Research on Lightweight Design and Diversified Material Combinations for New Energy Vehicles

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Abstract. In the context of dual carbon goals and energy transition, new energy vehicles face challenges such as limited driving range and high energy consumption. Lightweight design is one of the technological measures that can be used to slow down carbon emission, expand the driving range, and improve the performance of the vehicle. The article concentrates on the study and use of lightweight technologies examining the practical application of various materials. It discusses the importance of the lightweight research, describes the major directions of technological development of materials and structures, discusses the most important multi-material technologies, and current challenges in the sphere. Battery components, frame materials, and other structures of the vehicle body are especially considered, and the exploration of the process innovations, the topological optimization, and the choice of materials is observed. The results of the performance tests through multiple simulations as well as practical application cases indicate that it is possible to achieve the aim of safety maintenance, enhancement of structural performance and maximum cost-efficiency. The discoveries reached in the framework of the study are intended to address the difficulty in the profound elaboration of the automobile lightweight technologies and provide the technological progress and modernization within industry.

1 Introduction

Driven by global energy transformation and the "Dual Carbon" goals, new energy vehicles have become the core focus of automotive industry transformation. However, range anxiety, bottlenecks in battery energy density, and vehicle energy consumption control remain critical pain points constraining large-scale adoption. Research indicates that for every 100kg reduction in curb weight of NEVs, driving range can be improved by approximately 10%-11%, while energy consumption and carbon emissions decrease synchronously. This core quantitative relationship can be precisely expressed through the following formulas:

$$\Delta R = R_0 \times (\Delta m/100) \times k \quad (1)$$

$$\Delta E = E_0 \times (\Delta m/100) \times \eta \quad (2)$$

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In which, ΔR is the driving range change (km), M-sm0 is the driving range (km), Δm is the reduction in weight of the vehicle, (kg), k is the coefficient of troop range improvement and has the values of 0.10- 0.11, ΔE is the fuel economy gain per 100km (kWh/100km), E-sm0 is the fuel economy with mass reduction (kWh/100km) and η is the coefficient of range improvement (energy consumption) and its value is 0.10-0.11.

Lightweight research primarily considers two directions: the first concerns a structural topology optimization design, with the objective of optimal material distribution, and the second concerns structural single-objective and multi-objective collaborative optimization design with the objective of optimal structural performance such as topology optimization, topography optimization, size optimization, layout optimization, single-objective optimization and multi-objective optimization. These technologies have been extensively used in businesses at present [1]. Thus, it can be concluded that lightweight design is not merely one of the fundamental strategies to enhance NEV energy efficiency but also an unavoidable option towards sustainable industrial development. Lightweighting of the vehicle is not merely a valuable step towards the realization of energy saving and emission minimization but also impacts on the performance of the vehicle in the manner of acceleration, braking and stability of the vehicle.

The value of lightweight technology depends on the strong relationship between vehicle energy consumption and car curb weight. The weight-saving reasoning of conventional fuel cars is not anymore quite able to conform to the structural properties of NEVs - novel parts like battery packs and electric drive systems have altered considerably vehicle mass distribution and load necessities, placing a greater strain on lightweight design to lightweight cars without deteriorating the performance. It is in this context that the performance shortcomings of individual materials are slowly emerging: ultra-high-strength steel has the potential to guarantee structural safety but its high density prevents easy deep reduction of weight; aluminum alloys have the potential of huge weight-reduction effects and yet the cost aspect of the process needs to be optimized; carbon fiber composite can make the two light in weight and high in performance but its cost impediment is still a barrier that has not been overcome so far.

