





A Review of Failure Mechanisms, Simulation and Testing Methods in the Marine Transmission Systems Context

Aerk Dimria , Adil Saeed^a , Zulfiqar Ahmad Khan^{a,b,*} , Muhammad Qasim Shah^a 

^aDepartment of Design and Engineering, Bournemouth University, Poole, BH12 5BB, UK,

^bDepartment of Mechanical Engineering, New Uzbekistan University, Tashkent, Uzbekistan.

Keywords:

Marine Gearing
Tribocorrosion
Failure mechanisms
Simulation
Testing
Reliability analysis
Offshore renewable energy
Surface engineering

ABSTRACT

The operational viability of offshore renewable energy systems is constrained by the reliability of gear transmission assemblies. This paper provides an exhaustive review of state-of-the-art literature concerning marine gearing, synthesising the multi-physics synergies between mechanical loading and environmental aggression. This review characterises the technical evolution from deterministic industrial standards toward high-fidelity frameworks that account for the coupling of contact fatigue, progressive wear, and electrochemical corrosion. Key focuses include the modelling of emerging subsurface-initiated modes, such as Tooth Interior Fatigue Fracture (TIFF), through depth-dependent material property gradients and multiaxial fatigue criteria. The review evaluates advanced numerical strategies, including the Extended Finite Element Method (XFEM) for autonomous crack path prediction and Rigid-Flexible Multibody Dynamics (MBS) for resolving system-level responses to stochastic Non-Torque Loads (NTLs). Furthermore, experimental validation protocols within the Very High Cycle Fatigue (VHCF) regime and quantitative non-destructive diagnostics, such as Acoustic Emission (AE), are assessed for their role in calibrating Digital Twin and Prognostic Health Management (PHM) frameworks. Finally, considerations are proposed to guide future research, linking microscopic material integrity and macroscopic system reliability for the next generation of offshore renewable energy assets.

* Corresponding author:

Zulfiqar Ahmad Khan 
E-mail: zkhan@bournemouth.ac.uk

Received: 6 April 2026

Revised: 5 May 2026

Accepted: 9 June 2026



© 2026 Published by Faculty of Engineering

1. INTRODUCTION

The reliability of gear transmission systems underpins the operational viability of modern industrial sectors, ranging from aerospace and railway transport to industrial robotics [1]. In the

renewable energy sector, gearboxes constitute one of the most failure-prone subassemblies. Specifically, gearbox-related faults account for approximately 12% of total wind turbine failures, driving a disproportionately high share of maintenance costs and system downtime [2].

These components must endure harsh operational conditions, characterised by high temperatures, humidity, and chemical exposure, which frequently induce premature failures well before the intended design life concludes [3].

Marine environments impose additional mechanical burdens necessitating specialised structural engineering. A tribological perspective is vital in this context, as the convergence of contact stresses, corrosive seawater ingress, and lubrication challenges directly dictates system survivability. Tidal turbine gearboxes, for instance, face notably higher failure risks than wind turbine systems due to the massive torque and thrust forces generated by water density, which is approximately 850 times greater than that of air [4,5]. While tidal energy systems require robust designs to endure 20- to 25-year lifespans under high-pressure underwater conditions, offshore wind systems must withstand stochastic wind loads and the increasing aero-elastic complexities of floating platforms as installations move further offshore [2,5]. The drivetrain configuration, whether utilising fixed-speed generators or full-rated power converters, further establishes the reliability prerequisites and the magnitude of cyclic torque loads the transmission must endure [2].

Previous review articles have addressed gear and gearbox reliability through vibration-based predictions, probabilistic approaches, or isolated macroscopic failure modes; however, these studies primarily assess components operating in standard industrial environments or onshore wind turbine applications [2,3,6-11]. This review provides added value by synthesising a multi-physics perspective that couples environmental aggression, microscopic tribological degradation, and macroscopic dynamics to address reliability in marine environments, which is essential for offshore renewable energy systems.

The literature search strategy was structured using the Problem, Intervention, Comparison, Outcome (PICO) framework. Search blocks were constructed by combining keywords and synonyms using the Boolean operators AND and OR. Truncation (*) was applied to account for spelling variations and plurals. The exact search string is detailed in Table 1. To ensure broad literature coverage, all EBSCO databases were queried. Studies were subsequently included based on their relevance to gearbox reliability in offshore and marine environments.

Table 1. EBSCO search strategy.

Concept	Search string
Concept 1: Problem	Wear OR degrad*OR erosion OR fatigue OR corrosion OR deterioration OR abrasion OR decay
Concept 2: Intervention	Assess OR evaluate OR predict OR finite element OR analyse OR investigate OR model
Concept 3: Comparison	Performance OR error OR efficiency OR loss OR failure
Concept 4: Outcome	Life OR lifespan OR lifetime
Final String	#1 AND #2 AND #3 AND #4

The remainder of this paper is organised as follows: Section 2 introduces fundamental gear failure modes and initiation mechanisms, including contact fatigue, wear mechanisms, and combined corrosion-mechanical effects. Section 3 summarises advanced modelling and simulation methodologies, focusing on Finite Element Analysis (FEA), wear and fatigue modelling, Multi-Body Systems (MBS) dynamics, and crack propagation modelling. Section 4 reviews experimental testing and validation protocols, advanced diagnostic techniques for the real-time tracking of surface and subsurface degradation, and surface engineering strategies for wear mitigation and material integrity. Section 5 synthesises application-specific considerations for offshore and subsea environments and critically evaluates methodological approaches. Finally, Section 6 provides concluding remarks and recommendations for future research directions.

2. GEAR FAILURE MODES AND MECHANISMS

Modern gear engineering classifies transmission failures into three primary macroscopic modes: fatigue, wear, and deformation [1,3]. Table 2 illustrates the statistical scope of these failures, highlighting the predominance of fatigue-related breakage and surface pitting.

The degradation of gear systems is a multi-physics phenomenon in which mechanical loading, lubrication efficacy, material gradients, and environmental chemistry interact to determine component life. Traditional reliability frameworks, such as the "bathtub curve," categorise these failures into early-life infant mortality (assembly or manufacturing errors), random operational incidents, and late-stage wear-out [2]. However, as modern transmissions advance toward higher power densities, the boundaries between these stages blur,

necessitating a more granular classification based on physical initiation mechanisms.

Table 2. Statistical distribution of gear failure forms.

Failure form	Total faults (%)	Primary driver
Gear Breakage	41%	Bending Fatigue
Surface Pitting	31%	Contact Fatigue
Abrasive Wear	10%	Lubrication / Contamination
Surface Scratches	10%	Surface Distress
Other (Corrosion/Spalling)	8%	Environmental / Secondary Interaction

Source(s): Synthesised from [2]

Fatigue remains the dominant failure driver, accounting for over 70% of total faults in wind

energy and industrial applications [2]. This category is bifurcated into surface-initiated modes (e.g., micro-pitting and macro-pitting) and structural modes (e.g., root bending fatigue). Recent research highlights the essential role of the specific film thickness (Λ ratio); when $\Lambda < 1$, micro-contact induces micro-cracking and the "frosted" appearance characteristic of micro-pitting [11].

A significant shift in contemporary failure analysis is the focus on subsurface-initiated fatigue. Tooth Interior Fatigue Fracture (TIFF) and Tooth Flank Fracture (TFF) originate deep within the material, typically near the case-core boundary where residual tensile stresses interact with applied shear stresses [12,13]. Unlike surface pitting, these failures are often catastrophic and sudden, occurring without visible surface distress.

Table 3. Comprehensive classification of gear failure modes and mechanisms.

