



Article

Multiscale Modeling of Micro-Textured Gear: Interface Enriched Lubrication and Anti-Scuffing Load-Bearing Capacity

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Abstract

A multiscale contact model is developed for micro-textured gear interfaces incorporating Micro-Convex-Concave Asperity (MCCA) characteristics to elucidate the synergistic modulation between Interface Enriched Lubrication (IEL) performance and Anti-Scuffing Load-Bearing Capacity (ASLBC) of Micro-Textured Meshing Interfaces (MTMI) under transient Thermal Elastohydrodynamic Lubrication (TEHL) conditions. Homogenization theory is employed to quantify the effects of areal density and depth-to-diameter ratio on IEL characteristics. A time-resolved micro-elastohydrodynamic lubrication model, formulated through dimensionless discretization and adaptive mesh refinement, investigates the influences of autocorrelation length and MCCA amplitude on interfacial behavior. A correlation framework linking Micro-Element Texture (MET) geometric parameters to meshing ASLBC is established to identify optimal textures for simultaneous enhancement of IEL and ASLBC. Experimental observations demonstrate qualitative consistency with numerical predictions regarding the evolutionary trends of temperature fields and dynamic friction coefficients, providing preliminary physical validation for the proposed model. Univariate Sensitivity Analysis (USA) and Multiple Linear Regression (MLR) are further utilized to optimize microtexture parameters by elucidating the influences of MET sizes, area ratio, and configuration on meshing ASLBC and friction coefficients.

Keywords: textured gear; micro-element texture; interface enriched lubrication; anti-scuffing load-bearing capacity; single factor analysis; multivariate linear regression

1. Introduction

As high-end equipment advances toward higher power density and enhanced reliability, gear transmissions serving as fundamental power transfer mechanisms have become integral to critical applications spanning marine propulsion, aerospace powertrains, and renewable energy systems [1–3]. Consequently, gear systems face increasingly stringent demands regarding fatigue life and operational reliability. Under high-cycle alternating loads, gear pairs are susceptible to fatigue crack initiation and propagation at meshing interfaces, precipitating localized failure that severely degrades lubrication performance and load-bearing capacity [4–6]. The strategic incorporation of MET at these interfaces effectively modulates hydrodynamic lubrication regimes, thereby enhancing Interface Enriched Lubrication (IEL) characteristics and substantially improving the Anti-Scuffing Load-Bearing Capacity (ASLBC) while mitigating lubrication failure risks. When lubricant flows across



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Micro-Textured Meshing Interfaces (MTMI), Micro-Element Texture (MET) induces micro-hydrodynamic pressure effects, resulting in the formation of homogenized lubricant films that not only support contact loads but also function as micro/nanoscale lubricant reservoirs [7–9]. The synergistic optimization of MET topology, lubrication characteristics, and load-bearing capacity has emerged as a prominent research frontier in tribology. Previous studies have demonstrated that under starved lubrication conditions, MTMIs exhibit superior tribological performance compared to smooth interfaces, with vertical ellipsoidal dimple arrays showing optimal characteristics [10]. Coupled methodologies integrating three-dimensional line-contact Thermal Elastohydrodynamic Lubrication (TEHL) modeling with experimental validation have been developed to investigate MTMI lubrication mechanisms [11]. Specifically designed micro-groove MET configurations have achieved significant friction reduction through synergistic tribological testing and Computational Fluid Dynamics (CFD) simulations [12], with experimental results demonstrating substantial decreases in mean friction coefficient compared to untextured counterparts [13–15]. The influence of meshing interface micro-topography on contact fatigue and lubrication-bearing failure mechanisms has attracted increasing research attention [16–18]. Based on the Findley critical interface criterion under TEHL rolling–sliding line contact conditions, the evolution of fatigue life under non-steady-state single meshing point conditions has been investigated [19]. Furthermore, by accounting for the multi-factor coupling effects of interface roughness, lubrication state, and residual stress, multiaxial fatigue criteria have been employed to quantitatively characterize the contact fatigue behavior of wind turbine gearbox systems and evaluate the rolling–sliding contact fatigue damage characteristics of rough interfaces [20]. These studies demonstrate that interface roughness influences the contact fatigue life of gear pairs, while the introduction of residual compressive stress effectively suppresses fatigue damage initiation near the interface, thereby extending component service life [21–23].

