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Lightweight Design of EV Lower Battery Boxes Using Vinyl-Ester Prepreg Composites

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Abstract. With the rapid rise of electric vehicles, lightweight design of battery boxes has become a critical focus to enhance driving range and reduce carbon emissions. The lower battery box offers greater flexibility for structural and material innovation due to fewer functional constraints. This paper focused on the application of vinyl ester prepreg composites as a substitute for traditional metal structures to achieve weight reduction while maintaining safety. Previous research shows that most studies concentrate on simulation and topology optimization, while few directly analyze material performance. This study compared epoxy, phenolic, and vinyl ester prepregs, demonstrating that vinyl ester prepreg exhibits superior mechanical properties, hygrothermal aging resistance, and impact toughness. Furthermore, assembly using polyurethane adhesives ensures both bonding strength and airtightness. The study concluded that a hybrid structure combining prepreg composites and metal alloys can achieve a weight reduction target of 22.6% while meeting the performance requirements of electric vehicle lower battery boxes.

Keywords: Electric vehicles (EVs), Lower Battery Box, Vinyl-ester Prepreg, Lightweighting.

1. Introduction

In a developing environment, transportation plays a crucial role as it determines where resources are located and how they should be allocated, where a specific individual is and where they should be. However, as the demand for transportation increase, the supply does so too but increases various costs too: Global warming from resource consumption and emission, higher consumer prices, fuel inflation etc. The innovation and development of electric vehicles (EVs) provide a potential solution to this pressing issue, bringing reduced air pollution and greenhouse gas emissions, lower operating and maintenance costs. As development for EV continues, the lightweight requirement for EVs becomes more important, since reducing vehicle mass increases mileage and decreases more carbon emissions. Consequently, the focus has shifted to the lower box of the EV battery pack, as it accounts for the largest weight proportion of the entire system. Compared with the upper box, the lower box is subject to fewer design limitations, offering greater potential for weight reduction if properly researched. Traditionally, battery boxes have been manufactured from various metals and alloys. However, epoxy vinyl ester glass fiber prepreg, a hybrid resin widely applied in aerospace,

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automotive manufacturing, electronics, and construction, presents a promising alternative due to its excellent mechanical properties, chemical stability, and corrosion resistance.

An examination of research and experiments conducted, both inside and outside of China, reveals that research on EV battery packs can be divided into two broad categories. First are related with lightweight structural simulations. Saeed et al [1]. had carried out simulation modelling of battery pack structures with planning methods and topology optimization with computations on optimal topological arrangement of mass fraction and envelope parameters to offer data support of structural design. Their findings highlighted the importance of topology optimization as a systematic way to find efficient load paths that can minimize the amount of redundant material and provide stiffness. Furthermore, Liu et al [2]. used finite element simulation as the means of performing the static mechanical and modal analysis followed by optimizing the design according to the results of the simulation process. They reported a 26.3% weight reduction in their work, which was achieved while maintaining the structural performance of the optimized battery pack under both static and dynamic loads, showing the feasibility of simulation-based designs. On the same note, Arora et al [3]. designed an integrated frame battery tray frame, simulated it in the static under varying working conditions and minimized the structure using OptiStruct finally minimizing the weight by 30 percent and showing the benefits of such integrated tray design compared to traditional modular designs.

Secondly, the following researchers are more concerned with the mechanical qualities of lower battery packs. In lightweight design, not everything is theoretical or simulated, other important considerations that need to be experimented include the lower battery pack's durability, strength, toughness, malleability, and plasticity. As an illustration, Shao et al [4]. showed that the failure displacement of the floor of the battery pack housing is unrelated to plate thickness, implying that material layout and geometry see a greater influence than mere dimensional scale. To better predict crash-related failures, Xia et al [5]. developed a testing algorithm to assess the different impact forces registered by battery packs in varying displacement scenarios using a finite element testing algorithm. The bulk of this background research, however, focuses on solving this problem using simulations or controlled variables, with little discussion on concrete materials in which to reduce weight. Other researchers have however explored materials using simulation studies, which give a theoretical understanding of lighter battery packs. An example is provided by Burd et al [6]., who produced an integrated aluminium alloy battery pack through the investment casting technique, and a stress-strain analysis revealed that the highest stress was well below the yield strength, which was too strong. Mass was then minimized by 15.05 percent through a dimensional optimization, indicating that overdesign is not a permanent feature. Xiong et al [7]. developed an optimized in-house housing structure by substituting galvanized steel with Al-Mg aluminium alloy and varying the thickness, which results in a rationalized design and made the housing structure better in weight and performance. Similarly, Wang et al [8]. furthered this research direction by suggesting a hybrid metal-composite enclosure using high strength steel, aluminium and carbon fibre reinforced polymer (CFRP). They greatly enhanced the crashworthiness without compromising the lightweight profile of the battery-pack enclosures, which means that hybrid structures are a bright way of moving forward with the battery-pack enclosures. Nevertheless, as the above research shows, studies on materials and manufacturing processes remain limited. The weight-reduction effect of replacing one metal with another is not significant, while the high manufacturing cost of carbon fibre reinforced composites hinders their large-scale adoption.

