

Nanotechnology-Enabled Innovations in High-Strength Lightweight Vehicle Design for Enhanced Safety and Energy Efficiency

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Abstract. Global warming and resource depletion are two of the most pressing issues confronting modern society, with the automotive industry being a significant contributor to energy consumption and environmental impact. Additionally, rising fatalities from traffic accidents have highlighted the need for improved vehicle safety. This paper explores the transformative role of nanotechnology in developing high-strength, lightweight materials that enhance both vehicle safety and fuel efficiency. By incorporating nanocomposites, known for their low density, superior strength, heat resistance, and scratch resilience, vehicles can achieve significant weight reductions without compromising performance. These advancements reduce vehicle failure rates, increase passenger survival in accidents, and contribute to energy savings, whether in electric or internal combustion engine vehicles. The paper also discusses the potential of lightweight vehicles in reducing fuel consumption and carbon emissions, making them key players in combating climate change and addressing resource shortages. Through a comprehensive analysis of nanotechnology's impact on material science, this study highlights its critical role in shaping the future of sustainable vehicle design.

Keywords: Nanotechnology, lightweight vehicle, high strength, energy efficiency.

1. Introduction

With the rapid development of different kinds of vehicles, different kinds of problems with vehicles are becoming more common. According to the World Health Organization, there were approximately 1.19 million people who died in road traffic accidents in 2021 [1]. An increasing number of people have begun to pay more attention to the security of vehicles. A high-strength vehicle can protect people from accidents. Therefore, people have started to pursue high-strength vehicles to increase security.

Moreover, global warming and fossil depletion are famous problems that conventional internal combustion engine vehicles face nowadays. For electric vehicles (EVs), short endurance mileage is a main issue. Lightweight vehicles can not only reduce the fuel consumption of internal combustion engines but also increase the endurance mileage of EVs, so it is necessary to produce lightweight vehicles. However, high-strength and lightweight vehicles are difficult to invent because of the limitations of materials. Some materials, such as irons, have relatively high strength but large weight. Some materials, such as wood, are relatively light but low-strength.

Nowadays, people have already created alloys and high-strength steel which have high strength and light weight, such as magnesium alloy. However, alloy and high-strength steel have many drawbacks. For example, some high-strength steels contain plenty of carbon [2]. Lots of carbon makes high-strength steel difficult to weld. Recently, nanotechnology has developed rapidly. Nanotechnology can change the properties of materials, so nanotechnology provides more materials that have high strength and light weight. The presence of nanotechnology provides the possibility for people to pursue better vehicles. Therefore, nanotechnology plays an important role not only in making high-strength and lightweight vehicles but also in further solving hot issues of the world.

This article aims to explain the principle of nanotechnology in making new materials and the role of nanotechnology in making high-strength and lightweight vehicles. The author will highlight the properties of alloys and high-strength steel to compare with nanocomposites in different aspects such

as toughness, heat resistance and scratch resistance to show the advantages of nanotechnology in making high-strength and lightweight vehicles.

2. The Principle of Nanotechnology for Making New Materials

Nanotechnology is a technology that changes the arrangement of very small particles at the nanoscale to create new large-scale materials [3]. The essential principle of nanotechnology is the size of particles because, at the nanoscale, the properties of materials will change enormously [3]. Therefore, scientists can control the arrangement and constituent of nanoparticles to get the properties they want. For example, the power of solar cells on the top of the cars can be improved by adding Ge nano-dots in Si semiconductor composite, and different materials can combine to bring out their best in each other [4]. According to the explanation and example above, it is easy to realize that nanotechnology provides a new way to create new materials with the properties that people want, and nanotechnology will play an important role in making high-strength and lightweight vehicles.

3. Nanotechnology in Decreasing the Weight of Vehicles

In order to reduce the weight of a vehicle, making a light frame is very important. The frame is the heaviest part in a vehicle so a light frame can greatly reduce the weight of the vehicle. The material of the frame is the key point. People want to find a material which has both light weight and great strength for making frames. Nowadays, People have already created many alloys, such as aluminum alloy, to reduce the weight of vehicles.