Primary Category	Secondary Category	Failure Mode	Mechanism & Technical Trigger	Identifying Characteristics	Source (s)
Fatigue	Surface Fatigue	Micro-pitting	Cyclic micro contact stress ($\Lambda < 1$) causing micro-cracking.	"Frosted" or matte grey appearance; pits 10 – 30 μ m.	[8,11]
		Macro-pitting	Subsurface shear cracks coalesce to detach material flakes.	Distinct craters/pits destroy the involute profile.	[2,3]
		Spalling	Severe coalescence of large pits or deep subsurface origins.	Large, irregular "scales" or chunks of material removal.	[14]
	Subsurface Fatigue	TIFF	Initiation at case-core boundary; common in two-way loaded gears.	Horizontal fracture plane separating the top half of the tooth.	[12,13]
		TFF	Deep initiation driven by core residual tensile stresses.	Sudden separation of flank chunks without surface wear.	[13]
Structural	Bending Fatigue	Cyclic root stress exceeds the material endurance limit.	Crack initiation at root fillet; "beach marks" visible.	[2,15]	
Wear	Adhesive	Scuffing	Elastohydrodynamic Lubrication (EHL) film breakdown leading to localised micro-welding.	Severe vertical tear marks; matte patches.	[3,8]
	Abrasive	Scoring / Scratching	Contaminants or hard particles cutting the tooth surface.	Parallel longitudinal grooves and furrows.	[3,8]
		Polishing	Fine abrasives remove surface asperities over time.	Mirror-like, shiny finish; alters profile accuracy.	[3]
Fretting	Fretting Wear	Small-amplitude oscillations at stationary interfaces.	Red/black abrasive dust ("cocoa"); interface pitting.	[3]	
Deformation	Plastic Flow	Cold Flow	Yielding due to extreme contact stress and rolling action.	Burr/fin formation at tooth tips ("wire edging").	[11]
		Rippling	High stress/low velocity "kneading" of the surface.	Wave-like formations perpendicular to sliding.	[3]
Environmental	Thermal	Tempering	Frictional heat reduces case hardness during operation.	Material softening; predisposition to plastic flow.	[3]
	Chemical	Corrosion Pitting	Electrochemical attack by moisture or acidic lubricant.	Localised pits with rust; sharp "gas spots."	[5,14]
	Combined Effects	Tribocorrosion	Combined mechanical wear and electrochemical dissolution.	Accelerated loss (Total > Wear + Corrosion).	[5]
	Hydrogen	Embrittlement	Atomic hydrogen diffusion creates brittle lattice zones.	White Etching Cracks (WEC); sudden brittle failure.	[9]

In harsh environments, such as offshore wind or tidal energy applications, chemical factors accelerate mechanical degradation. Tribocorrosion involves the combined removal of passive oxide layers by sliding contact, exposing fresh metal to rapid electrochemical attack [5]. Furthermore, the diffusion of atomic hydrogen into the metal lattice, often resulting from lubricant breakdown or moisture ingress, leads to Hydrogen Embrittlement (HE) and the formation of White Etching Cracks (WEC), a primary cause of premature failure in high-capacity bearings and gears [9]. Table 3 provides a comprehensive classification of these mechanisms.

2.1 Contact fatigue

Following gear breakage due to bending, surface contact fatigue is one of the most prevalent failure mechanisms, with pitting alone accounting for approximately 31% of documented transmission faults [2]. This failure mode involves the initiation and propagation of cracks under cyclic Hertzian contact stresses, eventually causing material detachment and surface voids [16]. Current literature differentiates between macro-pitting (visible surface craters) and micro-pitting (a localised form of surface fatigue typically associated with thin-film lubrication scenarios in wind turbine speed-increaser gearboxes) [11].

TFF and TIFC are identified as vital subsurface failure modes that diverge from traditional surface-initiated pitting. TIFC is specifically characterised by crack initiation within the interior case-core boundary or the material core, often occurring without observable surface distress. Current research designates TIFC as an emerging failure mode in modern transmissions where high power density, reduced component sizing, and stringent Noise, Vibration, and Harshness (NVH) requirements are prioritised [12].

Gear life prediction methodologies have transitioned from simple empirical S-N curves to evaluating depth-dependent material property gradients and assessing high-fidelity multiaxial fatigue criteria. The interaction between depth-dependent contact stresses and mechanical property gradients, produced by case-hardening, governs subsurface fatigue initiation [13]. Carburising reinforces surface layers with compressive residual stresses; however, this process simultaneously generates balancing tensile residual stresses within the transition zone and core [17]. Cracks initiate when the local multiaxial stress exceeds the material's depth-dependent fatigue strength, a threshold typically surpassed at the case-core interface where yield strength drops significantly [13]. Table 4 summarises the relevance of these analytical results.

Table 4. Commentary on advanced fatigue criteria methodology, results, key conclusions and contributions.

Study	Impact of multiaxial residual stress fields on subsurface failure	Influence of depth-dependent material property gradients
Methodology	Develops a numerical framework to map 3D residual stress distributions into fatigue life models.	Employs a Modified Fatemi-Socie parameter applied to a multilayered material model representing the case-core transition.
Key Results	Demonstrates that tensile residual stress peaks in the transition zone significantly reduce the fatigue threshold for interior cracking.	Quantifies the "crossover" zone at the case-core interface where yielding occurs due to the drop in local hardness/strength.
Primary Conclusion	Neglecting the multiaxial nature of residual stress leads to overestimating the reliability of carburised gears in high-load applications.	The case-core interface remains the most critical structural bottleneck, necessitating optimized carburizing depths to align peak stress with peak strength.
Strategic Contribution	Offers a refined stress-superposition method for high-fidelity gearbox Digital Twins.	Establishes the relationship between manufacturing-induced gradients and the risk of sudden, brittle subsurface fracture.

Source(s): Synthesised from [13,17]

Recent analysis further demonstrates that TIF cracks in automotive differential gears often form near the middle of the tooth width [12]. This localised initiation stems from the complex multiaxial stress state and the non-uniform distribution of residual stress components along the tooth width and rolling directions [17].

In carburised gears, the contact fatigue limit depends on depth-dependent mechanical properties produced during case-hardening [13]. Advanced models utilise thin-slicing techniques to divide the tooth into layers, determining specific fatigue parameters for each layer based on hardness and residual stress profiles [16]. Higher surface hardness increases resistance to micro-deformation and pitting, but the hardness gradient dictates the permissible shear stress depth [16]. Initial compressive residual stresses at the surface inhibit crack initiation by reducing the mean cycle stress. Conversely, balancing tensile residual stresses in the subsurface transition zones (where the case meets the core) can accelerate subsurface crack propagation [13,17].

Manufacturing processes can also introduce cracks and inclusions that act as local stress concentrators, promoting subsurface crack initiation. Ultrasonic inspection, a widely used Non-Destructive Testing (NDT) method, plays a key role in detecting these flaws early [18]. For large-scale applications, such as maritime azimuth thrusters, gears are designed for operational lifespans exceeding 25 years, necessitating analysis within the Very High Cycle Fatigue (VHCF) regime [18]. Total life prediction now encompasses both the initiation and propagation phases. Crack initiation is forecasted using multiaxial criteria (Brown-Miller/Fatemi-Socie) that consider surface roughness and EHL film thickness [13,16]. Crack propagation is predicted via the Extended Finite Element Method (XFEM) based on Linear Elastic Fracture Mechanics (LEFM). XFEM simulations demonstrate that cracks often propagate toward the tooth flank or root, depending on the instantaneous load-sharing ratio and material property gradients [16].

2.2 Wear mechanisms

Wear is an inevitable progressive material loss process accounting for approximately 10% of

documented gear failures [2]. In industrial applications, wear is treated as a dynamic degradation phenomenon driven by lubricant film breakdown or the introduction of foreign particles into the meshing zone [8]. Modern approaches for predicting abrasive wear centre on Archard's wear model, which correlates material removal with contact pressure and sliding distance. The theoretical basis is established by the Archard wear equation [19]:

$$\frac{dh}{ds} = k_D \times p \quad (1)$$

In this formulation, h denotes the wear depth, s represents the relative sliding distance, p is the contact pressure, and k_D is the wear coefficient. Research indicates that k_D is not a static material constant but a complex function of environmental conditions and lubrication regimes. In micro-gears and precision transmissions, local wear depth is predicted by integrating this equation with FEA contact solutions, allowing for the simulation of geometry evolution over millions of cycles. This methodology applies to macro systems when paired with relevant tribological experiments to identify the wear model.

The EHL state, quantified by the oil film thickness-to-surface roughness ratio (Λ ratio), serves as a reliable indicator of wear severity [8]. Analysis of high-performance gearboxes demonstrates that wear rates are non-linearly related to this ratio [11]. Table 5 summarises this relationship.

Table 5. Influence of lubrication regimes on wear severity.

Lubrication Regime	Λ Ratio Range	Wear Mechanism & Severity
Low lubrication	$\Lambda < 0.5$	Significant micro contact; high adhesive/abrasive wear rates.
Operating lubrication	$0.5 < \Lambda < 4$	Occasional micro contact; moderate progressive wear.
Full lubrication	$\Lambda > 4$	Surfaces fully separated; wear is negligible ($k_D \approx 0$).

Source(s): Synthesised from [8,11]

Plastic deformation during the initial running-in phase generates significant residual effects, which facilitate the early formation of surface-initiated cracks even before the system establishes a steady-state EHL film [11].

Furthermore, wear-induced material removal is non-uniform across the gear tooth flank. Analytical models and experimental observations confirm that wear depth is minimal near the pitch line, where relative sliding velocity is zero, and reaches its maximum at the tooth root and tip [8]. This non-uniform removal introduces a Geometric Transmission Error (GTE), which consequently modifies the Time-Varying Mesh Stiffness (TVMS) [1].

Wear rarely occurs as an isolated event; instead, it frequently accelerates secondary failure modes through complex coupling mechanisms. Progressive wear modifies the tooth profile, shifting the centre of pressure and amplifying the bending moment at the tooth root. This interaction intensifies root stresses, thereby accelerating the initiation and propagation of bending fatigue cracks [1].

