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Material Selection for Lightweight Electric Vehicle Battery Pack Enclosures

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Abstract

Electric vehicles (EVs) are becoming increasingly common, creating a growing demand for battery packs that are efficient, safe, and lightweight. The battery system accounts for a significant portion of a vehicle's total weight; therefore, the material selected for the battery enclosure directly influences driving range, energy efficiency, crashworthiness, and thermal safety. This paper reviews lightweight materials, battery pack architectures, thermal management strategies, and sustainability aspects associated with EV battery enclosures. It discusses conventional metals such as advanced high-strength steels, aluminum, and magnesium, as well as advanced polymer composites, including carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), sheet molding compound (SMC), and hybrid material systems. The paper also examines emerging thermal management approaches, including phase change materials (PCMs) and fire-resistant polymer composites designed to mitigate thermal runaway. Furthermore, recent battery architectures, such as Cell-to-Pack (CTP) and Cell-to-Body (CTB), are reviewed with respect to their manufacturability and serviceability. Finally, the environmental impacts of various structural materials are compared from a life-cycle perspective to support sustainable material selection for future EV battery systems. This review provides a comprehensive overview of material selection strategies for next-generation electric vehicle battery pack enclosures, with an emphasis on lightweight design, thermal safety, and sustainability.

Keywords: Electric Vehicles; Battery Pack Enclosure; Lightweight Materials; Material Selection; Thermal Management; Carbon Fiber Reinforced Polymer (CFRP); Cell-to-Pack (CTP); Sustainability.

1. Introduction

The car industry worldwide is changing rapidly because of the urgent need to reduce greenhouse gas emissions, environmental pollution, and dependence on fossil fuels. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) have emerged as promising solutions for sustainable transportation because they use energy efficiently, produce fewer emissions, and integrate well with renewable energy systems [1-3]. The increasing adoption of EVs has been driven by advancements in battery technology, supportive government policies, and growing environmental awareness. As a result, developing battery systems that are efficient, lightweight, and safe has become a major focus for automotive manufacturers.

Battery packs are the primary energy storage systems in EVs, and they directly affect vehicle performance, driving range, charging capability, safety, and cost. Lithium-ion batteries are widely used in modern EVs because they offer high energy density, long cycle life, and superior electrochemical performance compared with conventional battery technologies [1-4]. However, battery packs are also one of the heaviest components of an EV, accounting for approximately 25-40% of the vehicle's total weight. This additional weight negatively affects acceleration, handling, energy consumption, and overall vehicle performance. Therefore, designing lightweight battery packs has become one of the most important research areas for improving vehicle efficiency and extending driving range.

The battery pack enclosure does much more than simply house the battery cells. It provides structural support and mechanical protection against vibrations, impacts, and crashes. It also helps maintain thermal stability, provides electrical insulation, shields against electromagnetic interference (EMI), and protects the battery system from moisture and dust. In addition, the enclosure must be capable of containing thermal runaway events and preventing fire propagation between adjacent battery cells. Therefore, materials used for battery pack enclosures should possess high strength, low weight, excellent crashworthiness, good thermal conductivity, fire resistance, corrosion resistance, electrical insulation, and high fatigue durability [1-9].

Designing EV battery packs and selecting suitable materials present several engineering challenges. Excessive battery weight remains a major factor affecting vehicle range and performance. In addition, lithium-ion batteries generate considerable heat during charging and discharging because of electrochemical reactions and internal resistance. If this heat is not dissipated effectively, it can lead to localized overheating, uneven temperature distribution, battery degradation, reduced service life, and thermal runaway, potentially resulting in fire or explosion. Therefore, maintaining the battery temperature within an optimal operating range of approximately 20-40 °C is essential for ensuring safety, efficiency, and long-term battery reliability [2-5].

Battery Thermal Management Systems (BTMSs) have become vital components of modern EV battery packs. Researchers have extensively investigated various cooling techniques, including air cooling, liquid cooling, heat pipes, refrigerant cooling, and Phase Change Material (PCM)-based systems [2-5]. Among these methods, PCM-based systems have attracted significant attention because they provide passive cooling and possess high latent heat storage capacity. During the phase change process, PCMs absorb a large amount of heat while maintaining a nearly constant temperature.

Material selection plays a vital role in addressing the structural and thermal challenges associated with lightweight EV battery systems. Traditional steel enclosures offer excellent structural strength and low manufacturing cost; however, their high density significantly increases vehicle weight. Aluminum alloys have become widely adopted because of their excellent strength-to-weight ratio, corrosion resistance, thermal conductivity, and recyclability. In addition, advanced lightweight materials such as Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP), hybrid composites, graphene-enhanced nanocomposites, and aluminum foam structures are increasingly being explored for battery enclosure applications. Recent studies have also emphasized integrated material selection strategies that balance structural performance, thermal management, manufacturability, sustainability, and long-term engineering priorities for next-generation EV battery systems [5-9,16].