3.1. Aluminum Alloy

Aluminum alloy is an alloy that people make with aluminum plus other elements. One of the features of aluminum is that it has low density. The density of aluminum alloy is one-third of the density of mild steel [5]. If mild steel is replaced by aluminum alloy to make bodywork, the mass of the whole vehicle will decline by 10%. Therefore, aluminum alloy is a great material to reduce weight. However, the lightweight effect and ductility of aluminum alloy are far weaker than that of nanocomposites.

3.2. Carbon Fiber

Nowadays, many supercar manufacturers prefer to use large amounts of carbon fiber on their cars to reduce their weight. Carbon fiber is also popular for making EVs. For example, a lot of carbon fiber is used to make the frame of the electric car BMW i3 [6]. BWM named a new material carbon fiber reinforced Plastic (CFRP), which is very light but expensive. Although CFRP is very expensive, its weight reduction effect on vehicles is remarkable. The frame that CFRP makes is half the weight of steel and seven-tenths the weight of aluminum. Table 1 shows the comparison of weight between steel and CFRP [6].

Table 1. The weight reduction effect in car roofs by replacing CPRP with steel

Description	Weight
Steel roof	11.2 kg
Composite roof (CFRP)	5 to 5.5 kg
Weight reduction	6 to 6.6 kg

According to the data and research above, it is easy to conclude that carbon fiber can dramatically reduce the weight of EVs. Because of the reduction in weight, EVs will consume less energy per kilometer, which will increase the endurance mileage further.

3.3. Nanocomposites

For manufacturing cars, especially EVs, people have always wanted to pursue stronger and lighter materials, so nanocomposite is the most suitable material. These materials are usually made by adding nanoparticles to the original composite materials to make them have superior physical and chemical properties.

An important role of nanocomposites is that they have low density, which means that the EVs that are made of nanocomposites are lighter than the EVs made of conventional materials. As mentioned before, short endurance mileage is the most important problem faced by electric EVs. One effective solution is to increase the specific energy of the batteries, but it is not easy to achieve. Therefore, reducing the weight of EVs while maintaining strength is a useful way to extend their endurance mileage. Nanocomposites are the most suitable materials which have both high strength and light weight. For example, silicate nanoparticles are added to the polymer materials to make polymer matrix nanocomposites (PMNCS) [7]. PMNCS has very low density, so it is lightweight. At the same time, it has excellent physical and chemical properties, such as high mechanical properties and improved corrosion resistance. Therefore, nanocomposites like PMNCS become popular materials for electric vehicle manufacturing.

4. Nanotechnology in Increasing the Strength of Vehicles

For internal combustion engine vehicles, people never stop trying to get faster. As the speed increases, the strength of vehicles becomes more and more important. For EVs, the safety of some essential parts is also important, especially for batteries. Therefore, it is necessary to create materials that have high strength and reliability to increase the safety of vehicles.

4.1. High-Strength Steel

High-strength steel has high strength and good energy absorption. Therefore, it is widely used in automotive structural parts, safety parts and reinforcement parts [8]. However, high-strength steel has some disadvantages. One of the noticeable disadvantages of high-strength steel is low elongation. Low elongation might cause it is likely to break in production or accidents, which decreases the safety of the vehicle.

4.2. Carbon Fiber

In accidents, a material with great crashworthiness can guarantee the safety of passengers to a great extent [6]. Specific energy absorption (SEA) reflects the crashworthiness of a material. Compared to other composites, chopped carbon fiber (CCF) composite has the highest SEA. According to the comparison above, it is easy to find that carbon fiber composite has a high strength to increase the safety of passengers in accidents. However, carbon fiber also faces some drawbacks, such as poor wear resistance and high maintenance cost, which needs better materials to solve.

4.3. Nanocomposites

4.3.1. Nanoparticles increase the strength of the material

One of the significant roles of nanocomposites is that using nanocomposites to make EVs can increase the strength of their frame. For example, the inter-laminar fracture toughness of a material can be increased by using the combined effect of nano and micro-scale fiber reinforcement [9]. Fig. 1 shows the inter-laminar toughness of materials with different reinforcement types [9]. According to Fig. 1, it is easy to conclude that whatever the types of reinforcement, there is a significant improvement in the inter-laminar toughness of nanocomposites compared to that of the control group. This means that the strength of the materials is significantly improved by adding nano and microfibers to make nanocomposites.

