Mech. Sci., 17, 525–544, 2026
https://doi.org/10.5194/ms-17-525-2026

Mechanical
Sciences
Open Access

Review article: Hadal-zone gearbox multi-physics lubrication dynamics: synergistic effects of hydrostatic pressure and thermal suppression

Yongmei Wang[1], **Xigui Wang**[2], **Jiafu Ruan**[2], **Xi Chen**[3], **and Weiqiang Zou**[2]

[1]School of Motorcar Engineering, Heilongjiang Institute of Technology, No. 999, Hongqidajie Road,
Daowai District, Harbin 150036, China
[2]School of Mechatronics and Automation, Huaqiao University, No. 668 Jimei Avenue,
Jimei District, Xiamen 361021, China
[3]China Communications Construction Company (CCCC), Third Harbor Engineering Bureau Sixth Engineering
Co., Ltd. (Xiamen), No. 189, Huachang Road, Huli District, Xiamen, Fujian Province 361006, China

Correspondence: Xigui Wang (wyr20091207@126.com) and Xi Chen (chenxfhit@126.com)

Received: 6 February 2026 – Revised: 28 March 2026 – Accepted: 29 April 2026 – Published: 12 May 2026

Abstract. Deep-sea gear transmission systems face critical lubrication challenges due to the combined effects of extreme hydrostatic pressure and cryogenic temperatures. These environmental stressors cause exponential increases in lubricant viscosity, leading to poor fluidity, high start-up torque, and lubrication starvation. Seawater intrusion induces lubricant emulsification, additive deactivation, and electrochemical corrosion at meshing interfaces, collectively increasing the risk of lubrication failure and compromising long-term reliability. This study investigates lubrication degradation mechanisms in deep-sea environments and proposes targeted mitigation strategies. Through comprehensive characterization of deep-sea environmental parameters and their effects on lubricant rheological behaviour, we critically evaluate the applicability and limitations of conventional thermal elasto-hydrodynamic lubrication (TEHL) theory under extreme conditions. Our analysis reveals that established TEHL frameworks require substantial modification to accurately capture pressure–viscosity–temperature coupling effects and seawater contamination kinetics. Meshing interface texturing, as an effective strategy for friction reduction and wear mitigation, is examined to understand its mechanisms for enhancing lubricant film formation and tribological performance under starved lubrication conditions. Key findings demonstrate that optimized micro-texture architectures can effectively compensate for viscosity-induced fluidity loss and mitigate against the harmful effects of seawater ingress. Critical knowledge gaps are identified, and future research directions are outlined: (i) multi-physics coupling models integrating thermo-hydrodynamic, chemo-physical, and mechanical degradation processes; (ii) synergistic texture-coating design approaches; (iii) high-pressure, low-temperature experimental validation protocols; and (iv) engineering implementation frameworks for deep-sea gear transmission systems. This review establishes theoretical foundations and provides technical guidelines for robust lubrication design and long-term operational stability of deep-sea transmission equipment.

1 Introduction

The ocean harbours abundant biological, mineral, and energy resources, representing a strategic frontier for sustainable development and a vital space for future human progress (Brandt et al., 2016). The exploration and utilization of these distant and deep-sea resources rely on advanced equipment such as submersibles, seabed drilling systems, underwater robots, and tidal energy generators (Zhang et al., 2022; Gao et al., 2024; He et al., 2015). Within these sophisticated systems, gear transmissions play a pivotal role in power transmission and motion conversion; their performance directly dictates the operational capability, precision, and reliability of the entire equipment (Ruan et al., 2025b; Cao et al., 2024; Mia et al., 2010). Unlike terrestrial environments, this equipment typically operates hundreds or thousands of metres underwater, subject to extreme hydrostatic pressure, low temperatures, and a highly corrosive saline environment (Du et al., 2024; Shen et al., 2022). This coupled high-pressure and low-temperature setting poses unprecedented challenges to materials, structures, and lubrication. As equipment descends into deeper waters, the pressure differential across the gearbox increases dramatically. If uncontrolled, the immense external pressure can deform the housing structure and compromise sealing systems, leading to seawater intrusion (Zhao et al., 2025). To mitigate the immense pressure differentials in deep-sea environments, systems typically employ pressure-balancing devices to maintain pressure equilibrium in the gearbox. Figure 1 shows standard pressure compensation units, including the elastic bladder (see Fig. 1a) and moving piston (see Fig. 1b) types, along with the shuttle pin design featuring dual-bladder PBOF technology from Siemens DigiTRON (see Fig. 1c) (Song et al., 2021; Chen et al., 2025). Although this strategy protects the housing from deformation, it exposes the internal components to high ambient pressure, altering the lubricant's physicochemical properties. Specifically, high pressure significantly increases oil viscosity and flow resistance, potentially causing additive instability or changes in solubility. Consequently, this inevitably impairs lubricant film formation and load-bearing capacity, accelerates wear, and reduces the equipment's operational lifespan.

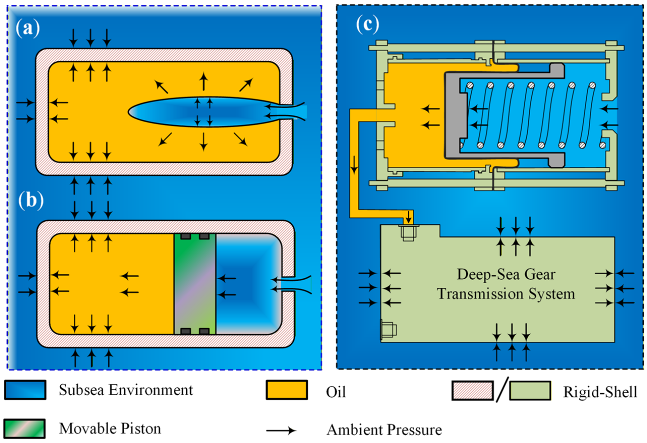


Figure 1. Schematic illustration of the mechanism of pressure-balanced units: **(a)** resilience-bladder type, **(b)** movable-piston type, **(c)** the shuttle pin design with dual-bladder PBOF technology of Siemens DigiTRON.

Under high-pressure conditions, the viscosity of lubricating oil increases exponentially, leading to a sharp decline in fluidity that can induce a semi-solid state (Sperka et al., 2016). This not only significantly increases churning power loss in the gearbox but also impedes timely backflow and oil replenishment, resulting in film rupture and exacerbated tooth surface wear (Cai et al., 2016; Li et al., 2025). The high-pressure environment places stringent demands on sealing systems; seal failure can lead to high-pressure seawater intrusion, contaminating the lubricant, corroding gear surfaces, and potentially triggering complex failures such as fretting corrosion (Gong et al., 2024; Chen et al., 2011). Furthermore, temperatures in most deep-sea regions remain between 2 and 4 °C year-round. These low temperatures further increase viscosity and reduce fluidity (Xiao et al., 2018). Under the combined effects of high pressure and low temperature, the dramatic rise in viscosity leads to higher starting torque and reduced pumping performance, making it challenging to supply lubricant to the meshing zone promptly and thereby causing lubrication starvation (Qian et al., 2024). Moreover, high pressure and low temperature alter critical thermo-physical parameters, such as density and thermal conductivity, compromising the accuracy of film thickness and temperature field calculations in thermal elasto-hydrodynamic lubrication (TEHL) analysis. In extreme cases, such as during cold starts, the drastic viscosity increase may prevent start-up altogether (Tošić et al., 2023; Wu et al., 2025). As the core theory for studying lubrication in high-load non-conformal contacts, TEHL comprehensively accounts for hydrodynamic effects, elastic deformation, and the lubricant's pressure-viscosity and temperature-viscosity characteristics, alongside thermal effects. It accurately describes key parameters in the meshing zone, such as film pressure, thickness, temperature field, and friction (Lv et al., 2022; Torres et al., 2023; Zhang and Zhang, 2021). By establishing numerical models that reflect the coupled effects of high pressure and low temperature, applying TEHL theory to deep-sea gear systems enables the quantitative analysis and prediction of lubrication characteristics under extreme operating conditions (Jian et al., 2020). However, relying solely on the passive selection of superior lubricants and base materials is often insufficient to address such harsh conditions fully. Interface texturing technology, an active tribological control strategy, has garnered significant attention in recent years (Yuan et al., 2025). This technique involves creating micro-scale pits or grooves with specific geometries and spatial arrangements on friction pair surfaces to improve lubrication, and suppress friction and wear.

Through mechanisms such as acting as oil reservoirs, generating secondary hydrodynamic effects, and trapping wear debris, interface texturing offers a promising solution for addressing the lubrication challenges faced by deep-sea gears under high loads and low speeds.

While traditional research on gear lubrication has achieved substantial success under conventional conditions, it remains inadequate for addressing extreme marine environments characterized by high pressure and low temperatures. Adequate lubrication is essential for reducing friction and wear, lowering energy consumption, and extending equipment service life; however, traditional lubrication theories and methods often prove insufficient in deep-sea, high-pressure, and low-temperature environments. Consequently, this article reviews and evaluates the progress of two core research areas – EHL theory and interface texturing technology – in the context of marine gear transmission systems. Through an in-depth analysis of the mechanisms by which extreme environments affect lubrication performance, future research prospects are outlined. This study aims to provide theoretical support for the reliable design and operation of marine transmission systems, offering valuable insights and engineering guidance for enhancing the performance and reliability of deep-sea equipment. The integration of advanced machine learning architectures, including random forest ensembles, deep neural networks, and multi-modal learning paradigms, holds substantial potential for enhancing micro-texture performance prediction capabilities. Incorporating these multiscale homogenization techniques into predictive models is expected to improve the fidelity of parameter estimation. However, it must be acknowledged that data-intensive approaches inherently demand extensive high-fidelity datasets and impose significant computational burdens during model training and validation phases. In this context, physics-based mathematical modelling retains its advantageous position as a computationally efficient and economically viable approach for predicting the tribological performance of gear pairs.

2 Lubricant interactions in deep-sea extremes: environmental characteristics and tribological system responses

2.1 Multi-scale characteristics of deep-sea pressure and temperature

In contrast to terrestrial operating environments, gear systems operate in a significantly more severe service, compounded by high pressure and low temperatures. As operational depths reach several thousand metres, systems must adapt to these extreme conditions. The deep sea, commonly defined as depths exceeding 200 m or, more strictly, below 1000 m, constitutes over 95 % of the Earth's habitable biosphere, and represents the planet's most extensive and least understood ecosystem (Tortorella et al., 2018). Seawater temperature drops noticeably with depth, stabilizing only after passing through the thermocline into the abyssal and hadal zones (Skropeta and Wei, 2014). Beginning at approximately 200 m depth, seasonal and interannual temperature fluctuations essentially vanish, creating a highly stable cold environment throughout the global deep ocean where water temperatures are consistently maintained between 0 and 4 °C (Amano et al., 2022; Peacock and Ouillon, 2023). Concurrently, hydrostatic pressure increases sharply, rising linearly at a gradient of about 0.1 MPa per 10 m, exceeding 110 MPa at the extreme depths of the Mariana Trench (Scheffer and Gieg, 2023; Wang et al., 2020). Furthermore, light intensity decays exponentially with depth, with 99 % of incident light dissipated by 150 m, rendering the environment below 250 m virtually devoid of light (Paul et al., 2011; Sun and Wang, 2017). Chemically, seawater acts as a strong electrolyte, rich in chloride ions and dissolved oxygen, and constitutes a naturally corrosive environment (Wood, 2017). In this aqueous setting, metals form microscopic anodic and cathodic regions where anodic metal dissolution and cathodic oxygen reduction reactions occur. Notably, the high concentration of chloride ions is highly aggressive and can break down the passivation film on metal surfaces, thereby initiating and accelerating localized corrosion (Von der Ohe et al., 2010). Prolonged exposure to this high-salinity, high-humidity environment poses severe electrochemical corrosion challenges for metallic materials. This not only compromises the load-bearing capacity of materials but also contributes to the premature failure of gear transmission systems.

2.2 Thermodynamic and rheological property evolution of lubricants under high pressure, low temperature

At low temperatures, the thermal motion of molecules is suppressed, allowing intermolecular forces to dominate and molecular structures to become more ordered. This phenomenon increases flow resistance and elevates viscosity. As temperature rises, however, intermolecular separation expands and cohesive forces decline; the resulting enhancement in molecular thermal motion reduces flow resistance, manifesting macroscopically as a substantial decrease in viscosity (Himanshu et al., 2026; Bair et al., 2018). Meanwhile, increasing pressure compresses lubricant molecules, reducing the average intermolecular distance and free volume. These intensified interactions lead to a marked increase in flow resistance and an exponential increase in viscosity (Boussaid et al., 2024). Within the framework of EHL theory, lubricant viscosity is commonly defined as a function of both pressure and temperature. Researchers have developed various empirical and semi-empirical models to characterize the dependence of lubricant viscosity on temperature and pressure. These models generally fall into three categories: viscosity-temperature equations, viscosity-pressure equations, and coupled viscosity-temperature-pressure equations, which account for both factors simultaneously. Among viscosity-temperature models, the Reynolds equation is suitable for narrow temperature ranges, whereas the Andrade equation, despite its simple form, has limited predictive capability over broad temperature spans (Su et al., 2024; Xu et al., 2023a; Zhang et al., 2024). The Slotte equation more accurately describes viscosity changes across wide temperature variations, although its parameters are fluid specific (Seeton, 2006). The Vogel–Fulcher–Tammann (VTF) equation, grounded in free volume theory, is particularly effective for describing viscosity behaviour near the glass transition (Levit et al., 2019). The Walther equation, recommended as an ASTM standard, serves as the basis for generating viscosity-temperature charts. Regarding viscosity–pressure relationships, the Barus equation is simple but applicable only to low pressures; the Roelands equation offers superior accuracy over a wider pressure range; and the Cameron equation can be viewed as a modification of the Barus model suited for high-pressure conditions (Bair, 2022; Andersson et al., 2021). In practical operating scenarios such as EHL, temperature and pressure often fluctuate drastically and simultaneously, necessitating the use of coupled models. For instance, the Barus–Reynolds combination is straightforward but inherits the high-pressure inaccuracies of the Barus model. Since its introduction in 1966, the Roelands equation has gained widespread recognition for its accuracy and universality across diverse conditions.

