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Multifunctional Composites with Integrated Energy Storage: Structural Batteries for Next-Generation Electric Vehicles

Rameshwar P. Bhalerao[1], Samadhan M. Jadhav[2], Akash M. Waghmare[3], Yogesh B. Gaikwad[4]

Assistant Professor, Department of Mech., Engineering[1-4]

Bhagwant Institute of Technology, Barshi, MH, India

samadhanjadhav36@gmail.com

Abstract: *The electric car trend in the automotive industry is creating an increased need for lighter and more efficient ways to store electricity for vehicles so as to address the range limitations and the added weight of conventional battery packs. Therefore, the use of structural batteries has emerged as a new way to create multi-functionality from composite materials. In this paper, we review recent developments in the area of structural battery composite materials for the purpose of improving the performance of electric vehicle (EV) designs by reviewing various types of structural battery composite architectures; the mechanical-electrochemical relationships within these composites; the challenges related to manufacturing structural battery composites; and, the performance characteristics of structural battery composites. Additionally, we examine carbon fiber based structural electrode, solid state electrolyte, and novel cell architectural concepts that may be able to decrease vehicle mass by 20-30% by simultaneously reducing the overall energy density of the structural battery while increasing structural integrity. We discuss key technical challenges that include issues related to interface compatibility, thermal management, safety concerns, and scalability of structural batteries. Finally, we provide a summary of future directions to develop commercially viable structural batteries that can eliminate the distinctions currently existing between the structural component and the energy storage component of electric vehicles.*

Keywords: Structural batteries, multifunctional composites, electric vehicles, carbon fiber electrodes, solid-state electrolytes, lightweight design, energy storage

I. INTRODUCTION

The automobile market has experienced a transformation of its basic structure. The automobile industry has been subject to pressures from regulatory bodies and consumers to develop environmentally sustainable transportation options to minimize dependence on fossil fuels and to mitigate the effects of climate change. Electric vehicles (EVs) have developed into an appealing option to satisfy this demand. Unfortunately, current EV designs have several obstacles which include short ranges of travel per charge, time consuming recharge processes, and excessive weight of EVs caused by traditional battery pack configurations [1]. The traditional design philosophy for EVs separates energy storage and structural components into two distinct areas; they do not overlap functionally. Traditional lithium-ion battery pack configurations are placed inside protective housing which adds weight to the EV without providing any structural support. This type of configuration leads to low use of mass and lower levels of energy efficiency [3]. The idea of using structural battery composite materials that can provide both mechanical load-bearing capabilities and electrochemical energy storage represents a revolutionary approach to overcome the above mentioned limitations of EVs. Structural batteries are a new category of multifunctional composite materials in which the individual materials perform multiple functions. These include: 1) electrochemically storing electrical energy, 2) mechanically supporting external loads, and 3) physically connecting to other structural elements [4]. By creating a separation between structural and energy storage components, structural batteries allow designers to fundamentally reimagine vehicle architecture.

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Some theoretical studies indicate that the implementation of structural batteries may be able to reduce the mass of an entire vehicle by 20-30 percent and maintain or improve crash worthiness, and increase effective energy density when compared with the use of conventional EVs [5]. To develop structural batteries will require addressing challenges that are unprecedented in terms of their complexity at the interface of materials science, electrochemistry, mechanical engineering, and manufacturing. The electrochemical and mechanical functions imposed upon structural battery materials will require different properties than those required for structural or electrochemical performance alone. Specifically, electrochemical performance will require materials with high ionic conductivity and electrochemical stability while structural performance will require materials with high stiffness, high tensile strength and high fracture toughness [6]. In addition, there will exist complex interaction between mechanical deformation and electrochemical process, resulting in novel failure modes and safety considerations that are absent in traditional systems.

