful yet stable chemical double bond to increase the tensile strength and wear resistance. Compared to conventional fillers such as carbon black, silica particles in the nano-sized scale reduce rolling resistance and improve wet condition traction by improving frictional properties. Improvements in abrasion resistance of an automotive tire induce improvements in cornering capability, rapid steering response while reducing Noise, Vibration, and Harshness (NVH). The overall lifetime of a tire is increased while also ensuring a reduced rate of air loss. When used in rubber-based composites such as tires, a lower wt % of nanoclay exhibited the exact extent of reinforcement as a much higher wt % of carbon black and increased surface energy of such particles aid in improving interaction with rubber molecules within tires to allow for coherent integration of nano-based fillers in tires.

2.2.8 Powertrain and emissions control applications

Carbon Nanotubes (CNT) are tested for implementation in catalytic converters. CNTs are used on a ceramic carrier as an intermediary layer, and the catalytic converter showed a significant reduction in Carbon Monoxide (CO) ppm and Hydrocarbon (HC) %. In conventional catalytic converters, it is found that the platinum contained in the system often agglomerates at high temperatures, reducing available surface area for conversion of gaseous emissions.

Nanomaterials within the range of 25–75 nm have been found to prevent this agglomeration and reduce the size and number of catalytic converters required in an automobile. Piezo-based diesel fuel injector valves that have nanomaterials embedded in them allow for very refined fuel injection into combustion chambers via control of distances at the nanoscale [46]. Nano-based porous materials also find application in particulate filtration, such as for soot filtration.

2.2.9 Textile/interior fitting applications

Nanomaterials used within automotive interior textiles provide significant anti-bacterial and anti-odor properties. By utilizing the hydrophobic properties of nanomaterials, anti-stain/self-cleaning interior and exterior textile fittings can be achieved. CNTs are effective in creating flame-resistant automotive textiles. Nanofibers show great potential for use in automotive textile fittings such as seat belts, airbags, and boot carpets, due to properties such as reduced weight and improved noise insulation. Nanofibers can be used in air and soot filters placed within automotive interiors, with findings proving a lower pressure loss of fluid (air) passing through such filters. Nanoclay polymer composites exhibit reduced flammability potential due to a highly reduced heat release rate. The fit and finish of components made from such materials are improved due to the lower deformation of a material under variations in temperature.

2.2.10 Surface contacts (friction) and lubricants application

Automotive engineering has extensive use of nanomaterials and can be significantly affected by them. Not only does it provide a more significant opportunity for workers to make changes in automotive parts, but it also allows the vehicle to be more durable, dirt impervious, anti-reflective, and many more things [47]. Two materials are required to reduce the friction coefficient of sliding contacts. For composite coatings AHC + NL, the matrix may be a solid and hard-wearing anodic oxide coating (AHC). In contrast, the solid lubricant is a nanomaterial (NL) with low stiffness, such as misty carbon nanotubes (GC). It is essential to ensure that the oiling characteristics of oils (viscosity) are maintained and that compressors and engines are adequately cooled, leading to their cooling [48]. The shear strength of copper nanowires is determined by the temperature that rises because of friction. Good thermal conductivity: Copper nanowires within low thermal conductivity: The number of aluminum oxide cells is increasingly growing their temperature during cast iron sliding. The registered friction coefficient in opposition to AHC + GC was lower compared to the AHCC pairing. Finally, we can produce composite coatings together with ceramic matrix, including carbon nanotubes and metal nanowires. It will help us decrease friction against the cast iron during the coating in the air. Nanoparticle coatings may stop corrosive substances from corroding in vehicles. They reduce frictional, break, and tear damage, which lowers the level of fuel efficiency [49]. Nanolubricants that are nanomaterials embedded in a substrate lube have been produced to improve the efficiency of mechanical parts at extreme temps, reducing wear in surface motion, which would be expected in heating systems and industrialized uses. The functions of lubricants are changed by applying appropriate substances to meet the needs of particular formulations [50]. The ability to move parts and function combinations to survive high temperatures and severe pressures is dependent on the use of elevated lubricating oils. As a result, the need to find appropriate valuation lubricants can work through intense stress, strong resistance, and wear-resistant situations. The development of YSZ nanofluids, mainly on the surface, protects the substrate's layer against wear. The lubricating performance improves dramatically as a result of this action. The stiffness of the lubricant's CSZ nanomaterials stops the layer from becoming dried off [51].