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2. Experiments with glass fiber materials

Previous studies indicate that most scholars have relied on simulations and theoretical methods to address lightweight battery pack design. Some simulated different structural configurations and developed software to optimize the topological arrangement of the battery pack, while others focused on analysing its mechanical properties [6-9]. In contrast, this research emphasizes the materials and processes involved in using glass fibre prepregs to reduce weight and manufacture lower battery packs. Therefore, this paper investigates the application of glass fibre composites to the lower housing of battery packs in new energy vehicles.

First experiment evaluates the mechanical characteristics of three prepreg candidate materials. Three prepregs were chosen as lower battery box applications, EP-prepreg, Phe-prepreg and VE-prepreg. All the prepregs had been set with identical parameters to keep the balance and precision: 40 percent resin content, 400 gsm glass fibre fabric and one-layered thickness of 0.3 mm when laminated. It was observed that VE-prepreg laminate under under-molding conditions of 125 C, 10 Mpa and 600 seconds presents better tensile and flexural characteristics than the two. Particularly, VE-prepreg had tensile strength of 468 Mpa, flexural modulus of 33 Gpa, flexural strength of 556 Mpa, flexural modulus of 25 Gpa, short-beam shear strength of 66.4 Mpa. Comparatively, the epoxy laminate achieved tensile strength of 452 Mpa, elastic modulus of 31 Gpa, flexural strength of 511 Mpa, flexural of 21 Gpa, and short-beam shear strength of 47.5 Mpa whereas the phenolic laminate achieved tensile strength of 447 Mpa, elastic modulus of 18.3 Gpa, flexural strength of 601 Mpa, flexural modulus of 29.6 Gpa. To conclude, these findings show that although the phenolic laminate had comparatively high flexural strength, its tensile and interlaminar shear strengths compared with the other two, however, was worse. Epoxy laminate had an intermediate performance, but still compared with VE-prepreg laminate, it doesn’t stand out too much. Moreover, one attribute of VE-prepreg is its curing mechanism compared to that of epoxy and phenolic prepregs, the vinyl ester resin cures through free-radical polymerization, unlike the slower reaction-rate and lower polymerization-degree of epoxy and phenolic prepregs, and provides a higher-rate of crosslinking, allowing more rapid cure at lower temperatures and a greater extent of network formation. Furthermore, its greater short-beam shear strength emphasizes enhanced resistance to interlaminar stresses, commonly the source of delamination failure in composite laminates. Combined, these results demonstrate that VE-prepreg exhibits the most desirable mechanical performance under high-efficiency molding conditions of the automotive sector of three applicants.

In addition, the lower battery box material must withstand extreme environmental temperature changes. Among the various factors influencing composite material aging, hygrothermal aging is particularly significant [9]. To evaluate this, the three specimens were subjected to a high–low temperature alternating hygrothermal test. Tensile strength results ranked as follows: vinyl ester prepreg > epoxy prepreg > phenolic prepreg. The calculated attenuation rates were 25% for epoxy, 27% for phenolic, and 17% for vinyl ester. Hygrothermal aging of resins is complex, and one contributing factor is oxidation. Once again, VE-prepreg showed superior resistance, making it the most suitable candidate for further validation in the compression molding process.

Vehicle underbody scraping is a common road traffic accident, especially affecting the battery pack located at the lowest part of the vehicle. At present, industry practices primarily include whole-vehicle scraping tests and ball-drop impact tests to evaluate the safety of battery systems under underbody collision conditions. To address the limitations of existing methods, this study improved the ball-drop impact test method and evaluation criteria to better assess battery pack durability. The results showed that the phenolic prepreg laminate exhibited the lowest impact toughness (123.9 kJ/m²), due to its molecular structure, where two phenol molecules connected by a methylene group

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restrict chain rotations, increase steric hindrance, and lead to brittleness. The vinyl ester prepreg laminate showed the highest impact toughness (206.2 kJ/m²), while the epoxy prepreg laminate was intermediate (186.0 kJ/m²). However, epoxy prepreg suffers from disadvantages such as high internal stress, brittleness, poor impact resistance, and susceptibility to cracking, which limit its suitability for use in lower battery boxes [10].