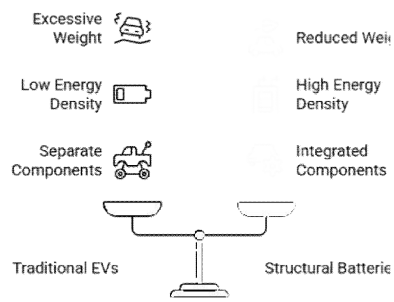

Figure 1. Traditional EV's Batteries Vs. Structural Batteries. (Source: Original)

The purpose of this paper is to provide a detailed analysis of the latest developments in structural battery composites for the next generation of electric vehicles. In section II, the fundamental design principles and material architectures for structural battery composites will be examined. In section III, the electrochemical-mechanical properties of carbon fiber based structural electrodes will be analyzed. In section IV, the various types of electrolyte systems used in structural battery composites, such as polymer and solid state electrolytes, will be discussed. In section V, the structural battery cell architectures and integration methods will be evaluated. In section VI, the performance metrics and tradeoffs of structural battery composites will be assessed. In section VII, the manufacturing and scaling challenges associated with structural battery composites will be addressed. In section VIII, the safety and reliability issues associated with structural battery composites will be examined. Finally, in section X, the paper will be concluded.

II. FUNDAMENTAL DESIGN PRINCIPLES

A. Multi-functionality Concept

Structural batteries can be made using a variety of different multifunctional material types that combine at least two of these functions to create one part, which has the potential for reducing the amount of space in an aircraft due to the elimination of multiple parts for each function; as opposed to traditional aircraft design, where each function is completed by a separate part [7]. A measure of how well multifunctional parts combine their various functions to save space and weight is represented by the multi-functionality index, η, which is expressed as follows:

$$\eta = (m_1 + m_2)/ m_{12} \quad (1)$$

where m_1 and m_2 represent the masses of the two independent components that would have been required to complete the two respective functions separately, and m_{12} represents the mass of the multifunctional component that completes both functions in one [8]. When the value of η exceeds 1, it indicates that there is a mass saving with respect to the total system mass if separate systems were used instead of the structural battery.

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B. Performance Trade-offs

Structural Batteries must satisfy multiple competing demands in order to optimize performance within various Performance Domains. The primary Trade-Offs between Performance Domains are:

1. High-Energy Density Materials vs. Good Mechanical Properties: Electrode materials that have high energy storage capability typically lack good mechanical properties. Carbon fiber electrodes have the best mechanical performance of all structural battery materials; however, their energy storage capabilities (specific capacity) are much lower than those of other structural battery materials [9].

2. Good Ionic Conductivity vs. Good Structural Integrity: Liquid electrolytes provide better ionic conductivity than all other forms of electrolytes. However, they also compromise the structural integrity of a structural battery. Solid polymer electrolytes provide both the mechanical strength of a structural battery as well as improved ionic conductivity when compared to liquid electrolytes [10].

3. High Power Density vs. Improved Safety: Thin electrolyte layers improve the power density of structural batteries; however, thin electrolyte layers can compromise mechanical integrity of the structural battery and can create an increased risk of short circuiting when subjected to an impact load [11].

C. Design Space

Structural battery design is constrained by several characteristics: Specific Energy (Wh/kg), Elastic Modulus (GPa), Tensile Strength (MPa) & Multifunctional Efficiency. Using Material Property Charts in the style of Ashby, it has been shown that Structural Batteries reside within a unique area in between traditional composites and energy storage systems [12]. Research conducted recently indicates that Structural Batteries having an Energy Density of 50 – 100 Wh/kg and an Elastic Modulus of 25 – 50 GPa can be achieved utilizing today's materials which represent 20 – 40 % of conventional Lithium-Ion Battery Energy Density and provide the same structural properties as Glass Fiber Composites [13].

III. CARBON FIBER STRUCTURAL ELECTRODES

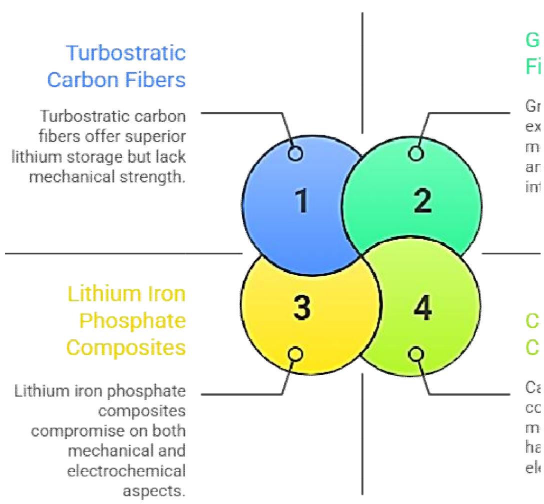

Figure 2. Carbon Fibre Properties and Applications. (Source: Original)