2.2.11 Fuel applications

For fuel, using nanotechnology, we can develop fuel additives that will make the fuel less pollutant. We can also make batteries that can be more durable, be charged rapidly, and used in an electric car near the future of the coming generation. It can be used in active and passive safety, i.e., it can help us minimize accidents or during the collision [52]. Fuel systems-MWCNTs enhance/introduce conductivity in fuel lines while maintaining elongation and barrier properties to increase fuel efficiency. We can use a different method like lightweight material to decrease load, minimize heat loss due to exhaust, including conduction through the engine body, and reduce frictional losses [53]. For Nanocor's nanoclays, the fastest-growing barrier application is beverages hybrid. For fuel system parts, MWCNTs have been used in nylon 12 and are being studied. Buckytubes are plastic compounds that identity as a system of knots or coils inside the polymer host, resulting in high flexibility, power, and physiological and electricity permeability at small loads. Titanium dioxide is used in cosmetics, cleaning products and wall paint as a chemical catalyst, filtration systems as an anti-bacterial agent, and solar cells. Also, Urea and glycine are the most popular and tempting fuels for delivering excellent uniforms [54].

2.2.12 The impact of nanomaterials in the chemistry of various automotive components

Nanomaterials have a very low mass due to their small size. Gravitational forces become irrelevant as a result of this. The uncertainty theory is based on and is only applicable to nanoparticles. It does not apply to macroscale materials. The energy difference between a nanoparticle's conduction and valence bands widens as its size exceeds the Bohr exciton radius.. The ability based on quantum dots to change the color (wavelength) of light produced by altering their dimensions is well-known. At higher dimensions, a quantum dot of substance X emits more long wavelengths The confinement effect is thought to have a significant character in the size dependence characteristics of a nanoparticle. The Li-air cell is a viable replacement for Li cells because it can be mass-produced. The main goal of research and innovation in the battery sector could be to commodify study results since it is closely related to a corporation's long and short sustainability in the globalization market. The Li-air device must be considered at the vehicle level. The oxygen depletion only at the cathode in Li-air cells demonstrates the complexity and complexity of electrochemistry transformations. Poor Li 2 O 2 oxidation kinetic studies [55]. A large proportion of the overall vehicle weight will be made up of plastics and polymer composites soon. The reinforcement of biodegradable plastics with natural fibers results in a green composite that bacteria or enzymes can quickly break down. As opposed to synthetic fibers, natural fibers often provide significant cost advantages and benefits associated with processing. The fibers of the leaves, also called strong fibers, extend along the length of the leaves. Chemical modifications can enhance the properties of fiber composites available in the environment, even though hydrophilic inborn fibers and aquaphobic polymeric matrices are incompatible. In the chemical vapor phase, accumulation feeding molecules are processed in a container, and the resultant organism is applied to a layer. Dry milling is being used to induce chemical processes. Particle size is determined by the reactant mix chemistry, the conditions of milling, and heat treatment [56].

Salt melts at 1083 K because of the heat produced through the reaction when salt reacts with oxygen gas, and further metal particle seeding occurs in molten NaCl, which protects them from aggregation and development. Instead of metallic materials like conventional SHS, carbon has been used as a process fuel, resulting in a gaseous reaction. The high rate of CO_2 release makes it easier to make highly porous powders with particle sizes ranging from 50 to 800 nm. SC-made micro titania as a thin layer in stain solar cells resulted in a high light-to-electricity transformation quality [57]. Covalent connections show chemical strategies could strengthen inter-facial relations between the liner and framework to prevent variable dissociation from the particle's surface. Nanomaterials with diameters ranging from 25 to 75 nm have been discovered to avoid agglomeration and minimize the size and number of catalytic converters required in a vehicle. The material Nanotubes and micro are used in refrigerants to improve heat transmission performance and possibly decrease the magnitude of automobile refrigeration systems [49]. Catalyst CO oxidation has already been established as a commercially important mechanism. There still are two paths to elevated catalyzed operation per mass that are closely linked. The first includes increasing the number of activated locations by pulverizing products through powder. One uses chemical ability adjustment to circumvent the higher oxidation barrier response stage at the nano-or electron. At the same time, the other includes circumventing the higher oxidation boundary response phase only on a small scale [58].