To provide a unified description of viscosity behaviour from the liquid to the glassy state, researchers have also developed comprehensive models such as the WLF-Yasutomi model. By integrating the WLF equation into the Tait equation of state, this model effectively predicts viscosity variations across a range of pressures and temperatures within a single framework. Continuously refined through experimental fitting, it has become one of the most representative models in current use (Lei et al., 2017; Gupta et al., 2020a; Ewen et al., 2018). Under high-pressure operating conditions typical of deep-sea environments, hydrostatic pressures reaching tens of megapascals are sufficient to induce a significant increase in the base viscosity of lubricating oil. In Hertzian contact zones, pressures can surge to the gigapascal (GPa) range, increasing viscosity by several orders of magnitude. Accurately modelling such drastic variations is critical for TEHL analysis. The low-temperature environment of the deep sea can elevate lubricant viscosity by 1 to 2 orders of magnitude compared to ambient conditions. While increased viscosity theoretically facilitates the formation of thicker oil films, the adverse effects of severely reduced fluidity are more pronounced and often constitute the primary cause of lubrication failure. The synergistic effect of high pressure and low temperature drives the lubricating oil into an extreme high-viscosity state, where its behaviour approximates that of an amorphous solid, exhibiting high internal friction and shear stress. This state further acts as a significant source of churning losses and temperature escalation in the contact zone. Precise characterization and simulation of the viscosity–pressure–temperature relationship under these coupled high-pressure and low-temperature conditions are crucial prerequisites for reliable lubrication analysis and design, and the experimental data under such extreme conditions remain extremely scarce.

2.3 Lubricant density: a foundation basis for thermo-physical property evaluation and performance prediction

Beyond viscosity, thermo-physical properties such as density, thermal conductivity, and specific heat capacity are pivotal in TEHL analysis because they directly affect the solution of the mass conservation and energy equations. These properties depend significantly on temperature and pressure, a sensitivity that intensifies under extreme operating conditions. Density, a key parameter, substantially affects the fluid mass flowing through the contact zone and the oil film thickness. Research indicates that density typically decreases with rising temperature and increases with rising pressure (Xu et al., 2023b). Owing to its concise form and ease of application, the Dowson–Higginson equation is widely used in engineering calculations:

$$\rho\,(p,T)=\rho_{\mathrm{R}}\left\{\frac{5.9\times10^{8}+1.34p}{5.9\times10^{8}+p}-\beta_{\mathrm{DH}}\,(T-T_{\mathrm{R}})\right\}, \tag{1}$$

where ρ_{R} is the reference density, T_{R} is the reference temperature, and β_{DH} is the density-temperature coefficient.

To further enhance prediction accuracy across a wide range of pressures and temperatures, the Tait (Hartung, 2022) equation of state is more precise than the Dowson–Higginson equation:

$$\rho\,(p,T)=\frac{\rho_{\mathrm{R}}}{\{1+\alpha_{\upsilon}\,(T-T_{\mathrm{R}})\}\left\{1-\frac{1}{1+K_0'}\ln\left[1+\frac{(1+K_0')p}{K_{\infty}e^{-\beta_{\mathrm{K}}T}}\right]\right\}}, \tag{2}$$

where α_{υ} is the coefficient of volumetric thermal expansion, K_0' is the variation of the isothermal bulk modulus at absolute zero temperature, K_{∞} is the isothermal bulk modulus at absolute zero temperature, and β_{K} is the temperature coefficient of the isothermal bulk modulus.

Thermal conductivity and specific heat capacity define a lubricant's heat transfer capability and thermal storage capacity, respectively. Together, these parameters govern the temperature distribution in the TEHL contact zone. While both properties exhibit pressure and temperature dependence, their sensitivity to these variables is generally less pronounced than that of viscosity and density. Thermal conductivity typically increases slightly with rising pressure and temperature, whereas specific heat capacity is predominantly temperature dependent, with pressure effects being negligible. In low-temperature environments, reduced thermal conductivity impedes the dissipation of shear-induced heat, leading to localized temperature spikes. This phenomenon may

Table 1. Parameters related to lubrication media for deep-sea gear transmission system.

Type	Model	Formula	Equation number
Viscosity–temperature correlation	Reynolds	$\eta=\eta_0 e^{-\beta(T-T_0)}$	(1)
	Andrade–Erying	$\eta=\eta_0 e^{\frac{\alpha}{T}}$	(2)
	Slotte	$\eta=\frac{s}{(\alpha+T)^m}$	(3)
	Vogel	$\eta=\eta_0 e^{b/(T+\theta)}$	(4)
	Walther	$(v+a)=bd^{1/T^c}$	(5)
Viscosity–pressure correlation	Barus	$\eta=\eta_0 e^{\alpha p}$	(6)
	Roelands	$\eta=\eta_0 e^{\{(\ln\eta_0+9.67)[-1+(1+p_0 p)^z]\}}$	(7)
	Cameron	$\eta=\eta_0(1+cp)^{16}$	(8)
Viscosity–temperature– pressure correlation	Barus and Reynolds	$\eta=\eta_0 e^{[\alpha p-\beta(T-T_0)]}$	(9)
	Roelands	$\eta=\eta_0 e^{\left\{(\ln\eta_0+9.67)\left[\left(1+5.1\times10^{-9}p\right)^{0.69}\times\left(\frac{T-138}{T_0-138}\right)^{-1.1}-1\right]\right\}}$	(10)
	WLF-Yasutomi	$\eta=\eta_g e^{\left(\log(10)\frac{-C_1(T-T_g(p))F(p)}{C_2+(T-T_g(p))F(p)}\right)}$	(11)

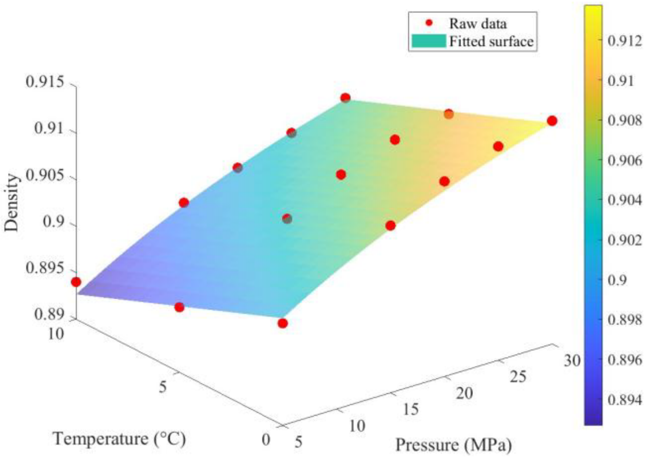


Figure 2. The density variation with respect to pressure and temperature.

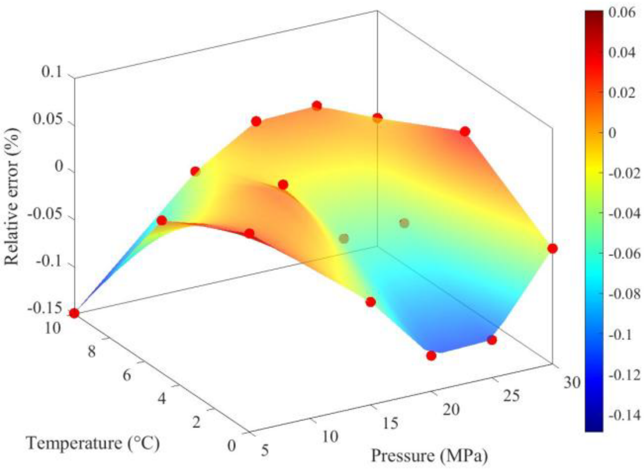


Figure 3. Relative error meshing interface of density.

trigger a complex coupled feedback loop characterized by escalating temperatures, reduced viscosity, and corresponding variations in heat generation.

In deep-sea environments, the combination of low temperatures and high pressures affects lubricant rheological behaviour, as illustrated in Figs. 2 and 3. Low temperatures suppress molecular thermal motion and strengthen intermolecular forces, resulting in a substantial increase in viscosity. High pressures further amplify this effect by reducing intermolecular spacing, potentially inducing non-Newtonian behaviour or even solidification. When these factors act synergistically, the coupled conditions severely impair lubricant fluidity and film-forming capability, potentially causing equipment start-up failures or exacerbated friction and wear. Given the stringent operational requirements for marine lubrication systems under extreme temperature-pressure conditions, systematic investigation of the thermo-physical evolution of lubricating oils is imperative.

2.4 Multi-scale degradation of deep-sea gearbox lubricants induced by seawater ingress: damage mechanisms, performance evolution, and intrusion mitigation strategies

Sealing systems represent a critical weak point in deep-sea equipment. Subjected to sustained high differential pres-

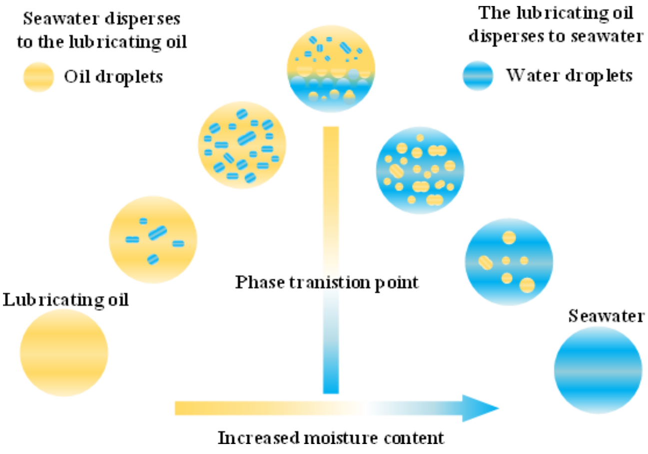


Figure 4. Schematic diagram of oil-water two-phase state.

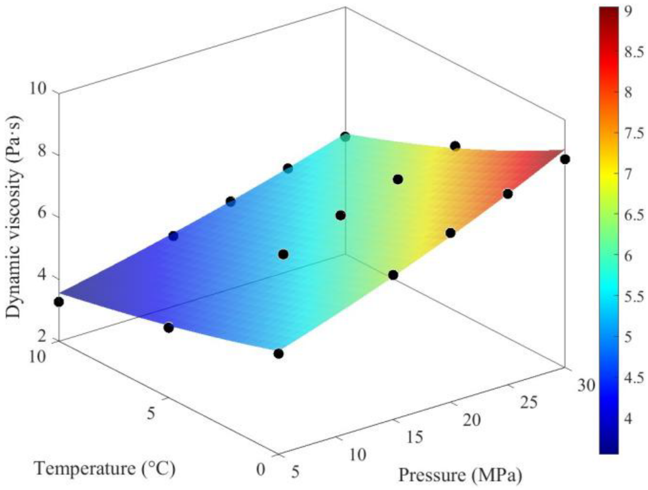


Figure 5. VG320 lubricant Roelands equation fitting.

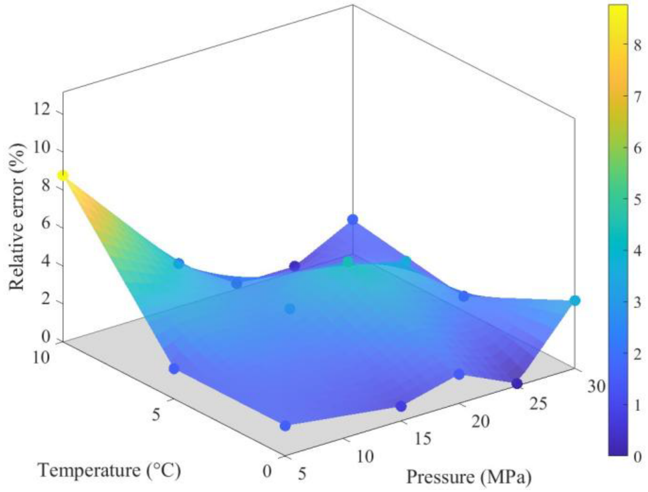


Figure 6. Fitting relative distribution changes.

sures, they face a significant risk of failure. If seawater infiltrates the gearbox, it drastically reduces the lubricant's apparent viscosity, impairing film formation and shifting from hydrodynamic to mixed or boundary lubrication, thereby accelerating wear on friction pairs (Zhou et al., 2024). As illustrated in Fig. 4, the phase behaviour of oil-water mixtures is complex. At water concentrations below the saturation limit, water dissolves into the oil, creating a homogeneous solution with a viscosity lower than that of the pure base oil (Harika et al., 2011).

Beyond this limit, an unstable two-phase system develops, characterized by water dispersed as fine droplets. While the initial addition of water slightly increases viscosity due to heightened interfacial tension (Ouyang et al., 2023), exceeding a critical concentration triggers an emulsion inversion from water-in-oil (W/O) to oil-in-water (O/W). This results in a precipitous decline in viscosity and a consequent loss of the lubricating film's load-bearing capacity. Moreover, electrolytes and chloride ions inherent in seawater can disrupt the oil-water interfacial tension and compromise the metal's passive film. The synergistic effect of mechanical wear and electrochemical corrosion significantly accelerates material degradation, fostering a vicious cycle of corrosion-promoting wear and wear-promoting corrosion (Tian et al., 2022; Wang et al., 2012; Liu et al., 2024). Moreover, seawater can induce hydrolysis or chemical reactions with extreme pressure and anti-wear additives, thereby neutralizing the efficacy and inhibiting protective film formation under boundary lubrication regimes (Ijaz Malik et al., 2023). Seawater also disrupts the suspension stability of additives and accelerates the hydrolytic degradation of ester-based environmentally friendly lubricants. The resulting production of acidic species and sludge intensifies the corrosion of metal components (Litwin et al., 2024; Hossain et al., 2018). The deterioration not only diminishes lubrication performance but also risks clogging filters and oil passages, potentially leading to oil starvation and threatening the integrity of the lubrication system.