3. Analysis of lower battery pack design and structure

The reason for reducing weight in the lower battery packs of electric vehicles is to improve efficiency and minimize environmental impact from greenhouse gas emissions. The lower battery pack serves to protect and support the vehicle's battery modules and internal electronic components, effectively preventing any loosening of the battery modules during operation and ensuring safe operation under various harsh conditions [11]. The lower battery pack must provide a basic level of protection, durability, safety and affordability. The basic requirements examined that the material of the lower battery box must meet are as follows. To avoid passenger safety, the battery enclosure must be tough and rigid to withstand load deformations and stress concentration in a safe range. This brings out the vibration performance, which is another consideration as the natural frequency of battery pack cannot be equal to the resonance frequency of the vehicle systems, hence will assure the passengers that, they will not have a bad ride when in the vehicle [12]. The collision safety performance is also of the priority: the battery case must minimize the direct influence on the battery cells and modules and sustain their integrity as well as the vehicle safety. Further, since the battery will be generating heat in the process, the enclosure must provide a good thermal solution with good heat dissipation equipment and air-outlets to help it to release the excess heat in a prompt manner, preventing serious risks to safety. Protective performance, sealing, waterproofing and dustproofing is also a means which assist in the protection of the electrical system, and the required is fully sealed design which is necessary to enhance safety in driving and to eliminate harmful effects to the circuitry [13]. The design should also be in a way that it enables easy loading and offloading and portability of the enclosure whereby it can easily undergo routine maintenance or replacement of the electrical parts in it without exerting strains that may compromise its functionality [14]. Lightweighting is also a major factor whereby lowering the weight of the battery box improves the energy consumption, power and the driving distance. This reduces energy wastage besides ensuring that the mileage of the vehicle is put to the best use thus making it important both in terms of performance and safety. In the current design, the lower battery pack integrates both epoxy vinyl ester glass fibre prepreg material and metal alloys, addressing both structural and functional requirements. Equally important is the assembly of the lower battery pack with accessories and its integration with the vehicle body, which requires careful sealing and joint performance. Among existing connection methods, adhesive bonding is advantageous because it involves drilling holes that prevent stress concentration without compromising laminate strength. Over long-term use, adhesive bonding provides excellent insulation, fatigue resistance, limits microcrack propagation, and ensures reliable safety, sealing, and vibration damping, while preventing galvanic corrosion between dissimilar materials [15].

Therefore, the assembly structure employs a combination of adhesive bonding and bolted connections. Structural adhesives, known for their excellent bonding strength and mechanical properties, are widely applied in automotive manufacturing, particularly in locations subjected to combined loads such as tension, shear, impact, and vibration. Beyond their sealing function, adhesives enhance the stiffness and modal performance of connected components [16]. The introduction of automotive structural adhesives has addressed challenges associated with resistance

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spot welding, such as accessibility, welding cracks, stress concentration, and weak welds. However, few structural adhesives achieve strong bonding between steel and composite materials like epoxy vinyl ester glass-fiber prepreg. Two-component polyurethane adhesives, in particular, satisfy both the bonding strength requirements of steel and glass-fiber composites while ensuring airtightness. Assembly studies of the lower housing using polyurethane structural adhesive demonstrated that, with an adhesive dosage of 41.4 g/m² and a curing time of 24 hours, the pull-off strength reached 270.49 N/cm², and airtightness testing confirmed that the assembled product met the enclosure protection requirements.

4. Improvements in economic, environmental and manufacturing process

Although previous studies have explored the use of improved resins for the lower battery box and investigated lightweight designs, there remain two key areas for further consideration: economic and environmental improvements, and manufacturing process enhancements. From an economic and environmental perspective, the use of GFRP-SMC panels wherever possible is highly recommended. Full life-cycle assessments indicate that SMC exhibits the lowest environmental impact in four out of six categories, with a global warming potential (GWP) approximately 13.2% lower than steel and 3.9% lower than aluminum. In a production run of 10,000 units, the manufacturing GWP can be reduced by up to 65.6%, and total lifecycle GWP by 13.2%. SMC also allows bosses, seal tracks, and ports to be molded directly into the part, reducing the number of components and potential leak paths. Suppliers report 20% to 50% less weight than metal and 25% to 75% lower tooling cost. Overall, that helps both cost and footprint. Furthermore, with the material usage, keep metal only where needed and make it recycled aluminum, what that means is, remelting aluminum uses 95% less energy than making it from pure ore, industry guidance says the same and notes large U.S. secondary content . Also, the power source behind primary aluminum is the main driver of its impact, buying from low-carbon electricity suppliers cuts those emissions a lot . Then, show the payoff in use. Even with regen, less mass still helps. DOE’s rule of thumb: 10% lighter vehicle means 6% to 8% better fuel economy (ICE baseline), and other studies show similar gains when you right-size the powertrain. For EVs that means more range now, and later the option to use fewer cells. Lastly, plan for recycling: consider thermoplastic covers. Thermoplastic top covers (e.g., PC LFT-D/DLFT) run fast, are easier to recycle, and have vendor data like 20% weight saving, 50% productivity increase, and lower part cost vs. SMC metal. Trinseo and Envalior show thermoplastic stacks that meet battery-safety tests. The above is Economic & Environmental Improvements for the lower batter box. Now to the second improvement, Manufacturing Process Improvements.