2.2.13 Effect on human life and environment

The environmental impact of nanotechnology still seems to be uncertain. To make our lives convenient and straightforward, the critical factor in achieving such facilities is technology. In the current situation, nanoparticles have the most robust performance for most materials [59]. The liberation of nanofibers in the course of data interpretation at the same workplace, the slicing and scrubbing of composite materials containing polymer fibers. CNT is considered to cause a potential respiratory threat and can cause angiogenesis. The use of green nanocomposites made from sustainable and environmentally friendly materials is expected to increase in bioplastics. This idea was pioneered by Mercedes Benz, in which coconut fibers were used over 9 years in commercial vehicles. Aluminum production has resulted in an environmental burden than the materials like steel are produced [30]. The potential usefulness of nanotechnology in medicine is set to spur healthcare coverage. The prevention, diagnosis, and treatment fields of medicine are all affected. A special binding agent modifies each FET nanodevice individually. This technology can detect nitro and peroxide derivatives, as well as several other explosives. Nanotechnologies may also be used to detect and react in building and vehicle defense. Nano-sized materials in the atmosphere pose the most significant risk of pulmonary and cardiovascular disease. The dangers of nanomaterials use are a top priority because of their proposed delivery for commercial processes and the likelihood of contamination for both organisms and the environment, both directly or by discharge into the environment [60]. ENMs can cause an inflammatory response, as evidenced by nitrite development and accumulation in the extracellular medium. No molecule plays a role in various cellular functions, including proliferation, differentiation, and apoptosis. The cellular endpoints used in this analysis are effective in predicting the possible toxicity of an inhaled. WS2 did not evoke a substantially different response from the negative control even at the maximum dose measured. Similarly, MoS2 demonstrated negligible cellular and chemical activity [61].

3 Results and discussion

Nanotechnology contributes to significant changes within the transportation industries, thereby reworking their outlook. With nanotechnology in automobiles, the reliability and durability of paint coatings, body parts, engines, tires, and compartments are improved by incorporating various nanoparticles like CNTs, Al_2O_3, TiO_2 [1, 5]. Studies demonstrate that nanomaterial reinforced steel and supported quadridirectional grids can be used to build 3D geometric roofing [7]. Applying inexperienced nanocomposites in automobile body panels shows potential for comparable mechanical performance with the artificial ones [8]. Biodegradability issues are one downside that must be addressed with bio-based composites applications, particularly ones managing structural components of exterior panels for future vehicles [9, 10]. Nanomaterials can be implemented in various automobile sections such as body parts, chassis, tires, and engines. Figure 3 exhibits the potential for their usage in body sub-components. However, their use is also related to specific health and environmental-based risks. Nanomaterial-based plastics have been found to increase weight savings of up to 25% and 80% concerning conventional plastics and steel, respectively. Nanoparticles have found value in improving heterogeneous catalysis where catalytically active derivatives of the former are released onto a porous substrate to aid in cleaning emissions. For applications

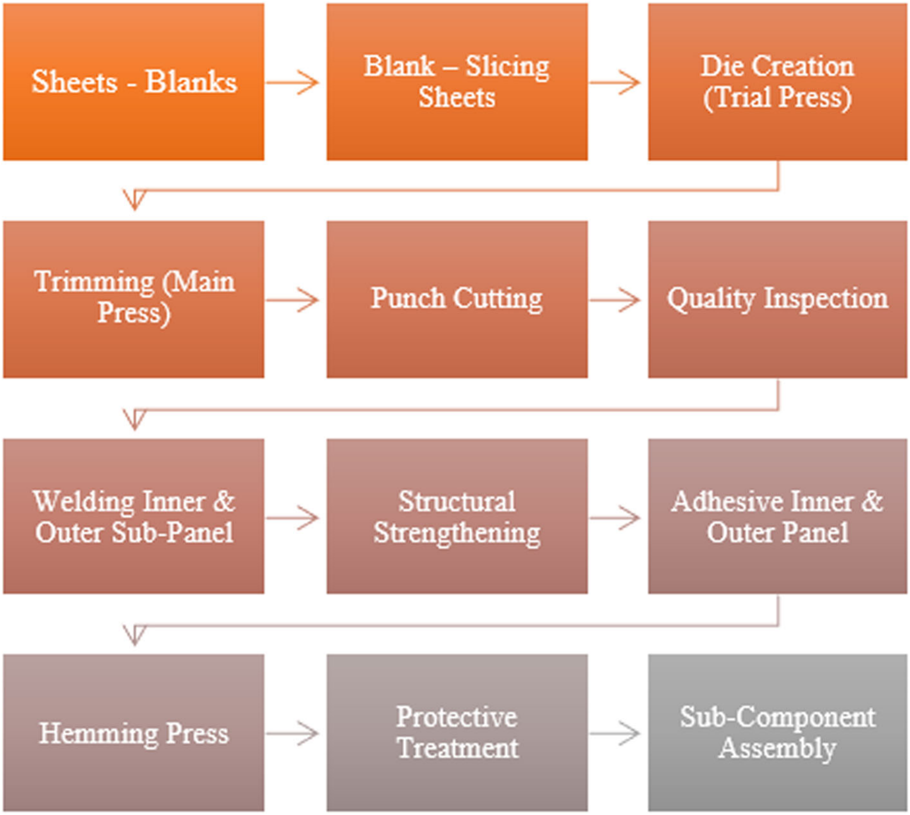

Fig. 3 General process flow for manufacturing body-subcomponents (Ex. Doors, Hood)