Furthermore, metallic wear debris released into the lubricant acts as abrasive particles that initiate surface pitting, effectively curtailing the system's contact fatigue life [1,2]. Importantly, this wear debris does not merely act mechanically; the continuous removal of surface material exposes "fresh," chemically active metal to the lubricant and environment. This depassivation facilitates rapid surface oxidation and chemical attack, creating a direct bridge to the electrochemical and corrosive degradation mechanisms [5] analysed in Section 2.3.

2.3 Corrosion and synergistic effects

In maritime and offshore industrial applications, the mechanical reliability of gear transmission systems is compromised by the convergence of cyclic loading and chemical aggression [2]. Corrosion-related failure modes are identified as a primary constraint for components operating in environments where seawater exposure is constant [2,5]. Current research emphasises that these mechanisms are not merely additive but synergistic; the presence of a corrosive medium accelerates mechanical degradation processes [5].

Corrosion fatigue is characterised by accelerated fatigue crack growth under the dual influence of cyclic stress and electrochemical reactions. Advanced modelling indicates that the electrochemical environment within a fatigue crack differs significantly from the bulk seawater

environment due to restricted mass transport. The propagation rate is governed by ion transportation, specifically the movement of Cl^- and H^+ ions, driven by diffusion, migration, and convection within the crack [20].

Cathodic Protection also influences reliability in offshore environments. While it is utilised to mitigate surface corrosion, it significantly enhances hydrogen production at the crack tip. This hydrogen diffuses into the metal lattice, inducing HE, which is documented to accelerate crack propagation rates beyond those observed in standard corrosive environments by reducing the material's cohesive strength.

Tribocorrosion represents the combined effect of mechanical wear and chemical corrosion, where the removal of the protective passive film by sliding or rolling contact exposes fresh metal to the corrosive medium. In tidal energy systems, this is exacerbated by high-pressure underwater environments and the impact of suspended sediment, which induces abrasive wear [5].

Current research into tidal turbine components demonstrates that erosion-driven degradation, initiated by cavitation-induced microjets and abrasive particle impacts, progresses from micro-scale pitting to significant material loss [5]. Surface roughening caused by this chemical-mechanical synergy disrupts hydrodynamic performance and creates stress concentration sites that facilitate the initiation of contact fatigue cracks, as modelled in multiaxial fatigue criteria [5,17]. In large-scale marine gearboxes, such as those used in azimuth thrusters, degradation is further influenced by the breakdown of the EHL film due to seawater ingress [18]. The introduction of moisture into the lubricant reduces the Λ ratio, facilitating micro-contact and allowing the corrosive medium to initiate surface-level fatigue cracks [2,11]. This ingress is frequently linked to sealing failures, which are documented as a primary risk factor in offshore reliability [2]. Advanced simulations, such as the Extended Finite Element Method (XFEM), are now being adapted to incorporate these chemical propagation rates, allowing for more accurate predictions of the remaining useful life (RUL) in corrosive environments [16,20]. Table 6 summarises current literature, differentiating between these mechanisms based on the dominant environmental driver and the resulting failure.

Table 6. Comparison of corrosion-mechanical interaction modes.

Mechanism	Primary Driver	Dominant Interaction	Impact
Corrosion Fatigue	Cyclic Tensile Stress	Crack-tip electrochemical acidification and ion transport.	Rapid propagation of subsurface fractures; reduced cycles to failure.
HE	Cathodic protection	Atomic hydrogen diffuses into the metal lattice.	Sudden brittle failure, particularly in high-strength case-hardened layers.
Tribocorrosion	Sliding/Rolling Contact	Mechanical depassivation followed by rapid oxidation.	Accelerated material loss and gear profile alteration.
Erosion-Corrosion	High-Velocity Flow	Cavitation microjets and abrasive particle impact.	Surface pitting and roughening on blades and gear flanks.

Source(s): Synthesised from [5,20]

3. MODELLING AND SIMULATION METHODOLOGIES

FEA is an established methodology for stress analysis in modern gear research, allowing for the simulation of complex geometries and non-linear boundary conditions [8,21]. While FEA remains the standard for evaluating global structural integrity and assembly-level load response [22,23], the field has branched into specialised frameworks to resolve the micro-mechanics of the contact interface and subsurface material gradients [13,24].

Contemporary FEA focuses on integrating depth-dependent material property gradients produced by case-hardening [13,16]. Elastic-plastic constitutive models are developed to explicitly account for hardness profiles and initial residual stress gradients [17,18]. Using a "thin-slicing" technique, researchers discretise the gear tooth into multiple layers, assigning unique fatigue performance parameters and yield strengths to each layer [13,16]. This approach is essential for

predicting subsurface initiation; while compressive surface stresses inhibit crack opening, balancing tensile stresses in the core often accelerates fracture growth once they penetrate the case-core interface [17,18].

To predict total fatigue life, FEA frameworks utilise XFEM and the Virtual Crack Extension (VCE) method to evaluate the Stress Intensity Factor (SIF) and propagation paths [16,25]. XFEM provides the autonomy required to simulate bifurcated crack paths—such as the transition from root-fillet cracks to "hoop fractures" in thin-rimmed gears—without the need for constant remeshing [26,27]. Complementing this, the VCE method serves as a stable numerical engine for calculating energy release rates, particularly during the transition of subsurface cracks into surface-manifested pitting [25]. By integrating these methods, modern simulations can capture the effects of asymmetric pressure angles and gear modules on the fatigue threshold, providing a far more accurate Remaining Useful Life (RUL) estimation than traditional empirical models [25,26].

Table 7. Comparison of simulation methodologies in gear research.

Methodology	Core Functional Approach	Utility	Key Sources
XFEM	Discontinuous enrichment of the FE mesh near singularities.	Predicting bifurcated/arbitrary paths (e.g., Hoop Fracture, Tooth Fracture).	[16,27]
VCE Method	Energy-based evaluation of SIFs.	Subsurface-to-surface pitting transition and stability.	[25]
Elastic-Plastic FEA	Non-linear discretisation with property gradients.	Root fatigue and TFF/TIFF initiation in carburised gears.	[13,16,17]
Hybrid FE-Analytical	FEA for global deformation; analytical for contact.	Large-scale life-cycle wear-fatigue coupling studies.	[1,28]
MBS	Rigid-flexible dynamic coupling of system components.	Simulating transients and Non-Torque Loads (NTLs).	[8,21]
Baseline FEA	Standard linear-elastic discretisation of the assembly.	Baseline for global structural loads and mesh sensitivity.	[22,23]

The computational intensity of simulating millions of contact cycles has driven the development of Hybrid FEA-Analytical models [1,28]. In these frameworks, FEA is restricted to calculating global systematic elastic deformations, specifically carrier and housing compliance, which are subsequently converted into meshing deviation parameters for analytical contact solvers [21,28]. This hierarchical approach allows for the efficient evaluation of how macro-structural deformations couple with micro-scale surface damage [1,28].

Table 7 presents a comparison of simulation methodologies and details their use in research.

3.1 Wear and fatigue coupling models

Integrating wear evolution and fatigue mechanisms into a unified dynamic framework is recognised as the leading approach for predicting the life-cycle reliability of gear systems [28]. Traditional models often evaluate wear and fatigue as isolated phenomena; however, recent advancements utilise coupled frameworks to account for continuous deterioration mechanisms where surface wear alters the gear tooth profile, subsequently redistributing contact loads and influencing fatigue crack initiation [1].

Accurate gear life prediction requires transitioning from static assessments to dynamic models that account for the progressive alteration of tooth geometry. The coupling of wear and dynamics is achieved by integrating tribological wear evolution laws, most commonly Archard's equation, directly into the system's differential equations of motion [8]. In this framework, wear is treated as a path-dependent process where the incremental material loss at any point on the tooth flank is calculated as a function of the time-varying contact pressure (P) and local sliding distance.

Mathematically, this relationship is often represented within a hybrid framework where the geometric profile deviation is updated iteratively over discrete cycles. The mesh stiffness (k_m) is no longer treated as a static function but as a variable dependent on wear depth and time. Research indicates that as wear modifies the involute profile, the resulting redistribution of contact pressure can shift the peak stress location [28], potentially accelerating the transition from surface pitting to catastrophic TIF. According to the frameworks established by Zhang

To capture the complex feedback between changing geometry and dynamic loads, researchers employ a multi-step iterative loop summarised in Fig 1.