A. Carbon Fiber as Multifunctional Material

Carbon fibers (CFs) are the ideal basis for structural electrodes due to a combination of high mechanical properties (strength >3 GPa, Young's modulus >200 GPa), electrical conductivity, and electrochemical activity [14]. Among the different types of CFs, those based on polyacrylonitrile (PAN) have been studied extensively in recent years. This is primarily because PAN-based carbon fibers offer a balance between the physical and chemical properties required for

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applications in battery systems. As such, the influence that the micro-structure of the carbon fiber has upon its mechanical and electrochemical properties is significant. High crystalline graphitic carbon fibers offer high levels of mechanical property and poor lithium intercalation capacities; this is due to the fact that the density of the graphitic crystal structure is too great for the insertion of lithium ions. In contrast, disordered graphene layer-based turbostratic carbon materials can store large amounts of lithium but display inferior mechanical properties [15].

B. Negative Electrode (Anode) Configurations

Due to their high mechanical strength (>3GPa), elastic modulus (>200Gpa) and also their ability to conduct electricity and participate in electrochemistry; Carbon Fibers (CFs) offer a good base for structural electrodes [14]. PAN-based CFs are among the most commonly researched due to their availability on the market and acceptable properties. The micro-structure of the carbon fibers will directly affect both mechanical and electrochemical performance. Due to their very high crystallinity, graphitic carbon fibers have higher mechanical properties than turbostratic carbon fiber however they do not allow as much lithium into the fiber due to their dense crystal structure. On the other hand, due to the presence of the disordered graphene layers in the turbostratic carbon fiber, it has an increased amount of lithium that can be stored within the fiber however it does not have as many of the same mechanical properties as the graphitic carbon fiber.

C. Positive Electrode (Cathode) Configurations

The cathode is a difficult part to develop due to few options available for the structure of carbon based positive electrodes. A recent study has shown that lithium iron phosphate ($LiFePO_4$) particles can be used and applied to a surface using carbon fiber, providing a capacity of 120-140mAh/g per electrode [19]. This addition of cathode particles to the structure has reduced the mechanical properties of the carbon fiber by approximately 40-60% from its original state. Carbon fiber can also act as a current collector to support traditional cathode materials in a three dimensional battery design. Lithium Nickel Manganese Cobalt Oxide (NMC) nanoparticles were deposited on a woven carbon fabric using electrophoretic deposition to provide improved rate capabilities and mechanical integrity [20]. The three dimensional nature of the carbon fiber provided an electrically conductive pathway through the entire structure, allowing it to accommodate the expansion of the material during charging/discharging. Newer cathode materials such as organosulfur compounds and conducting polymers are being developed as structural battery compatible materials because they are flexible and can be used in conjunction with a polymer electrolyte [21]. PDBM was infiltrated into a carbon fiber laminate and achieved a specific capacity of 200-250mAh/g with retained mechanical properties.

D. Electrochemical-Mechanical Coupling

The relationship between mechanical loadings and electrochemical reaction processes on carbon fibers is a complex multi-physics phenomenon. The intercalation of lithium into graphite causes an increase of volume (typically around 8-12%) which causes internal stresses to develop within the material, and under mechanical loadings these stresses can cause micro-cracking and delamination [22] as well as change the ionic transport paths and the contact resistance at the interfaces between electrodes and electrolytes. Multi-physics modeling methods that couple electrochemical kinetics with continuum mechanics indicate that applying tensile stress can reduce the rate of lithium intercalation by approximately 15-30%, primarily because of increased activation energy required for lithium to migrate; conversely compressive stresses can improve the capacity of the battery by up to 20% by improving the electrode/electrolyte contact [23], thus this must be factored into structural battery designs to ensure reliable operation under operational load conditions.