in piston liners within an ICE, nanomaterial usage has decreased overall engine weight by up to 1 kg, increasing the system's overall efficiency.

Additionally, a nanoparticle with chemicals finishes linking stuff network [8] to stabilize the uniformly spread nano-domains. The visco-elastic nature of stuff nanocomposites used in tire treads results in a hysteresis loop below the loading–unloading method, i.e., the dynamic physical phenomenon loss is reduced by 50% compared to silicon dioxide NPs conventionally This is attributed to the stable and uniform distribution of NPs within the entire matrix. CNT-induced three-dimensional network implemented in polymer matrices to strengthen nanocomposites exhibit an increase in toughness of approximately 470%. This is attributed to the high aspect ratio of CNTs which allow for energy dispersal and improved energy absorption capabilities. Furthermore, the introduction of CNTs in polymer matrices is connected to an increase in overall thermal stability. CNTs in ceramic composites are proposed to improve the toughness, creep resistance, damage tolerance, and thermal stability of the entire matrix. This is attributed to the ability of CNTs to contain deformations by shearing under contact loading, thereby providing enhanced load carrying capacities. For CNTs embedded into metal matrices, it is found that with a minimal concentration of 1.6 vol% of CNT, an approximate 350% increase in compressive yield strength is achieved. For a 6.5 vol% inclusion of CNT in an Al base matrix, approximately 333%, and a 184% increase in hardness and tensile strength are achieved. The existence of any aggregate or grouping of reinforcing particles throughout the development of these skills matrixes, as well as the uniform distribution of enhancing objects throughout the development of these skills matrixes. The incorporation of reinforced crystals inside the nanocrystallite structure and any aggregate or grouping of reinforcing crystals during the development of these skills matrixes. A great extent of dispersion and adhesiveness has been found to provide enhanced tensile modulus, which allows for usage of such a material where the application is semi-structural, such as in automotive doors and fenders. However, this does not necessarily guarantee a higher value for material failure strength. By achieving the above, a nanocomposite derivative of a polycarbonate film exhibited up to a 79% increase in tensile strength and elongation of factor 10 at failure [62]. Cellulose-based nanomaterials are advantageous due to increased availability, renewability, and reduced environmental toxicity. Due to their high-volume fraction, such materials can significantly reduce weight to meet future vehicle emissions requirements and, additionally, provide an alternative to working around the rising prices of conventional fuels. Cellulose-based materials can replace fiberglass-based materials as the former allows for a 10% relative weight decrease while being produced at a rate up to 40% higher with additional energy savings. Cellulose-based fibers have long been used as reinforcement material for plastic composites such as body panels and headliners by automakers [63]. Nanocomposite materials have been found in industries such as the aerospace industry. However, the cost of raw materials is high along with a long manufacturing cycle time. Therefore, such materials used in structural components for automotive industries cannot match the cost requirements due to their complicated manufacturing procedures. On the other hand, polymer nanocomposites use a small number of filters to manipulate properties and can be processed at high rates via processes such as injection molding. However, suppose the adhesiveness of filler to a matrix is poor. In that case, agglomeration of fillers can occur, causing defects, although this can be overcome by proper dispersion of nanoparticles within the mixture. Thus, the most substantial barrier to producing effective nanocomposites is ensuring uniform dispersion and high interfacial adhesive properties. The performance of a nanomaterial is highly dependent on the size, aspect ratio, specific surface area, method/effectiveness of dispersion, and compatibility with the base matrix, of which efficient dispersion is the most crucial parameter. The proper dispersion and alignment of nano-based fillers in the polymer matrix can improve