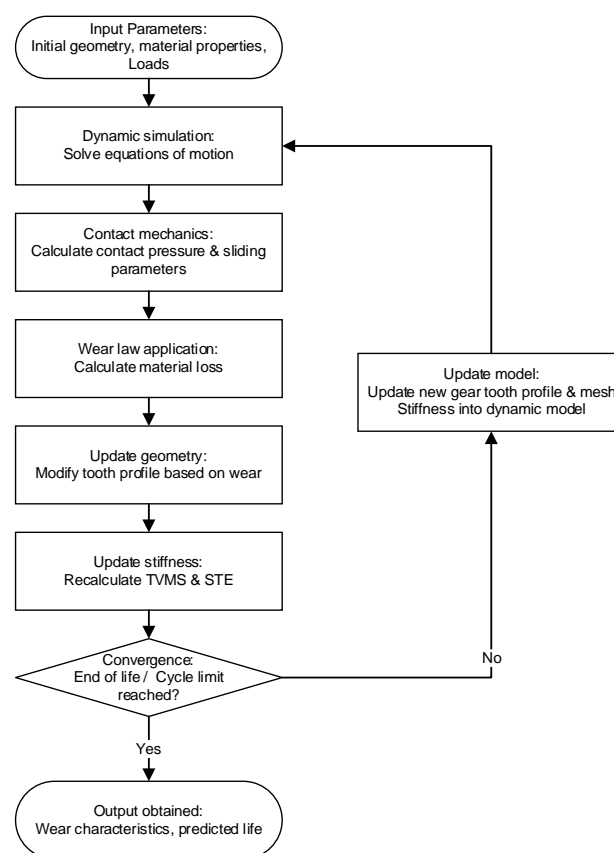


Fig 1. The multi-step iterative loop used in dynamic modelling. Source(s): Synthesised from [1,8,28].

The primary mechanism of coupling is the alteration of the TVMS. Surface wear causes a non-uniform removal of material, predominantly at the tooth root and tip, leading to a reduction in the effective contact area and a decrease in mesh stiffness [1]. In multi-stage gear systems, systematic elastic deformations are quantified using equivalent meshing deviation parameters, which are imported into hybrid FEA-analytical contact models to acquire the dynamic load distribution under non-ideal conditions [28].

In recent studies, gear reliability has shifted from treating fatigue and wear as independent damage processes to evaluating them as coupled, mutually reinforcing phenomena [1,8,24]. This interaction is modelled through iterative coupling loops where surface wear modifies the gear geometry, subsequently altering the contact mechanics and dynamic loads that drive fatigue initiation [8,25]. According to the frameworks established by Zhang

et al. (2021) and Yan et al. (2022), the wear depth, calculated via Archard's law, is used to update the gear tooth profile after discrete operational intervals. This profile evolution increases the GTE and reduces the TVMS, resulting in an amplified Dynamic Transmission Error (DTE) [1,8]. This amplification creates a "cascading-deterioration" cycle where higher dynamic loads increase contact pressures and sliding friction, further accelerating the material removal rate and shortening the fatigue initiation life [1,28].

Wear-induced geometric changes also trigger a shift in contact stress distribution, moving peak pressures away from the pitch line toward the addendum and dedendum [24,28]. This redistribution modifies the multiaxial stress state

underneath the contact surface, which is a key driver for the competition between surface-initiated micro-pitting and subsurface-initiated pitting [29]. Zhang et al. identified that tooth surface micro-topography, specifically the Root Mean Square (RMS) of surface roughness, governs this competing mechanism; as wear alters the roughness profile, the specific film thickness (Λ ratio) often drops, predisposing the gear to destructive pitting [11,29]. Furthermore, surface integrity factors such as manganese phosphate conversion coatings can mitigate this combined effect by reducing the friction coefficient and providing solid lubrication, thereby extending the contact fatigue life even under high-load conditions [30,31]. Table 8 presents these wear-fatigue interactions and highlights their impact.

Table 8. Review of wear-fatigue coupling interactions.

Coupling Mechanism	Interaction Description	Impact	Key Sources
Wear ↔ TVMS	Profile loss thins the tooth cross-section, reducing mesh stiffness.	Increases dynamic load factors and root stress.	[1,8,25]
Wear ↔ Stress Shifting	Material removal shifts peak pressure toward addendum/dedendum.	Shifts failure mode from pitting to TIFF/TFF.	[16,24,28]
Roughness ↔ Fatigue	Wear alters the Λ ratio and micro-level stress.	Competitive transition between pitting/micro-pitting.	[11,29,30]
Coating ↔ Friction	Thin-layer coatings modify the surface shear stress.	Extends life by inhibiting surface fatigue initiation.	[30-32]

3.2 Multi-Body systems (MBS)

MBS provides a framework for system-level analysis, simulating the non-linear interactions between gears, bearings, and flexible housings under non-stationary operational conditions [8,21]. These models establish the boundary conditions, specifically, time-varying reaction forces and relative displacements, required for granular component-level assessments of emerging failure modes such as TIFF and TFF [12,21]. In the development of large-scale offshore assets, including the 5 MW high-speed reference gearbox, MBS is employed to evaluate internal load distributions across planetary and parallel stages, identifying stress concentrations before physical prototyping [2,21]. Table 9 presents MBS modelling parameters, methodologies, and utilities.

Leading methodologies emphasise rigid-flexible coupled frameworks to account for the structural compliance of shafts, large-diameter gears, and housings [1,21]. In this approach, flexible bodies are developed in FEA software and integrated

into the MBS environment using reduced Degrees of Freedom (DOF) to capture dynamic elastic behaviour while maintaining computational efficiency [21]. This integration is essential because systematic elastic deformations of the carrier and housing directly alter gear pair alignment and internal load-sharing ratios, potentially inducing edge loading and accelerating localised wear [21,28]. Hybrid models quantify these interactions by importing equivalent meshing deviation parameters into contact mechanics solvers to resolve non-ideal meshing conditions [28].

MBS is also uniquely capable of resolving NTLs, such as bending moments and axial thrusts transmitted from the rotor to the gearbox in wind and tidal energy applications [15,22]. Comparative data from the Gearbox Reliability Collaborative (GRC) Round Robin indicate that models incorporating detailed bearing stiffness matrices and flexible supports are required to accurately predict main shaft displacements and internal gear misalignments [22].

MBS may also serve as the physics-based foundation for Digital Twins by simulating how localised internal faults, such as gear wear or spalling, propagate through the drivetrain to manifest as detectable global vibration

signatures [3,4,8]. This will allow for the decoupling of environmental noise from genuine fault-induced modulations in complex, multi-stage transmissions [8,33].

Table 9. MBS modelling parameters and methodologies.

Parameter / Method	Mechanism of Interaction	Utility	Key Sources
Rigid-Flexible Coupling	FE-reduced flexible bodies (housings/shafts) in MBS.	Captures structural compliance and misalignments.	[1,2,21]
Non-Torque Loads (NTLs)	Resolving rotor bending moments and axial thrusts.	Corrects load distribution in planetary stages.	[15,21,22]
Hybrid Contact Models	Fusing MBS global loads with analytical contact mechanics.	Resolves localised stress for TIFF/TFF prediction.	[12,16,28]
Fault Propagation	Mapping internal damage to external vibration signals.	Physics basis for PHM and Digital Twin frameworks.	[3,4,8])
Stochastic Dynamics	Integration of random wind/wave load spectra.	Characterises fatigue life under variable conditions.	[2,15,34]
Mesh Stiffness	State-dependent update of TVMS based on wear.	Accurately models the "progressive-degradation" loop.	[1,8,25]

3.3 Crack propagation modelling

The simulation of crack trajectories and the calculation of remaining operational life in gear systems are fundamentally grounded in LEFM, which identifies the SIF as the primary determinant for material separation [16,25]. In high-performance drivetrains, propagation is modelled as a response to mixed-mode loading conditions where tooth root bending (Mode I) and surface contact fatigue (Mode II) interact to dictate the failure path [16,26]. Table 10 presents fracture modelling parameters, influencing mechanisms, and modelling approaches.

XFEM is established as the primary numerical framework for modelling these discontinuities, as it facilitates crack growth simulation without the requirement for continuous re-meshing [16,27]. Within XFEM, the displacement function is enriched with additional DOFs to represent the crack tip and face, allowing for autonomous path tracking through the gear's complex geometry [16]. Complementing this, the VCE method is utilised as a stable numerical engine for evaluating energy release rates, specifically during the transition of subsurface-initiated cracks into surface-manifested pitting [25]. These methodologies allow researchers to integrate crack growth laws, such as Paris' Law, across millions of load cycles to estimate RUL with significantly higher precision than traditional empirical standards [16,20].

The trajectory of internal fractures, such as TIFF, is highly sensitive to manufacturing-induced material gradients [12,17]. Studies demonstrate that the gradient of yield strength and fatigue parameters, quantified through a "thin-slicing" multilayer technique, determines the essential depth of crack initiation [13]. Furthermore, research highlights that while compressive residual stresses near the surface inhibit growth, balancing tensile stresses in the core material lowers the fatigue threshold and accelerates propagation once the crack tip reaches the case-core interface [17,18]. These interactions are increasingly modelled using multiaxial criteria, such as Fatemi-Socie or Brown-Miller, to predict the deviation of the crack from its initial initiation plane [16,17].