The fitting results of the Roelands model demonstrate high consistency with experimental data in terms of pressure and temperature trends. The constructed response interface effectively captures the overall distribution of the experimental data points, intuitively illustrating the variation in viscosity under different operating conditions (Fig. 5). Error analysis indicates that the residual sum of squares is 0.3926, with an average relative error of 2.29 % and a maximum relative error of 8.78 %. The low average error reflects the overall reliability of the model fitting, while the relatively high maximum error suggests some deviations under specific conditions.

Figure 6 further illustrates the distribution of relative errors across the pressure-temperature parameter space: most data points exhibit small errors, with significant deviations observed only in a few cases. This distribution pattern

Table 2. Dynamic viscosity of lubricating oil under different temperatures and pressures.

Temperature	5 MPa	15 MPa	20 MPa	25 MPa	30 MPa
0°	5.2584	6.6763	7.4744	8.1742	8.7312
5°	4.2642	5.5105	6.2095	6.8115	7.3204
10°	3.2655	4.2734	4.8230	5.3308	5.7945

aligns with the aforementioned statistical results. The variation of lubricant viscosity with temperature and pressure constitutes a fundamental issue in lubrication engineering. The viscosity–temperature relationship characterizes the decrease in viscosity as temperature increases. In this study, the Roelands viscosity–pressure–temperature correlation is fitted using MATLAB to obtain the dynamic viscosity of the lubricant under various temperature and pressure conditions, as presented in Table 2.

3 Multi-scale TEHL modelling for deep-sea tribological interfaces: adaptive mechanisms, convergence challenges, and methodological frontiers

3.1 Multi-physics coupling effects on lubrication regime transitions in deep-sea gear meshing interfaces

The Stribeck curve delineates three distinct lubrication regimes for mechanical contacts: full-film, mixed, and boundary lubrication. Full-film lubrication principally comprises hydrodynamic lubrication and EHL. In the context of heavily loaded gear pairs, the operating regime typically spans the spectrum from EHL to mixed lubrication. Figure 7 schematically delineates the characteristic features of these regimes and their transition dynamics. Under hydrodynamic and elasto-hydrodynamic conditions, contacting surfaces are entirely separated by a lubricant film of adequate thickness. Friction primarily arises from the internal shearing of lubricant molecules. In this state, the coefficient of friction is markedly low, wear is negligible, and the system operates under ideal lubrication conditions. Boundary lubrication stands in stark contrast; here, the lubricant film is extremely thin or non-existent, and the load is borne almost entirely by direct asperity contact. Consequently, this regime is characterized by high friction coefficients and severe wear. Mixed lubrication represents the intermediate state, where the load is distributed between the fluid film and asperity contacts, resulting in complex tribological behaviour.

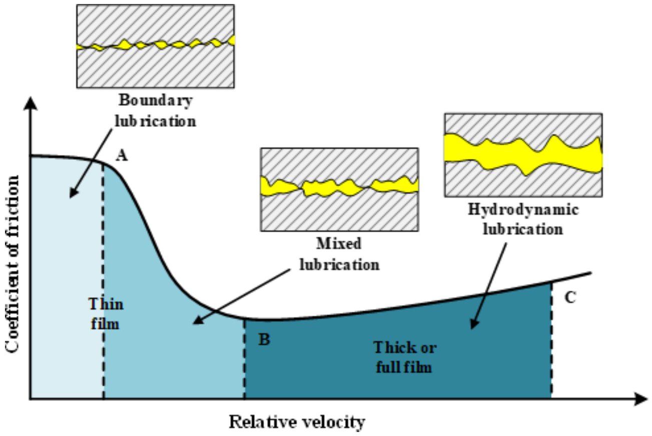


Figure 7. Transition of lubrication regimes.

Under the high-pressure, low-temperature conditions unique to deep-sea environments, lubricant viscosity increases exponentially, influencing the lubrication regime. Within the full-film regime, increased viscosity promotes the formation of a thicker lubricant film, thereby bolstering surface protection. In the mixed regime, higher viscosity mitigates direct asperity contact, reducing wear. In the boundary regime, protection relies primarily on surface-adsorbed chemical films. Nevertheless, the extreme viscosity elevation in such severe environments complicates the lubricant's rheological behaviour, posing a potential threat to the transmission system's operational reliability. High hydrostatic pressure in the deep sea can induce the glass transition of lubricants, leading to a sharp increase in the molecular relaxation time and a shift in dynamic behaviour from liquid like to solid like, thereby forming a macroscopic friction plateau (Gonon et al., 2025; Bair, 2019). At low temperatures, lubricants exhibit diverse phase behaviours: mineral oils may exhibit shear-thinning and yield stress driven by paraffin crystallization, whereas synthetic oils may undergo a glass transition, leading to a nonlinear increase in viscosity (Conrad et al., 2021). These transitions significantly compromise the spreading capability of the oil film, expediting the shift from EHL to mixed or even boundary lubrication regimes (Cui et al., 2023; Li et al., 2022). Models of rough surface contact further confirm that increased surface roughness or reduced load shortens the window for the onset of mixed lubrication; notably, wear frequently initiates at the point of minimum film thickness along the contact zone periphery (Chong et al., 2019). In light of the limitations of conventional lubricants in marine settings, solid lubricants suitable for extreme temperatures have emerged as a critical solution. This category encompasses layered materials, soft metals, MAX phases, and stable fluorides and oxides. Self-lubricating composites manufactured via powder metallurgy or thermal spraying techniques provide adequate lubrication across a broad temperature range (Kumar et al., 2022). Environmentally friendly gel lubricants retain advantageous rheological properties at low temperatures, showing promise for use in polar and deep-sea applications (Gorbacheva et al., 2021).

3.2 TEHL theory for gears operating under high-pressure and low-temperature conditions

The theory of TEHL for gears comprehensively accounts for the coupling effects of elastic deformation, thermal phenomena, and hydrodynamic lubrication during meshing. This approach enables a more realistic prediction of oil film thickness, pressure distribution, and temperature within the contact zone, thereby facilitating the assessment of performance indicators such as friction, wear, and fatigue (Maier et al., 2017). Building upon isothermal EHL theory, TEHL introduces the energy equation to account for frictional heating. The formulation centres on solving a system of highly nonlinear partial differential equations that characterize the physical state of the lubricated contact.

A comprehensive TEHL numerical model generally comprises the Reynolds equation, the film thickness equation, the load balance equation, the energy equation, and rheology equations governing the viscosity–pressure–temperature relationship. Numerical techniques are utilized to determine the pressure, thickness, and temperature distributions of the lubricant film. Figure 8 presents a schematic diagram of the pressure distribution and the variation in film thickness. The lubrication regime of gear meshing falls within the EHL domain, requiring the concurrent consideration of elastic deformation in the contacting bodies and variations in lubricant viscosity. During actual operation, gear surfaces endure extreme contact pressures, combined rolling and sliding motions, and transient thermal effects, creating a complex TEHL scenario. TEHL theory comprehensively accounts for the coupling among thermal effects, elastic deformation, and hydrodynamics, providing a realistic representation of the lubrication state. Under high-pressure and high-speed transmission, transient temperature elevations in the contact zone further intensify this complexity. The mechanism by which unbalanced radial forces in high-pressure internal gear pumps induce gear deformation is elucidated, thereby shifting the dominant frequency of pressure pulsation and integrating dynamic loads with a mixed EHL model (Liu et al., 2019). The evolutionary patterns of gear lubrication parameters under high loads and speeds is clarified (Xiao et al., 2018). Nevertheless, extreme operating conditions present severe challenges to lubrication stability. Results demonstrate that upon reaching critical load and speed values, the friction coefficient increases sharply when oil temperature exceeds the flash point, precipitating lubrication failure and severe wear (Duan et al., 2023). Thermally induced temperature rise reduces lubricant viscosity and increases oil film compressive deformation, yielding tangential stiffness significantly exceeding isothermal predictions, as demonstrated by the established stiffness model (Yin et al., 2021). This phenomenon is particularly pronounced in the tooth root region, where loads are concentrated. A finite-element coupling model is developed to investigate mixed lubrication in planetary gear systems under low-speed, heavy-load conditions, accounting for local temperature rises from asperity contact, film rupture, and thermal deformation (Wang et al., 2026a).

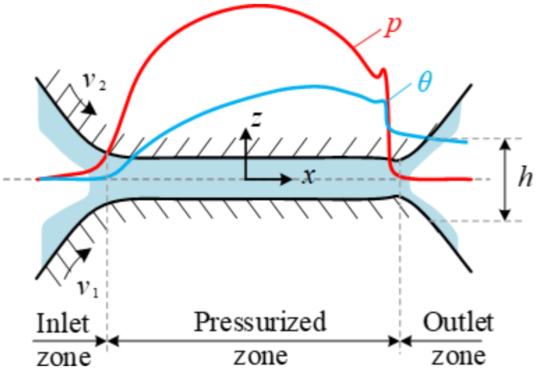


Figure 8. Schematic of pressure distribution and film thickness variation in the lubricating film.

In contrast, low-temperature environments significantly impact lubricant properties and system behaviour. Existing literature demonstrates that temperature reduction drastically increases lubricant viscosity while inducing significant rheological transformations (Su et al., 2023). This results not only in oil film thickening and abnormal fluctuations in the traction coefficient but also in exacerbated rolling-element slippage. To accurately capture rheological behaviour under low-temperature, high-viscosity conditions, a modified Herschel–Bulkley model is proposed, which exhibits superior accuracy in fitting experimental data and calculating engineering traction coefficients compared to traditional H-B and T-J models. Moreover, a mechanical-thermal coupled model reveals that increased grease viscosity at low temperatures in high-speed train bearings leads to film thickening and aggravated slippage, identifying these factors as intrinsic causes of early failures in cold-region rail bearings (Liu et al., 2022). Lastly, employing a viscous-hyperelastic mixed lubrication model, the proposed model demonstrated that in deep-sea environments defined by high pressure, low temperatures, and corrosion, the model offers significantly better prediction accuracy for water film stiffness than traditional linear models, offering critical theoretical support for the design of water-lubricated gear transmissions (Wang et al., 2025a).

3.3 Applicability and challenges of EHL in deep-sea environments

Under ultra-high hydrostatic pressure, conventional viscosity–pressure relationships often fail to characterize lubricant behaviour accurately. As pressure approaches the glass transition point, the constitutive behaviour deviates significantly from standard models (Ziegltrum et al., 2018; Sivayogan et al., 2020). Furthermore, high pressure compresses the lubricant substantially, increasing its density. This change directly impacts the accuracy of mass conservation and oil film thickness predictions in TEHL calculations (Mounayer and Habchi, 2023). The deep-sea environment creates a unique cold-exterior, hot-interior scenario. While the system is externally cooled by low-temperature seawater, the internal high-speed shearing of gear surfaces generates substantial frictional heat. This severe temperature gradient complicates heat conduction and convection, imposing stricter requirements for calculating oil film temperature fields and flash temperatures (Yin et al., 2020). Although strong external cooling helps to suppress temperature rise and maintain higher oil film viscosity, it complicates thermal management. Consequently, TEHL modelling requires modified boundary conditions to reflect forced convection with seawater, and the impact of thermal management measures, such as insulation layers or active cooling, on the system's thermal balance must be accounted for (MacLaren and Kadiric, 2024; Li et al., 2022). Extremely low ambient temperatures cause a sharp increase in lubricant viscosity and reduced fluidity (Castaño and Velázquez, 2021). Although high viscosity theoretically promotes thicker oil film formation, the lubricant may fail to replenish the contact zone in time under low-speed conditions where hydrodynamic effects are weak. This can force gears into a mixed or boundary lubrication regime, significantly increasing the risk of wear (Kolivand et al., 2021). During operation, shear heat in the meshing zone gradually raises the oil temperature, reducing viscosity and potentially shifting the lubrication state towards full-film EHL (Zhao et al., 2024). However, the deep-sea, low-temperature environment acts as a continuous cold sink, absorbing system heat and maintaining a thermal equilibrium temperature far below normal operating conditions, thereby further affecting lubricant performance and oil film formation. The combination of high hydrostatic pressure and Hertzian contact pressure leads to extremely high lubricant viscosity in the contact zone. This excessive viscosity increases viscous shear forces, leading to a higher friction coefficient and a significant temperature rise. The resulting temperature rise reduces viscosity, thereby limiting the sustained growth of oil film thickness (Fang et al., 2025). Since gear meshing is inherently a transient process with continuously changing contact geometry, load, and speed, extreme physical property variations in the deep sea can cause severe fluctuations in lubrication state within a single meshing cycle, making prediction and control more difficult (Wang et al., 2019; Shi et al., 2021).

The viscosity resulting from high pressure increases the computational difficulty of solving the TEHL governing equations, often leading to convergence and stability issues in numerical simulations. In these conditions, lubricants may exhibit solid-like shear behaviour, leading to a drastic increase in friction and challenging the validity of the traditional Reynolds equation, which is predicated on fluid assumptions (Amine et al., 2023). Although recent research has focused on material property models for extreme environments, a model that accurately describes lubricant rheology under the simultaneous influence of low temperature, ultra-high pressure, and high shear rates is still lacking (Saxena et al., 2025). Moreover, the interplay between time-varying frictional heat and rough surfaces with multi-scale fractal characteristics adds further complexity to the analysis of TEHL behaviour (Ruan et al., 2025b).