the stiffness of the overall material. Compared to glass fibers, nanocomposites show a great extent of reinforcement with a lower increase in wt. %. Due to the minuscule scale of nanoparticles, the surface finish of the nanocomposites was higher due to glass fibers having fibers within the micrometer range. Conventional fillers used in automotive parts such as talc, calcium carbonate, glass fiber provide adequate stiffness but at relatively higher complications in production and with higher required concentrations of the filler. Nanomaterial-based fillers are effective even at less than 5% concentrations in providing required enhancements in mechanical or electrical properties, such as with the use of nanoclays [64]. According to the fracturing hardness findings, the existence of ZrO2 has a significant impact on the fracturing strength of nanocomposite [65]. When less than 5 wt% of Nylon-6 clay nanocomposites is supplemented, the tensile strength of the material increased by more than half, and Young's modulus increased by a factor of two. An increase in heat distortion temperature is also observed. Materials implementing nanoclay have been used in engine components such as engine covers. Nylon hybrid nanoclay is also used in gasoline blends due to enhanced resistance to the transference of the blend compared to conventional nylon-6. Therefore, it reduces emissions. Glass sections used within automobiles contribute to a large proportion of the overall vehicle weight. Using nano-based coating, required optical properties such as UV protection and anti-fogging can be achieved at a lower weight. Studies show that aluminum-intensive vehicle design attains mass reduction of 25%, leading to reductions in total life cycle energy consumption by up to 20% and carbonic acid gas emissions by up to 17% [14]. When fuel savings gains of reduced mass of lightweight aluminum are considered, the overall usage prices can approach value parity or possibly a web profit connected to standard vehicle construction. Predominant vehicle body structure types and their conventional materials are highlighted in Table 3. Polymer-based nanomaterial composites offer various mechanical properties such as increased thermal stability, fire resistance, and minimal surface defects. Body panels, interior fittings, and fuel tanks in automobiles made from these materials offer substantial scratch and surface damage resistance. Automotive interiors, appliances, and electronic housings, and power tools are industrial applications. However, these applications rely on the advanced thermoplastic polyolefin (TPO) material's lightweight, high performance, and cost-efficacy. The existence of the restricted region as a reinforcement mechanism has yet to be satisfactorily clarified, and property changes have yet to be validated using standard processing techniques on commercially available nanocomposites [66]. Nanomaterials are now used in a wide range of aerospace and automotive applications [67]. Carbon-based nanomaterials form lattice structures that minimize defect concentration, thereby providing higher hardness and strength when compared with conventional steel. Nanoparticles are exceptionally effective, requiring a tiny percentage by weight and a substrate to exhibit enhanced mechanical and thermal properties. Nanomaterials are expected to increase manufacturing rates, reduce weight and improve thermal stability, properties that, when aggregated and used in semi-structural automotive parts such as grills and door panels, account for a very significant reduction in overall weight. With this weight reduction, vehicle powertrains run more efficiently, reducing the consumption of fossil fuels and making it possible for automotive manufacturers to achieve their CO_2 emissions targets. It is found that a 10% reduction in weight can be attributed to a maximum of 3.6% reduction in CO_2 emissions. Nanoparticles in a crystalline phase, when used in engine coating, provide improved hardness and toughness, decreased residual stress, increased thermal coefficient of expansion, and enhanced tribological properties. Nanomaterial-based plastics have been found to increase weight savings of up to 25% and 80% concerning conventional plastics and steel, respectively. For applications in piston liners within an ICE, nanomaterial usage has decreased overall engine weight by up to 1 kg, increasing the system's overall