Although extensive research has established the decisive role of interface roughness in contact fatigue behavior, experimental results indicate that the contact fatigue life of micro-textured gears does not degrade significantly following the introduction of METs. Instead, interface micro-textures are expected to enhance lubrication performance and prolong the load-bearing fatigue life of meshing pairs [24,25]. To validate this hypothesis, comprehensive experimental and finite element simulation studies have been conducted. Rolling contact fatigue tests using cylindrical specimens with micro-textures have demonstrated that refined micro-dimple textures effectively prolong load-bearing fatigue life [26,27]. Additionally, investigations using a bearing test rig have examined the influence of transverse dimple-type METs on the load-bearing fatigue life of rolling bearings under boundary lubrication conditions, revealing that ball bearings with cross-patterned METs achieve a threefold increase in fatigue life compared to non-textured bearings [28]. However, the interface roughness levels of existing experimental specimens remain relatively high, and related studies have not adequately addressed the effects of roughness morphology [29]. The coupled interaction mechanisms and independent contributions of micro-textures and interface roughness to the load-bearing fatigue life of gear pairs remain insufficiently characterized [30–32]. A finite element-based numerical investigation has examined the influence of micro-texture patterns on the subinterface stress field [33], demonstrating that uniformly distributed METs effectively mitigate maximum subinterface shear stresses, thereby retarding fatigue crack initiation and propagation and suppressing contact fatigue failure. Notably, interface roughness topography is not incorporated into this analytical model.

Micro-textured gear meshing interfaces typically operate under TEHL conditions, exhibiting multiscale morphological characteristics encompassing macro-scale gear geometry, MET topography, and micro-scale interface roughness [34–36]. Although existing studies

have established tribological models for interface micro-textures under TEHL conditions to predict the lubrication characteristics and load-bearing fatigue life of gear pairs, current modeling approaches generally overlook the coupling effects among MET configuration parameters, spatial distribution patterns, and lubrication-load-bearing performance [37–39]. Furthermore, the understanding of how actual interface roughness parameters influence the load-bearing fatigue performance of micro-textured interfaces remains insufficient. Therefore, it is imperative to construct a comprehensive theoretical model for micro-textured gear meshing applicable to rough line-contact TEHL problems, integrating multiscale morphological features to elucidate the lubrication evolution mechanisms at micro-textured contact interfaces and their intrinsic influence on subsequent load-bearing fatigue performance.

Taking ISO 14635 and ISO 6336-20/21 as benchmarks, existing standards assume smooth gear meshing interfaces, simplifying the contact interface as a macroscopically homogeneous field. However, the introduction of interface micro-textures on gear teeth challenges this theoretical boundary. The standard flash temperature calculation, grounded in Hertz theory, fails to account for the modulation of local flash temperature by micro-texture geometric parameters (depth, area ratio, orientation angle). Moreover, it does not incorporate heterogeneous lubrication effects such as texture-induced oil film rupture, micro-cavitation, and secondary hydrodynamic pressure. As a result, the scuffing assessment of textured gears exhibits systematic deviations. To address this issue, this study develops a cross-scale modeling framework for the scuffing failure of micro-textured gears. An integrated analysis framework is constructed that couples the geometric features of micro-textures, local transient flash temperature, and the dynamics of oil film rupture. This framework reveals the regulatory effects of texture parameters on critical scuffing conditions, providing theoretical support for extending ISO standards to textured gear meshing interfaces and advancing the evolution of scuffing load-bearing capacity calculations from the smooth-interface paradigm to a texture-integrated paradigm.

Existing studies often treat micro-scale texture optimization and macro-scale lubrication performance improvement as decoupled problems, either optimizing local texture configurations in isolation or focusing solely on the homogenized macro-scale lubrication behavior. However, local texture optimization cannot guarantee macro-scale anti-scuffing load-bearing capacity; conversely, macro-scale analyses that decouple from texture details fail to capture the true failure mechanisms. This cross-scale theoretical isolation is precisely the root cause of the frequent failures observed under transient meshing conditions. More critically, certain texture configurations, despite enhancing IEL effects to improve hydrodynamic load-bearing capacity, induce localized stress concentrations that may serve as nucleation sites for scuffing failure. This inherent lubrication gain–strength loss paradox has been systematically overlooked in the existing literature, which pursues single-objective lubrication performance optimization. Prior research largely remains at the qualitative level of textures that can improve lubrication, whereas engineering practice urgently demands quantitative design criteria that answer the question: to enhance scuffing resistance, how should the aspect ratio and area density of textures be synergistically configured? Through USA and MLR, this study aims to bridge the gap in these quantitative design criteria and establish a texture parameter synergy optimization paradigm oriented toward ASLBC enhancement. Table 1 presents a comparative analysis of existing studies on the lubrication performance and anti-scuffing load-carrying capacity of micro-textured gears.