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IV. ELECTROLYTE SYSTEMS

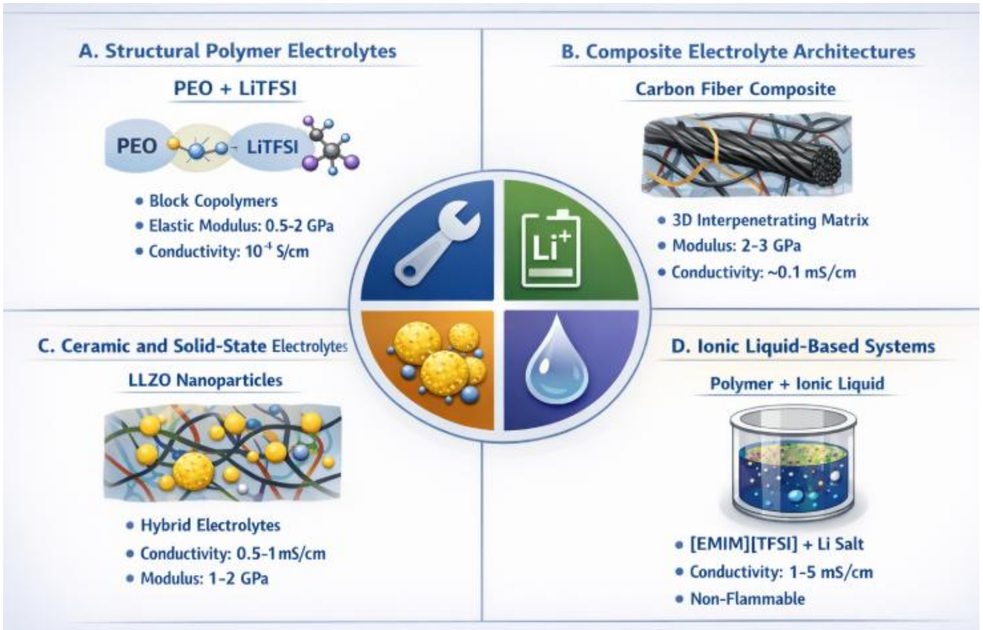

Figure 3. Electrolyte Systems. (Source: Original)

A. Structural Polymer Electrolytes

Structural electrolytes are required to be conductive enough to allow ion movement during battery operation and also serve as the matrix within the composite structure; thus they require a fine balance between mechanical stiffness and ion movement [24]. Electrolytes, which are composed of polymer matrices such as polyethylene oxide (PEO), polyvinylidene fluoride (PVDF) and polymethylmethacrylate (PMMA), have been thoroughly researched as potential electrolyte materials. The combination of PEO with lithium bis(trifluoromethane-sulfonate)imide (LiTFSI) represents the best known of these combinations in terms of the ionic conductivity range (10^(-4) to 10^(-5) S/cm) that is achieved at room temperature [25]. Pure PEO is characterized by very low mechanical strength (elastic modulus less than 1 GPa) and therefore cannot meet the requirements for structural uses. Therefore, numerous studies have concentrated on increasing mechanical strength through cross-linking, copolymerization and by developing nanocomposites. Block copolymer electrolytes feature micro-phase separated domains; the soft phase provides ionic transport and the hard phase contributes mechanical support. For example polystyrene-block-polyethylene oxide (PS-b-PEO) exhibit an elastic modulus of 0.5 - 2 GPa and ionic conductivity of 10^(-4) S/cm at 60 degrees C; therefore there is substantial progress being made toward improving multi-functionality.

B. Composite Electrolyte Architectures

The most favourable way to achieve mechanical stability as well as electrochemical properties is through the creation of a composite electrolyte architecture which combines polymer electrolytes with structural reinforcing materials. Carbon fiber fabric that has been impregnated with polymer electrolytes creates a three-dimensional inter-penetrating matrix in which the carbon fibers provide mechanical support and the polymer phase facilitates ion movement [27]. Structural bicontinuous electrolytes developed from reactive inter-penetrating polymer networks have demonstrated excellent performance characteristics. An elastic modulus of 2-3 GPA, ionic conductivity of approximately 0.1 mS/cm at ambient conditions and an electrochemical window of over 4.5V have been achieved by combining a bifunctional epoxy system with PEO-LiTFSI [28]. The cross linked epoxy phase provides mechanical strength while the continuous PEO phase allows for lithium movement.

