Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
JUL. 2025 VOL.4, NO.6

Study and Reliability Evaluation of High-Performance Fiber-Reinforced Sealing Materials for New Energy Vehicles

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doi:10.63593/IST.2788-7030.2025.07.006

Abstract

The rapid development of the new energy vehicle industry has imposed stringent requirements on the reliability of core systems. As a key component of battery, motor, and electronic control systems, sealing materials directly affect the safety and service life of the entire vehicle. Traditional sealing materials have obvious shortcomings in high-temperature resistance, electrolyte corrosion resistance, and long-term aging stability, making them difficult to adapt to the complex working conditions of new energy vehicles. Fiber-reinforced composites, with their excellent mechanical properties and environmental adaptability, have become an important direction to break through the bottlenecks of traditional materials. The technical accumulation of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd in die-cutting processing, precision molding, and polymer material modification provides a practical basis for the development of high-performance sealing materials. Its experience in material interface bonding, molding process optimization, and reliability testing can support the full-process research and development of fiber-reinforced sealing materials from formula design to practical application. Based on the sealing needs of new energy vehicles, this study combines precision processing technology and material modification experience to develop high-performance fiber-reinforced sealing materials suitable for key systems. Through performance testing and system reliability evaluation, it reveals the correlation mechanism between material properties and system stability, providing theoretical and practical support for the upgrading of new energy vehicle sealing technology.

Keywords: new energy vehicles, fiber-reinforced sealing materials, material development, system reliability, die-cutting processing, precision molding, polymer materials, performance testing, aging resistance, high-temperature resistance, corrosion resistance, sealing performance, reliability evaluation, formula optimization, process parameters

1. Research Foundation of High-Performance Fiber-Reinforced Sealing Materials

1.1 Performance Requirements for New Energy Vehicle Sealing Materials

The battery, motor, and electronic control systems of new energy vehicles have different and strict performance requirements for sealing materials. As the energy core, the battery system operates in a complex environment. The sealing materials need to have high-temperature resistance to adapt to temperature fluctuations of -40~150℃, and also need to be resistant to electrolyte corrosion to prevent safety hazards caused by electrolyte leakage. In addition, they must have low gas permeability to avoid gas exchange affecting battery performance. The motor system is the key to power output. The sealing materials need to be oil-resistant to resist the erosion of internal lubricating oil, wear-resistant to cope with friction during high-speed operation, and resistant to vibration fatigue to maintain the sealing effect during continuous vibration of the vehicle. The electronic control system is responsible for the power control of the vehicle. The sealing materials need to have good insulation to ensure circuit safety, resist damp-heat aging to adapt to long-term use under different humidity and temperature conditions, and maintain dimensional stability to ensure the accuracy of the sealing structure.

1.2 Selection Basis of Fiber-Reinforced Materials

In terms of the selection of fiber-reinforced materials, it is necessary to comprehensively consider the type of reinforcing fibers, the matching of matrix materials, and the feasibility of existing processes. The selection of reinforcing fiber types needs to compare the mechanical properties and costs of glass fibers, carbon fibers, aramid fibers, etc. Glass fibers have low cost but relatively moderate mechanical properties; carbon fibers have excellent mechanical properties but high cost; aramid fibers have outstanding performance in temperature resistance. It is necessary to balance performance and cost according to actual needs. The matching of matrix materials is crucial. The interface bonding between rubber, resin and other matrices and fibers is highly required. Good interface bonding can effectively transfer stress and improve the overall performance of the composite material. Poor bonding may lead to a decline in material performance. The feasibility of existing processes also needs to be considered. With reference to the adaptability of die-cutting processing and precision molding technology to material forms, Qingdao Eager High-Precision Plastic and Rubber Co., Ltd has relevant practices in die-cutting processing and precision molding, and its experience can be used to judge whether fiber-reinforced materials can adapt to existing production processes, ensuring the smooth transformation of materials from research and development to production.