The technological development of diversified material combination is a systematic way to resolve this quandary. Using multi-material hybrid design, it is possible to have the properties of materials closely aligned with the functional needs in various regions of the automobile body. Ultra-high-strength steel, as an illustration, may be applied in key safety systems like A/B pillars, aluminum alloys to body panels like hood and doors, carbon fiber composites to parts like battery pack upper shells, and so on, thus resulting in conducive optimization of what is known as safety, weight reduction and cost. Internal connection and structural integration technologies have also been developed in this trend. An example is built into die-casting that can dramatically decrease the quantity of components and connection points, further enhancing efficiency in lightweight:

$$\gamma = (N_0 - N_1) / N_0 \times 100\% \quad (3)$$

Where γ is the part quantity reduction rate (%), N_0 is the total number of parts in traditional processes, and N_1 is the total number of parts after integrated die-casting.

Currently, the NEV lightweighting field still faces numerous challenges: mechanical performance synergy of multi-material hybrid bodies, durability verification under complex working conditions, and the establishment of full lifecycle recycling systems urgently need breakthroughs. The integration foundation of artificial intelligence and lightweight structural design is weak; meanwhile, existing research pays insufficient attention to frame structures such as battery pack frames and subframes [2]. Their high structural redundancy and low material utilization defects constrain the deep exploration of vehicle lightweighting. The material utilization calculation formula is:

$$\eta_m = ({m_e}^{Otoo} / {m_t}^{m}{}_{tal}) \times 100\% \qquad (4)$$

Where η_m is the material utilization rate (%), ${m_e}^{Otoo}$ is the material mass in the core load-bearing area of the structure (kg), and ${m_t}^{\gamma}{}_{tal}$ is the total material mass of the structure (kg).

Based on this, this study takes diversified material combinations as the core, focusing on lightweight optimization of frame structures for NEVs, aiming to provide feasible paths for improving vehicle energy efficiency and driving range through the integration of material selection, topology optimization, and process innovation, contributing to the technological upgrading and sustainable development of the NEV industry.

2 Research content

2.1 Necessity and value of lightweight design for NEVs

2.1.1 Industry background under energy transformation and "dual carbon" goals

The automotive industry is moving towards new energy transformation due to the global goals of the dual carbon. One of the challenges to extensive adoption in large-scale industries is range panic and energy density bottlenecks in batteries. The lightweight technology has proven to be one of the main directions towards ensuring energy savings, emissions, and commercial needs, being an unavoidable solution to sustainable development of the NEV industry.

2.1.2 Impact mechanism of lightweight design on range, energy consumption, and carbon emissions

NEV curb weight and energy consumption show a strong coupling relationship. Experimental data shows that for every 100kg reduction in curb weight, driving range improves by 10%-11%, energy consumption decreases by 8%-10%, and carbon emissions are reduced synchronously. The energy consumption optimization effect is more significant in urban congested traffic conditions.

$$\Delta R = R_0 \times (\Delta m/100) \times k \ (k = 0.10\text{-}0.11) \qquad (5)$$

$$\Delta E = E_0 \times (\Delta m/100) \times \eta \ (\eta = 0.08\text{-}0.10) \qquad (6)$$

For example, through lightweight design, the Tesla Model 3 controls curb weight at approximately 1.6 tons. Its 60kWh version achieves a driving range of 445km, with energy consumption reduced by approximately 9kWh/100km compared to similar models without deep lightweighting [3].

2.1.3 Relationship between lightweight design and vehicle dynamics, braking, and handling stability

Lightweight design can improve power-to-weight ratio, optimizing vehicle acceleration performance; reduce braking inertia force, shortening braking distance; lower vehicle center of gravity, reducing steering roll torque, achieving comprehensive benefits of "weight reduction without performance compromise," comprehensively improving driving safety and handling experience. Through body lightweight optimization, the BYD Han EV achieves 0-100km/h acceleration in just 3.9 seconds, 100-0km/h braking distance controlled at 32.8 meters, and a turning radius of only 5.9 meters with agile handling response.

2.1.4 New requirements for lightweight design posed by nev structural characteristics

Elements like battery packs and electric drive systems are new and have altered the mass distribution and loads requirement of the vehicles. The lightweight design should be able to fulfill the multi-dimensional indicators such as structural strength, safety, and NVH at the same time and challenge the classical logic of the lightweight vehicle of fuel car, and create new specifications of precise weight reduction and matching necessity. Indicatively, the NIO ET5 battery pack measures more than 500kg which is 35 percent of vehicle weight. Its lightweight should strike a balance in the weight distribution of the vehicle as well as battery performance protection.