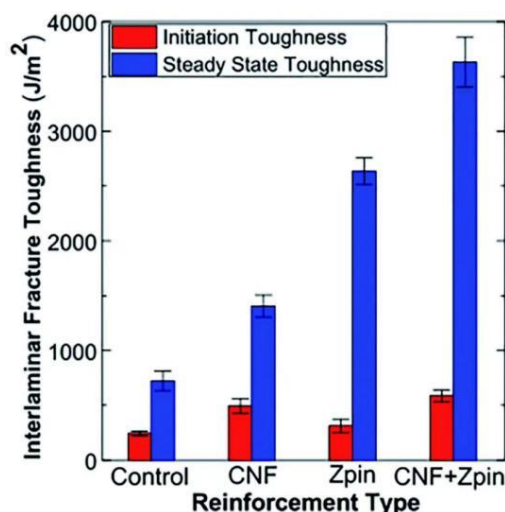


Figure 1. Comparison of inter-laminar fracture toughness against various combinations of composite reinforcements [9].

4.3.2. Thermal management with nanoparticles

Safety and reliability are also major aspects that people focus on. For EVs, the safety of batteries is very significant. During the discharge of the battery, releasing heat energy is inevitable. For internal combustion engine vehicles, the reliability of the internal combustion engine is also important. When internal combustion is operating, the temperature in it is extremely high. Therefore, it is necessary to create a material that has high-temperature resistance and great thermal stability. Nowadays, people have made many high-temperature-resistant polymers. However, these materials might change their shape or mechanical properties under high temperatures.

Nanoparticles usually have special properties because of their high surface area-volume ratio, so it is possible to improve the thermal conductivity of materials by adding nanoparticles. For example, the thermal conductivity of Phase Change Material (PCM) is enhanced by adding Cu, MWCT or CuO nanoparticles [10]. Table 2 shows the different properties of Phase Change materials, which are enhanced by different nanoparticles [10]. According to Table 2, it is clear to conclude that as the concentration of nanoparticles increases, the heat transfer coefficient increases, whatever the type of nanoparticles. A material with excellent thermal conductivity can transfer the thermal energy released by the battery quickly to avoid battery overheating and fire. Therefore, nanoparticles increase the thermal conductivity of materials, which can increase the safety of the battery of EVs. Some materials have high thermal stability initially. However, in order to make these materials maintain their thermal stability for a long time, nanoparticles are added into them to make them have a stronger ability to thermal energy transfer. For example, thermal interface materials (TIM) matrix components are polymers that have strong thermal stability [11]. According to the addition of nanoparticles, thermal energy is released through the thermally conductive pathways that are formed by nanoparticles [11]. Therefore, the thermal stability of TIM increases because of the increase in its thermal conductivity, which can guarantee a longer life for the parts of internal combustion engines. Taking all the factors into account, it is reasonable to conclude that nanoparticles are effective in improving the ability of thermal management, especially for batteries and internal combustion engines. Therefore, the strength and reliability of the vehicles are improved because the use of nanoparticles increases the strength of the essential parts of vehicles.

Table 2. Properties of nano-enhanced PCM (nePCM) [10].

Nanoparticle	Concentration	Density (kg/m ³)	Specific heat [J/(kg·K)]	Heat transfer coefficient [W/(m ² K)]	Viscosity [kg/(m·s)]
Cu	0.02	967.7	2009.05	0.22116	6.365 x 10 ⁻³
	0.04	1130.4	1745.61	0.2389	10.05 x 10 ⁻³
	0.06	1293.1	1548.45	0.258	15.87x10 ⁻³
MWCT	0.02	820.9	2317.29	0.2277	6.365 x 10 ⁻³
	0.04	836.8	2257.9	0.2488	10.05 x10 ⁻³
	0.06	852.7	2200.78	0.26407	15.87x10 ⁻³
CuO	0.02	915.2	2124.435	0.2163	6.365 x 10 ⁻³
	0.04	1025.4	1923.755	0.2341	10.05 x10 ⁻³
	0.06	1135.6	1762.40331	0.25343	15.87x10 ⁻³

