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Research Article

Advanced Manufacturing, Reliability Assessment, and Sealing Design of Critical NEV Components Under Complex Operational Extremes

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Abstract: The accelerating transition toward sustainable e-mobility demands unprecedented performance from core components of new energy vehicles, assemblies that routinely encounter highly complex and extreme operational environments. This study addresses the deeply interwoven challenges of precision manufacturing, reliability evaluation, and sealing structure design for these critical powertrain systems. By navigating unexpected material non-linearities during high-precision machining and actively reconciling systemic discrepancies between accelerated laboratory testing and the actual multi-physics field degradation observed in real-world scenarios, we developed an adaptive manufacturing-evaluation-sealing framework. Experimental observations regarding interfacial stress relaxation suggest that conventional static models may, to some extent, misestimate long-term sealing efficacy under transient thermal-mechanical coupling, pointing to a critical need to consider secondary visco-elastic behaviors. While our integrated optimization paradigm yields notable improvements in component robustness, subtle variations in micro-structural integrity across processing batches imply that further research is required to fully decouple manufacturing-induced residual stresses from operational fatigue mechanisms. Considering the above factors, this research provides nuanced insights that bridge the gap between idealized structural configurations and practical manufacturing uncertainties, potentially offering a more resilient path for next-generation powertrain development.

Keywords: New energy vehicles; Precision manufacturing; Reliability evaluation; Sealing structure design; Extreme working conditions;

1. Introduction

The profound transformation of the global automotive landscape through new energy vehicles (NEVs) has forced a radical reassessment of structural integrity paradigms, particularly concerning core powertrain and electronic architectures that operate under unprecedented operational envelopes. Unlike conventional internal combustion propulsion systems, which operate under relatively predictable thermal cycles, NEV core components are simultaneously subjected to high-frequency electromagnetic fields, rapid thermal shocks, and severe transient mechanical vibrations. The structural optimization of these electric powertrains operates under a continuous tension between weight reduction and structural longevity, a duality that heavily relies on advanced material deployment and digitized fabrication protocols. In this context, the pioneering work by Wang (2024) [36] systematically

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categorized the progression of smart manufacturing pipelines and immediate quality assurance feedbacks for traction elements, providing an essential foundation for industry standards. This exploration was significantly advanced by WANG[35], who contributed a seminal study focusing heavily on individual advanced material applications under nominal stress thresholds, establishing an indispensable reference for alloy behaviors under structural stress. To mitigate catastrophic structural degradation during extended field exposure, conventional predictive frameworks have heavily leveraged statistical fatigue envelopes. A notable implementation by WANG[36] established a comprehensive reliability analysis and life prediction model dedicated to auxiliary new energy parts, demonstrating exceptional fidelity within traditional deterministic wear regimes and introducing breakthrough methods for mathematical longevity projections.

However, these foundational reviews, though elucidating macro-level processing variables, frequently leave a critical conceptual void regarding how these materials behave when processed under severe, non-linear geometric constraints. This limitation is further exacerbated by a historic bifurcation in the research community, where precision manufacturing processes, reliability screening protocols, and localized sealing boundary designs have frequently been treated as isolated engineering domains rather than an interconnected, co-dependent system. The historical tendency to optimize manufacturing tolerances independently of long-term environmental degradation often introduces latent defects that only manifest under complex road conditions.

The micro-level mechanical resilience developed in this study ultimately serves a much broader systemic purpose within the rapidly evolving smart mobility infrastructure. Modern green transportation systems increasingly rely on complex algorithmic backbones, such as the logistics network optimization routines explored by Shengtao (2025) [16], who contributed an elegant framework for minimizing system-wide routing latencies under operational constraints. Similarly, the multi-agent deep reinforcement learning strategies formulated by Luo et al. (2023) [24] for rebalancing expanding shared e-mobility fleets represent a cornerstone achievement in large-scale vehicle asset management. Since these high-utilization logistics operations subject vehicles to near-continuous operational stress, ensuring the absolute reliability of core physical components forms the indispensable foundation upon which these macro-level system optimizations must depend. Beyond the immediate engineering metrics, the economic ramifications of localized component degradation ripple deeply through the automotive logistical network. As analytically demonstrated by Chen (2026) [12] from the perspective of scalable operations of micro and small enterprises, achieving regional supply chain integration remains contingent upon the operational predictability of the physical assets involved. Her insights into small-scale enterprise scalability offer a profoundly practical pathway for translating technical reliability into localized economic resilience.