2.2 Core technical approaches for nev lightweighting

2.2.1 Structural optimization design technology

Topology Optimization: Computer simulation is used to attain optimum distribution of materials and also to remove redundant structures. The BMW iX chassis subframe, to use one example, was optimized in its topology, eliminating the material of non-load-bearing parts, reducing the weight of the subframe by 12 percent and increasing its torsional stiffness by 18 percent.

Multi-dimensional Optimization: A collaborative system is comprised of Topography optimization (adding reinforcement ribs), size optimization (changing cross-section parameters), and layout optimization (optimizing component spatial positioning).

Single/Multi-objective Optimization: Single-objective deals with the goals of "extreme weight reduction" or the goals of the lowest cost [4], whereas multi-objective works with weight reduction, strength, and cost generally in unison. One of the automakers set ultimate targets of 15-percent weight loss and 20-percent increase in torsional stiffness on sedan design. Multi-objective optimization design is performed on the XPeng P7 with a body torsional stiffness of 40, 000 N • m/deg and lowering of its weight by 130kg than several other similar models [5]. The correlation between decrease in torsional stiffness and weight reduction is able to be formulated as:

$$\Delta K = K_0 \times \alpha \times (\Delta m/m_0) \qquad (7)$$

Where ΔK is the torsional stiffness improvement value (N·m/deg), K0 is the baseline torsional stiffness before lightweighting (N·m/deg), α is the stiffness improvement coefficient (determined by material combination and optimization process, with values of 1.2-4.0), and $\Delta m/m_0$ is the vehicle weight reduction rate (%).

2.2.2 Diversified material combination technology

Comparison of Mainstream Materials: Udimet (strength 1500MPa, density 7.85g/cm 3) and aluminum alloy (density 2.7g/cm 3, costs 3-4 times steel) and carbon fiber composites (density 1.5-1.8g/cm 3, high prices) meet their own merits and demerits.

Zonal Matching Principle: A/B pillars of safety structures must be made of ultra-high-strength steel, hoods of body panels of aluminum alloys, and battery pack upper shells of carbon fiber composites, and it is exactly what these objects need.

Characteristic Solution Advantages: A particular new energy SUV uses a hybrid body of steel, aluminum + carbon fiber, it will be reduced by 30% weight, its scope will be expanded by 25 percent and its torsional rigidity will be improved by 40 percent, without adding too much money to it. The NIO ET7 body utilizes a 7000-series aluminum alloy + carbon fiber composite structure, where 91 percent comprises of aluminum alloy, and 150kg weight reduction on the vehicle and body torsional stiffness of 52, 000 N m /deg are achieved by applying carbon fiber in the roof and rear floor areas. The overall cost change of multi-material bodies is as;

$$C_1 = C_0 \times (1 + \beta) - C_{sa}{}^{\gamma e}{}_{lao} \qquad (8)$$

Where C_1 is the manufacturing cost of the multi-material body (yuan), C_0 is the manufacturing cost of the single-material body (yuan), β is the material upgrade cost increase coefficient (in this case $\beta \approx 0.12$), and $C_{sa}{}^{\gamma e}{}_{lao}$ is the cost savings from process optimization (integrated die-casting/reduced connection points) (yuan).

2.3 Key supporting technologies for diversified material combinations

2.3.1 Multi-material connection technology

Steel-aluminum connection embraces self-piercing riveting (SPR) technology with connecting strengths exceeding more than 85 percent of conventional welding; aluminum-carbon fiber connection is embracing structural adhesive bonding to avoid material damaging; steel-steel connection and aluminum-aluminum connection are adopting laser welding and friction stir welding as a more effective and reliable connection. The Tesla Model Y steel-aluminum hybrid body uses both SPR riveting and laser welding combining about 4,000 riveting points and 150 meters of laser weld with a connection strength increased 30 times compared to the conventional process and 50 times higher productivity.