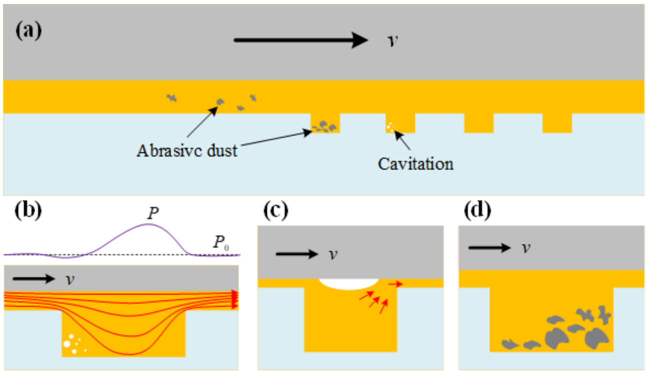


Figure 9. Schematic diagram of the anti-wear mechanisms of interface texturing under different operating conditions.

4 Meshing interface texturing technology and its application prospects in deep-sea gear lubrication

4.1 Mechanisms of friction reduction and wear resistance in micro-textured meshing interfaces

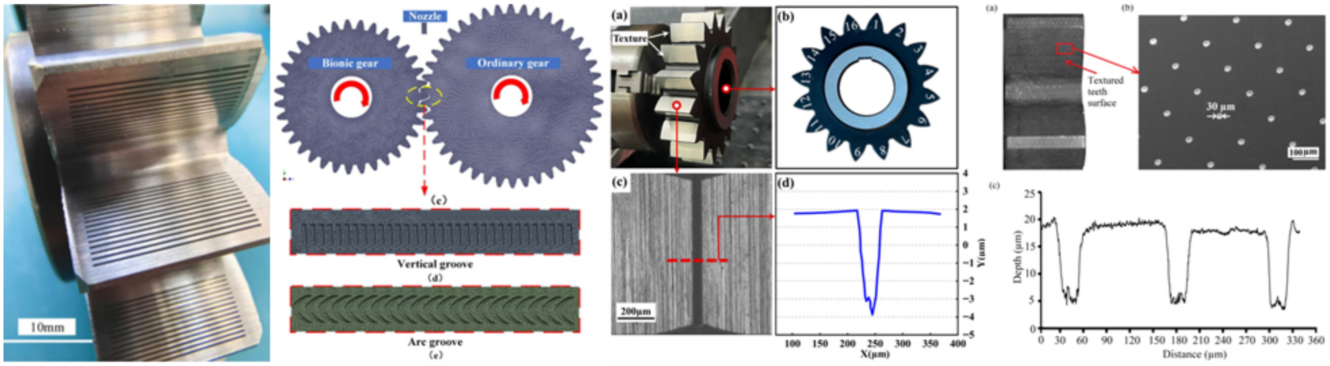
Meshing interface texturing entails the precise design and fabrication of micro- and nanoscale surface features, such as pits or grooves with specific geometries and spatial distributions, on friction pairs. This approach actively tailors the tribological properties of the interface (Zhou et al., 2024; Xu et al., 2023b). By modifying surface morphology, texturing regulates lubricant flow and optimizes contact stress distribution, thereby enhancing macroscopic tribological performance. Specific benefits include reduced friction coefficients, improved load-bearing capacity, minimized wear, and effective containment of wear debris (Braumann et al., 2025). Driven by advancements in precision manufacturing, particularly laser processing, the technique has been widely adopted in mechanical seals and bearings. Moreover, it holds considerable promise for mitigating lubrication challenges in heavily loaded, high-speed gear systems (Arumugaprabu et al., 2018; Watanabe et al., 2025).

The tribological benefits of interface texturing, specifically friction reduction and wear resistance, stem from the synergy of multiple mechanisms: hydrodynamic pressure enhancement, secondary lubrication, debris entrapment, and surface strengthening. Figure 9a depicts the mechanisms of debris entrapment and cavitation generation on textured surfaces. In hydrodynamic or mixed lubrication regimes, microtextures establish microscopic wedge-shaped gaps that disrupt the parallel flow of the lubricant film, inducing a convergent zone downstream of the structures (Chen et al., 2021). Based on the Reynolds equation, this convergent zone generates additional hydrodynamic pressure, increasing the oil film thickness and separating the contact surfaces. By converting solid–solid contact to fluid shear, this mechanism significantly mitigates friction and wear (Guo et al., 2022; Gropper et al., 2016) (Fig. 9b). During boundary lubrication or transient phases, such as start-stop operations, interface textures act as micro-reservoirs (Wang et al., 2024; Yin et al., 2023). Stored lubricant is released to compensate for insufficiencies in the main oil film, creating a secondary lubricating film that delays or avoids dry contact. This capability markedly improves the reliability of gears operating under severe conditions, such as low speed and heavy load (Vishnoi et al., 2021; Shen et al., 2021) (Fig. 9c). Additionally, interface textures serve to trap and isolate wear debris, thereby preventing three-body abrasion at the interface (Mao et al., 2020; Maldonado-Cortés et al., 2021) (Fig. 9d). Moreover, high-energy beam machining techniques, such as laser texturing, induce rapid thermal cycling that modifies the microstructure surrounding the textures. This results in fine-grain strengthening and increased dislocation density, forming hardened zones with elevated micro-hardness that further bolster the material's resistance to plastic deformation and wear (Moradi et al., 2019). These interface texturing mechanisms prove particularly effective in marine environments. Under high-pressure conditions, the textures' capacity to store oil compensates for lubricant displacement, thereby maintaining the integrity of the lubricating film. In humid or water-rich environments, the geometric structure helps to collect and divert water, thereby alleviating lubricant emulsification. Additionally, during cold starts, the lubricant reservoir in the textures rapidly activates, forming a film that markedly reduces wear during the critical start-up period.

4.2 Micro-texturing technologies for gear meshing interfaces: from lubrication mechanisms to anti-scuffing load-bearing applications

Gear surface texturing is regarded as a pivotal approach for enhancing the tribological performance of gears. Its research scope has progressively evolved from early investigations of simple geometric configurations to the deep integration of biomimetic designs and multi-parameter collaborative optimization. Preliminary explorations primarily focused on analysing the mechanisms by which basic geometric features, such as circles and grooves, influence gear performance. Comparative studies have demonstrated that circular pits are effective in reducing the friction coefficient (Wang et al., 2023). Meanwhile, parameter optimization studies have confirmed that rationally designed groove textures can significantly decrease the surface damage rate and improve anti-adhesion capability (Chang et al., 2023), as illustrated in Fig. 10a. Inspired by surface morphologies found in nature, biomimetic texturing has emerged as a significant research direction. A striped surface inspired by intertidal bivalves is developed, which improved the contact fatigue resistance of gears by more than 20 % (Lei et al., 2024; Zhang et al., 2025). Figure 10b displays the curved groove texture designed by drawing inspiration from the *Pecten maximus* (great scallop); this design exhibited superior performance in reducing the friction coefficient, wear depth, and operating temperature. A biomimetic hexagonal texture with bidirectional grooves is designed (Wang et al., 2025a), which significantly enhanced thermal management and prolonged gear service life through improved convective heat transfer and lubricant distribution (Fig. 10c). To further improve performance, the research focus has shifted towards the precise optimization of key texture parameters and their coupling effects in multi-physics fields. Through the modelling and analysis of rhombic microtextures, it has been demonstrated that these textures are capable of reducing the friction coefficient by up to 22.96 %, while concurrently revealing the coupling influence of texture parameters on lubrication and vibration performance (Wang et al., 2026b). Systematic comparative analysis of various biomimetic micro-textures identifies the crescent configuration as optimal, attributable to its superior hydrodynamic lubrication performance and enhanced debris entrapment capability, thereby achieving significant reductions in friction and wear. Furthermore, the adaptability of such textures to diverse operating conditions represents a critical research priority (Zhao et al., 2019). It is noted that micro-cylindrical pits exhibit exceptional suitability for vibration suppression and debris entrapment under fully lubricated conditions (Gupta et al., 2018, 2020b, 2022). Vertical ellipsoid pits offer superior cooling and vibration suppression in lubrication-starved scenarios, as illustrated in Fig. 10d. A manufacturing technique integrating power grinding with flexible topology modification is proposed, which enables the prediction and active control of gear interface textures, thereby effectively reducing vibration and noise (Tang et al., 2025). Parametric studies elucidated the nonlinear interplay between surface texture characteristics and dual functional responses, and between debris capture capability and meshing stiffness, offering theoretical insights for robust texture design across variable operating regimes (Zhang et al., 2025; Chen et al., 2023).

The fabrication of high-performance textures relies on manufacturing technologies characterized by high precision, high efficiency, and low damage. Current mainstream processes are categorized into subtractive, additive, and material-transfer types, with subtractive manufacturing being the most widely used. Among subtractive techniques, laser processing, particularly femtosecond laser processing, has emerged as the preferred method due to its high precision and flexibility. By adjusting parameters such as laser power and scanning speed, texture morphology can be precisely controlled and surface hardness enhanced. Challenges regarding the heat-affected zone and slag must be addressed (Sharma et al., 2021; Salguero et al., 2019). Chemical etching uses etchants to remove material directionally; it is suitable for



(a) (b) (c) (d)

Figure 10. Different gear meshing interface textures.

mass production and preserves the mechanical properties of the substrate, yet it is limited by corrosiveness and processing speed (Xu et al., 2018, 2019; Brăileanu et al., 2025). Micro-grinding enables superior surface quality and the fabrication of complex micro-grooves, whereas abrasive flow machining offers excellent uniformity on complex tooth surfaces but presents challenges in shape control (Zhou et al., 2024; Fu et al., 2020). Abrasive water jet machining removes material via high-speed abrasive impingement, offering potential for high efficiency and environmental friendliness (Jagadish and Ray, 2019; Natarajan et al., 2020; Shi et al., 2017). Electrical discharge machining, while suitable for hard conductive materials, is associated with issues such as recast layers and low efficiency. Regarding additive techniques, 3D printing (additive manufacturing) can fabricate complex 3D structures but currently faces limitations related to material grain structure and cracking (Hong et al., 2017; Naat et al., 2024; Li et al., 2018). Material-transfer techniques (such as micro-texture rolling) leverage plastic deformation to transfer patterns, offering high efficiency and consistency. However, challenges exist when processing high hardness or complex textures. A process combining laser pre-treatment with abrasive flow machining is adopted, which significantly enhanced the quality and wear resistance of the tooth surfaces. Currently, process selection requires careful consideration of material characteristics and costs (Wos et al., 2020; Petare et al., 2020). Looking ahead, driven by the development of hybrid processes (e.g. laser-electrochemical combinations, the integration of abrasive water jet with milling) and digital control technologies, the manufacturing of gear interface textures is poised to evolve towards greater efficiency and precision.

4.3 Meshing-interface-enriched lubrication considering micro-texture effects

To accurately predict and design the lubrication performance of textured gears, theoretical research has evolved from simple isothermal models to complex multi-physics simulations. Early studies were primarily based on isothermal assumptions, focusing on analysing the influence of texture parameters on lubrication. Experimental results confirm that the oil film thickness increases proportionally with the micro-dimple area ratio (Li et al., 2018). The respective contributions of groove patterns and laser surface textures to hydrodynamic effect enhancement are experimentally validated (Zhao et al., 2021). Transient EHL theory is utilized to elucidate the synergistic influences of composite curvature radius, entrainment velocity, and external load on the lubrication performance (Petare et al., 2019; Pei et al., 2019). Texture orientation is further examined to decode its anisotropic coupling effects on lubricant entrainment and pressure build-up. These insights lay the groundwork for physics-informed optimization of geometric texture parameters, facilitating the robust design of micro-textured interfaces towards superior load-bearing capacity and friction reduction (Morales-Espejel et al., 2018). Advancing lubrication research has increasingly focused on complex interfacial behaviour and thermodynamic coupling effects. Parametric dependencies of texture-induced cavitation, characterized by rotational speed, load, and geometric configuration, reveal the evolution mechanisms of interfacial cavitation in micro-textured lubrication regimes (Wang et al., 2020). A comprehensive model accounting for the coupling between surface roughness and micro-textures has been established. The results demonstrate that optimizing the aspect ratio can reduce tooth surface stress by approximately 50 %, thereby significantly extending fatigue life. Given the pronounced thermal effects under high-speed, heavy-load conditions, current research has shifted towards TEHL and dynamic-coupling models (Xiao et al., 2025). A 3D thermoelastic-dynamic contact model is proposed (Liu et al., 2018). Mixed lubrication analysis and interface friction-dynamics coupling models were employed to elucidate the intricate effects of surface textures on contact stiffness, damping characteristics, and system vibrations. The findings demonstrate that the interplay between surface roughness and texture geometry is directly correlated with the dynamic stability and thermal behaviour of gear systems (Cheng et al., 2023; Ruan et al., 2022).

In light of the complexity inherent in the continuous dynamic process of gear meshing, research trends are shifting from single-point analysis towards multi-scale coupling and system-level simulation. On the one hand, micro-texture macro-meshing multi-scale coupling analysis has emerged as a prominent research area. This approach embeds local lubrication boundaries that account for texture effects into macroscopic dynamic models, thereby enabling precise mapping between microstructural features and macroscopic motion. On the other hand, research focuses on system-level evaluation, comprehensively considering the influence of textured gear pairs on the transmission's overall efficiency, vibration, noise, and temperature rise. These frontier directions not only deepen the understanding of the underlying mechanisms of textures but also provide critical support for the global optimization of high-performance gear transmission systems; however, their implementation also imposes higher demands on computational capabilities and numerical algorithms.