In thin-rimmed gears common in complex transmission systems, propagation trajectories are affected by geometric constraints such as the Backup Ratio (BR). Tests show that low BRs shift the propagation path from a standard tooth-root breakage toward the gear rim. This results in catastrophic "hoop fracture," where the crack propagates through the rim rather than across the tooth width [27]. These paths are also influenced by the drive-side pressure angle and gear module, particularly in asymmetric gear designs where the SIF distribution is non-uniform across the face width [26].

A vital combined mechanical effect exists between fracture and wear; a localised crack reduces structural stiffness, altering the contact trajectory and inducing "scuffing-like" wear at the crack mouth [1,2]. This material removal thins the effective cross-section, increasing the stress intensity range and creating a cascading-deterioration cycle that accelerates the transition to final fracture [1]. In offshore and maritime energy contexts, this process is exacerbated by

coupled corrosion-fatigue effects. The transport of corrosive ions (Cl^-) and the diffusion of atomic hydrogen (H^+) to the crack tip significantly lower the material's fatigue threshold and promote intergranular cracking [5,20]. By integrating these chemical "acceleration factors" into modified Paris Law derivatives, modern prognostic models can estimate RUL with higher fidelity in chemically aggressive marine environments [2,5,20].

Table 10. Comparison of fracture modelling parameters.

Parameter	Influencing Mechanism	Modelling Approach	Key Sources
SIF	Determines the instantaneous rate and stability of crack growth.	Strain Energy Release Rate / XFEM / VCE	[16,25,26]
BR	Controls whether propagation is tooth-oriented or rim-oriented.	FEA Parametric Study / Geometric Constraints	[26,27]
Yield Strength Gradient	Determines the threshold for subsurface initiation at carburised layers.	Thin-slicing Multilayer FEA	[13,16]
Residual Stress	Modifies the effective mean stress at the advancing crack tip.	Superposition Method in LEFM / Multiaxial Criteria	[17,18]
Ion Transport (Cl^- , H^+)	Lowers threshold for growth via chemical tip-softening/embrittlement.	Multi-physics coupling of LEFM and Diffusion Laws	[5,20]

4. EXPERIMENTAL TESTING AND VALIDATION

Standardised experimental validation is a key requirement for verifying the accuracy of numerical simulations and characterising the fatigue endurance of transmission components [16,23]. These protocols serve two primary functions: calibrating material constitutive models and empirically substantiating theoretical life predictions under controlled or stochastic loading [17,34]. Table 11 presents a summary of testing protocols, their objectives and their utility.

Back-to-back gear test rigs (such as FZG or specialised fatigue rigs) are the primary tools for evaluating localised damage mechanisms under strictly controlled torque and speed conditions [16,35]. These rigs facilitate the assessment of surface contact fatigue by monitoring lubricant film thickness and wear particle generation through metallurgical and oil analysis [35,36]. In the study of carburised gears, these setups are critical for calibrating Rolling Contact Fatigue (RCF) models; initial residual stress and hardness profiles are measured from test specimens and integrated into FEA to correlate experimental pit initiation with predicted stress cycles [16,17].

For emerging materials and surface treatments, specialised rig setups are used to compare experimental stress values of hard-coated gears with theoretical Hertzian contact stresses, validating the performance enhancements of hard coatings or bionic textures [31,37].

Large-scale industrial validation is spearheaded by initiatives such as the GRC, which utilises multi-megawatt gearbox dynamometer test rigs [21,22]. These facilities correlate global experimental load distributions with high-fidelity MBS modelling to identify internal misalignments and NTL effects that are not apparent in small-scale testing [22]. Furthermore, full-scale rig tests provide the necessary environment for Seeded Fault Testing, where artificial damage is introduced to validate the efficacy of vibration-based condition monitoring and PHM algorithms [3,8].

For maritime propulsion systems, such as azimuth thrusters, traditional 10^7 -cycle fatigue testing is insufficient. Specialised rigs are designed to evaluate large-sized bevel gears within the VHCF regime, accounting for long operational lifetimes of up to 25 years [18]. These protocols often incorporate NDT to identify subsurface fractures and track their propagation toward the surface [9,18].

Finally, to bridge the gap between laboratory and field conditions, Windmill Rig Tests utilise protocols that simulate random wind speed and turbulence [34]. These tests quantify cumulative

fatigue damage under variable amplitude loading, providing a baseline for life prediction in the stochastic environments typical of offshore energy assets [15,34].

Table 11. Summary of testing protocols and their utility.

Protocol / Rig Type	Core Objective	Utility	Key Sources
Back-to-Back Rigs	Controlled RCF and wear monitoring.	Calibrates $S - N$ curves and lubrication models.	[16,35]
Dynamometer	System-level load distribution validation.	Identifies NTLs and internal misalignments.	[21,22]
VHCF Marine Rigs	Long-lifetime (25-year) fatigue testing.	Characterises subsurface initiation in large gears.	[18]
Stochastic Rig Tests	Variable amplitude/turbulence simulation.	Quantifies damage in non-stationary conditions.	[15,34]
Seeded Fault Tests	Validation of PHM and vibration sensors.	Establishes fault-signature libraries for Digital Twins.	[3]
Coating/Texture Rigs	Tribological and heat dissipation testing.	Validates bionic and hard-coat enhancements.	[31,37]

4.1 Advanced diagnostic techniques

The evolution of gear testing protocols has transitioned from qualitative visual inspection to high-precision, quantitative diagnostic techniques that enable the real-time tracking of both surface and subsurface degradation [16]. These advanced methods are essential for characterising complex, non-linear failure modes such as micro-pitting and interior fatigue fractures, where early-stage damage initiation occurs beyond the resolution of the naked eye [18]. Table 12 presents these advanced diagnostic techniques and their utility.

In high-reliability sectors such as marine propulsion and offshore wind, detecting subsurface initiation is an important prognostic requirement to avoid high costs [15,18]. NDT methodologies, specifically Ultrasonic Testing (UT) and Acoustic Emission (AE), are now standard for monitoring the "incubation" and stable growth phases of subsurface cracks [18,23]. AE is particularly effective for identifying incipient defects in bearings and gear teeth by capturing high-frequency elastic waves generated by crack-tip plastic deformation or secondary grain boundary friction [9,23]. These techniques provide the empirical "ground truth" necessary to validate multiaxial fatigue criteria (e.g., Brown-Miller) and calibrate fracture mechanics models for TIFF and WEC [9,16].

Understanding the transition from mild wear to catastrophic surface failure requires a granular assessment of surface integrity [35]. Scanning Electron Microscopy (SEM) is utilised to analyse tooth flank morphology, revealing the transition from micro-abrasion to spalling, while Energy Dispersive Spectroscopy (EDS) and X-ray Diffraction (XRD) identify chemical signatures of lubricant film breakdown or tribocorrosion [31,37]. This chemical mapping is vital for evaluating advanced surface treatments, such as bionic textures or hard coatings, by quantifying material transfer and phase stability under high contact pressures [31,37].

To eliminate the subjectivity of traditional rating scales (e.g., AGMA or ISO damage levels), researchers now employ automated image analysis to quantify surface distress [16]. By processing high-resolution digital captures of the tooth flank, algorithms can precisely calculate the percentage of the contact area affected by pitting and track its growth rate across millions of cycles [16]. This quantitative feedback loop is essential for calibrating numerical wear models, such as Archard's equation, and determining the exact transition point where surface material loss begins to compromise the TVMS of the system [1,25].

The diagnostic framework is completed by correlating material loss with wear debris

characteristics via oil analysis [35]. Periodic sampling during rig tests allows for the evaluation of the EHL state by monitoring particle concentration and morphology [35,36]. Advanced

particle counting and shape recognition are used to distinguish between benign "running-in" debris and the large, jagged particles associated with progressive fatigue pitting [35,36].

Table 12. Comparison of advanced diagnostic techniques for gear reliability.

Technique	Primary Measurement	Failure Mode Targeted	Utility	Key Sources
UT / AE	Acoustic impedance & wave reflection.	Subsurface Fatigue (TIFF/WEC).	Detects internal cracks without disassembly.	[9,18,23]
Automated Image Analysis	Pixel-based area quantification.	Surface Pitting & Spalling.	Provides objective, repeatable damage metrics.	[16,25]
SEM / EDS / XRD	Electron backscatter & chemical spectra.	Adhesive Wear / Tribocorrosion.	Identifies micro-failure and material transfer.	[31,37]
Oil & Wear Debris	Particle morphology & concentration.	Lubricant Failure / Progressive Wear.	Real-time monitoring of EHL and wear rate.	[35,36]
Non-Destructive Inspection (NDI)	High-resolution surface topography.	Micro-pitting & Scuffing.	Tracks topography evolution during "running-in".	[29]

4.2 Surface Engineering and Materials

Experimental research is increasingly focused on evaluating advanced surface treatments and material modifications to enhance gear resistance to combined wear and contact fatigue [31,37]. The efficacy of these treatments is validated by correlating manufacturing parameters, such as coating thickness or case depth, with operational longevity through microstructural analysis and high-cycle RCF tests [13,16]. Table 13 presents a comparative analysis of surface engineering strategies for gear reliability.