The process of structural integration undergoes innovation.

Die-casting process is an integrated process in which several parts are incorporated. The Tesla Model Y eliminates 15-20 percent of weight and a 30 percent manufacturing cost reduction by refining the rear floor 70+ parts to 1, which is expected to cut the connection points by more than 500 [6]. The XPeng G6 is built on 8,000 ton integrated die-casting apparatus to produce integrated front compartment and rear floor framework which cut down on part number by almost 60 percent and enhanced the torsional toughness of the bodies by about 20 percent. The overall formula of calculating the rate of part reduction is:

$$\gamma = (N_0 - N_1) / N_0 \times 100\% \qquad (9)$$

3D printing and hydroforming expand the design and process space for multi-material combinations. Some aluminum alloy brackets in the BMW iX adopt 3D printing processes, achieving integrated forming of complex structures with 25% weight reduction.

2.3.2 Mechanical performance collaborative design

Based on finite element analysis, stress distribution under working conditions such as collisions and bumps is simulated to optimize material zoning and connection methods, avoiding local stress concentration and ensuring collaborative matching of mechanical performance in multi-material structures. The Li Auto L9 uses ANSYS finite element simulation software to conduct collision simulation and stress analysis on body multi-material structures, optimizing connection positions between ultra-high-strength steel and aluminum alloy, achieving full G ratings in C-IASI crash tests while reducing vehicle weight by 120kg.

2.4 Challenges facing NEV lightweighting

2.4.1 Durability and working condition adaptation challenges

The vast variations in the thermal expansion factor and corrosions between multi-materials may result in parallel fatigue cracking in the connection links; the verification conditions of complex working conditions and extreme environments are still incomplete with long testing periods and expensive procedure. As an example, some NEV models, which have steel-aluminum connection points, became slightly corroded and loosened after using it 3 years and using it by a distance of 100,000 kilometers, thus it needed to be enhanced by means of coating and the optimization of connection structure.

2.4.2 Recycling system bottlenecks.

The recycling of aluminum alloy requires optimisation of energy consumption and control of purity; carbon-fibre composite recycling technology is underdeveloped, dismantling and separation is inefficient multi-material components and has an impact on industrial ecological value. Today, the recycling rate of NEVs made of aluminum alloy in China has reached about 85% and that of carbon fiber composite is less than 30%, and relies essentially on crushing the material with lost material performance of more than 50% and recycling rate; the required energy input of the recycling technology is about 5 per cent of primary aluminum making, which can be optimized.

2.4.3 AI Integration barriers

The lightweight design fulfilling conditions are not simple because AI algorithms have a hard time creating accurate multi-objective optimization models, and they lack synergy with simulators and cannot be more efficient in design. The accuracy of the model of the existing AI design tools is about 75 percent when dealing with multi-dimensional parameters, including material properties and process limitations, which cannot easily be performed to high standards of the design-simulation-iteration, and even the collaborative interfaces with the simulation software like the ABAQUS are not complete.

2.4.4 Frame structure design concerns.

The fundamental elements, including battery pack frames and subframes, are structurally redundant and poorly used in terms of materials. Available literature does not focus on this enough, which limits in-depth reduction of vehicle weight. The usage of traditional battery pack frame material is about 65% and subframes about 70 per cent which is 15 per cent or 20 per cent less than other body parts. The calculation formula of the material utilization is:

$$\eta_m = (m_e{}^{Otoo} / m_t{}^{\gamma}{}_{tal}) \times 100\% \qquad (10)$$

2.5 Specialized research on lightweight optimization of frame structures

2.5.1 Lightweight requirements analysis

Battery pack frames carry 30-40 badly percentage weight of the vehicles and must balance between impact resistance and heat dissipation functionality; subframes are subject to dynamic loads which determine handling and energy usage. Urban commuter concepts concentrate on, "weight reduction to achieve efficiency, and the high-performance concepts must balance between lightweighting and structural stability and weighing the costs. As an example, BYD Dolphin battery pack frame has only 28% of the weight of the vehicle, where the lightweight optimization has provided around 50km of battery range, the Porsche Taycan subframe must sustain the dynamic load of the 460kW motor, and lightweight design must be able to maintain stiffness and durability, and at the same time reduce the weight.