Recent advancements in EV battery technology have introduced innovative concepts such as Cell-to-Pack (CTP) designs and structural battery packs. Tesla's structural battery pack integrates battery cells directly into the vehicle chassis, reducing redundant structural components while significantly improving vehicle stiffness and energy efficiency [10]. This paper provides a systematic review of material selection strategies for lightweight EV battery pack enclosures by examining recent developments in materials, battery architectures, thermal management, and sustainability [1-16].

2. Literature Review

A considerable amount of research has been conducted on the design of electric vehicle (EV) battery pack enclosures and the selection of suitable materials in recent years. Researchers have focused on achieving an optimal balance between lightweight design, structural strength, crashworthiness, thermal management, manufacturability, and cost. Since battery packs account for nearly 25-40% of an EV's total weight, reducing the weight of the battery enclosure while maintaining structural integrity and thermal stability has become a key objective in modern EV development [1-5].

Dhoke and Dalavi [1] presented a critical review on the lightweight design of battery pack enclosures for electric vehicles. They reported that inadequate enclosure design may lead to structural cracking, excessive vibration, noise, and battery damage. Their review analyzed various lightweight materials, including advanced high-strength steel, aluminum alloys, magnesium alloys, Carbon Fiber Reinforced Polymer (CFRP), and hybrid structures. The study reported weight reductions of approximately 42% by replacing aluminum structures with composite materials and up to 48.86% in optimized CFRP-aluminum hybrid battery enclosure designs.

Durgam *et al.* [2] published a comprehensive review on material selection for hybrid and electric vehicle battery pack thermal management. Their study focused on materials and cooling techniques used in battery thermal management systems and concluded that Phase Change Material (PCM)-based thermal management systems provide effective passive cooling, improve temperature uniformity, and significantly reduce the risk of thermal runaway.

Wazeer *et al.* [3] reviewed the application of Phase Change Materials (PCMs) for battery thermal management in electric and hybrid vehicles. They discussed several approaches for enhancing the thermal conductivity of PCMs, including the incorporation of metal foams, expanded graphite, graphene nanoparticles, and carbon nanotubes. Their findings indicated that nanoparticle-enhanced PCMs significantly improve heat dissipation and thermal stability in lithium-ion battery packs.

Azzopardi *et al.* [5] reviewed recent advances in battery pack polymer composites and discussed the increasing use of polymer composite materials in EV battery enclosures. The authors reported that composite battery structures can achieve weight reductions exceeding 50% compared with conventional metallic enclosures. The review also highlighted advanced manufacturing techniques such as Resin Transfer Molding (RTM), compression molding, and hybrid sandwich composite structures.

Recent studies have further emphasized that effective material selection should not be based solely on weight reduction but should also consider structural performance, thermal safety, manufacturability, sustainability, and long-term engineering priorities for next-generation EV battery systems [5,16].

Recent research has also focused on advanced optimization techniques for battery pack design. Multi-Objective Genetic Algorithm (MOGA), Non-dominated Sorting Genetic Algorithm II (NSGA-II), topology optimization, and surrogate modelling have been widely applied to optimize battery enclosure structures. These approaches have consistently achieved weight reductions ranging from approximately 9% to 48% while satisfying mechanical, thermal, and crashworthiness requirements [6-15].

3. Material Systems for Lightweight Battery Packs

3.1. Regular Steels and Advanced High Strength Steels (AHSS/UHSS)

Regular steels are the least expensive, easy to shape, provide strong crash protection, and have well-established recycling systems. However, they add the most weight. To address this limitation, Advanced High-Strength Steels (AHSS) and Ultra-High-Strength Steels (UHSS) are used. These materials allow the use of thinner components while maintaining excellent impact resistance. Pan et al. [6] showed that using AHSS with optimized sizing reduced the weight of a battery pack enclosure by 10.41%. AHSS offers a practical approach to lightweight design without the high cost associated with advanced composites.

3.2. Aluminum Alloys and Aluminum Foams

Aluminum alloys are now the preferred choice for high-end EV battery enclosures. They provide a practical balance by reducing weight by approximately 30-40% compared with traditional steel designs. Baumeister et al. [7] investigated aluminum hybrid foam sandwich battery housings and found that they offer high specific stiffness, excellent penetration resistance, and a thermal conductivity of approximately 0.4 W/m·K, which is much lower than that of solid aluminum, thereby providing natural insulation against thermal runaway. In addition, Yay et al. [15] reported that an optimized aluminum foam-filled battery box absorbed 50.71% more energy and reduced the maximum crushing force by 11.56% during side-pole crash tests.