4.4 Multi-scale micro-texturing meshing interface for deep-sea gear transmission environmental challenge

In recent years, numerous scholars have conducted experimental investigations into the tribological performance of interface textures in marine environments. These studies typically employ experimental setups that simulate marine conditions, such as seawater-lubricated bearing test rigs and high-pressure chamber friction testers, to validate the efficacy of interface textures. A study focusing on marine propeller hub bearings demonstrated that surface texturing technology can significantly enhance tribological performance, reducing the friction coefficient by 20 %–30 % and the wear volume by 40 %–50 %. This improvement is particularly pronounced under starved lubrication conditions, as the textures provide a continuous lubricant supply, thereby reducing the likelihood of direct metal-to-metal contact. Another investigation into the tribological properties of textured titanium alloys under dry friction and perfluoropolyether oil lubrication found that appropriately designed interface textures can significantly improve the wear resistance of titanium alloys, especially in harsh environments. This is of great significance for titanium alloy gears, which are widely utilized in marine equipment. Furthermore, research has explored the tribological performance of a combined system involving surface texturing and ionic liquid lubrication in marine settings. The results indicated that the two exhibit a synergistic effect, capable of further enhancing the wear and corrosion resistance of gears. This provides novel insights for the development of specialized gear lubrication systems tailored to marine environments.

Although surface texturing technology has demonstrated promising results in laboratory studies, its practical application in marine gear transmission systems faces several challenges, including high fabrication costs, long-term durability, and the impact on gear strength. These issues require further investigation and resolution to facilitate the engineering application of this technology. While current research on gear surface texturing specifically for marine environments is limited, analysis of the underlying mechanisms suggests that interface textures hold immense potential for addressing marine environmental challenges. The oil storage capacity of textures can supply essential lubrication to the meshing zone during the start-up phase, characterized by low temperatures, high viscosity, and poor lubricant fluidity, thereby preventing dry friction. Furthermore, when lubricant viscosity decreases due to seawater contamination, the secondary hydrodynamic effect generated by textures can partially compensate for the loss of load-carrying capacity, helping to maintain the necessary oil film thickness. While interface textures themselves do not possess intrinsic corrosion resistance, they provide a physical carrier for integrating anti-corrosion and friction-reduction technologies. Conversely, a purely textured surface may even accelerate localized corrosion due to the increased surface area and the formation of occluded cells. Therefore, it is essential to consider surface texturing and anti-corrosion coating technologies in synergy.

4.5 Development of experimental platform and design of test protocols

Addressing the anti-scuffing load-bearing failure of meshing pairs in high-speed, heavy-duty gear transmissions, this study incorporates the IEL effect of micro-textures to analyse the temperature field and friction characteristics, with experimental validation of the proposed theoretical model. The experimental specimens feature circular MET interfaces fabricated by mask-guided microbial jet machining (MGMJM), as shown in Fig. 11. The experimental platform setup and multi-condition testing scheme are illustrated in Fig. 12.

The processing efficiency can be quantitatively evaluated through the material etching rate (MER), which is defined as the volume of material removed per unit of time. When characterizing the micro-element contact morphology of the textured interface of the experimental specimen, a 3D video microscope (KH-8700, Hirox) and a scanning electron microscope (SU5000, HITACHI) are employed to obtain the microscopic morphology of the textured interface and the relevant data of micro-element contact quality achieved by different processing methods. In the roughness testing of the textured interface, based on the sampling method of micro-texture element forms, three representative functional micro-texture configurations on the processed textured interface are carefully selected as the measurement areas. By numerically calculating the average surface roughness value (Sa) of the micro-fabricated textured interface of the micro-biological

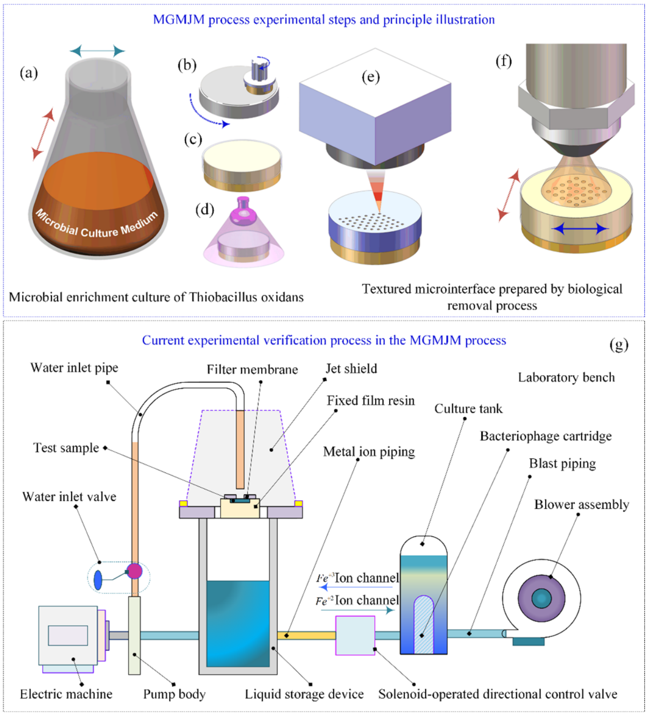


Figure 11. Process flowchart for fabricating functional textured surfaces using MGMJM. **(a)** Microbial strain amplification culture. **(b)** Sample grinding and polishing process. **(c)** Thin film-masking coating process. **(d)** Ultraviolet-light curing process. **(e)** Selective removal process of the mask film layer. **(f)** Preparation of textured interface micro-element configuration using MGMJM. **(g)** MGMJM experimental verification platform.

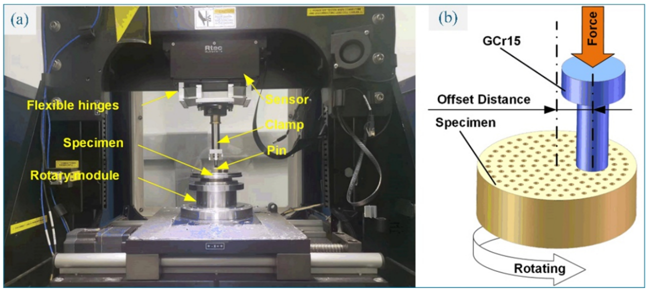


Figure 12. Tribological performance testing of micro-elements contact of textured interfaces. **(a)** Experimental performance verification setup. **(b)** Friction testing device.

chemical etching and combining the standard deviation of the three data sets to accurately characterize the error range, reliable data support is provided for subsequent analysis and research.

Phosphor bronze tin alloy (with total copper and tin content > 95 %) as the experimental material is employed. During the sample preparation stage, the alloy rod was first machined into cylindrical specimens with a diameter of 25 mm and height of 10 mm. The Brinell hardness of this material is approximately 90 HB. As shown in Fig. 13a–e, the samples were fabricated through precision machining. In the laser processing procedure, to effectively achieve selective removal of the mask while minimizing laser ablation damage to the substrate, laser parameters with wavelengths closely matching the absorption peak of the mask are specifically selected for processing.

Through numerical simulation, the pressure and temperature distribution characteristics in local contact areas are investigated, revealing the influence mechanisms of key parameters, including interface mean contact pressure, sliding velocity, lubricant bulk temperature, MET radius, and depth, on the coupled pressure-temperature fields at the interface. Grounded in the preceding analysis, five core governing factors are considered to investigate the underlying mechanism through which interface lubrication characteristics affect meshing load-bearing capacity.

5 Conclusions and prospects

This study presents a systematic review of how the distinctive and harsh marine environment, characterized by extreme hydrostatic pressure and cryogenic temperatures, influences the lubrication performance of gear transmission systems. Centred on EHL theory and surface micro-texturing technology, it synthesizes recent research advances, identifies critical scientific gaps, and outlines key technical challenges in deep-sea tribological applications.

5.1 Summary of findings and conclusions

The marine environment, characterized by high pressure and low temperature, poses multiple challenges for gear lubrication by significantly altering the viscosity-pressure, viscosity-temperature, density, and thermo-physical properties of lubricants. The ultra-high viscosity resulting from the coupling of high pressure and low temperature is a core issue, leading to problems such as poor fluidity, difficult start-up, high churning losses, and lubricant starvation. Furthermore, the risks of emulsification, corrosion, and additive failure associated with seawater intrusion further exacerbate the likelihood of lubrication failure.

EHL theory has effectively guided the design of gear lubrication systems. However, the drastic temperature and pressure changes in extreme deep-sea environments render the viscosity-pressure characteristics, rheological behaviour, and thermal effects of lubricants non-negligible, prompting the evolution of gear EHL theory towards TEHL. Although current TEHL research has established transient numerical model coupling thermal effects, non-Newtonian rheology, and realistic surface topography, simulation studies specifically targeting deep-sea high-pressure and low-temperature environments remain limited. The primary bottlenecks are the lack of lubricant property data under extreme operat-

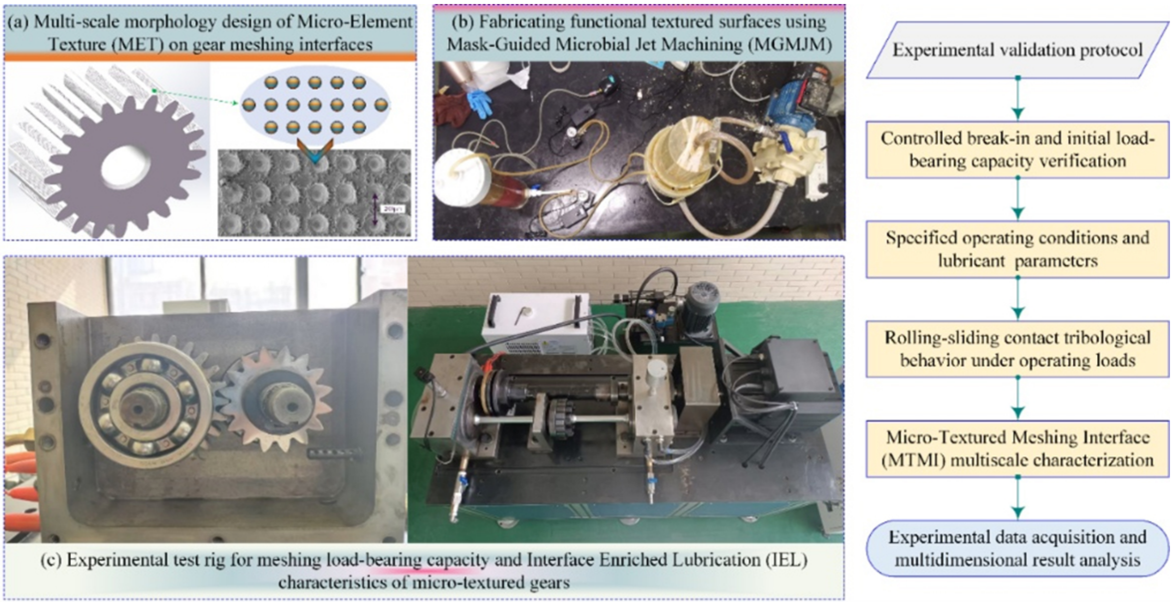


Figure 13. Experimental platform development and test protocol design.

ing conditions and numerical convergence challenges arising from multi-field coupling.

Interface texture technology effectively enhances the storage, flow, and load-carrying capacity of lubricants by fabricating microstructures on the gear surface, thereby reducing gear friction and wear. Optimal interface texture design can significantly improve the tribological performance of gears under mixed and boundary lubrication conditions, making it theoretically suitable for addressing challenges such as low-temperature start-up and low-speed, heavy-load operations in deep-sea gears. However, to fully harness the potential of interface textures, it is necessary to optimize their parameters for specific operating conditions and address long-term reliability issues in deep-sea environments.

5.2 Future research perspectives

Despite significant progress in research on deep-sea gear transmission lubrication, existing theories and technologies still face numerous bottlenecks under the combined challenges of extremely high pressure, low temperature, and severe corrosion, necessitating further in-depth exploration.

High pressure and low temperature significantly alter the physical properties of lubricants. At the same time, seawater corrosion fundamentally undermines both lubricant performance and tooth surface integrity, posing a risk of failure to traditional TEHL theory. Currently, detailed mechanistic studies on how seawater corrosion affects the TEHL oil film thickness, pressure distribution, and temperature fields are scarce. Furthermore, there is a lack of systematic understanding of the evolutionary patterns of gear material wear and lubricant ageing under multi-field coupling. Theoretical research on synergistic design, optimization methods, and case studies of gear interface textures and anti-corrosion coatings is limited, with applications in high-pressure, low-temperature marine environments still in their infancy. Additionally, laboratory simulations struggle to fully replicate actual deep-sea operating conditions, meaning the long-term durability of integrated texture-coating surfaces and their impact on system dynamic characteristics require further verification. To date, no comprehensive literature exists that integrates TEHL, interface textures, anti-corrosion coatings, and specialty lubricants to provide a complete technical framework for addressing these issues.

The sealing system has been identified as a critical bottleneck constraining equipment reliability. Once seal failure occurs, seawater ingress will trigger a cascade of degradation mechanisms. Therefore, the sealing system should be prioritized as the primary focus for reliability design and condition monitoring; preventing seawater intrusion is the fundamental means to interrupt this vicious cycle. In operational practice, oil emulsification degree and additive condition should serve as indirect indicators for assessing seal health status, rather than solely focusing on external leakage as a superficial phenomenon.

As marine equipment evolves towards greater depths and extended mission endurance, future research should focus on developing multi-physics coupling simulation models to achieve precise prediction and optimization of the corrosion-coating-texture-lubrication system. It is essential to establish high-fidelity experimental testing platforms, combined with in situ long-term monitoring and real-time condition sensing technologies, to provide reliable data support for new materials and designs. Concurrently, by integrating multidisciplinary technologies from materials science, fluid mechanics, and data science, the engineering application of lubricants and integrated texture-coating manufacturing processes should be promoted, ultimately achieving high reliability and long service life for gear transmission systems in marine environments.