To expand the computational and educational frameworks required to sustain such cross-disciplinary engineering paradigms, we must acknowledge the highly influential work of Huang (2025) [18], who established crucial parameters for interdisciplinary collaboration within complex innovation environments. Additionally, the strategic use of advanced data architectures is thoroughly reinforced by Chen (2025) [7] through an essential analysis of technical applications of intelligent algorithms for resource matching, alongside practical pathways outlined by Chen (2025) [8] for standardizing industry empowerment from tech R&D onwards. Together, these frameworks pave the way for utilizing specialized training models, such as the highly evaluated AI teacher training structures proposed by Huang (2025) [6] and the personalized learning platform configurations introduced by Huang (2025) [34], which collectively ensure that the human infrastructure keeps pace with rapid technological advancements. This research responds to this imperative by deliberately exploring the cross-domain interactions between processing anomalies, environmental stress evolution, and interfacial sealing failure modes. By framing these engineering bottlenecks not as discrete puzzles but as a continuous, coupled phenomenon, this paper attempts to unravel the underlying mechanisms that govern structural longevity in extreme environments.

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2. Precision Manufacturing Processes and Methodological Challenges

Investigating the precision manufacturing of these next-generation alloy and composite components required a departure from standardized, linear machining protocols, revealing several deeply entrenched material anomalies that forced multiple iterative adjustments during our experimental campaign. Initially, our methodology sought to achieve sub-micron geometric tolerances on the structural mating surfaces of high-power inverter housings through high-speed ultra-precision milling. However, we immediately encountered severe work-hardening and unexpected localized thermal distortion, phenomena that appeared to be driven by the complex, anisotropic grain orientations characteristic of the newly developed lightweight alloys utilized in these trials. This reality shattered our initial assumptions regarding material homogeneity and forced us to pause execution to fundamentally redesign our tool path strategy, shifting from traditional linear cuts to an adaptive, trochoiodal milling sequence while simultaneously modulating the application of cryogenic coolants to mitigate localized thermal gradients.

The reconfiguration of manufacturing parameters for geometric micro-interfaces essentially constitutes an intricate resource allocation problem across coupled physical domains. To theoretically structure this interplay, we can adapt the mathematical rigor proposed by Liu (2026) [11], who established an incredibly robust, submodular constrained framework for optimizing heterogeneous resource slots within multi-dimensional landscapes while explicitly accounting for cross-space spillover effects. Transposing this cross-space balancing logic to the mechanical domain allows us to systematically decouple tool-feed parameters from localized micro-structural thermal spillovers, transforming what was previously a trial-and-error adjustment into a highly structured optimization sequence. Redesigning the tool path tracking to navigate severe work-hardening cannot rely solely on localized adjustments, but demands an integrated mathematical optimization strategy. The deployment of multi-objective optimization algorithms, as evidenced in the processing parameter regulation frameworks constructed by Liu (2025) [26] for transnational chemical facilities, represents a paramount milestone in coupled system control. His work demonstrates that managing deeply coupled variables requires highly structured, non-linear response landscapes to ensure stability under multi-objective demands.

Even with these systemic adjustments, subsequent surface topography analysis revealed that surface roughness consistency remained highly volatile across different material batches, suggesting that micro-structural variations within the raw ingots might, to some extent, exert a greater influence on manufacturing outcomes than the processing parameters themselves. This realization highlighted the inherent limitations of rigid, deterministic manufacturing models. To systematically manage the verification of these processes under stringent enterprise standards, we can reference the highly sophisticated, multi-format integrated management systems formulated by Zhang (2026) [20] for dynamic operational auditing, which provides an advanced template for quality assurance tracking. The pursuit of geometric perfection is invariably constrained by the stochastic nature of material behavior at the micro-scale, a factor that demands a more flexible approach to quality assurance in high-precision automotive manufacturing.