3.3. Magnesium Alloys

Magnesium alloys are the lightest among all structural metals, making them theoretically capable of achieving greater weight reduction than aluminum. D'Errico [14] pointed out that magnesium has significant potential for sustainable automotive lightweighting. However, magnesium is not yet widely used for large battery enclosures because of challenges such as galvanic corrosion, high flammability during machining or high-temperature events, and less-developed joining techniques for large structural components.

3.4. Plastic Composites: CFRP, GFRP, SMC, and CFRTP

Advanced polymer composites offer the greatest potential for weight reduction. Schludi and Joos [8] showed that composite and sandwich battery housings can be approximately 40% lighter while also providing good fire insulation and crash performance. Shaikh et al. [9] used Finite Element Analysis (FEA) combined with Machine Learning (ML) for carbon-fiber organ sheet battery enclosures and found that the number and thickness of layers are the primary factors governing crash performance. Glass Fiber Reinforced Polymers (GFRP) and Sheet Molding Compounds (SMC) are less expensive and easier to manufacture at scale than CFRP, although they provide a lower strength-to-weight ratio.

3.5. Mixed and Multi-Material Systems

Using a single material generally does not satisfy all the requirements related to weight, crash safety, thermal management, and cost. Consequently, hybrid systems that combine multiple materials are becoming increasingly popular. Dhoke and Dalavi [1] highlighted optimization approaches that combine Advanced High-Strength Steel (AHSS), aluminum, and composite materials. Some studies have reported theoretical weight reductions of up to 48.86%; however, these values are based on specific optimization models. In practice, these systems include metal-composite sandwich structures, foam-filled metallic components, and composite reinforcements integrated into selected regions of steel structures.

4. Structural and Architectural Design Techniques

Lightweight design is not achieved solely through material selection but also through structural optimization and architectural design. Techniques such as topology optimization, Non-dominated Sorting Genetic Algorithm II (NSGA-II), multi-objective optimization, and reliability-based design are widely used to improve battery pack performance while minimizing weight. Wang et al. [11] demonstrated that multi-objective lightweight design effectively balances structural weight with crashworthiness and overall structural performance.

More recently, battery pack architectures have evolved from Module-to-Pack (MTP) systems to Cell-to-Pack (CTP) and, increasingly, Cell-to-Body (CTB) or Cell-to-Chassis (CTC) integration. Belingardi and Scattina [10] pointed out that integrating battery cells directly into the vehicle body or chassis can reduce the total battery system weight by approximately 10-15% while significantly improving overall vehicle torsional stiffness. Some CTB designs have achieved torsional stiffness values exceeding 40,000 Nm/deg, representing an improvement of approximately 70% over conventional battery pack designs.

However, this high level of structural integration also changes the material and joining requirements of battery systems. Structural adhesives become the primary load-transfer mechanism, requiring shear strengths exceeding 20 MPa while ensuring long-term structural integrity, durability, and serviceability [10,11].

5. Thermal Management, Fire Safety and Mechanical Protection

Thermal management in battery pack enclosures involves a challenging balance between efficient heat dissipation and thermal insulation. The enclosure must effectively transfer heat to the Battery Thermal Management System (BTMS) while simultaneously limiting the propagation of thermal runaway between battery cells. To address this challenge, Phase Change Materials (PCMs) have been extensively investigated. PCMs, such as paraffin, absorb latent heat during phase transition, thereby reducing temperature fluctuations and improving thermal stability. Since pure paraffin has relatively low thermal conductivity, it is often combined with expanded graphite (EG) or boron nitride (BN) to enhance heat transfer performance [2-4].

Fire safety is another critical consideration, particularly for polymer composite battery enclosures, which may be susceptible to combustion under extreme conditions. Azzopardi et al. [5] reviewed the incorporation of flame retardants such as Aluminum Trihydroxide (ATH), Magnesium Hydroxide (MH), and Ammonium Polyphosphate (APP) into polymer resin systems. In addition, structural barriers, paraffin-silica aerogels, and intumescent ceramic coatings have been investigated to prevent the propagation of thermal runaway and improve the overall fire resistance of battery pack enclosures [4,5].