Table 3 Automotive body structures

Body structure	Application	Material	Refs.
Self-supporting body structure	Passenger vehicles: Profile structure, closing structure and automotive outer body panel	Deep drawn steel/aluminum sheets	[22]
Ladder frame structure	Off-road vehicles, commercial vehicles	Steel is majorly used; Aluminium profiles also used	[22]
Monocoque structure	Load bearing members, A-pillar, roof-post for improvised load carrying capacity	Carbon fiber reinforced plastics (CFRP) and Glass Fiber Reinforced Plastics (GFRP)	[22]
Profile based structure (Space-Frame)	Profile-based construction as seen in Audi R8 and Audi A8	Structure-aluminum profiles Closing structures- Metal sheets or CFRP help in carrying the shear forces acting on the body structure Outer skin- Plastics or aluminum stampings	[22]
Mixed construction concept	Combination of multiple automobile body structure manufacturing techniques in a unified car body structure	Combination of common materials like steel, high-strength steels, carbon fiber, glass fiber, aluminum, plastics, etc.	[22]

efficiency. Hardness increases with decreasing particle size for nanomaterial additions larger than 100 nm. However, as the hardness of the nanomaterial additive increases compared to the overall material, the potential for scratching and mark formation increases. Therefore, deciding the size of nanoparticles is critical to avoid scenarios wherein the nanoparticles might be larger than the gaps within surfaces they are supposed to deposit. Due to their high surface area to volume ratio, nanoparticles have high surface energy, and to attain a state of equilibrium, they tend to agglomerate. This phenomenon, however, affects the extent of friction and wear protection properties. Dispersion stability refers to the extent to which particles do not accumulate at a substantial rate. Therefore, a stable suspension and dispersion are imperative to achieving an effective lubricant mixture. The inclusion of a 16 vol% CNT within such a matrix is attributed to a 91% and 140% reduction in COF and wear rate, respectively. This can be achieved via methodologies such as ultra-sonication and homogenization. Stokes law can be used to calculate the sedimentation rate and, therefore, the stability of the suspension.

$$V = \frac{2}{9}\left[\frac{R^2(\rho - \rho')}{\eta} * g\right]$$

where R = radius of particles, η = dynamic viscosity of fluid, ρ = density of particles, ρ' = density of fluid.

It is found that particle velocity is directly proportional to the square of particle radius, thereby signifying that more significant particles sediment at a higher rate due to agglomeration.

Table 4 Nanocomposite fillers

Composite filler material	Effect	Application	Refs.
Glass fibers (surface coated fillers)	Improved adhesion of fillers due to high surface/volume ratio	Improves the elastic modulus of the composite materials, improving mar and scratch resistance	[12]
Talc, $CaCO_3$, nanofillers	Increased temperature resistance	Suitable for automotive parts prone to high temperature	[12]
Polyolefin elastomers	Fewer high-stress prone regions which decrease any significant chance for compromise in safety	Improved rheology owing to enhanced physical and mechanical properties. Improved polymer shear thinning and associated melt elasticity	[12]
Carbon nanotubes	Lower	Electromagnetic shielding, additives, and reinforcement	[12]

Graphene is not used on a large scale due to its costly nature; however, it is often employed as it is lighter and more robust [20] (200 times stronger than steel carbon fiber, steel, and aluminum component). Subsequently, graphene can create economical energy batteries, which might improve or replace lithium-particle batteries in the coming years. Various other nanomaterials and their industrial applications are highlighted in Table 4. When used for powertrain tribology-based applications such as hard/low friction coatings for components with high revolution rates, nanocomposites containing SiC, C, BN3, etc., can significantly reduce mechanical losses. This effect is visualized through the Hall–Petch equation, which relates improvement in strength to sizing reduction from micro to nanoparticles [12]. The reduction in mechanical losses attributes minimized component wear, thinner coating requirements, and reduced need for lubricant quantity. Because they can be produced using an in-situ intercalation polymerization approach, polymer/non-polymeric-based nanocomposites have the potential to reduce manufacturing costs and simplify processing. Nanoparticles in a crystalline phase, when used in engine coating, provide improved hardness and toughness, decreased residual stress, increased thermal coefficient of expansion, and enhanced tribological properties. Several automobile companies accept graphene to boost existing car manufacturing much further by making it harder and lightweight. It is expected that as graphene is used in the automotive sector, automobiles with enhanced impact efficiency, performance, and protection will be the preferred option of buyers [68].