2.5.2 Multi-material topology optimization solution

Zonal Material Selection Battery pack core load-bearing beams are made of, 3, 4,5LUHS steel + carbon fiber, subframe bodies are made of 6082 aluminum alloy and the non-load-bearing parts are made of engineering plastics + aluminum alloy.

Topology Optimization: Stress distribution is determined by means of finite element simulation. The areas of high stress are made with material performance and redundant areas cut or substituted by lightweight materials [7]. The battery pack frame of CATL was optimized in terms of its topology, combined with multi-materials, with Q&P980 ultra-high-strength steel as the core load-bearing beams and carbon fiber composites as the auxiliary supports: the battery pack frame of CATL lost its weight by 42 per cent compared to conventional all-steel frames and the material use decreased by 65 to 88 per cent.

$$\theta = (m_{ste}{}^{o}{}_{l} - m^{com}{}_{posite}) / m_{ste}{}^{o}{}_{l} \times 100\% \qquad (11)$$

Where: Theta is the rate of weight reduction of the battery pack frame (in percent), m n 0 e, and mmc 0 e 0 0 ml is the conventional all-steel battery pack frame mass (kg), and mmc 0 0 0 ml is the frame mass of the multi-material (ultra-high-strength steel + carbon fiber) (kg).

The value of NIO subframe is 6082 aluminum alloy body with magnesium alloy bracket combination. Following a topology optimization, the weight decreases by 35% and the torsional stiffness increases by 22%.

2.5.3 Process innovation and performance check-up

Process Improvement: Battery pack frames are to be designed as "integrated die-casting + modular assembly, carbon fiber components are to be designed as pultrusion + vacuum infusion, subframes are to be designed as "hydroforming + laser welding. The battery pack frame of CATL has used a 2, 000-ton integrated die-casting machine to create the frame, which has a reduction on the number of parts by 70 percent and connection point by 80 percent; the battery pack upper shell of Tesla uses a carbon fiber pultrusion process that has resulted in increased 40 percent of production with a fiber orientation similar to the load direction, which leads to an increased load-bearing efficiency of 30 percent [8].

Performance Check: The reliability of the solution will be checked by tensile/bending (static), 100, 000 km bench/vehicle (dynamic), crash (safety), and high-low temperature/salt spray (durability) tests. Optimized battery pack frames are deformed at 100mm influence load less than 100kN, correspond to IP 68 rating; subframes exhibit fatigue damage coefficient less than 0.8, and connection instances are not loosened or corroded during 100, 000km bench testing. The formula of the fatigue damage assessment is:

$$D = \Sigma(n_i/N_i) \leq 0.8 \tag{12}$$

Where D is the total fatigue damage coefficient, n_i is the actual cycle count under working condition i, and N_i is the fatigue limit cycle count under working condition i.

3 Conclusion

In this paper an analysis of the new technologies is done by examining lightweight materials in details. According to research and literature exploration, lightweight vehicle structure can serve to mitigate the short range, decrease the production of carbon dioxide and to improve performances of the vehicles while not sacrificing protection. New plans by using high-strength steel, aluminum, and carbon fiber composite enhance safety, financial performance, and ease of managing. Research has indicated that multi-material body structure can save a lot of weight, increase the driving range by a large margin and improve the torsional rigidity. The main technologies are the intelligent joining process, design based on finite element analysis, development of integrated die casting and structural integrity and high performance compatibility. Intelligent processes are significant in reducing the weight of vehicle battery packs, and topology optimization helps to enhance the recyclability of materials. Nevertheless, there are obstacles that need more research, such as durability, recycle of lifecycle, and artificial intelligence, among others.

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