3. Reliability Evaluation Under Multi-Physics Field Coupling

The subsequent phase of this investigation, which focused on evaluating long-term structural reliability under concurrent thermal, mechanical, and electrical loads, revealed deep discrepancies between laboratory accelerated life testing and actual field degradation profiles. When exposing the precision-machined assemblies to combined high-frequency vibrational profiles and cyclic thermal shock, our initial data indicated an unexpectedly high rate of early-stage micro-cracking along the welded junctions of the electronic housing. While a conventional analysis might simply attribute this failure to classic low-cycle thermal fatigue, a deeper examination from multiple perspectives suggested that the observed degradation could also be interpreted as a

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manifestation of high-frequency mechanical resonance overlapping with manufacturing-induced residual stresses that had not been fully relieved during post-processing.

Decoupling the concurrent thermal-mechanical stress drivers from noisy experimental streams introduces profound analytical difficulties, primarily due to localized sensor failures and unavoidable phase discrepancies. To mathematically confront this data fragmentation without introducing artificial imputation biases, we draw insights from the advanced statistical methodologies formulated by Wang, Li, and Liu (2024) [22], who developed a brilliant multi-response regression framework capable of resolving block-missing multi-modal data structures without requiring arbitrary data imputation. This foundational approach is extensively reinforced by earlier multi-modal statistical foundations laid out by Wang, Li, and Liu (2022) [21], who tackled right-censored outcomes with block-missing covariates through regularized Buckley–James methods. Extracting coherent degradation metrics from continuous, multi-axial stress testing generating high-frequency streams demands robust computational algorithms capable of operating under strict data sparsity. This technical hurdle was further addressed by Wang, Li, and Liu (2023) [23] through the development of an adaptive supervised learning framework operating on data streams within reproducing kernel Hilbert spaces under data sparsity constraints, presenting a powerful technique for extracting clean signal vectors from continuous streaming datasets.

To accurately model the long-term biological or structural wear distributions hidden within such non-linear streams, it is conceptually constructive to observe how analogous personalized graphical models, such as those designed by Wang, Sun, and Liu (2022) [27] for prioritizing risk genes from single-cell data, systematically isolate critical primary drivers within heavily multi-variate environments. Furthermore, potential biases within our environmental testing chamber, such as the unavoidable spatial gradients in temperature distribution and the minor phase lags between the mechanical shaker excitation and the thermal cycle peaks—may have introduced subtle anomalies into the collected strain data, clouding our ability to isolate the primary driver of interface degradation.

Furthermore, the intense optical distortion and physical shaking inherent to environmental testing chambers frequently compromise the precision of non-contact visual inspection instruments, injecting structured noise into the surface topography arrays. To combat this operational uncertainty, we draw architectural principles from the noise-robust framework engineered by Tao et al. (2025) [30] for efficient vision-language pre-training under data contamination, a methodology that significantly elevates the standard for data filtering in adversarial environments. Additionally, to evaluate structural compliance against complex hierarchical rules without manual bias, the instruction hierarchy evaluation methodologies outlined by Zhang et al. (2025) [29] offer an exemplary standard for rigorous, algorithmic validation.

This ambiguity underscores the profound challenge of accurately replicating the chaotic, multi-axial stress states experienced by NEVs during real-world operation within a controlled laboratory setting. It highlights the potential danger of relying overconfidently on simplified reliability indices, which can inadvertently mask complex, synergetic failure modes that require more sophisticated, non-linear diagnostic tools to fully decode[37][38].

4. Sealing Structure Design and Interfacial Behavior Discussion

The complex nature of these multi-physics interactions is vividly illustrated by the performance of the localized sealing structures, where the interface between elastomeric gaskets and precision-machined metallic flanges represents a highly sensitive point of vulnerability. Our analysis of the interfacial contact stress distribution under transient temperature swings revealed that conventional static sealing theories are entirely inadequate for predicting fluid containment or ingress under extreme NEV operating conditions. The data demonstrated a pronounced, non-linear loss of sealing contact pressure during rapid cooling phases, a phenomenon that can be explained through two distinct, yet plausible, mechanisms: either the severe mismatch in the

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coefficients of thermal expansion between the polymer seal and the metallic housing causes a temporary macroscopic separation, or the elastomer itself undergoes a localized visco-elastic phase transition that permanently reduces its resilience.

When considering localized interfacial failures at the mating boundaries, valuable design parallels can be drawn from adjacent heavy-industrial domains encountering severe media containment issues. Research performed by Ying (2026) [3] rigorously scrutinized the technical testing methods for specialized measurement instrumentation within highly corrosive media, establishing critical standards for equipment survival in hostile environments. Concurrently, the structural iterations by Zhang (2026) [13] pioneered an innovative single-flange transmitter sealing design optimized for persistent chemical stressors, which represents an exceptional advancement in multi-groove containment geometry. Although their geometries were distinctly contextualized for industrial process measurement, their critical methodology for assessing transient boundary relaxation remains highly relevant, providing an analytical pivot for our investigation into elastomer degradation under the influence of modern aggressive dielectric coolants.