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C. Ceramic and Solid-State Electrolytes

Compared to polymers, inorganic solid-state electrolytes provide higher ionic conductivity and better electrochemical stability, however, they have disadvantages such as brittle fractures and poor compatibility between electrode materials [29]. Solid electrolytes like lithium lanthanum titanium oxide (LLTO) and garnet-type lithium lanthanum zirconate ($Li_7La_3Zr_2O_{12}$), demonstrate ionic conductivities of approximately 10^{-3} S/cm; however, their elastic modulus is greater than 100 GPa and their fracture toughness is very poor. In hybrid approaches that combine ceramic particulates into a polymer matrix, researchers are attempting to synergistically combine the benefits of both types of materials. Particulate reinforced polymer matrices containing 10-20 volume percent LLZO nanoparticles has been shown to improve ionic conductivity due to the faster transport pathways provided by the nanoparticles, while also increasing the mechanical strength of the polymer matrix [30]. Researchers have demonstrated ionic conductivities of 0.5-1 mS/cm at room temperature and elastic moduli of 1-2 GPa. Another method to develop thin-film solid electrolytes involves depositing them onto carbon fiber surfaces using atomic layer deposition or magnetron sputtering [31]. Lithium phosphorus oxynitride (LiPON) film (thickness = 100-500 nm) deposited on carbon fibers provides excellent interfacial contact and electrochemical stability, while having minimal impact upon the mechanical properties of the carbon fibers.

D. Ionic Liquid-Based Systems

The properties of ILs provide many advantages that include, negligible vapour pressure, nonflammable, large electrochemical windows and can be easily altered by selecting different cations or anions [32]. Their higher viscosities result in lower ionic conductivities than conventional organic electrolyte solutions. Polymer Ionic Liquid Composite Electrolytes (PILCE) are made using a combination of ILs and structural polymer matrixes. The swelling of PVDF-HFP membranes with 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide ([EMIM] [TFSI]) which contains dissolved lithium salts has achieved ionic conductivity levels between 1-5 mS/cm, along with improved mechanical properties and safer use when compared to liquid electrolytes [33].

V. CELL ARCHITECTURE AND INTEGRATION

A. Laminated Cell Designs

A straightforward structural battery design simply integrates conventional lithium-ion battery pouch cells with structural elements. The structural battery uses a stack and laminate of carbon fiber electrodes on either side of structural polymer electrolyte layers that have been formed together using heat and pressure. In this way, the structural battery design can utilize the well-established manufacturing methods of batteries but has lower mechanical properties than expected because of the relatively soft nature of the polymer electrolyte layers used. Studies on optimizing the thickness of structural battery layers show there is a trade-off between its electrochemical performance and its mechanical performance. An optimal electrolyte layer for structural batteries will be in the range of 50 to 100 μm and will provide a sufficient degree of ionic resistance as well as an acceptable degree of mechanical integrity; however, if the electrolyte layer is made too thin it may cause short circuiting when subjected to mechanical loads [35]. Multilayer structural battery architectures utilizing 10 to 20 pairs of electrodes will produce specific areas of approximately 1 to 2 mAh/cm² with in plane elastic moduli ranging from 30 to 50 GPa.

B. Three-Dimensional Architectures

Recent designs have utilized a three-dimensional structural configuration to improve the electrochemical as well as mechanical performance of the battery. A woven carbon fiber fabric has allowed for through-the-thickness ionic transfer in addition to better mechanical properties than those of a unidirectional laminate [36]. The braid pattern allows for mechanical interlock in addition to an increase in the resistance to delamination. Tubular braiding is another new concept that uses braids to encircle polymer electrolyte core carbon fiber electrode materials to create "battery yarns," which can then be woven together to produce various geometric forms of mechanically robust batteries [37] that have demonstrated high energy densities (specific energies) of 40-60 Wh/kg, along with high tensile strength (in excess of 500 MPa), thus enabling their use as part of load bearing vehicle structural components.

C. Hierarchical Designs

Structural batteries utilize hierarchical structures to increase battery performance by using three different scale sizes; at the micro-scale, nanostructure (carbon nanotubes and graphene) will be added onto carbon fibers to increase battery capacity [38]. The structure of the battery will be optimized at the meso-scale to provide an efficient method of transferring loads and providing electrochemical access to all parts of the battery. Finally, at the macro-scale, structural battery panels can be designed for a variety of structural applications. It has been demonstrated recently that adding 1-5% wt carbon nanotubes into structural electrolyte systems will improve ionic conductivity (and create a pathway for transport through percolation) and mechanical properties (provide additional strength due to fiber reinforcement) and have improved the two metrics simultaneously by approximately 30-50% [39].