The lubrication phenomenon is found to be enhanced when nanomaterials-based additives are inserted into lubricants. Surface coatings may be used to adjust the layer compatibility of packaging for different liquids and pastes [69] that may be used as lubricants. Although plastic nanostructured membranes have specific characteristics like enhanced mechanical and fuel impact resistance, nano-coatings can customize the physical characteristics evenly with limited additions of nanofillers. Lubricant mixtures that contain these additives are referred to as nanolubricants. Ali et al. [20] study showed a 2.5% increase in mechanical efficiency in an ICE when Al_2O_3-TiO_2 nanoparticles were mixed in engine oil. The improvement in lubrication is observed via the mechanisms that nanomaterial additives follow to the surface. The minuscule size of nanoparticles allows for them to enter contact areas to deliver adequate lubrication. When used in lubricants, they do not react with other additives yet show high potential for film formation to increase temperature resistance and durability. The efficacy of nanoparticles is highly dependent on their affinity with the base oil, sizing, and stability of the dispersion. The boundary region for lubrication zones is of great importance when considering the effects of increased surface friction. Within this region, if the film thickness is inadequate for enduring harsh rubbing between surfaces or if the viscosity is low, abrasion and adhesive wear will cause grooves and crack formation on the respective surfaces. Nano-based additives, however, can work to fit into these gaps that are formed to renew the smoothness of the surface essentially. In crystalline form in iron-based coatings, nanomaterials can replace conventional cast iron-based engine piston ring liners to reduce friction and engine weight. This coating is thermally sprayed onto the required surface [70]. Iron carbide crystals in the nanoscale have been found to provide hard surfaces but low COF when sprayed/coated onto cylinder walls. Power losses in an ICE account for up to 19% of the total energy created during the combustion cycle. The friction between the piston ring and its liner contributes 40–50% of the total energy loss. In general, boundary/mixed lubrication occurs at the TDC and BDC of a piston stroke, while HD lubrication occurs mid-stroke. HD friction is found to increase when the engine is running at high speed-low loading conditions. The total friction experienced by the piston ring is attributed to boundary friction at TDC/BDC and viscous friction produced by the shearing of lubricant during the stroke. Under boundary lubrication conditions, if the lubricant film becomes too thin, the load will be taken by the surface contacts rather than the lubricant itself. Nanolubricants, therefore, prove to be optimal solutions as they form tribofilms at contact surfaces to separate sliding contacts. Their properties can be attributed to their minimal size, high specific surface area, lower elastic modulus, and comparatively high hardness level. In addition, TiO_2 nanoparticles have been found to provide stable levels of friction when used as additives in lubricants due to the tribological film thus formed. SiO2 nanoparticles have been found to contribute significantly to the corrosion protection properties of automobile surface coatings. Nano-based paint coatings (nanovarnish) have higher scratch resistance due to the dense packing of nanoparticles within them. Fragile layers of nanocoatings for headlamps and mirrors create optical surfaces that are easier to clean and more durable. Nanomaterials are already implemented in multiple layer forms to formulate anti-reflection coatings used in the automotive industry. Buses use nanolayers ingrained into glass sheets to form a protective glazing layer that shields their occupants from UV radiation from the sun. The use of nanomaterial-based surface coatings for brake pads has shown an increase in the overall life of the brake pad and a decrease in the noise produced during braking. SiO2 nanoparticles are used to increase the long-term corrosion protection of Cr (III)-based coatings, as seen in Table 5. Specific agents that are inherent corrosion inhibitors due to the passivation reaction are often highly soluble, causing them to wash away. These agents can be embedded within nanocontainers, allowing for greater discharge control and entrapment of these agents in the matrix of a coating substance. TiO_2 nanoparticles show potential for use as coatings providing resistance to weather-based effects. The electrochromic effects of nanoparticles allow for their implementation in bright windows wherein the tint intensity of the window can be altered via changes in the passing voltage [71]. Within an H2 fuel cell, CNTs find potential in applications of electrodes within the system. Nanomaterials used in ultra-capacitors for EVs provide high usage cycling rates without depreciation of power quality while also showing higher endurance toward mechanical shock and vibration. In such an ultra-capacitor, CNTs can significantly increase the surface area for ion collection, increasing energy storage capacity by a minimum of 25% compared to conventional EV batteries [72]. Within batteries, silicon-based nanowires increase the battery charging rate and discharge progress significantly while also allowing for a battery with a higher overall capacity [73]. With the use of such CNT networks, a minuscule amount of concentration (0.1 wt. %) can vastly increase electrical conductivity levels without adversely affecting other desired performance parameters [74]. Additionally, due to the increase in surface area and strain in the matrix due to CNTs, electrical resistivity is expected to increase. Sol–gel technique-based coating matrices containing Al_2O_3 nanoparticles improve abrasion resistance, and due to the size of the nano-based filler particles, the coating has a high level of transparency. Aluminum oxide-based nanoparticles can also provide anti-glare and anti-smudge mirrors due to their hydrophobic properties [75].

Nanomaterials such as carbon black have been widely used as filler material in automotive tires. However, current research shows the potential to reduce overall rolling resistance, improve tire life and wet surface friction while lowering weight. In addition, the implementation of nanomaterials within an automotive chassis can improve fire resistance properties for interior sections and weather resistance for exterior sections.

Nanotechnology uses two main conceptual approaches, namely the ‘bottom-up’ and ‘top-down’ approaches. In the former, individual atoms are arranged to minimize the haphazardness of the structure, while in the latter, nanomaterials are built for larger units without regulation at the atomic level [76]. The properties of nanomaterials can be modified due to their increased relative surface area and quantum effects. Therefore, depending on the diameter of said nanomaterial, its electrical and thermal conductivity can be increased while also improving its mechanical properties. Table 6 highlights the suitability of these materials within automotive body panels.