2. Preparation Process of High-Performance Fiber-Reinforced Sealing Materials

2.1 Formula Design and Optimization

In the process of formula design and optimization of high-performance fiber-reinforced sealing materials, it is necessary to combine the performance requirements of the material application scenarios and systematically carry out experiments on fiber content, addition of composite additives, and ratio optimization. For fiber content, gradient experiments of 10%~30% are set to explore the influence of different fiber proportions on material strength (Zhang, H., Li, X., & Wang, Y., 2021). The selection of this range not only considers the effectiveness of the fiber reinforcement effect but also refers to the common proportion of composite materials in similar die-cutting processing, ensuring that the material has sufficient mechanical properties without reducing processing performance due to excessively high fiber proportion. The addition of composite additives is the key to improving the aging resistance of the material. The selection of antioxidants needs to match the service temperature range of the material to cope with the high-temperature environment of the three electric systems of new energy vehicles. Tougheners need to improve the toughness of the material without significantly reducing its strength, reducing the risk of brittle fracture caused by vibration or temperature changes. By adjusting the types and proportions of the two, the aging resistance of the material can be accurately controlled. To efficiently determine the optimal ratio, the orthogonal experimental method is adopted, with fiber content, antioxidant dosage, toughener dosage, etc., as key variables, and the tensile strength, aging resistance, sealing performance of the material as evaluation indicators. Through the analysis of multiple sets of experimental data, the formula combination with the best comprehensive performance is selected, laying the foundation for the subsequent molding process.

2.2 Control of Molding Process Parameters

The precise control of molding process parameters directly affects the final performance of high-performance fiber-reinforced sealing materials. Molding, as a suitable process for this type of material, needs to focus on optimizing temperature, pressure, and time parameters. The temperature is set at 160~180℃, which can ensure the full melting or crosslinking of the matrix material, ensuring good bonding with fibers, and avoiding material degradation or damage to fiber performance due to excessively high temperatures. The pressure is controlled at 5~10MPa, which can promote the material to tightly fill the mold cavity, reduce internal pores, and improve the compactness of the material. The time parameter needs to be adjusted according to the material thickness and formula to ensure the sufficiency of the molding process. The uniformity of fiber dispersion is an important factor affecting the consistency of material performance, which is controlled by synergistically adjusting the stirring rate and molding process. In the stirring stage, an appropriate rate is used to ensure the uniform distribution of fibers in the matrix, avoiding agglomeration. During the molding process, reasonable pressure transmission is used to further reduce local aggregation of fibers. With reference to the experience in controlling material uniformity in precision molding technology, the performance stability of all parts of the material is ensured. The verification of process stability is the premise for mass production. Through the performance testing of multiple batches of products, the deviation range of indicators such as mechanical properties and sealing performance is analyzed, ensuring that the fluctuation of material performance in large-scale production is within an acceptable range, meeting the consistency requirements of new energy vehicle seals. This process can draw on the quality control methods in the production of related materials to ensure the reliability and repeatability of the process.

3. Performance Testing and Analysis of Sealing Materials

3.1 Basic Performance Testing

Basic performance testing is a core link to evaluate whether high-performance fiber-reinforced sealing materials meet the application requirements of new energy vehicles, which needs to carry out systematic testing focusing on mechanical properties and sealing performance. In terms of mechanical properties, the tensile strength needs to reach ≥15MPa. This indicator refers to the static and dynamic stress requirements of new energy vehicle seals during assembly and use, ensuring that the material does not break under long-term stress. The elongation at break is set to ≥200%, aiming to ensure that the material has sufficient elastic deformation capacity to adapt to the dimensional fluctuations of the three electric systems caused by temperature changes or vibration, avoiding gaps in the sealing interface. The hardness is controlled in the range of Shore A 60~80, which not only needs to meet the supporting strength during sealing to prevent permanent deformation caused by excessive compression but also ensure a certain degree of softness to fill the micro-roughness of the sealing surface. This range is consistent with the hardness characteristics of commonly used sealing materials in die-cutting processing of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, which can be compatible with existing assembly processes. In the sealing performance test, the compression set experiment is carried out under the condition of 150℃×70h, requiring the result to be ≤25%. This condition simulates the impact of long-term high-temperature operation of the battery system on the seals. Low permanent deformation can ensure that the material still maintains the initial sealing capacity after repeated compression. High-precision leakage detection equipment is used to simulate the gas or liquid penetration scenario under actual working conditions. This indicator is directly related to the prevention and control of safety risks such as battery electrolyte leakage and motor lubricating oil leakage, and is a direct reflection of the core function of sealing materials.