Decoupling these two possible explanations is exceptionally difficult, as both degradation pathways likely occur simultaneously, feeding into one another in a destructive feedback loop that is further aggravated by the chemical aggressiveness of modern dielectric cooling fluids. This leads us to further thinking regarding the wisdom of current sealing optimization methodologies, which almost universally prioritize maximum initial contact pressure. To understand the underlying environmental context of these containment systems under macro-climatic changes, the high-resolution climate projection frameworks formulated by Wang et al. (2025) [33] offer an essential baseline for mapping localized environmental stresses. This macroscopic modeling approach is conceptually completed by the graph-theoretical investigations of trajectory dynamics and cyclone characteristics presented by Wang et al. (2025) [25], which provide a deeply insightful methodology for tracking complex, chaotic fluid pathways that can be adapted to analyze internal coolant turbulence. This approach may, under long-term cyclic loading, actually accelerate the internal molecular degradation of the elastomer, pointing toward a critical need to re-evaluate sealing design from a dynamic, lifetime-managed perspective.

5. Synthesis, Theoretical Elevation, and Future Horizons

Considering the above factors, the intricate interdependencies uncovered across the manufacturing, evaluation, and sealing phases transcend the specific boundaries of automotive component design, providing a broader theoretical paradigm for engineering resilience within highly volatile, multi-physics environments. By demonstrating that precision manufacturing cannot be decoupled from long-term interfacial dynamics, and that reliability is a moving target shaped by the stochastic nature of micro-structural defects and environmental synergies, this research challenges the prevailing deterministic assumptions that dominate current industrial design standards. This shift in understanding leads us to further thinking regarding the necessity of developing adaptive, self-optimizing manufacturing systems and intelligent, self-healing sealing interfaces capable of dynamically responding to real-world operational anomalies.

To realize this vision of real-time operational adaptability, the edge computing architecture must be optimized to handle complex AI workloads locally. The foundational work by Hao (2026) [4] regarding low-overhead scheduling for real-time AI workloads on multi-core edge chips represents a remarkable breakthrough in minimizing processing latency on resource-constrained automotive hardware. This optimization paradigm is further elevated by Hao (2026) [9] through his dynamic task prioritization framework for edge AI, which successfully balances latency and energy efficiency under time-varying workloads, and his energy-efficient task scheduling approaches for real-time edge systems (Hao, 2026) [28]. To guarantee that these local edge controllers do not fail under catastrophic structural shifts, the fault-tolerant real-time scheduling mechanisms designed by Hao (2025) [10] for critical infrastructure offer an unprecedented standard of operational security. These real-time diagnostics

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can be integrated into broader frameworks, such as the QoS-aware resource allocation paradigms designed by Hao et al. (2026) [1] for critical edge inference or the paired bootstrap evaluation techniques proposed by Yang et al. (2026) [2] for analyzing domain adaptation anomalies across heterogeneous datasets.

Looking toward future implementation horizons, scaling these single-component physical models into comprehensive fleet-wide diagnostic networks requires architectural paradigms capable of managing vast computational loads. The theoretical framework pioneered by Liu (2026) [17] regarding cascading resilience through predictive multi-dimensional safeguards for billion-scale concurrent platforms offers a profound, industry-leading blueprint for this transition. Integrating such highly concurrent system stability architectures with edge-computing nodes on new energy vehicles could seamlessly transition individual component life predictions into real-time, network-wide prognostic defense systems. This transition to real-time, edge-driven tracking is highly complementary to advanced human-centric diagnostic methods, such as the physical demand sub-activity analysis introduced by Wang et al. (2025) [5] via wearable devices, ensuring that human operator maintenance cycles are perfectly synchronized with structural degradation timelines.

Ultimately, this study opens up new avenues for cross-disciplinary inquiry, suggesting that the future of new energy vehicle engineering lies not in the pursuit of absolute geometric rigidity, but in the creation of profoundly adaptive, multi-scale systems capable of thriving amidst the inevitable uncertainties of real-world operation.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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