Data availability. No data sets were used in this article.

Author contributions. Conceptualization: X. G. Wang. and Y. M. Wang. Methodology: W. Q. Zou. Software: J. F. Ruan. Validation: X. G. Wang, Y. M. Wang, and J. F. Ruan. Formal analysis: W. Q. Zou. Investigation: J. F. Ruan. Resources: Y. M. Wang. Data curation: W. Q. Zou. Writing (original draft preparation): W. Q. Zou and X. G. Wang. Writing (review and editing): X. G. Wang, Y. M. Wang, and J. F. Ruan. Visualization: J. F. Ruan. Supervision: J. F. Ruan and W. Q. Zou. Project administration: Y. M. Wang and W. Q. Zou. All authors have read and agreed to the published version of the article.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Acknowledgements. The authors would like to thank the Huaqiao University (HQU) and Heilongjiang Institute of Technology (HLJIT) for their support. The authors sincerely appreciate all participants for their contributions.

Financial support. This research was funded by the National Natural Science Foundation of China (project approval no. 52475257), the National Key Research and Development Program of China (grant no. 2023YFB3406301), the Fund Project for Technological Field of National Defense Science and Technology Plan 173 (grant nos. 2024-JCJQ-JJ-2020 and 2024-JCJQ-JJ-2043), and the Marine Propulsion Research and Development (MPRD) Program (grant no. MG20220203).

Review statement. This paper was edited by Zhiwei Zhu and reviewed by two anonymous referees.

References

Amano, C., Zhao, Z., Sintes, E., Reinthaler, T., Stefanschitz, J., Kisadur, M., Utsumi, M., and Herndl, G. J.: Limited carbon cycling due to high-pressure effects on the deep-sea microbiome, Nat. Geosci., 15, 1041–1047, https://doi.org/10.1038/s41561-022-01081-3, 2022.

Amine, G., Fillot, N., Philippon, D., Devaux, N., Dufils, J., and Macron, E.: Dual experimental-numerical study of oil film thickness and friction in a wide elliptical TEHL contact: From pure rolling to opposite sliding, Tribol. Int., 184, 108466, https://doi.org/10.1016/j.triboint.2023.108466, 2023.

Andersson, H., Holmberg, L. J., Simonsson, K., Hilding, D., Schill, M., Borrvall, T., Sigfridsson, E., and Leidermark, D.: Simulation of leakage flow through dynamic sealing gaps in hydraulic percussion units using a co-simulation approach, Simul. Model. Pract. Th., 111, 102351, https://doi.org/10.1016/j.simpat.2021.102351, 2021.

Arumugaprabu, V., Ko, T. J., Kumaran, T., Kurniawan, R., and Uthayakumar, M.: A brief review on importance of surface texturing in materials to improve the tribological performance, Rev. Adv. Mater. Sci., 53, 40–48, https://doi.org/10.1515/rams-2018-0003, 2018.

Bair, S.: The viscosity at the glass transition of a liquid lubricant, Friction, 7, 86–91, https://doi.org/10.1007/s40544-018-0210-1, 2019.

Bair, S.: The unresolved definition of the pressure-viscosity coefficient, Sci. Rep., 12, 3422, https://doi.org/10.1038/s41598-022-07470-3, 2022.

Bair, S. S., Andersson, O., Qureshi, F. S., and Schirru, M. M.: New EHL modeling data for the reference liquids squalane and squalane plus polyisoprene, Tribol. T., 61, 247–255, https://doi.org/10.1080/10402004.2017.1310339, 2018.

Boussaid, M., Haddadine, N., Benmounah, A., Dahal, J., Bouslah, N., Benaboura A., and El-Shall, S.: Viscosity-boosting effects of polymer additives in automotive lubricants, Polym. Bull., 81, 6995–7011, https://doi.org/10.1007/s00289-023-05028-5, 2024.

Brăileanu, P. I., Mocanu, M.-T., Dobrescu, T. G., Pascu, N. E., and Dobrotă, D.: Structure and Texture Synergies in Fused Deposition Modeling (FDM) Polymers: A Comparative Evaluation of Tribological and Mechanical Properties, Polymers, 17, 2159. https://doi.org/10.3390/polym17152159, 2025.

Brandt, A., Gutt, J., Hildebrandt, M., Pawlowski, J., Schwendner, J., Soltwedel, T., and Thomsen, L.: Cutting the umbilical: new technological perspectives in benthic deep-sea research, J. Mar. Sci. Eng., 4, 36, https://doi.org/10.3390/jmse4020036, 2016.

Braumann, L., de Viteri, V. S., Morhard, B., Lohner, T., Ochoa, J., and Amri, H.: Tribology technologies for gears in loss of lubrication conditions: a review, J. Mater. Sci.-Mater. Eng., 20, 29, https://doi.org/10.1186/s40712-024-00204-5, 2025.

Cai, M., Wu, S., and Yang, C.: Effect of low temperature and high pressure on deep-sea oil-filled brushless DC motors, Mar. Technol. Soc. J., 50, 83–93, https://doi.org/10.4031/MTSJ.50.2.8, 2016.

Cao, W., Yu, Z., Yang, G., Li, X., and Wang, A.: Study on the Evolution of Volume Efficiency of Gear Pump in Deep Sea Extreme Environment, Chin. Hydraul. Pneumat., 48, 28–36, https://doi.org/10.11832/j.issn.1000-4858.2024.11.004, 2024.

Castaño, T. P. and Velázquez, J. J. L.: On the dynamics of thin layers of viscous flows inside another viscous fluid, J. Differ. Equations, 300, 252–311, https://doi.org/10.1016/j.jde.2021.07.043, 2021.

Chang, X., Renqing, D., Liao, L., Zhu, P., Lin, B., Huang, Y., and Luo, S.: Study on hydrodynamic lubrication and friction reduction performance of spur gear with groove texture, Tribol. Int., 177, 107978, https://doi.org/10.1016/j.triboint.2022.107978, 2023.

Chen, B., Wang, J., and Yan, F.: Friction and wear behaviors of several polymers sliding against GCr15 and 316 steel under the lubrication of sea water, Tribol. Lett., 42, 17–25, https://doi.org/10.1007/s11249-010-9743-9, 2011.

Chen, K., Yang, X., Zhang, Y., Yang, H., Lv, G., and Gao, Y.: Research progress of improving surface friction properties by surface texture technology, The Int. J. Adv. Manuf. Technol., 116, 2797–2821, https://doi.org/10.1007/s00170-021-07614-1, 2021.

Chen, Z., Zhou, J., Liu, B., Fu, H., Meng, X., Ji, J., Zhang, Y., Hua, X., Xu, X., and Fu, Y.: Meshing frictional characteristics of spur gears under dry friction and heavy loads: Effects of the preset pitting-like micro-textures array, Tribol. Int., 180, 108296, https://doi.org/10.1016/j.triboint.2023.108296, 2023.

Chen, Z., Dai, Y., Wu, S., and Yang, C.: Active Pressure-Compensation Technology for Deep-Sea Fluid Samplers, IEEE J. Oceanic Eng., 50, 2456–2467, https://doi.org/10.1109/JOE.2025.3558814, 2025.

Cheng, G., Ma, J., Li, J., Sun, K., Wang, K., and Wang, Y.: Study on the dynamic characteristics of gears considering surface topography in a mixed lubrication state, Lubricants, 12, 7, https://doi.org/10.3390/lubricants12010007, 2023.

Chong, W. W. F., Hamdan, S. H., Wong, K. J., and Yusup, S.: Modelling transitions in regimes of lubrication for rough surface contact, Lubricants, 7, 77, https://doi.org/10.3390/lubricants7090077, 2019.

Conrad, A., Hodapp, A., Hochstein, B., Willenbacher, N., and Jacob, K. H.: Low-temperature rheology and thermoanalytical investigation of lubricating oils: Comparison of phase transition, viscosity, and pour point, Lubricants, 9, 99, https://doi.org/10.3390/lubricants9100099, 2021.

Cui, W., Chen, H., Zhao, J., Ma, Q., Xu, Q., and Ma, T.: Progresses on cryo-tribology: lubrication mechanisms, detection methods and applications, Int. J. Extreme Manuf., 5, 022004, https://doi.org/10.1088/2631-7990/acc2fa, 2023.

Du, K., Xi, W., Huang, S., and Zhou, J.: Deep-sea mineral resource mining: a historical review, developmental progress, and insights, Mining, Metall. Explor., 41, 173-192, https://doi.org/10.1007/s42461-023-00909-9, 2024.

Duan, Z., Wu, T., Glowacz, A., Gupta, M. K., and Królczyk, G.: Analysis of the line contact tribo-lubrication pair and failure mechanism under the extreme conditions, Tribol. Int., 185, 108505, https://doi.org/10.1016/j.triboint.2023.108505, 2023.

Ewen, J. P., Heyes, D. M., and Dini, D.: Advances in nonequilibrium molecular dynamics simulations of lubricants and additives, Friction, 6, 349–386, https://doi.org/10.1007/s40544-018-0207-9, 2018.

Fang, J., Cao, H., Bai, P., Meng, Y., Ma, L., and Tian, Y.: High-pressure rheological properties of polyalphaolefin and ester oil blends and their impact on lubrication, Tribol. Int., 201, 110262, https://doi.org/10.1016/j.triboint.2024.110262, 2025.

Fu, Y., Gao, H., Yan, Q., Wang, X., and Wang, X.: An efficient approach to improving the finishing properties of abrasive flow machining with the analyses of initial surface texture of workpiece, The Int. J. Adv. Manufact. Technol., 107, 2417–2432, https://doi.org/10.1007/s00170-020-05173-5, 2020.

Gao, H., Wu, D., Gao, C., Xu, C., and Yang, X.: Development of a six-degree-of-freedom deep-sea water-hydraulic manipulator, J. Mar. Sci. Eng., 12, 1696, https://doi.org/10.3390/jmse12101696, 2024.

Gong, P., Wen, X., Bai, P., Yue, L., Ding, J., Tian, Y., and Li, L.: Influence of Low Concentration Seawater on the Friction Corrosion Performance of Water–Glycol Fire-Resistant Hydraulic Fluid, J. Bio- and Tribo-Corrosion, 10, 49, https://doi.org/10.1007/s40735-024-00855-z, 2024.

Gonon, M., Philippon, D., Margueritat, J., Lafarge, L., Vergne, P., and Martinie, L.: New Insight into the Correlation Between Lubricant Glass Transition and friction Plateau in Highly Loaded Contacts, Tribol. Lett. 73, 150, https://doi.org/10.1007/s11249-025-02077-x, 2025.

Gorbacheva, S. N., Yadykova, A. Y., and Ilyin, S. O.: Rheological and tribological properties of low-temperature greases based on cellulose acetate butyrate gel, Carbohyd. Polym., 272, 118509, https://doi.org/10.1016/j.carbpol.2021.118509, 2021.

Gropper, D., Wang, L., and Harvey, T. J.: Hydrodynamic lubrication of textured surfaces: A review of modeling techniques and key findings, Tribol. Int., 94, 509–529, https://doi.org/10.1016/j.triboint.2015.10.009, 2016.

Guo, Q., Zheng, L., Zhong, Y., Wang, S., and Ren, L.: Numerical simulation of hydrodynamic lubrication performance for continuous groove-textured surface, Tribol. Int., 167, 107411, https://doi.org/10.1016/j.triboint.2021.107411, 2022.

Gupta, N., Tandon, N., and Pandey, R. K.: An exploration of the performance behaviors of lubricated textured and conventional spur gearsets, Tribol. Int., 128, 376–385, https://doi.org/10.1016/j.triboint.2018.07.044, 2018.

Gupta, N., Tandon, N., Pandey, R. K., Vidyasagar, K. E. C., and Kalyanasundaram, D.: Tribological and vibration studies of textured spur gear pairs under fully flooded and starved lubrication conditions, Tribol. Trans., 63, 1103–1120, https://doi.org/10.1080/10402004.2020.1794093, 2020a.

Gupta, N., Tandon, N., Pandey, R. K., Vidyasagar, K. E. C., and Kalyanasundaram, D.: Tribodynamic studies of textured gearsets lubricated with fresh and MoS2 blended greases, Tribol. Int., 165, 107247, https://doi.org/10.1016/j.triboint.2021.107247, 2022.

Gupta, P. K., Taketa, J., and Price, C. M.: Thermal interactions in rolling bearings, Proceedings of the Institution of Mechanical Engineers, Part J: J. Eng. Tribol., 234, 1233-1253, https://doi.org/10.1177/1350650119886234, 2020b.

Harika, E., Jarny, S., Monnet, P., Bouyer, J., and Fillon, M.: Effect of water pollution on rheological properties of lubricating oil, Appl. Rheol., 21, 12613, https://doi.org/10.3933/ApplRheol-21-12613, 2011.

Hartung, H. A.: Density-Temperature-Pressure Relations for Liquid Lubricants, J. Fluid. Eng., 78, 941–946, https://doi.org/10.1115/1.4013876, 2022.

He, Y., Chen, C., Bu, C., and Han, J.: A polar rover for large-scale scientific surveys: design, implementation and field test results, Int. J. Adv. Robot. Sys. 12, 145, https://doi.org/10.5772/60974, 2015.

Himanshu, G., Tauheed, M., and Pradeep, K.: Review of condition monitoring approaches for ball screws, Adv. Eng. Info., 71, Part A, 104206, https://doi.org/10.1016/j.aei.2025.104206, 2026.