6. Manufacturability, Joining, Cost, and Sustainability

The economic feasibility of a battery pack enclosure largely depends on its manufacturability. Steel and aluminum benefit from well-established automotive manufacturing processes such as stamping, extrusion, casting, and advanced welding techniques. In contrast, advanced thermoset composites generally require longer manufacturing cycles; however, emerging processes such as automated compression molding, Resin Transfer Molding (RTM), and thermoplastic composite manufacturing are helping to improve production efficiency. For multi-material and Cell-to-Body (CTB) assemblies, conventional welding is increasingly being replaced by structural adhesives, self-piercing rivets (SPR), and flow-drill screws (FDS) [5,10].

Lai et al. [12] conducted a cradle-to-cradle life-cycle assessment of battery enclosures manufactured from steel, aluminum alloy, and Carbon Fiber Sheet Molding Compound (CF-SMC). Their study found that aluminum battery enclosures provide the best overall environmental performance throughout the vehicle life cycle, reducing carbon emissions by approximately 44.4% compared with steel, primarily because nearly 92% of aluminum can be recycled. In contrast, CF-SMC reduced carbon emissions by approximately 34.6% but resulted in higher environmental impacts during the manufacturing stage [12].

7. Comparative Discussion and Material Selection Guidelines

Based on the available literature, it is evident that there is no single best material for EV battery pack enclosures. Gökciler and Geren [13] applied a penalty-based material selection methodology and concluded that aluminum alloys generally provide the best balance between weight reduction, manufacturing cost, and overall performance under normal operating conditions. In contrast, Carbon Fiber Reinforced Polymer (CFRP) offers superior specific energy absorption during severe crash events because of its exceptional strength-to-weight ratio. In addition, CFRP provides excellent electromagnetic interference (EMI) shielding and can effectively contribute to thermal runaway containment when appropriately designed and treated [5,8,13].

Overall, material selection should be based on the specific application requirements, considering factors such as structural performance, crashworthiness, thermal management, manufacturability, cost, recyclability, and environmental sustainability. Hybrid and multi-material systems are increasingly being recognized as promising solutions because they combine the advantages of different materials while minimizing their individual limitations [1,5,12,13,16].

8. Research Gaps and Future Directions

Despite significant advancements in lightweight EV battery pack technologies, several important research gaps remain. First, there is a lack of standardized frameworks that integrate end-of-life environmental impacts, recyclability, and repairability into the early stages of material selection and structural optimization. Second, many existing studies rely primarily on numerical simulations, highlighting the need for comprehensive experimental validation that simultaneously evaluates vibration, crashworthiness, thermal management, and thermal runaway behaviour under realistic operating conditions [11,12].

Furthermore, as Cell-to-Body (CTB) and Cell-to-Chassis (CTC) battery architectures continue to evolve, there is an increasing need for reversible or debondable structural adhesives that facilitate sustainable disassembly, repair, and recycling of battery systems. In addition, further research is required to improve the large-scale manufacturing of fire-resistant thermoplastic composites and recycled carbon fiber materials to address the sustainability challenges associated with conventional thermoset composites [5,10,12].

Future research is expected to focus on multifunctional material systems that combine structural support, thermal management using advanced Phase Change Materials (PCMs) or aerogels, electromagnetic interference (EMI) shielding, and embedded structural health monitoring sensors. The integration of these advanced materials with artificial intelligence (AI), digital twins, and predictive engineering tools is expected to play a significant role in the development of next-generation lightweight EV battery systems [4,5,16].

9. Conclusions

The best material for an EV battery pack enclosure is not a fixed choice; it depends on the specific vehicle and its application. The shift from Module-to-Pack (MTP) to Cell-to-Body (CTB) and Cell-to-Chassis (CTC) designs means that battery pack enclosures are becoming primary structural components, increasing the need for materials with high specific stiffness and advanced joining techniques. While advanced polymer composites, such as Carbon Fiber Reinforced Polymer (CFRP), can achieve significant weight reductions of approximately 40-56%, their widespread adoption is still limited by high manufacturing costs, stringent fire safety requirements, and recycling challenges. On the other hand, Advanced High-Strength Steel (AHSS) is an affordable and recyclable alternative that can reduce weight by approximately 10%; however, its higher density still imposes a weight penalty that affects vehicle driving range.

At present, for most EV battery packs, optimized aluminum alloys provide the best balance between weight reduction, manufacturing cost, and ease of production. They offer considerable weight savings and provide excellent environmental performance when efficient recycling systems are in place. The most promising path forward is the use of multi-material hybrid systems and multifunctional composites, in which advanced lightweight materials are strategically placed where they are most needed for crash protection and thermal management, rather than simply replacing one material with another throughout the entire structure.

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