From a manufacturing process perspective, SMC compression molding is the most practical baseline for trays and covers, as automotive programs routinely achieve short cycle times of approximately 2–4 minutes. EV-battery trials have demonstrated roughly 2-minute cures at about 320 °F on representative parts. To consistently reach those times in series, start by placing and preheating the charge so material flows evenly and voids stay low; then keep flame-retardant fillers only as high as needed for compliance so viscosity remains workable; and finally, design the tool to mold in seal seats, lifting points, cable ports, and screw bosses so drilling and other secondary operations can be skipped altogether. When stiffness or crash/NVH targets push beyond what SMC thickness and ribbing can deliver, the next step is to use high-pressure RTM only for those specific sub-modules. Low-pressure RTM is typically 30–60 minutes per shot, whereas HP-RTM runs in single-digit minutes; development programs and supplier data report cures at or below five minutes and even about two minutes in mold with suitable resin systems. Unlike low-pressure RTM, which typically requires 30–60 minutes per shot, HP-RTM can cure in single-digit minutes, with

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development programs and supplier data showing curing times of five minutes or less, and in some cases as short as two minutes using suitable resin systems. Limiting HP-RTM to critical areas provides performance headroom while controlling capital and material costs.

Additionally, room-temperature structural bonding combined with foam-in-place gasketing reduces both energy use and rework on the production line. Modern RT adhesives reliably bond aluminum to composite lids, providing fast handling strength and high crash durability while eliminating ovens and reducing floor space requirements. For sealing, two-component PU FIPFG creates a continuous, re-openable gasket that becomes tack-free in approximately 3.5 minutes at room temperature and ready for screw-down in about 35 minutes, thereby reducing dwell time and improving first-pass yield. To secure these gains, design for manufacturability, assembly (DFMA), and supplier energy data should be incorporated from the outset. For composite materials, specifications should include fire-resistance class, smoke/toxicity ratings, target cycle times, and molding windows, with operational efficiency verified on production tooling prior to SOP. For metals, the percentage of recycled content and electricity mix used in production should be documented, as the power source heavily influences the footprint of primary aluminum; sourcing from low-carbon electricity suppliers materially reduces embedded emissions. Part consolidation should continue wherever possible, leveraging SMC's ability to mold in features, reducing bill of materials (BOM), minimizing leak paths, shortening assembly time, and improving both takt and overall quality.

5. Conclusion

Ultimately, this paper emphasized the possibility of solving one of the most urgent issues in the development of electric vehicles composites solutions. To achieve a considerable reduction in weight on the lower battery box of the EV without compromising its safety, durability, or manufacturability. Through the study of the lower battery housing that does not have the constraints as in the upper enclosure, the work finds a powerful design window of innovation in terms of material selection and structural arrangement.

The material vinyl-ester (VE) glass-fiber prepreg is the most balanced composite candidate among all, as it offers high mechanical strength, high level of resilience to environmental stress and high-quality impact performance. Although epoxy and phenolic systems have some benefits, they showed lower stability in the entire range of requirements. VE-prepreg, by contrast, offers the durability and reliability required of a highly critical safety part, and also offers lightweighting to the level accessible to mass production.

The paper also indicated that reduction of weight cannot be based on materials only. Sealing integrity, assembly plans, and serviceability are also critical in the action of ensuring that the housing is capable of operating in the actual automotive environment. The use of composite-metal hybrid structure along with structural adhesive bonding offer an effective route to combine dissimilar materials, as well as high-level sealing and mechanical integrity demands. These hybrid solutions are not only able to ease production, through fewer parts and less secondary operations but also help create a more resilient and scalable manufacturing process.

Collectively, these results prove that lightweight composite lower housings are technically, as well as industrially, possible. The use of lightweight components does not stop at the component level: making the battery enclosure lightweight makes the vehicle more efficient in general, increases the driving range, and reduces the amount of energy used to travel a kilometer. At the larger level, the lower material demand and energy consumption in operations is translated into significant environmental gain over the life cycle of the vehicle. In a change of focus when

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discussing the traditional simulation-based topological designs to proven materials-and-process based designs, this paper highlights the need to bridge the gap between laboratory innovation and a solution that is manufacturable. The effective implementation of VE-prepreg in a hybrid structural concept offers a technical base and a practical guide to the future policies of lightweighting the electric vehicles. Finally, this paper shows how specific material and assembly innovations can support the twin objectives of sustainable mobility and industrial scalability.

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