4.3.3. Nanocoating

Nanocoating is an advanced material handling technology. The various properties of the material are improved by adding a nanometer-thickness coating to the surface of the material. Nanocoating is usually made by nanoparticles which have excellent physical and chemical properties. The most noticeable advantage of nanocoating is that it can improve the material's resistance to chips and scratches. Fig. 2 is the comparison between the surface appearance with nanocoating and that without nanocoating after dry abrasion [12]. According to Fig. 2, it is simple to find that the surface with nanocoating has a greater appearance than that without nanocoating after dry abrasion. Therefore, people can add nanocoating to the surface of the frames to make them have greater strength. This can reduce the cost of repainting. Additionally, nanocoating is added to the surface of essential parts in vehicles to improve their strength and extend their life.

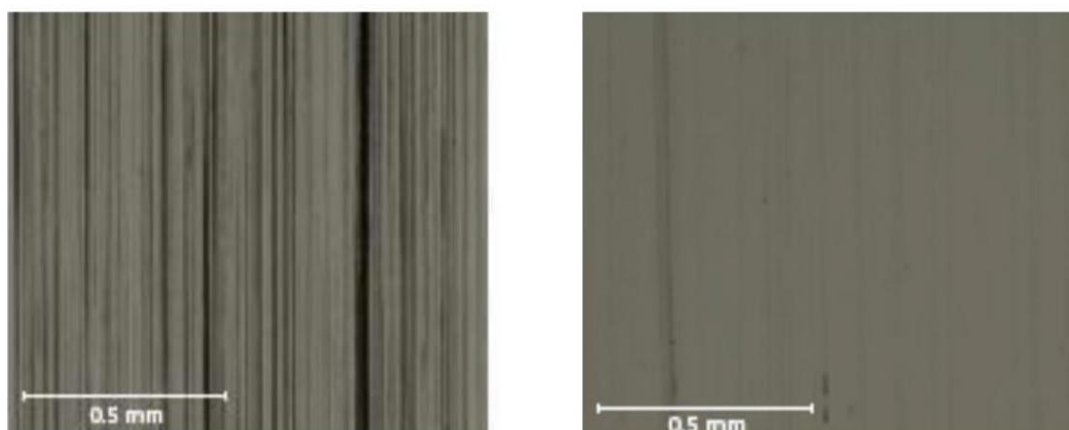


Figure 2. Surface appearance of an automotive refinishing clearcoat (2-pack acrylic/isocyanate) containing 2.2%/without nanoparticles after dry abrasion test [12].

5. Conclusion

This paper illustrates the huge demand for high-strength and lightweight materials in automobiles at present by analyzing the death toll from automobile accidents, global warming, and resource depletion. Nowadays, lots of people are killed in road traffic accidents. People tend to pursue vehicles with high security and high reliability. Moreover, as global warming and resource depletion become more serious, vehicles with low energy consumption are more popular. For both EVs and internal combustion engine vehicles, reducing the weight of vehicles is a good way to extend endurance mileage and save energy. However, some strong materials are too heavy which will increase the energy consumption if they are used on the vehicle. In opposite, some materials with light weight have low strength, which still cannot make people satisfied. Therefore, using nanotechnology to make the material with both high strength and light weight is very significant.

The research also provides the basic principle of nanotechnology changing the properties of materials, the role of nanotechnology in reducing the weight of vehicles and the different aspects of vehicles that nanotechnology can strengthen. Specifically, this paper demonstrates the properties of some materials that people already produced, such as aluminum alloy, high-strength steel and carbon fiber, and compares them with the advanced materials made by nanotechnology. Although these materials have relatively high strength and light weight, they still have some drawbacks, such as high cost and hard to make. Nanocomposites not only reduce the weight of vehicles but also improve the strength of materials. By adding nanoparticles, nanocomposites are able to have high toughness, excellent thermal conductivity and great thermal stability. Moreover, nanocoating plays an important role in improving scratch resistance to decline repair costs.

In the future, studies should further research how to reduce the costs of nanotechnology to make it pervasive and commercial. Additionally, the security of nanotechnology is very important. Future studies should further explore the effect of nanotechnology on people's health and environment, making nanotechnology environmentally friendly and harmless to people.

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