Hong, Y., Zhang, P., Lee, K. H., and Lee, C. H.: Friction and wear of textured surfaces produced by 3D printing, Sci. China Technol. Sci., 60, 1400–1406, https://doi.org/10.1007/s11431-016-9066-0, 2017.

Hossain, M. A., Iqbal, M. A. M., Julkapli, N. M., Kong, P. S., Ching, J. J., and Lee, H. V.: Development of catalyst complexes for upgrading biomass into ester-based biolubricants for automotive applications: a review, RSC Adv., 8, 5559–5577, https://doi.org/10.1039/C7RA11824D, 2018.

Ijaz Malik, M. A., Kalam, M. A., Mujtaba, M. A., and Almomani, F.: A review of recent advances in the synthesis of environmentally friendly, sustainable, and nontoxic bio-lubricants: Recommendations for the future implementations, Environ. Technol. Inno., 32, 103366, https://doi.org/10.1016/j.eti.2023.103366, 2023.

Jagadish, B. S. and Ray, A.: Prediction of surface roughness quality of green abrasive water jet machining: a soft computing approach, J. Intell. Manuf., 30, 2965–2979, https://doi.org/10.1007/s10845-015-1169-7, 2019.

Jian, G., Wang, Y., Luo, H., and Li, Y.: Thermal Elastohydrodynamic Lubrication of X-Gears System Based on Time-Varying Meshing Stiffness, Tribology, 40, 21–29, https://doi.org/10.16078/j.tribology.2019097, 2020.

Kolivand, A., Li, S., and Zhang, Q.: Modeling on contact fatigue under starved lubrication condition, Meccanica, 56, 211–225, https://doi.org/10.1007/s11012-020-01284-1, 2021.

Kumar, R., Hussain ova, I., Rahmani, R., and Antonov, M.: Solid lubrication at high-temperatures-A review, Materials, 15, 1695, https://doi.org/10.3390/ma15051695, 2022.

Lei, M., Yu, K., Lu, H., and Qi, H. J.: Influence of structural relaxation on thermomechanical and shape memory, Polymer, 109, 216–228, https://doi.org/10.1016/j.polymer.2016.12.047, 2017.

Lei, P. X., Zhang, P. L., Song, S. J., Liu, Z. Y., Yan, H., Sun, T. Z., Lu, Q. H., Chen, Y., Gromov, V., and Shi, H. C.: Research status of laser surface texturing on tribological and wetting properties of materials: A review, Optik, 298, 171581, https://doi.org/10.1016/j.ijleo.2023.171581, 2024.

Levit, R., Martinez-Garcia, J. C., Ochoa, D. A., and García, J.: The generalized Vogel-Fulcher-Tamman equation for describing the dynamics of relaxer ferroelectrics, Sci. Rep., 9, 12390, https://doi.org/10.1038/s41598-019-48864-0, 2019.

Li, B., Mao, Z., Song, B., Tian, W., Wang, Y., Sundén, B., and Lu, C.: Thermal management performance improvement of phase change material for autonomous underwater vehicles' battery module by optimizing fin design based on quantitative evaluation method, Int. J. Energy Res., 46, 15756–15772, https://doi.org/10.1002/er.8273, 2022.

Li, R., Shi, X., Lu, X., Sun, W., and Liu, H.: Study on Mixed Lubrication Characteristics of Helical Gears of Marine Diesel Engine under Real Machining Surface, J. Mechan. Eng., 61, 290–304, https://doi.org/10.3901/JME.2025.01.290, 2025.

Li, Z., Chen, J., Shen, J., and Liu, K.: Elastic Deformation of Surface Topography under Line Contact and Sliding-rolling Conditions, J. Mech. Eng., 54, 142–148, https://doi.org/10.3901/jme.2018.05.142, 2018.

Litwin, W., Barszczewska, A., Piątkowska, E., Szwoch, I., Matuszewski, L., and Kahsin, M.: Influence of lubrication water contamination by solid particles of mineral origin on marine strut propeller shafts bearings of ships, Pol. Maritim. Res., 31, 187–196, https://doi.org/10.2478/pomr-2024-0062, 2024.

Liu, L., Yang, C., and Sheng, Y. Y.: Wear model based on real-time surface roughness and its effect on lubrication regimes, Tribol. Int., 126, 16–20, https://doi.org/10.1016/j.triboint.2018.05.010, 2018.

Liu, Y., Wang, B., Yang, S., Liao, Y., and Guo, T.: Characteristic analysis of mechanical thermal coupling model for bearing rotor system of high-speed train, Appl. Mathe. Mechan., 43, 1381–1398, https://doi.org/10.1007/s10483-022-2893-5, 2022.

Liu, Y., Ma, G., Ma, X., Li, H., Guo, P., Wang, A., and Ke, P.: Corrosion and tribocorrosion performance degradation mechanism of multilayered graphite-like carbon (GLC) coatings under deep-sea immersion in the western Pacific, Corros. Sci., 239, 112418, https://doi.org/10.1016/j.corsci.2024.112418, 2024.

Liu, Y. Y., Li, Y. R., and Wang, L. Q.: Experimental and theoretical studies on the pressure fluctuation of an internal gear pump with a high pressure, P. I. Mech. Eng. C-J. Mec., 233, 987–996, https://doi.org/10.1177/0954406218758796, 2019.

Lv, F., Zhang, X., Ji, C., and Rao, Z.: Theoretical and experimental investigation on local turbulence effect on mixed-lubrication journal bearing during speeding up, Phys. Fluid., 34, 113104, https://doi.org/10.1063/5.0122039, 2022.

MacLaren, A. and Kadiric, A.: Elastohydrodynamic Traction and Film Thickness at High Speeds, Tribol. Lett., 72, https://doi.org/10.1007/s11249-024-01894-w, 2024.

Maier, E., Ziegltrum, A., Lohner, T., and Stahl, K.: Characterization of TEHL contacts of thermoplastic gears, Forsch. Ingenieurwes., 81, 317–324, https://doi.org/10.1007/s10010-017-0230-4, 2017.

Maldonado-Cortés, D., Peña-Parás, L., Martínez, N. R., Leal, M. P., and Correa, D. I. Q.: Tribological characterization of different geometries generated with laser surface texturing for tooling applications, Wear, 477, 203856, https://doi.org/10.1016/j.wear.2021.203856, 2021.

Mao, B., Siddaiah, A., Liao, Y. L., and Menezes, P. L.: Laser surface texturing and related techniques for enhancing tribological performance of engineering materials: A review, J. Manuf. Process., 53, 153–173, https://doi.org/10.1016/j.jmapro.2020.02.009, 2020.

Mia, S., Mizukami, S., Fukuda, R., Morita, S., and Ohno, N.: High-pressure behavior and tribological properties of wind turbine gear oil, J. Mech. Sci. Technol., 24, 111–114, https://doi.org/10.1007/s12206-009-1179-5, 2010.

Moradi, M., Arabi, H., Nasab, S. J., and Benyounis, K. Y.: A comparative study of laser surface hardening of AISI 410 and 420 martensitic stainless steels by using diode laser, Opt. Laser Technol., 111, 347–357, https://doi.org/10.1016/j.optlastec.2018.10.013, 2019.

Morales-Espejel, G. E., Rycerz, P., and Kadiric, A.: Prediction of micropitting damage in gear teeth contacts considering the concurrent effects of surface fatigue and mild wear, Wear, 398–399, 99–115, https://doi.org/10.1016/j.wear.2017.11.016, 2018.

Mounayer, J. and Habchi, W.: Exact model order reduction for the full-system finite element solution of thermal elastohydrodynamic lubrication problems, Lubricants, 11, 61, https://doi.org/10.3390/lubricants11020061, 2023.

Naat, N., Boutar, Y., Mezlini, S., de Silva, L. F. M., Alrasheedi, N. H., and Hajlaoui, K.: Study of the effect of bio-inspired surface texture on the shear strength of bonded 3D-printed materials: Comparison between stainless steel and polycarbonate joints, Int. J. Adhesion Adhesives, 131, 103658, https://doi.org/10.1016/j.ijadhadh.2024.103658, 2024.

Natarajan, Y., Murugesan, P. K., Mohan, M., and Ali Khan, S. A. L.: Abrasive Water Jet Machining process: A state of art of review, J. Manuf. Process., 49, 271–322, https://doi.org/10.1016/j.jmapro.2019.11.030, 2020.

Ouyang, W., Yan, Z., Zhou, X., Luo, B., Wang, B., and Huang, J.: A thermal hydrodynamic model for emulsified oil-lubricated tilting-pad thrust bearings, Lubricants, 11, 529, https://doi.org/10.3390/lubricants11120529, 2023.

Paul, V. J., Ritson-Williams, R., and Sharp, K.: Marine chemical ecology in benthic environments, Nat. Prod. Rep., 28, 345–387, https://doi.org/10.1039/C0NP00040J, 2011.

Peacock, T. and Ouillon, R.: The fluid mechanics of deep-sea mining, Annu. Rev. Fluid Mech., 55, 403–430, https://doi.org/10.1146/annurev-fluid-031822-010257, 2023.

Pei, X., Pu, W., Zhang, Y., and Huang, L.: Surface topography and friction coefficient evolution during sliding wear in a mixed lubricated rolling-sliding contact, Tribol. Int., 137, 303–312, https://doi.org/10.1016/j.triboint.2019.05.013, 2019.

Petare, A., Deshwal, G., Palani, I. A, and Jain, N. K.: Laser texturing of helical and straight bevel gears to enhance finishing performance of AFF process, The Int. J. Adv. Manuf. Technol., 110, 2221–2238, https://doi.org/10.1007/s00170-020-06007-0, 2020.

Petare, A. C., Mishra, A., Palani, I. A., and Jain, N. K.: Study of laser texturing assisted abrasive flow finishing for enhancing surface quality and microgeometry of spur gears, The Int. J. Adv. Manuf. Technol., 101, 785–799, https://doi.org/10.1007/s00170-018-2944-3, 2019.

Ruan, J., Wang, X., Wang, Y., and Chen, L.: Study on anti-scuffing load-bearing thermoelastic lubricating properties of meshing gears with contact interface micro-texture morphology, J. Tribol., 144, 101202, https://doi.org/10.1115/1.4054400, 2022.

Ruan, J., Wang, X., Wang, Y., and Zou, W.: Mechanistic Analysis of Textured IEL and Meshing ASLBC Synergy in Heavy Loads: Characterizing Predefined Micro-Element Configurations, Machines, 13, 842, https://doi.org/10.3390/machines13090842, 2025a.

Ruan, J., Wang, X., Wang, Y., and Zou, W.: Multiscale Fractal Analysis of Thermo-Mechanical Coupling in Textured Tribological Interfaces, Symmetry, 17, 1799, https://doi.org/10.3390/sym17111799, 2025b.

Salguero, J., Del Sol, I., Vazquez-Martinez, J. M., Schertzer, M. J., and Iglesias, P. Effect of laser parameters on the tribological behavior of Ti6Al4V titanium microtextures under lubricated conditions, Wear, 426–427, Part B, 1272–1279, https://doi.org/10.1016/j.wear.2018.12.029, 2019.

Saxena, A., Jacobs, G., König, F., and Reimers, M.: Influences of contact parameters on the wear-protective boundary layer formation in rolling-sliding contacts, Wear, 580–581, 206259, https://doi.org/10.1016/j.wear.2025.206259, 2025.

Seeton, C. J.: Viscosity-temperature correlation for liquids, Tribol. Lett., 22, 67–78, https://doi.org/10.1007/s11249-006-9071-2, 2006.

Sharma, R., Pradhan, S., and Bathe, R. N.: Design and fabrication of honeycomb micro-texture using femtosecond laser machine, Mater. Manuf. Process., 36, 1314–1322, https://doi.org/10.1080/10426914.2021.1906898, 2021.

Scheffer, G. and Gieg, L. M.: The mystery of piezophiles: Understudied microorganisms from the deep, dark subsurface, Microorganisms, 11, 1629, https://doi.org/10.3390/microorganisms11071629, 2023.

Shen, Y., Chen, M., Du, Y., and Li, M.: Key mechanical issues and technical challenges of deep-sea mining development system, Mech. Eng., 44, 1005–1020, https://doi.org/10.6052/1000-0879-22-060, 2022.

Shen, Z. H., Wang, F. C., Chen, Z. G., Ruan, X. P., Zeng, H. H., Wang, J. H., An, Y. R., and Fan, X. L.: Numerical simulation of lubrication performance on chevron textured surface under hydrodynamic lubrication, Tribol. Int., 154, 106704, https://doi.org/10.1016/j.triboint.2020.106704, 2021.

Shi, L., Fang, Y., Dai, Q., Huang, W., and Wang, X.: Surface texturing on SiC by multiphase jet machining with microdiamond abrasives, Mater. Manuf. Process., 33, 1415–1421, https://doi.org/10.1080/10426914.2017.1401723, 2017.

Shi, X., Lu, X., He, T., Sun, W., Tong, Q., Ma, X., Zhao, B., and Zhu, D.: Predictions of friction and flash temperature in marine gears based on a 3D line contact mixed lubrication model considering measured surface roughness, J. Cent. South Univ., 28, 1570–1583, https://doi.org/10.1007/s11771-021-4716-8, 2021.

Sivayogan, G., Rahmani, R., and Rahnejat, H.: Lubricated loaded tooth contact analysis and non-Newtonian thermoelastohydrodynamics of high-performance spur gear transmission systems, Lubricants, 8, 20, https://doi.org/10.3390/lubricants8020020, 2020.

Skropeta, D. and Wei, L.: Recent advances in deep-sea natural products, Nat. Prod. Rep., 31, 999–1025, https://doi.org/10.1039/C3NP70118B, 2014.

Song, W. and Cui, W.: An overview of underwater connectors, J. Mar. Sci. Eng., 9, 813, https://doi.org/10.3390/jmse9080813, 2021.