Carburising is established as the standard industrial process for heavy-duty gears, creating a functional gradient of hardness and compressive residual stress [17,21]. Experimental mapping of these components utilises XRD and micro-indentation to plot the initial stress and hardness profiles across the case-core interface [16,17]. These gradients directly dictate the transition between failure modes; while high surface hardness inhibits abrasive wear, the depth of the effective case determines the threshold for subsurface-initiated failures like TIFF [12,17]. Specifically, these gradients shift the maximum shear stress away from the surface. However, if the core material lacks sufficient yield strength, crack initiation occurs at the case-core boundary, where residual stress transitions from compressive to tensile [13,16].

A significant advancement in surface engineering is the application of bionic textures to tooth flanks to improve lubrication and thermal management [37]. Inspired by biological surfaces, these patterns, consisting of micro-pits or grooves, serve as lubricant reservoirs and traps for abrasive wear debris [37]. Experimental wear tests indicate that bionic textures significantly reduce the Coefficient of Friction (COF) and localised contact temperatures during high-load meshing [37]. This reduction is critical for delaying the onset of adhesive wear and scuffing, effectively maintaining the TVMS of the gearbox over extended operational periods [1,37].

The application of hard coatings, such as $Al_2O_3 - 40\%TiO_2$, $Cr_3C_2 - 20\%NiCr$ and $WC - 10\%Co - 4\%Cr$, is increasingly evaluated to enhance the durability of mild steel gears in harsh environments [31]. Deposited via detonation thermal spray, these coatings are analysed using SEM and EDS to verify phase integrity and material transfer resistance [31]. Experimental results demonstrate that WC-based coatings provide superior resistance to abrasive wear, making them ideal for gears operating in low-lubrication or particulate-heavy conditions [31]. Similarly, low-frictional coatings on polymer gears are utilised to mitigate the contact stress shifts caused by sliding friction, preventing the premature thermal softening observed in non-metallic transmissions [32].

The experimental data gathered from these diverse surface treatments are essential for the high-fidelity calibration of numerical life-prediction models. Specifically, they allow for the identification of the "critical plane" in multiaxial fatigue criteria, where surface engineering significantly modifies the local stress-strain state to inhibit crack initiation [13,16]. Furthermore, contemporary research

highlights the potential for synergistic treatments, such as applying bionic texturing onto previously carburised surfaces, to provide a multi-layered defence against both subsurface fatigue and surface scuffing [1,37]. This integrated approach represents an emerging frontier for maximising gear reliability in applications such as offshore wind and tidal energy [2,15].

Table 13. Comparative analysis of surface engineering strategies for gear reliability.

Treatment Method	Primary Mechanism	Failure Mode	Strategic Advantage	Key Sources
Carburizing	Hardness and residual stress gradients.	Surface Pitting & TIFF	High load-bearing capacity and core strength.	[13,16]
Bionic Texture	Lubricant retention & debris trapping.	Scuffing & Adhesive Wear	Superior heat dissipation and friction reduction.	[1,37]
Hard Coatings	Increased surface hardness/stability.	Extreme Abrasive Wear	Prevents degradation in low-lubrication states.	[31,32]
Shot Peening	Enhanced surface compressive residual stress.	Root Bending Fatigue	Inhibits crack initiation at the tooth root fillet.	[12,16]
Mn-Phosphate	Solid lubricating conversion layer.	Micro-pitting & Wear	Reduces friction during the "running-in" phase.	[11,30]

5. DISCUSSION: CONSIDERATIONS FOR MARINE GEARING RELIABILITY

The preceding sections have characterised leading methodologies in gear failure mechanisms, high-fidelity numerical simulation, and advanced experimental validation. Moving beyond the literature, this section synthesises key considerations from these research domains specifically for marine transmission systems. It serves as a strategic, forward-looking reference for future research, prioritising knowledge gaps and connecting macroscopic marine operational burdens to microscopic material degradation. Table 14 consolidates these considerations, highlighting relevant research domains, marine drivers, and the methodologies utilised to assess and resolve them.

5.1 Marine loads: Stochasticity, high density, and MBS limitations

Marine gearing is distinguished from its industrial counterparts by the extreme nature of its input loads. Offshore wind gearboxes are affected by stochastic aero-elastic loads and wind turbulence [15,34], while tidal turbines must withstand hydrodynamic torque and thrust forces an order of magnitude higher due to the fluid density of seawater [4]. MBS is the essential tool for resolving

these loads, and utilising rigid-flexible coupled frameworks is mandatory to capture the structural compliance of large gears under NTLs [21,22].

However, the application of MBS is limited by high computational overheads when implementing localised, high-frequency contact stresses alongside global dynamic responses [28]. Furthermore, validating these models is hindered by the logistical challenges of continuous monitoring in remote offshore environments [5]. To address these limitations, future research must prioritise 5 MW and 10 MW reference models to standardise boundary conditions for gear load-sharing under wave-induced excitations [2,21].

5.2 Subsurface integrity, fatigue prediction uncertainty, and XFEM limitations

Unlike automotive gears, marine transmissions are designed for 20- to 25-year operational lifespans, pushing material performance into the VHCF regime [18]. The risk of TIFF is acute in marine gears due to stringent high-power-density requirements. High-fidelity FEA must incorporate multilayer gradient modelling (thin-slicing) to align peak subsurface shear stresses with the yield strength of carburised layers [13,16].

Despite these advancements, predicting fatigue life within the VHCF regime carries inherent uncertainty due to the significant scatter caused by microstructural defects and inclusion sensitivity [12,18]. Furthermore, while XFEM provides autonomy in simulating crack paths, its practical utility is limited by the computational intensity required for 3D arbitrary paths and the difficulty of accurately mapping complex multiaxial residual stress fields across millions of cycles [16,26,38]. Given these simulation challenges, structural mitigation remains essential; designers must maintain a BR > 1.2 to prevent the transition from typical tooth breakage to catastrophic rim-oriented hoop fracture [12,27].

5.3 Marine degradation cycle: Corrosion, wear, and fatigue

The primary driver of marine gear reliability is the combined effect of mechanical stress and electrochemical attack. This interaction creates a degradation cycle that significantly reduces RUL. Sealing failures lead to lubricant contamination, which reduces the Λ ratio and triggers tribocorrosion; here, mechanical wear depassivates the metal, leading to rapid oxidation [2,5]. Once initiated, cracks act as conduits for Cl^- and H^+ ion transport. In systems utilising Cathodic Protection, the subsequent production of atomic hydrogen facilitates HE, accelerating crack propagation via tip-softening [5,20].

To bridge the gap between theoretical chemistry and applied reliability, future RUL

models must integrate modified Paris Law derivatives encompassing chemical "acceleration factors" derived from crack-tip electrochemistry [16,20].

5.4 Strategic maintenance: PHM and digital twins

Due to the logistical complexity and high Operations and Maintenance (O&M) costs of offshore assets, leading strategies emphasise PHM and Digital Twin methodologies. The integration of AE for subsurface detection and oil debris analysis for surface wear monitoring provides the most robust health indicator for marine gearboxes [23,35,36]. Reliability Influencing Factors (RIF) and Dynamic Bayesian Networks (DBN) are the preferred methodologies for mapping these diagnostic signals into a probabilistic RUL estimate [15,39].

However, the implementation of Digital Twin methodologies faces several significant hurdles, primarily the challenge of developing accurate physics-based models that integrate seamlessly with actual measurements [8]. Furthermore, creating holistic smart system architectures remains a substantial obstacle; a Digital Twin must evaluate the entire system to accurately predict wear and maintenance needs, rather than focusing on isolated components [40]. Finally, obtaining reliable, long-term performance data is difficult, and the transmission of real-time diagnostic data through water in marine and deep-sea environments remains a persistent barrier [40,41].

Table 14. Key considerations for marine gearing research.