D. Integration with Vehicle Structures

To successfully integrate structural batteries into electric vehicles (EVs), they need to be able to fit within the already established framework of the vehicle as well as meet both safety and crashworthiness standards [40]. The body panel, floor structure and roof are all good candidates for integration of structural batteries due to their extensive surface area and average stress state. Finite element analysis has shown that by substituting a 20mm thick laminate of structural battery material for traditional floor panels, 5-10 kWh of additional energy can be stored without negatively impacting structural performance when subjected to typical operating load conditions [41]; however, impact testing requires significant design consideration to avoid cell damage and thermal runaway.

VI. PERFORMANCE METRICS AND TRADE-OFFS

A. Electrochemical Performance

Presently available structural battery prototypes provide 30–80 Wh/kg in terms of specific energy, and 50–150 Wh/L in terms of energy density; this amounts to approximately 15-30% of the capabilities of the current commercialized lithium-ion battery systems [42]. The present power densities of structural battery systems are limited due to the electrolyte thicknesses which are significantly greater than those used in commercial lithium-ion battery systems (i.e., thicker electrolyte layers), and due to lower ionic conductivities, which have resulted in relatively lower specific power values for structural battery systems (typically less than 100 W/kg). One of the major concerns associated with structural battery systems is their long-term durability or "cycle life." Both electrochemically-induced mechanical stress and externally applied loads contribute to the rapid onset of structural damage in structural battery systems. Laboratory tests on structural battery prototypes indicate that they can retain up to 70–80% of their initial capacities after 500–1,000 charge/discharge cycles in the absence of mechanical load [43]. When both electrochemical and mechanical loads are simultaneously applied to structural battery prototypes, however, the retained capacity decreases to 60–70% after the same number of cycles due to the formation of micro-cracks within the structural components, as well as degradation of the interfaces between the structural elements [43]. Due to the inherent limitations imposed by the use of thick electrolyte layers and the poor ionic conductivity of structural polymer electrolytes, most structural battery prototype systems operate at C/10 to C/5 discharge rates. Significant capacity loss occurs when these structural battery prototype systems are charged/discharged at faster rates (e.g., at C/2) [44]. In order for structural battery systems to be capable of rapid charging and discharging, advanced electrolyte design concepts and thin film approaches will be necessary to enhance the rate capability of structural battery systems to a level commensurate with conventional battery systems.

B. Mechanical Performance

The elastic modulus of structural battery systems can be 10-50 GPa depending upon the design parameters and architecture and the amount of fibers present within the system; these values are similar to those found in composite materials that include glass fibers however they are approximately 1/2 to 1/5 less than those of most common carbon fiber composites which have elastic modulus values of 50-150 GPa [45]. The reason for this difference is that structural battery systems typically have compliant polymer electrolyte layers that provide some degree of flexibility along with fiber volume fractions that are generally lower than those used in structural composites (typically 30-50% as compared

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to 50-65% in structural composites). Structural battery systems have tensile strengths of 200-600 MPa that are acceptable for semi-structural applications however their tensile strengths are not sufficient to support primary loads in aerospace applications [46]. Compressive strength is another area of concern when it comes to structural battery systems since polymer matrices do not perform well under compressive loading conditions and structural battery systems are normally limited to compressive strength values of 100-300 MPa. Fracture toughness and damage tolerance are also areas of interest when it comes to the use of structural battery systems in automotive applications however the fracture toughness and damage tolerance characteristics of structural battery systems are currently very poorly defined. In one study the Mode I fracture toughness values for structural battery systems were determined to be in the range of 0.3-0.8 MPa√m, values that are approximately 1/2 to 1/6 of the fracture toughness values associated with common composite systems; these results indicate that structural battery systems may have difficulty in absorbing impacts and maintaining crashworthiness [47].

C. Multifunctional Efficiency

To determine if structural batteries can be efficient in their multiple functions; it is necessary to compare structural battery mass to the total mass of structural battery function and other energy storage systems alone. Research has shown that structural batteries are mass competitive as long as they achieve an energy level of greater than or equal to 40-50 Wh/kg while simultaneously achieving an elastic modulus of 25 Gpa or higher [48]. If structural batteries were used on a typical electric vehicle that needs 60 kWh of battery power and 200 kg of body panel/floor structure; structural batteries with a 50 Wh/kg energy level and 30 Gpa modulus would have the potential to save 150-200 kg (15-20% savings) in overall weight of the combined structural battery and energy storage systems while still meeting structural performance requirements [49]. This study however assumed full replaceability and did not account for added mass due to additional required components such as thermal management and safety systems.