Sperka, P., Krupka, I., and Hartl, M.: Lubricant flow in thin-film elastohydrodynamic contact under extreme conditions, Friction, 4, 380–390, https://doi.org/10.1007/s40544-016-0134-6, 2016.

Su, B., Mao, S., Zhang, G., Li, H., and Cui, Y.: Dynamics-Based Calculation of the Friction Power Consumption of a Solid Lubricated Bearing in an Ultra-Low Temperature Environment, Lubricants, 11, 372, https://doi.org/10.3390/lubricants11090372, 2023.

Su, R., Cao, W., Jin, Z., Wang, Y., Ding, L., Maqsood, M., and Wang, D.: Deterioration Mechanism and Status Prediction of Hydrocarbon Lubricants under High Temperatures and Humid Environments, Lubricants, 12, 116, https://doi.org/10.3390/lubricants12040116, 2024.

Sun, D. and Wang, C.: A review of open ocean zooplankton ecology, Acta Ecol. Sin., 37, 3219–3231, https://doi.org/10.5846/stxb201603060393, 2017.

Tang, J. P., Han, J., Tian, X. Q., Li, Z. F., You, T. F., Li, G. H., and Xia, L.: Flexible modification and texture prediction and control method of internal gearing power honing tooth surface, Adv. Manuf., 13, 784–798, https://doi.org/10.1007/s40436-024-00501-4, 2025.

Tian, Y., Zhou, J., He, C., He, L., Li, X., and Sui, H.: The formation, stabilization and separation of oil-water emulsions: a review, Processes, 10, 738, https://doi.org/10.3390/pr10040738, 2022.

Torres, T., Changenet, C., Touret, T., and Guilbert, B.: A new experimental methodology to study convective heat transfer in oil jet lubricated gear units, Lubricants, 11, 408, https://doi.org/10.3390/lubricants11090408, 2023.

Tortorella, E., Tedesco, P., Palma Esposito, F., January, G. G., Fani, R., Jaspars, M., and De Pascale, D.: Antibiotics from deep-sea microorganisms: current discoveries and perspectives, Mar. Drugs, 16, 355, https://doi.org/10.3390/md16100355, 2018.

Tošić, M., Larsson, R., Stahl, K., and Lohner, T.: Thermal elastohydrodynamic analysis of a worm gear, Machines, 11, 89, https://doi.org/10.3390/machines11010089, 2023.

Vishnoi, M., Kumar, P., and Murtaza, Q.: Surface texturing techniques to enhance tribological performance: A review, Surfaces Interf., 27, 101463, https://doi.org/10.1016/j.surfin.2021.101463, 2021.

Von der Ohe, C. B., Johnsen, R., and Espallargas, N.: Modeling the multi-degradation mechanisms of combined tribocorrosion interacting with static and cyclic loaded surfaces of passive metals exposed to seawater, Wear, 269, 607–616, https://doi.org/10.1016/j.wear.2010.06.010, 2010.

Wang, J., Chen, J., Chen, B., Yan, F., and Xue, Q.: Wear behaviors and wear mechanisms of several alloys under simulated deep-sea environment covering seawater hydrostatic pressure, Tribol. Int., 56, 38–46, https://doi.org/10.1016/j.triboint.2012.06.021, 2012.

Wang, J., Yan, Z., Fang, X., Shen, Z., and Pan, X.: Observation and experimental investigation on cavitation effect of friction pair surface texture, Lubr. Sci., 32, 404–414, https://doi.org/10.1002/ls.1520, 2020.

Wang, L., Zhao, Q., Feng, W., and Xiang, G.: On the Film Stiffness Characteristics of Water-Lubricated Rubber Bearings in Deep-Sea Environments, Lubricants, 13, 451, https://doi.org/10.3390/lubricants13100451, 2025a.

Wang, W. H., Yuan, W., Guo, Q. J., Chi, B. T., Yin, F. S., Wang, N. N., and Yu, J.: Tribological properties of ductile cast iron with in-situ textures created through abrasive grinding and laser surface ablation, Tribology Int., 200, 110134, https://doi.org/10.1016/j.triboint.2024.110134, 2024.

Wang, Y., Luo, S., Gao, T., Mo, J., Wang, D., and Chang, X.: Biomimetic Hexagonal Texture with Dual-Orientation Groove Interconnectivity Enhances Lubrication and Tribological Performance of Gear Tooth Surfaces, Lubricants, 13, 420, https://doi.org/10.3390/lubricants13090420, 2025b.

Wang, Y. N., Meng, L. H., and Wang, B. G.: Progress in research on bioactive secondary metabolites from deep-sea derived microorganisms, Mar. Drugs, 18, 614, https://doi.org/10.3390/md18120614, 2020.

Wang, Z., Pu, W., He, T., Wang, J., and Cao, W.: Numerical simulation of transient mixed elastohydrodynamic lubrication for spiral bevel gears, Tribol. Int., 139, 67–77, https://doi.org/10.1016/j.triboint.2019.06.032, 2019.

Wang, Z., Ye, R., and Xiang, J.: The performance of textured surface in friction reducing: A review, Tribol. Int., 177, 108010, https://doi.org/10.1016/j.triboint.2022.108010, 2023.

Wang, Z., Dong, Q., Shi, X., Bai, X., and Li, T.: An Investigation Into the Thermal Behavior of Planetary Gear Systems Under Mixed Lubrication, J. Tribol., 148, 042204, https://doi.org/10.1115/1.4070303, 2026a.

Wang, Z., Wang, S., Wang, S., Xiao, Y., Dong, J., Xuan, Y., Zhang, L., and Wang, H.: Study on the Influence of Tooth Surface Microtexture on Dynamic Characteristics of Face Gear, Advances in Mechanical Transmission: Innovations and Applications, 798–809, (icmt-2 2025. Lecture Notes in Mechanical Engineering. Springer, Singapore), https://doi.org/10.1007/978-981-95-3650-4_70, 2026b.

Watanabe, I. A., Okubo, H., and Nakano, K.: In-situ electrical impedance observation for lubrication conditions of gears under actual operation, Tribol. Int., 210, 110777, https://doi.org/10.1016/j.triboint.2025.110777, 2025.

Wood, R. J. K.: Marine wear and tribocorrosion, Wear, 376–377, Part B, 893–910, https://doi.org/10.1016/j.wear.2017.01.076, 2017.

Wos, S., Koszela, W., and Pawlus, P.: Comparing tribological effects of various chevron-based surface textures under lubricated unidirectional sliding, Tribol. Int., 146, 106205, https://doi.org/10.1016/j.triboint.2020.106205, 2020.

Wu, J., He, T., Wang, D., Wang, L., Jiang, S., Wang, Y., Chen, K., Zhang, C., Shu, K., and Li, Z.: Transient mixed thermal elastohydrodynamic lubrication analysis of aero ball bearing under non-steady state conditions, Tribol. Int., 202, 110342, https://doi.org/10.1016/j.triboint.2024.110342, 2025.

Xiao, H., Zhang, F., Li, Z., Tang, Y., and Li, L.: Gear tribological and contact fatigue prediction with rough topography and groove texture under elastohydrodynamic lubrication, Meccanica, 60, 2641–2669, https://doi.org/10.1007/s11012-025-02019-w, 2025.

Xiao, Z., Li, Z., Shi, X., and Zhou, C.: Oil Film Damping Analysis in Non-Newtonian Transient Thermal Elastohydrodynamic Lubrication for Gear Transmission, J. Appl. Mech., 85, 035001, https://doi.org/10.1115/1.4038697, 2018.

Xu, C., Schall, D., and Barber, G.: Molecular dynamics simulation on the friction properties of confined nanofluids, Mater. Today Commun., 34, 105252, https://doi.org/10.1016/j.mtcomm.2022.105252, 2023a.

Xu, J., Lu, H., Cai, L., Liao, Y., and Lian, J.: Surface protection technology for metallic materials in marine environments, Materials, 16, 6822, https://doi.org/10.3390/ma16206822, 2023b.

Xu, R., Martinie, L., Vergne, P., Joly, L., and Fillo, N.: An Approach for Quantitative EHD Friction Prediction Based on Rheological Experiments and Molecular Dynamics Simulations, Tribol. Lett., 71, 69, https://doi.org/10.1007/s11249-023-01740-5, 2023.

Xu, Y., Yu, J., Geng, J., Abuflaha, R., Olson, D., Hu, X., and Tysoe, W. T.: Characterization of the tribological behavior of the textured steel surfaces fabricated by photolithographic etching, Tribol. Lett., 66, 55, https://doi.org/10.1007/s11249-018-1003-4, 2018.

Xu, Y., Zheng, Q., Abuflaha, R., Olson, D., Furlong, O., You, T., Zhang, Q., Hu, X., and Tysoe, W. T.: Influence of dimple shape on tribofilm formation and tribological properties of textured surfaces under full and starved lubrication, Tribol. Int., 136, 267–275, https://doi.org/10.1016/j.triboint.2019.03.047, 2019.

Yin, H., Zhang, X., Guo, Z., Xu, Y., Rao, X., and Yuan, C.: Synergetic effects of surface textures with modified copper nanoparticles lubricant additives on the tribological properties of cylinder liner-piston ring, Tribol. Int., 2023, Part A, 108085, https://doi.org/10.1016/j.triboint.2022.108085, 2023.

Yin, Z., Fan, Z., and Wang, M.: Thermal elastohydrodynamic lubrication characteristics of double involute gears at the graded position of tooth waist, Tribol. Int., 144, 106028, https://doi.org/10.1016/j.triboint.2019.106028, 2020.

Yin, Z., Fan, Z., and Jiang, F.: Oil film stiffness of double involute gears based on thermal EHL theory, Chin. J. Mech. Eng., 34, 60, https://doi.org/10.1186/s10033-021-00582-3, 2021.

Yuan, C., Shen, R., Dai, Q., Huang, W., and Wang, X.: Influence of Surface Texture on the Isothermal Elastohydrodynamic Lubrication Performance of Gears, Tribology, 45, 1033–1046, https://doi.org/10.16078/j.tribology.2024067, 2025.

Zhang, B., Sun, L., Zhao, N., and Li, J.: Applications of laser surface treatment in gears: a review, J. Mat. Eng. Perf., 34, 1–35, https://doi.org/10.1007/s11665-024-09945-y, 2025a.

Zhang, S. and Zhang, C.: A new deterministic model for mixed lubricated point contact with high accuracy, J. Tribol., 143, 102201, https://doi.org/10.1115/1.4049328, 2021.

Zhang, T., Wang, R., Wang, Y., Cheng, L., Wang, S., and Tan, M.: Design and locomotion control of a dactylopteridae-inspired biomimetic underwater vehicle with hybrid propulsion, IEEE T. Autom. Sci. Eng., 19, 2054–2066, https://doi.org/10.1109/TASE.2021.3070117, 2022.

Zhang, X., Yu, T., Ji, H., Guo, F., Duan, W., Liang, P., and Ma, L.: Analysis of Water-Lubricated Journal Bearings Assisted by a Small Quantity of Secondary Lubricating Medium with Navier–Stokes Equation and VOF Model, Lubricants, 12, 16, https://doi.org/10.3390/lubricants12010016, 2024.

Zhang, Z., Li, J., Zou, T., Hou, W., An, Y., and Liu, J.: Effect of bionic texture on wear resistance and heat dissipation performance of transmission gear, Tribol. Trans., 68, 531–557, https://doi.org/10.1080/10402004.2025.2488798, 2025b.

Zhao, E., Shao, B., Qiao, M., Quan, L., and Wang, C.: Influence of Temperature Rise on Local Lubrication and Friction Characteristics of Wet Clutch, Tribology, 44, 831–841, https://doi.org/10.16078/j.tribology.2023049, 2024.

Zhao, J., Li, Z., Zhang, H., and Zhu, R.: Effect of micro-textures on lubrication characteristics of spur gears under 3D line-contact EHL model, Ind. Lubr. Tribol., 73, 1132–1145, https://doi.org/10.1108/ILT-11-2020-0423, 2021.

Zhao, T., Wang, Y., He, Y., Zhu, Y., and Li, M.: Numerical simulation and experimental investigation on tribological properties of gear alloy surface biomimetic texture, Tribol. Trans., 66, 610–622, https://doi.org/10.1016/j.ijmecsci.2019.105095, 2019.

Zhao, Y., Li, N., Xie, K., Wang, C., Zhou, S., Zhang, X., and Ye, C.: Manufacturing of lithium battery toward deep-sea environment, International J. Extreme Manuf., 7, 022009, https://doi.org/10.1088/2631-7990/ad97f6, 2025.

Zhou, W., Tang, J., Rong, K., Li, Z., and Shao, W.: A parametric evaluation model of abrasive interaction for predicting tooth rough surface in spiral bevel gear grinding, J. Manuf. Process., 132, 659–676, https://doi.org/10.1016/j.jmapro.2024.11.012, 2024a.

Zhou, Z., Chen, D., Yuan, C., Dai, Q., Huang, W., and Wang, X.: State of Art in Tribological Design and Surface Texturing of Gear Surfaces, China Surf. Eng., 37, 61–78, https://doi.org/10.11933/j.issn.1007-9289.20230509003, 2024b.

Zhou, Z., Zhou, X., Huang, Q., Liu, X., Wang, L., and Xing, S.: Impact of oil-water emulsions on lubrication performance of ship stern bearings, Sci. Rep., 14, 31478, https://doi.org/10.1038/s41598-024-83253-2, 2024c.

Ziegltrum, A., Lohner, T., and Stahl, K.: TEHL simulation on the influence of lubricants on the frictional losses of DLC coated gears, Lubricants, 6, 17, https://doi.org/10.3390/lubricants6010017, 2018.