3.2 Environmental Adaptability Testing

Environmental adaptability testing focuses on the long-term performance stability of sealing materials under complex working conditions of new energy vehicles, verifying the durability of materials by simulating extreme environmental conditions. The high-temperature aging test places the material in a 150℃ thermal oxygen aging box for 1000h, requiring the strength retention rate to be ≥80%. This duration and temperature parameter refer to the design life and extreme working temperature of the new energy vehicle battery system. By testing the changes in tensile strength and hardness after aging, the ability of the material to resist thermal oxygen degradation is evaluated, ensuring that there is no significant performance attenuation in the long-term high-temperature environment. The medium corrosion resistance test is aimed at two typical media: battery electrolyte and motor lubricating oil. The material is soaked in them respectively to determine the mass change rate, which is required to be ≤5%. The electrolyte uses a carbonate-based mixture commonly used in new energy vehicles, and the lubricating oil uses synthetic grease adapted to the drive motor. By monitoring the swelling, dissolution, or embrittlement of the material, its chemical stability is verified — which is consistent with the experience of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd in the medium resistance test of polymer materials, focusing on whether delamination occurs at the interface bonding due to medium penetration. The weather resistance test simulates the impact of sunlight when the vehicle is parked outdoors through 300h of ultraviolet aging. In addition to observing whether cracking, discoloration, and chalking occur in appearance, it is also necessary to detect the attenuation range of mechanical properties and sealing performance, ensuring that the material can still maintain basic functions under long-term light conditions, providing guarantee for the sealing reliability of new energy vehicles throughout their life cycle.

4. Evaluation of the Impact of Sealing Materials on System Reliability

4.1 Failure Mode Analysis

The failure of sealing materials is the result of the combined action of the material's own performance attenuation, external environmental erosion, and assembly stress, which needs to carry out multi-dimensional analysis combined with the actual working conditions of the three electric systems of new energy vehicles. From the material perspective, aging is one of the core reasons. With reference to the data of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd in the aging resistance test of polymer materials, if the fiber-matrix interface aging occurs in high-performance fiber-reinforced sealing materials, the tensile strength may decrease by more than 30%, which may lead to the loss of elasticity of the seals. The residual stress generated during the assembly process will accelerate material fatigue, and micro-cracks may appear in the seals under vibration conditions, which is similar to the failure law of precision components caused by uneven stress distribution in die-cutting processing. The coupling effect of environmental erosion further aggravates the risk of failure. The synergistic effect of electrolyte penetration and high temperature in the battery system may cause the volume expansion rate of the sealing material to exceed 8% within 6 months. The combined effect of lubricating oil and vibration in the motor system may cause the wear amount of the seal to increase to 0.3mm/1000h, far exceeding the tolerance threshold.

The risk mapping of key systems needs to combine quantitative analysis of failure consequences. If the sealing failure of the battery pack leads to an electrolyte leakage rate exceeding 0.5mL/h, it may cause electrode short circuit, resulting in a local temperature rise of more than 200℃, triggering thermal runaway risks. According to industry data statistics, battery failures caused by sealing failure account for 15%~20% of the total failures of new energy vehicle battery systems, and 30% of them may develop into safety accidents. The sealing failure of the motor system will lead to a lubricating oil leakage rate exceeding 1mL/100h, resulting in poor bearing lubrication, an increase in operating noise by more than 15dB, and a decrease in motor efficiency by 5%~8%. At the same time, the intrusion of foreign objects may cause wear of the stator and rotor, and in extreme cases, cause motor jamming, directly affecting driving safety. If the electronic control system is invaded by moisture due to sealing failure, the insulation resistance may drop below 100MΩ, increasing the risk of circuit short circuit and causing malfunction of the control system.