D. Cost Considerations

The economic feasibility of Structural Batteries is based on Structural Batteries costing no more than a traditional Lithium Ion Battery to produce. Currently, prototype Structural Batteries are made from high expense materials (Aerospace Grade Carbon Fibers, Specialized Electrolyte Polymers) which require significant amounts of time to make and have been shown to cost between $500 and $1,000 per kWh of energy storage [50]. To achieve parity with current Lithium-Ion Batteries, lower-cost carbon fibers ($15/kg or less) will need to be used, scalable electrolyte production methods developed and Automated manufacturing techniques employed. Analysts indicate that once Structural Battery production exceeds 100,000 vehicles/year Structural Battery costs may drop to $150-$250/kWh as many structural component(s) are replaced by Structural Battery systems [51].

VII. MANUFACTURING AND SCALABILITY

A. Fabrication Methods

A variety of methods for fabricating structural batteries have been demonstrated:

1. Lamination: Prepregged (polymer impregnated) carbon fiber laminates containing electrode and electrolyte materials are bonded together under heat and pressure [52]. This method leverages traditional composite manufacturing methods but does not lend itself to a scalable process based on batch production.

2. Polymer infusion: Layers of dry carbon fibers are infused with precursors to the polymer electrolyte and then cured in-situ through polymerization [53]. Although this method can be used to produce relatively large format panels, it presents issues regarding the flow characteristics of the precursors and curing processes.

3. Automatic fiber placement: Carbon fiber tows that have been treated with electrode materials are placed using a robot while simultaneously being infused with polymer electrolytes [54]. The use of an automated fiber placement method allows for the creation of complex geometries as well as varying layer thicknesses; however, it requires substantial investment in equipment.

4. Roll-to-roll: A roll-to-roll continuous process for depositing layers of electrodes and electrolytes allows for large volume production; however, it is limited to flat geometries [55].

B. Quality Control and Consistency

To maintain consistency in electrochemical and mechanical performance across all sizes of structural battery formats, strict quality control is necessary. Some of the key barriers to achieving this consistency include:

1. Fiber wetting: When fibers do not have sufficient impregnation, it results in an incomplete filling of a fiber which will lead to voids in the composite; these voids will negatively affect the ionic conductivity and mechanical characteristics of the composite [56]. An additional layer of complexity may be added by using ultrasonic inspection techniques during manufacturing to monitor for void content.

2. Thickness uniformity: The electrolyte thickness could vary by as much as ±20%, leading to localized current densities, and ultimately premature failure of the structural battery [57]. To achieve precision lamination and to measure electrolyte thickness on-line, precise measuring techniques would be needed.

3. Interface quality: Electrode-electrolyte interfaces have a significant effect on electrochemical reaction rates and on how loads are transferred between the electrodes [58]. As such, electrode surface treatments and processing conditions must be precisely controlled to produce consistently bonded interfaces.

C. Scalability Challenges

There are several challenges when moving structural battery prototypes developed in a lab setting into an automotive scale production process:

1. Material availability: The current formulation of structural battery prototypes utilizes research grade materials which have a very limited availability at the commercial level [59]. There must be developed supply chains for specialty carbon fiber, polymer electrolyte, and battery salt used in commercial scale production.

2. Process integration: Currently, the electrochemical cell fabrication (dry room environment) has to be integrated with composite manufacturing (ambient) and will require new design concepts for facilities as well as new manufacturing protocols [60].

3. Yield and reliability: Automotive production cannot afford to produce parts that fail occasionally; automotive production requires that each part produced meets >99% yield requirements and has to operate reliably for at least multiple years [61]. Design and manufacturing processes must be robust.

VIII. SAFETY AND RELIABILITY

A. Electrical Safety

Short circuit is a major safety concern for structural battery systems because of the limited thickness of their electrolytes and mechanical loads on the electrodes that can create physical contact between them [62]. Separators in these systems can be damaged by either impact or fatigue loading; this will allow localized heating and thus initiate thermal runaway. The challenge with incorporating shutdown mechanisms (as exist in conventional batteries) into structural systems is that the temperature-sensitivity microspheres used as previously proposed for shutdown based upon the expansion of the electrolyte thickness at high temperatures have been shown to degrade mechanical properties of the structural component [63]. An alternative approach to using temperature sensitive microspheres is to use materials that limit the current flow through increasing the resistance when the material reaches a critical temperature.