This study addresses the multiscale topographical characteristics of meshing interfaces by developing a friction characteristic calculation model for MEMIs. Based on homogenization theory, numerical simulations of asperity contact and transient sliding friction behavior are conducted, and a modified oil film thickness equation is established. The underlying mechanisms governing the influence of MET parameters on IEL character-

istics are elucidated, enabling the optimal design of MET parameters. A time-varying micro-elastohydrodynamic lubrication numerical model for IEL is developed, employing a dimensionless discrete multi-level progressive mesh integration refinement algorithm to investigate the regulatory effects of MET parameters on gear IEL characteristics. Rough gear pair contact is characterized through authentic interface topography to more accurately simulate actual gear contact conditions. The friction coefficient at transient meshing points of MEMIs is derived through flash temperature analysis. A numerical calculation model for interface load-bearing characteristics is constructed to analyze the influence mechanisms of MET parameters on interface load-bearing performance, thereby identifying the optimal MET parameter combinations and distribution characteristics for enhancing meshing IEL performance and interface load-bearing capacity.

Table 1. Comparison with existing works on lubrication characteristics and anti-scuffing load-bearing capacity of micro-textured gears.

Research Category and Representative Literature	Whether Asperity Characteristics Are Considered	Whether Cross-Scale Coupling Is Included (μm -Scale Texture $\leftrightarrow$ mm-Scale Gear)	Whether Real Transient TEHL Is Considered	Whether Directly Linked to Anti-Scuffing Load-Bearing Capacity (ASLBC)	Main Limitations
Classical Smooth-Surface TEHL Models e.g., Li & Kahraman (2013), Zhu et al. (2015)	No	No	Yes/Mostly steady state	No	Surface topography is neglected, precluding the capture of texture-induced micro-elastohydrodynamic (micro-EHL) effects and resulting in either overestimation or underestimation of the actual lubricant film thickness.
Deterministic Micro-Textured EHL Models e.g., Mourier et al. (2006), Tala-Ighil et al. (2011)	Partially (textures idealized as regular topographies)	No (single scale)	Yes/Mostly steady state	No	The synergistic interaction between stochastic roughness and deterministic textures is neglected; the computational domain is restricted to local scales, precluding linkage to macroscopic gear-pair performance.
Texture-averaged flow models based on homogenization theory (e.g., Sahlin et al., 2005; Profito et al., 2017)	No	Yes (texture-to-global)	Yes/Mostly steady state	No	Texture effects are homogenized into equivalent flow resistance, sacrificing local cavitation, pressure ripples, and other transient micro-EHL details.

Table 1. Cont.

Research Category and Representative Literature	Whether Asperity Characteristics Are Considered	Whether Cross-Scale Coupling Is Included (μm-Scale Texture↔mm-Scale Gear)	Whether Real Transient TEHL Is Considered	Whether Directly Linked to Anti-Scuffing Load-Bearing Capacity (ASLBC)	Main Limitations
Mixed lubrication models considering micro-asperities e.g., Zhu & Cheng (1988), Masjedi & Khonsari (2015)	Yes (statistical or measured topography)	No	Yes/Transient	Partial (indirect prediction of fatigue)	Focus on random roughness; lacks systematic investigation of the coupled modulation mechanism between deterministic surface textures and random asperities; notably absent criteria for scuffing failure.
This study (present work)	Yes (original MCCA model)	Yes (homogenization theory + mesh-adaptive multiscale framework)	Yes (full transient meshing cycle)	Yes (first quantitative correlation between MET parameters and ASLBC)	More complex formulation and higher computational cost; micro-scale experimental validation limited to specific conditions.

2. Tribological Evolution Regulated by Micro-Texture Parameters

Existing literature has primarily addressed discrete geometric configurations and scale effects of MTMIs under TEHL conditions, leaving broader design spaces largely unexplored [40,41]. In particular, the coupling mechanisms between MET geometric parameters and the resulting load-bearing capacity and friction performance remain insufficiently understood [42]. A reference framework for subsequent higher-fidelity TEHL analyses is established. This section formulates a baseline hydrodynamic model under the assumptions of rigid-body kinematics, isothermal conditions, and constant thermophysical properties. To elucidate the influence of multiscale configuration parameters on the tribological characteristics and load-bearing capacity of MET, this study expands the design variable space to encompass critical parameters, including MET dimensions, area density, depth, and geometric morphology.