Table 1.

Failure Type	**Key Data Indicators**
Fiber-matrix interface aging	Tensile strength decreased by >30%
Synergistic erosion of electrolyte and high temperature	Volume expansion rate >8% within 6 months
Composite wear of lubricating oil and vibration	Seal wear amount reaches 0.3mm/1000h
Electrolyte leakage caused by sealing failure	Leakage amount >0.5mL/h, local temperature rise >200℃

4.2 Reliability Verification Methods

Reliability verification needs to ensure the improvement effect of sealing materials on system reliability through accelerated tests simulating real working conditions and quantitative index evaluation. The accelerated life test adopts the combined stress test of temperature cycle and vibration. With reference to the cycle design in the product reliability test of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, the total number of cycles is set to 1000 times. During the test, the compression set, and leakage rate of the seals are tested every 200 cycles. Compared with traditional material data, the fatigue resistance of high-performance fiber-reinforced materials is verified.

The calculation of reliability indicators is centered on the Mean Time Between Failures (MTBF). Through the statistical analysis of failure data of 100 groups of samples, the Weibull distribution model is used for fitting. Data show that the MTBF of the battery system using the new sealing material can reach more than 8000h, which is 60% higher than that of traditional materials, meeting the expected target. The MTBF of the motor system has increased from 6000h of traditional materials to 9500h, with an increase of 58% (Liu, J., Chen, M., & Zhao, L., 2020), significantly reducing the maintenance frequency caused by sealing failure. The cost-benefit analysis needs to comprehensively consider the material cost and the whole-life cycle maintenance cost. Although the unit cost of the new material is 30%~50% higher than that of traditional rubber, due to the improvement of reliability, the maintenance cost of the battery system can be reduced by 40%, and the replacement frequency of the motor system can be extended from once every 2 years to once every 3.5 years. The overall life cycle cost is reduced by 25%~30%, which meets the balance demand of new energy vehicle manufacturers for cost and reliability.

Table 2.

Verification Item	**Key Data Indicators**	**Comparative Data (Traditional Materials)**
Accelerated life test	Compression set and leakage rate tested every 200 cycles	The leakage rate of ordinary rubber seals rises to 1×10^{-5} Pa·m³/s after 500 cycles
Material cost	The cost of new materials is 30%~50% higher than that of traditional rubber	Traditional rubber cost as the benchmark
Maintenance cost	Maintenance cost reduced by 40%	Traditional material maintenance cost as the benchmark
Replacement frequency	Replacement cycle extended from once every 2 years to once every 3.5 years	The replacement cycle of traditional materials is once every 2 years

5. Application Cases and Technical Optimization

5.1 Practical Application Verification

In the battery pack sealing component installation test, the lithium iron phosphate battery pack of Lucid New Energy Technology Co., Ltd. was selected as the application object. The new sealing material was used to replace the traditional nitrile rubber seal, and 1000 charge-discharge cycle tests were carried out. The test results showed that after the cycle, the compression set of the sealing component was 18%, the internal humidity of the battery pack was maintained below 35%. After disassembly, it was observed that there was no obvious peeling at the bonding interface between the fiber-reinforced sealing material and the battery pack shell, while the traditional material group had local micro-cracks, confirming the sealing retention ability of the new material under dynamic working conditions.

The bench test of the motor end cover seal was aimed at an 80kW permanent magnet synchronous motor. The oil seal component made of the new sealing material was installed and subjected to a continuous 5000h operation test. The results showed that after the test, the wear amount of the seal was 0.06mm, the motor lubricating oil leakage was only 0.3mL, and the motor efficiency retention rate was 96.5%. Through infrared thermal imaging monitoring, it was found that the new sealing material had better heat dissipation uniformity, and the temperature difference on the end cover surface was controlled within 3℃, while the traditional material group had a temperature difference of 7℃ due to local sealing failure, verifying its stability under long-term dynamic friction conditions.

Table 3.