Research Domain	Key Marine Driver	Current Methodology	Key Sources
Loads & Dynamics	NTLs; Hydrodynamic Thrust; Wave Impact.	Flexible-Rigid MBS; 5MW Reference Models.	[21,22]
Material Strength	VHCF (25-year life); TIFF Risks.	Layered FEA; Multiaxial Criteria (Brown-Miller).	[17,18]
Environmental	Seawater Ingress; Cl^- & H^+ Ion Transport.	Multi-physics LEFM; Diffusion-Coupled XFEM.	[5,20]
Surface Engineering	Scuffing; Abrasive Wear; Corrosion.	Bionic Textures; WC-based Hard Coatings.	[31,37]
Condition Monitoring	Logistical Inaccessibility; High O&M Cost.	AE-based NDT; DBN; Digital Twin Feedback.	[23,39]

6. CONCLUSIONS AND RECOMMENDATIONS

The transition from terrestrial industrial gearboxes to marine transmission systems, spanning offshore wind turbines and tidal stream

energy, represents a significant shift in reliability requirements. The convergence of high-density hydrodynamic loads, stochastic environmental transients, and electrochemical aggression necessitates a departure from traditional

standards toward integrated, multi-physics reliability frameworks.

Main takeaways:

- Coupled degradation mechanisms in marine environments: Marine gear failure is rarely an isolated event. Subsurface modes like TIFF and TFF, driven by stochastic loads and high torque-to-weight ratios [4,12], are accelerated by balancing tensile residual stresses at the case-core interface of carburised gears [17,18]. Furthermore, seawater ingress facilitates tribocorrosion; ion transport lowers fatigue thresholds, while Cathodic Protection systems introduce risks of sudden, brittle HE failures [5,20].
- Advancement in dynamic simulation: Modern assessments require coupled dynamic simulations bridging component and system-level responses. Accurate design life prediction relies on FEA with multilayer gradient modelling (thin-slicing) [13,16], integrated with XFEM and the VCE method for simulating bifurcated crack paths and calculating SIFs without remeshing [16,25]. Additionally, MBS must incorporate Rigid-Flexible Coupling to resolve compliance impacts on gear alignment and load-sharing under NTLs [1,21,22].
- Experimental and diagnostic integration: Validation protocols must replicate long-duration marine burdens, specifically testing within the VHCF regime for marine environments [18]. This must be paired with AE and UT to detect subsurface fracture "incubation" [9,23]. Ultimately, Digital Twin development requires integrating these physics-based models and real-time diagnostic data using DBNs for probabilistic RUL estimation [8,39].

Based on the gaps identified in the current literature, future research should prioritise:

- Long-Term Corrosion-Wear Data: There is a lack of empirical data regarding the long-term combined effects of tribocorrosion and subsurface fatigue. Future test rigs should aim to incorporate electrochemical cells to simulate the seawater interface under high-cycle contact.

- Integrated Surface Engineering: Research into "multi-layered defence" strategies, such as the application of bionic textures over carburised and hard-coated surfaces, should be pursued to simultaneously mitigate abrasive wear, scuffing, and fatigue initiation.
- Holistic RUL Modelling: Future prognostic algorithms should move beyond single-failure-mode predictions. A comprehensive RUL model that accounts for the coupling of surface wear, electrochemical corrosion and subsurface crack propagation is essential for failure prediction in marine environments.

Use of generative AI

In the preparation of this work, the author(s) used Google Gemini to improve readability, language and tables. After using this tool, the author(s) reviewed and edited the content and take(s) full responsibility for the content of this work.

REFERENCES

- [1] X. Gao *et al.*, "Dynamic interactions of surface wear and tooth crack in gear transmission systems: An investigation of progressive-degradation mechanisms," *Wear*, vol. 571, p. 205861, Feb. 2025, doi: [10.1016/j.wear.2025.205861](https://doi.org/10.1016/j.wear.2025.205861).
- [2] D. Meng, P. Nie, S. Yang, X. Su, and C. Liao, "Reliability analysis of wind turbine gearboxes: past, progress and future prospects," *International Journal of Structural Integrity*, vol. 16, no. 1, pp. 4–38, Jan. 2025, doi: [10.1108/ijssi-08-2024-0129](https://doi.org/10.1108/ijssi-08-2024-0129).
- [3] P. Goswami and R. N. Rai, "A systematic review on failure modes and proposed methodology to artificially seed faults for promoting PHM studies in laboratory environment for an industrial gearbox," *Engineering Failure Analysis*, vol. 146, p. 107076, Jan. 2023, doi: [10.1016/j.engfailanal.2023.107076](https://doi.org/10.1016/j.engfailanal.2023.107076).
- [4] F. Elasha, D. Mba, M. Togneri, I. Masters, and J. A. Teixeira, "A hybrid prognostic methodology for tidal turbine gearboxes," *Renewable Energy*, vol. 114, pp. 1051–1061, Jul. 2017, doi: [10.1016/j.renene.2017.07.093](https://doi.org/10.1016/j.renene.2017.07.093).
- [5] P. Habibi, F. Abad, S. Dai, A. Mehmanparast, and S. Lotfian, "Failure analysis of tidal turbine blades: understanding erosion mechanisms and their impact on structural integrity," *Engineering Failure Analysis*, vol. 182, p. 110045, Aug. 2025, doi: [10.1016/j.engfailanal.2025.110045](https://doi.org/10.1016/j.engfailanal.2025.110045).

- [6] C. D. Constantino-Robles, F. A. C. Leonardo, J. H. Galván, Y. C. Alvarez, L. A. I. Carrera, and J. Rodríguez-Reséndiz, "Vibration-Based Predictive Maintenance for Wind Turbines: A PRISMA-Guided Systematic Review on methods, applications, and remaining useful life prediction," *Applied Mechanics*, vol. 7, no. 1, p. 11, Jan. 2026, doi: [10.3390/applmech7010011](https://doi.org/10.3390/applmech7010011).
- [7] I. U. Hassan, K. Panduru, and J. Walsh, "An In-Depth Study of Vibration Sensors for Condition Monitoring," *Sensors*, vol. 24, no. 3, p. 740, Jan. 2024, doi: [10.3390/s24030740](https://doi.org/10.3390/s24030740).
- [8] K. Feng, J. C. Ji, Q. Ni, and M. Beer, "A review of vibration-based gear wear monitoring and prediction techniques," *Mechanical Systems and Signal Processing*, vol. 182, p. 109605, Jul. 2022, doi: [10.1016/j.ymssp.2022.109605](https://doi.org/10.1016/j.ymssp.2022.109605).
- [9] R. M. Buil and D. R. Angulo, "Comparison of three predictive analysis methods for wind turbine gear boxes. A case study of satellite bearing wear and gear teeth surface damages," *DYNA*, vol. 96, no. 3, pp. 254–259, May 2021, doi: [10.6036/9685](https://doi.org/10.6036/9685).
- [10] K. Touimi, M. Benbouzid, and P. Tavner, "A Review-based Comparison of Drivetrain Options for Tidal Turbines," in *2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC)*, Shenzhen: IEEE, Nov. 2018, pp. 1–6, doi: [10.1109/PEAC.2018.8590460](https://doi.org/10.1109/PEAC.2018.8590460).
- [11] A. Clarke, H. Evans, and R. Snidle, "Understanding micropitting in gears," *Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science*, vol. 230, no. 7–8, pp. 1276–1289, Sep. 2015, doi: [10.1177/0954406215606934](https://doi.org/10.1177/0954406215606934).
- [12] A. Behvar, K. Tahmasbi, W. Savich, and M. Haghshenas, "Tooth interior fatigue fracture in automotive differential gears," *Engineering Failure Analysis*, vol. 156, p. 107829, Nov. 2023, doi: [10.1016/j.engfailanal.2023.107829](https://doi.org/10.1016/j.engfailanal.2023.107829).
- [13] W. Wang, H. Liu, C. Zhu, and Z. Sun, "Evaluation of contact fatigue life of a wind turbine carburized gear considering gradients of mechanical properties," *International Journal of Damage Mechanics*, vol. 28, no. 8, pp. 1170–1190, Nov. 2018, doi: [10.1177/1056789518814284](https://doi.org/10.1177/1056789518814284).
- [14] A. Beijger, E. Frank, and P. Bartoszkó, "Failure analysis of wind turbine planetary gear," *Energies*, vol. 14, no. 20, p. 6768, Oct. 2021, doi: [10.3390/en14206768](https://doi.org/10.3390/en14206768).
- [15] U. Bhardwaj, A. P. Teixeira, and C. G. Soares, "Reliability prediction of an offshore wind turbine gearbox," *Renewable Energy*, vol. 141, pp. 693–706, Apr. 2019, doi: [10.1016/j.renene.2019.03.136](https://doi.org/10.1016/j.renene.2019.03.136).
- [16] X. Sun, J. Zhao, S. Song, Y. Lu, H. Sun, and X. Tang, "A numerical model for total contact fatigue life prediction of carburized spur gears considering the surface integrity," *Meccanica*, vol. 60, no. 2, pp. 311–334, Jan. 2025, doi: [10.1007/s11012-025-01935-1](https://doi.org/10.1007/s11012-025-01935-1).
- [17] W. Wang, H. Liu, C. Zhu, X. Du, and J. Tang, "Effect of the residual stress on contact fatigue of a wind turbine carburized gear with multiaxial fatigue criteria," *International Journal of Mechanical Sciences*, vol. 151, pp. 263–273, Nov. 2018, doi: [10.1016/j.ijmecsci.2018.11.013](https://doi.org/10.1016/j.ijmecsci.2018.11.013).
- [18] E. P. K. Virtanen, S. Á. Böhme, G. Szanti, M. S. Kanerva, and A. Amanov, "Growth of subsurface fatigue fractures in Large-Size bevel gears," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 49, no. 2, pp. 640–652, Nov. 2025, doi: [10.1111/ffe.70130](https://doi.org/10.1111/ffe.70130).
- [19] V. Hegadekatte, J. Hilgert, O. Kraft, and N. Huber, "Multi time scale simulations for wear prediction in micro-gears," *Wear*, vol. 268, no. 1–2, pp. 316–324, Aug. 2009, doi: [10.1016/j.wear.2009.08.017](https://doi.org/10.1016/j.wear.2009.08.017).
- [20] V. Golshani, M. A. Eder, M. S. Jellesen, and A. B. Abrahamsen, "Modeling of the ion transportation within a corrosion fatigue crack," in *Proc. Wind Energy Science Conf. (WESC 2025)*, Nantes, France, Jun. 24–27, 2025, European Academy of Wind Energy, 2025.
- [21] A. R. Nejad, Y. Guo, Z. Gao, and T. Moan, "Development of a 5 MW reference gearbox for offshore wind turbines," *Wind Energy*, vol. 19, no. 6, pp. 1089–1106, Jul. 2015, doi: [10.1002/we.1884](https://doi.org/10.1002/we.1884).
- [22] F. Oyague, C. P. Butterfield, and S. Sheng, "NREL Gearbox Reliability Collaborative Analysis Round Robin: Preprint," *University of North Texas Digital Library (University of North Texas)*, May 2009, [Online]. Available: <https://digital.library.unt.edu/ark:/67531/metadc925965/>
- [23] J. Zhou et al., "Improving the reliability of industrial multi-MW wind turbines," *Insight - Non-Destructive Testing and Condition Monitoring*, vol. 59, no. 4, pp. 189–195, Apr. 2017, doi: [10.1784/insi.2017.59.4.189](https://doi.org/10.1784/insi.2017.59.4.189).
- [24] B. Zhang, H. Liu, C. Zhu, and Y. Ge, "Simulation of the fatigue-wear coupling mechanism of an aviation gear," *Friction*, vol. 9, no. 6, pp. 1616–1634, Dec. 2020, doi: [10.1007/s40544-020-0447-3](https://doi.org/10.1007/s40544-020-0447-3).
- [25] Y. Yan, C. Jiang, and W. Li, "Simulation on coupling effects between surface wear and fatigue in spur gear," *Engineering Failure Analysis*, vol. 134, p. 106055, Jan. 2022, doi: [10.1016/j.engfailanal.2022.106055](https://doi.org/10.1016/j.engfailanal.2022.106055).