Using high-pressure nanojet arrays for aerosol formation-based processes often seen in ICEs, losses due to surface tension can be minimized. H2 Fuel Cells have gas distribution layers for hydrogen and oxygen on either side of the Proton Exchange Membrane (PEM)/electrode requires a large surface area. The conventional PEM used in fuel cells can be improved when replaced by nanocomposites containing improved conductivity, permeability, and water management. Materials with irregular nanopores embedded in them that can achieve up to 80% porosity show great potential for this application.

4 Conclusions

Nanomaterials are proven to be a reliable material for automotive applications in the future; many researchers proved this through their work. The same is reviewed in this article; nanomaterials can improve the physical and chemical properties of automotive body panels by reducing the weight of vehicles while retaining the same strengthening power and durability provided by conventional materials. This results in less fuel usage, ultimately reducing NOx emissions and making future vehicles more eco-friendly. Furthermore, the vehicle body can be safeguarded from environmental effects by using water replant surface coats that give the vehicles a smooth lustre and protection from surface contaminants. However, it affects and improves the vehicle’s aerodynamic performance; components that are more reliable and lighter could increase the efficiency of electric vehicles. Many aspects have been covered in the latter subsections, where nanotechnology, explicitly speaking, nanocomposites, has a striking impact on the automotive body panel. About the review, we have observed improvement in functionalities for manufacturing nano-based body panels. However, several applications remain unexplored to the depth, like nanocomposites-based tires, automotive power systems like gas separation membranes in fuel cells, potential use in automotive ergonomics, and adhesive for composite body parts. For example, an adhesive avoids damage by forming a rust inhibitor coating over lubed materials [77]. However, some aspects of it prove to be disadvantageous to the environmental impact of nanomaterials discussed in this review. Nanotechnologies may also be used in vehicle security for identification and action.

Table 5 Nano-based surface coating enhancements

Coating material	Application	Failure	Nanoadditive Enhancement	Refs.
Chromium (IV)	Coatings for high anti-corrosion applications due to self-healing capability of chromium nanoparticles	Highly toxic behavior	Self-healing by nanopassivation technique via three-layer system containing Silicon dioxide (SiO_2) nanoparticles with intermediate layers of Cr (III) and Zinc (Zn)	
Chromium (III)	Similar to that of Chromium (IV) but with lower toxicity levels	Low efficiency		
Titanium (Ti) -Esters With Aluminum (Al) Flakes	Temperature resistant coatings that maximize thermal resistance to 800 °C	Temperature resistance up to 400–800 °C	Nanosized Magnesium (Mg) -Aluminum (Al) layered double hydroxides (LDH)	
Melamine and ammonium-polyphosphate	Conventional flame-retardant coatings	Can easily detach from the substrate due to loss of flame retardancy caused by reduction in char formation	SiO2 additive in the coating provides resistance up to a temperature of 1000 °C	

Table 6 Potential for usage in automotive body panels

Nano-composite	Application	Suitability for body panel	Refs.
Aluminum hybrid composites	Excellent properties are achieved when reinforcement is at nanoscale compared to single reinforced composites	Appropriate for the external body panel	[20]
Al-CNT composites	Al-CNT composite can overstate high-temperature deformation resistance of the composites	Appropriate for body regions prone to high temperatures	[20]
Silicon carbide	Suitable for clutch plates and brake disks due to improved thermal behavior		[20]
Si-Al composites	High modulus, toughness, stiffness, wear, abrasion, and corrosion resistance. Well suited for automotive driveshafts	Suitable for front and rear bulkhead	[20]
Graphene	Light and more robust (200 times stronger than steel carbon fiber, steel, and aluminum component) Groundbreaking interior components that can self-clean and thermally conductive fibers which Provide high-class car interiors. Graphene can also be used for making energy efficient batteries which can improve or replace lithium-ion batteries	Casing for battery packs in electric vehicles Appropriate for Aero-package The attractive interior of the automotive body	[20]

They can also support the textile industry by increasing productivity while reducing the use of toxic synthetics. Carbon nanofibers for improved strength properties, chemical inertness, and electron mobility are among nanostructures used in textile implementation [78]. There is an enormous domain of nanomaterials/nanotechnology waiting to be explored. This is a newly emerging field and maybe the game-changing point in the study, research, manufacturing of automobiles. It is predicted that using nano-based body panels will revolutionize the automotive industry in upcoming times [79]. The manufacturing and synthesis procedures can also be optimized to decrease the amount of pollution or waste [80–83].

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