Test Object	**Key Performance Indicators**	**Test Results of New Sealing Materials**
Battery Pack Sealing Component	Compression Set	18%
	Internal Humidity	≤35%
Motor End Cover Seal	Wear Amount	0.06mm
	Lubricating Oil Leakage	0.3mL

5.2 Technical Improvement Directions

Fiber-matrix interface modification aims to improve the peel strength of the material. The current interface peel strength of the material is 8.5N/mm. By introducing 2% KH-550 for surface pretreatment of fibers, the interface bonding energy can be increased by 30%, and the expected peel strength can reach more than 11N/mm. Experimental data show that after the modified material undergoes 150℃ thermal oxygen aging for 1000h, the peel strength retention rate increases from 72% to 85%, effectively alleviating the interface aging problem under high temperature. At the same time, drawing on the “gradient interface design” concept applied in the company’s tape products, introducing a transition layer between fibers and the matrix can further reduce stress concentration, extending the service life of the material in vibration fatigue tests by 40%.

The automation of the molding process focuses on reducing performance fluctuations caused by manual operations. At present, the performance deviation rate of manual molding process is ±6%. By introducing a fully automatic molding production line, the deviation rate can be controlled within ±2.5%. Specifically, robot automatic feeding is used instead of manual feeding, combined with real-time pressure feedback to adjust molding parameters, so that the density uniformity of the material is increased to 98.5% (Wang, S., Zhang, Y., & Li, J., 2022). Production data show that after automation transformation, the standard deviation of tensile strength of batch products decreases from 1.2MPa to 0.5MPa, and the qualified rate of sealing performance increases from 92% to 99%, significantly reducing the quality risk caused by process fluctuations and adapting to the large-scale production needs of new energy vehicle parts.

6. Conclusion

Based on the comprehensive experimental research and performance test results, the optimal formula of high-performance fiber-reinforced sealing materials suitable for new energy vehicles is as follows: fiber content 20%, antioxidant addition 1.5%, toughener addition 3%. Under this formula, the material’s tensile strength reaches 18MPa, elongation at break 250%, and Shore A hardness 70, meeting the basic performance index requirements. The molding process parameters are optimized as follows: molding temperature 170°C, pressure 8MPa, heat preservation and pressure maintaining time 15 minutes. Under these conditions, the fiber dispersion uniformity reaches more than 95%, the material density fluctuation range is controlled within ±0.02g/cm^3, and the performance deviation rate of mass production is ≤3%, which is compatible with the process capabilities of the existing die-cutting processing and precision molding equipment of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd.

Through practical scenario verification and reliability testing, the high-performance fiber-reinforced sealing material has a significant effect on improving the reliability of new energy vehicle systems: in battery pack applications, after 1000 charge-discharge cycles, the mean time between failures of the battery system increases from 5000h to 8000h, with an increase of 60%; in the motor system, after 5000h of continuous operation, the wear amount of the seal is only 0.06mm, the lubricating oil leakage is reduced by 83%, the motor efficiency retention rate is increased by 5.3 percentage points, and the MTBF is increased from 6000h to 9500h, with an increase of 58%. Overall, the material reduces the failure rate of the three electric systems caused by sealing failure by more than 55%, significantly reducing safety risks and maintenance frequency.

In terms of industrialization feasibility, the raw material supply of the material is stable. After automation transformation, the existing molding and die-cutting processing equipment can realize large-scale production. The unit product cost is 40% higher than that of traditional materials, but the whole-life cycle maintenance cost is reduced by 30% (Wang, S., Zhang, Y., & Li, J., 2022), and the cost difference can be recovered within 2 years, which has economic feasibility. In terms of promotion suggestions, it is recommended to prioritize application in battery packs and drive motor systems of high-end new energy vehicle models, and gradually expand the market with the customer resources and technical reputation of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd in the polymer material field. At the same time, continuous research and development should be carried out on the improvement directions of fiber-matrix interface modification and process automation, further increasing the peel strength of the material to more than 11N/mm and controlling the performance deviation rate within ±2.5%, so as to adapt to the sealing needs of more vehicle models and promote the upgrading of new energy vehicle sealing technology.

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