- [26] N. V. Namboothiri and P. Marimuthu, "Influence of drive side pressure angle on fracture characteristics of asymmetric spur gear," *Engineering Failure Analysis*, vol. 131, p. 105865, Nov. 2021, doi: [10.1016/j.engfailanal.2021.105865](https://doi.org/10.1016/j.engfailanal.2021.105865).
- [27] F. Curà, A. Mura, and C. Rosso, "Influence of high speed on crack propagation path in thin rim gears," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 40, no. 1, pp. 120–129, Jun. 2016, doi: [10.1111/ffe.12481](https://doi.org/10.1111/ffe.12481).
- [28] Y. Huangfu, X. Dong, K. Chen, and Z. Peng, "Coupling mechanism between systematic elastic deformation and gear surface damage," *International Journal of Mechanical Sciences*, vol. 238, p. 107850, Oct. 2022, doi: [10.1016/j.ijmecsci.2022.107850](https://doi.org/10.1016/j.ijmecsci.2022.107850).
- [29] B. Zhang, H. Liu, C. Zhu, and Z. Li, "Numerical simulation of competing mechanism between pitting and micro-pitting of a wind turbine gear considering surface roughness," *Engineering Failure Analysis*, vol. 104, pp. 1–12, May 2019, doi: [10.1016/j.engfailanal.2019.05.016](https://doi.org/10.1016/j.engfailanal.2019.05.016).
- [30] L. Zang, Y. Chen, W. Hou, T. Sun, Y. Wu, and B. Zhao, "Effect of manganese phosphate conversion coating with different crystal sizes on fatigue life of 20MnCrS5 steel helical gears," *Tribology International*, vol. 186, p. 108622, May 2023, doi: [10.1016/j.triboint.2023.108622](https://doi.org/10.1016/j.triboint.2023.108622).
- [31] M. K. Shoba, K. M. Mohan, K. Parthiban, K. Pazhanivel, and N. Ramadoss, "Microstructure, mechanical, and wear characteristics of Hard-Coated C45 Mild Steel for Spur Gear applications," *Journal of Materials Engineering and Performance*, vol. 33, no. 10, pp. 4712–4725, May 2023, doi: [10.1007/s11665-023-08287-5](https://doi.org/10.1007/s11665-023-08287-5).
- [32] S.-M. Bae, K.-J. Seo, and D.-E. Kim, "Effect of friction on the contact stress of a coated polymer gear," *Friction*, vol. 8, no. 6, pp. 1169–1177, Jul. 2020, doi: [10.1007/s40544-020-0363-6](https://doi.org/10.1007/s40544-020-0363-6).
- [33] M. T. Islam, A. Joarder, and M. K. Hossain, "A Comprehensive Study on Gearbox Condition Monitoring Using Vibration Analysis," *North American Academic Research*, vol. 7, no. 12, pp. 1–11, Dec. 2024, doi: [10.5281/zenodo.14271397](https://doi.org/10.5281/zenodo.14271397).
- [34] Y. Qiu, Y. Feng, W. Yang, Y. Xu, D. Infield, and J. Li, "Wind turbulence impacts to onshore and offshore wind turbines gearbox fatigue life," in *Proc. 3rd Renewable Power Generation Conf. (RPG 2014)*, Naples, Italy, 2014, pp. 1–5, doi: [10.1049/cp.2014.0903](https://doi.org/10.1049/cp.2014.0903).
- [35] A. Muniyappa, S. Chandramohan, and S. Seethapathy, "Detection and Diagnosis of Gear Tooth Wear through Metallurgical and Oil Analysis," *Tribology Online*, vol. 5, no. 2, pp. 102–110, Jan. 2010, doi: [10.2474/trol.5.102](https://doi.org/10.2474/trol.5.102).
- [36] S. Sheng, "Monitoring of Wind Turbine Gearbox Condition through Oil and Wear Debris Analysis: A Full-Scale Testing Perspective," *Tribology Transactions*, vol. 59, no. 1, pp. 149–162, Jun. 2015, doi: [10.1080/10402004.2015.1055621](https://doi.org/10.1080/10402004.2015.1055621).
- [37] Z. Zhang, J. Li, T. Zou, W. Hou, Y. An, and J. Liu, "Effect of bionic texture on wear resistance and heat dissipation performance of transmission gear," *Tribology Transactions*, vol. 68, no. 3, pp. 531–557, Apr. 2025, doi: [10.1080/10402004.2025.2488798](https://doi.org/10.1080/10402004.2025.2488798).
- [38] M. Gargourimotlagh, J. Hazrati, W. Ji, and M. De Rooij, "Hardness-dependent surface roughness threshold governing rolling contact fatigue crack initiation," *International Journal of Mechanical Sciences*, vol. 309, p. 111020, Nov. 2025, doi: [10.1016/j.ijmecsci.2025.111020](https://doi.org/10.1016/j.ijmecsci.2025.111020).
- [39] T. Elusakin and M. Shafiee, "Fault diagnosis of offshore wind turbine gearboxes using a dynamic Bayesian network," *International Journal of Sustainable Energy*, vol. 41, no. 11, pp. 1849–1867, Sep. 2022, doi: [10.1080/14786451.2022.2119390](https://doi.org/10.1080/14786451.2022.2119390).
- [40] D. Sarode et al., "Corrosion-Resistant materials for ocean structures: Innovations, mechanisms, and applications," *Sustainable Marine Structures*, Jul. 2025, doi: [10.36956/sms.v7i3.2335](https://doi.org/10.36956/sms.v7i3.2335).
- [41] G. Li and W. Zhu, "A review on Up-to-Date gearbox technologies and maintenance of tidal current energy converters," *Energies*, vol. 15, no. 23, p. 9236, Dec. 2022, doi: [10.3390/en15239236](https://doi.org/10.3390/en15239236).