B. Thermal Management

Thermal issues generated in a structure due to heat during charge/discharge cycles, as well as potential thermal runaway events, are significant enough that thermal management must be designed into a structural battery so as to maintain structural integrity and performance [64]. Structural batteries will have to remove heat through their thickness alone, unlike conventional battery packs which use a separate cooling system. Due to the limited through-thickness thermal conductivity of carbon fiber laminates (typically between 0.5 - 1.0 W/m·K), an alternative approach to enhance thermal management of structural batteries is necessary [65]. The addition of graphene nanoplatelets or carbon nanotubes into a polymer electrolyte may significantly improve (by 200 - 300%) the thermal conductivity of the composite material while maintaining both ionic transport and structural/mechanical properties.

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C. Mechanical Damage and Failure Modes

Thermal issues generated in a structure due to heat during charge/discharge cycles, as well as potential thermal runaway events, are significant enough that thermal management must be designed into a structural battery so as to maintain structural integrity and performance [64]. Structural batteries will have to remove heat through their thickness alone, unlike conventional battery packs which use a separate cooling system. Due to the limited through-thickness thermal conductivity of carbon fiber laminates (typically between 0.5 - 1.0 W/m·K), an alternative approach to enhance thermal management of structural batteries is necessary [65]. The addition of graphene nanoplatelets or carbon nanotubes into a polymer electrolyte may significantly improve (by 200 - 300%) the thermal conductivity of the composite material while maintaining both ionic transport and structural/mechanical properties.

D. Crashworthiness

Structural Automotive Batteries (SABs) must have a similar crash safety performance as existing vehicles. SABs must be designed so they will not create electrical hazard in the event of an energy absorbing impact event. The challenge is to design the SAB to absorb energy through controlled, progressive damage mechanism to dissipate kinetic energy without creating the possibility of electrode contact or thermal runaway. Crash simulation studies of automotive floor structures that contain SABs indicate that when properly engineered, the energy absorbing capability of these systems can approach those found in current conventional vehicle structures; while preventing electrochemical hazards. A number of key engineering strategies are required for successful implementation of SABs including compartmentalizing the system to prevent short circuits; providing multiple levels of electrical isolation in case of failure; and locating SABs strategically outside areas where crushing is likely to occur.

X. CONCLUSIONS

Batteries that serve both as an electrical source and structural component in vehicles can significantly reduce mass in EV's (electric vehicles) while improving the overall energy efficiency through multifunctional designs. Laboratory scale demonstration of structural battery feasibility has been accomplished through various means including carbon fiber electrodes, structural polymer electrolytes, and multi-functional architectural demonstrations; with laboratory scale structural battery demonstration having achieved the following characteristics: elastic modulus range of 10-50 GPa, and specific energy ranges of 30-80 Wh/kg. Despite these recent advancements, there is still much to be accomplished prior to commercial deployment. The main areas requiring additional advancement to achieve the necessary conditions to allow for commercial use of structural batteries include:

1. Improvement in performance: Increasing the specific energy of structural batteries to values greater than 100 Wh/kg, and increasing their elastic modulus to values greater than 40 GPa by developing new materials and architectures.

2. Improvement in durability: Developing structural batteries capable of retaining at least 80% of their capacity after being cycled at least 1500 to 2000 times under a combination of electrochemical and mechanical loads.

3. Development of scalable manufacturing techniques: Development of low-cost, large-volume manufacturing processes that will produce structural batteries at production costs less than $200/kWh.

4. Safety validation: Comprehensive testing and certification of structural batteries to demonstrate that they are at least equal to, if not better than, current conventional battery systems in terms of safety.

5. System integration: Developing vehicle architectures that take full advantage of the properties of structural batteries while satisfying all regulatory and performance requirements.

As can be seen from this example, the intersection of the fields of materials science, electrochemistry, and structural engineering involved in the development of structural batteries represents the type of interdisciplinary collaboration needed to develop the next generation of vehicle technologies. Although significant technological barriers exist to overcome before structural batteries can become commercially viable, the potential benefits of 20-30% reductions in vehicle mass and improvements in energy efficiency provide sufficient motivation to continue researching and developing structural battery technology. Successful commercialization of structural battery technology has the potential to revolutionize not just electric vehicles, but many other applications where mass and volume are key limiting factors.

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