A comparative evaluation of USA and MLR is conducted to assess their respective efficacies in parameter optimization. The governing mechanisms by which MET parameters modulate the tribological behavior of meshing interfaces are systematically investigated, thereby clarifying the coupling between IEL and ASLBC. Optimization results demonstrate that the MLR-based approach achieves a further 5.1% reduction in friction coefficient relative to the USA method. An analytical homogenization framework is formulated to characterize the tribological response of MTMIs under transient operating conditions. By incorporating time-dependent excitations, namely velocity perturbations and friction-induced thermomechanical loads, a coupled computational methodology rooted in MCCA theory is developed to predict sliding friction dynamics. This thinking paradigm elucidates the multiscale mechanisms through which microtexture geometric attributes modulate IEL performance. Consequently, a quantitative mapping between MET descriptors and

IEL metrics is established, enabling the rational design and parametric optimization of the texturing gear meshing interface.

Four representative MET patterns are systematically investigated to encompass the key geometric attributes governing IEL performance: (i) isotropy versus anisotropy (Square/Circular versus Rectangular/Transverse-slit), and (ii) dimple-type versus groove-type mechanisms (Square/Rectangular/Circular versus Transverse-slit). This structured selection matrix enables the decoupled analysis of shape-directed hydrodynamic effects and orientation-dependent oil retention behaviors, which is essential for micro-texture optimization under the bidirectional velocity conditions inherent to gear meshing interfaces. Figure 1 presents four distinct two-dimensional interfacial configurations: square-arrayed, rectangular-arrayed, circular-arrayed, and transverse slit patterns. The square-patterned MTMI consists of 16 uniformly arranged square-METs, each with a lateral dimension (edge length) b . The contact fraction is defined as the ratio of the textured meshing zone to the nominal interfacial area. The rectangular, circular, and slit configurations are likewise uniformly distributed, characterized by side lengths c (rectangular-MET), radius r (circular-MET), and width d (transverse slit-MET), respectively, where the longitudinal dimension of the transverse slit is denoted as L . The side length a of the square-arrayed MTMI serves as an independent design variable to ensure geometric orthogonality with respect to the area ratio S . The interdependence among the MET geometric descriptors (a, b, L) and the area ratio S is mathematically formulated in Equation (1).

$$a = \frac{4b}{\sqrt{S}} = \frac{4c\sqrt{1.5}}{\sqrt{S}} = \frac{4r\sqrt{\pi}}{\sqrt{S}} = \frac{L}{\sqrt{S}} \quad (1)$$

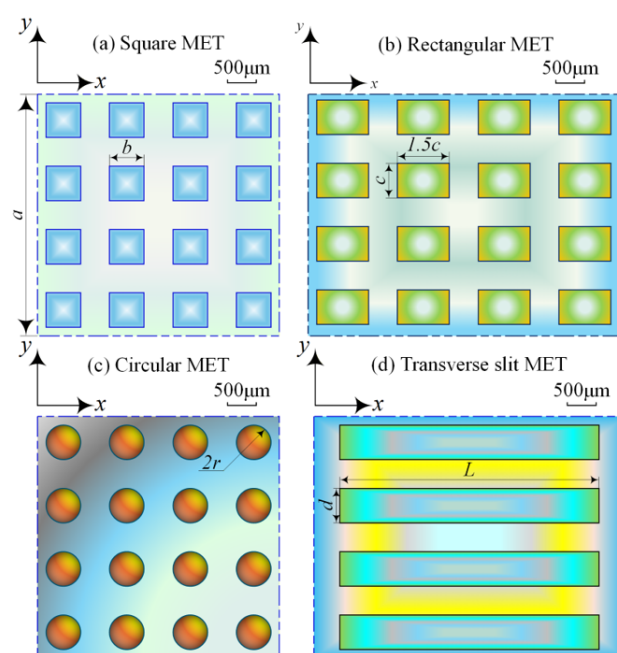


Figure 1. Geometric configuration modeling of MTMI and multiscale characterization of MET. In this study, four distinct MET geometric configurations are considered: (a) Square-MET, (b) Rectangular-MET, (c) Circular-MET, and (d) Transverse-slit-MET.

The boundary conditions for the MET fluid domain are specified as depicted in Figure 2. The three-dimensional geometric model is created in SolidWorks 2024 and subsequently imported into ANSYS Fluent 2025 R1 for computational fluid dynamics (CFD) simulations. An automated tetrahedral unstructured mesh is generated using Fluent's built-in meshing utility, with a growth rate of 1.2 to achieve progressive mesh

refinement. Considering the low Reynolds number regime characteristic of the lubricant bulk flow domain, which indicates laminar flow conditions, the laminar viscous model is adopted for the numerical solution. The fluid properties are specified as follows: density and dynamic viscosity. A pressure-based solver employing the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm is utilized for pressure–velocity coupling. Spatial discretization is implemented using a second-order scheme for the pressure term and a second-order upwind scheme for the momentum equations.

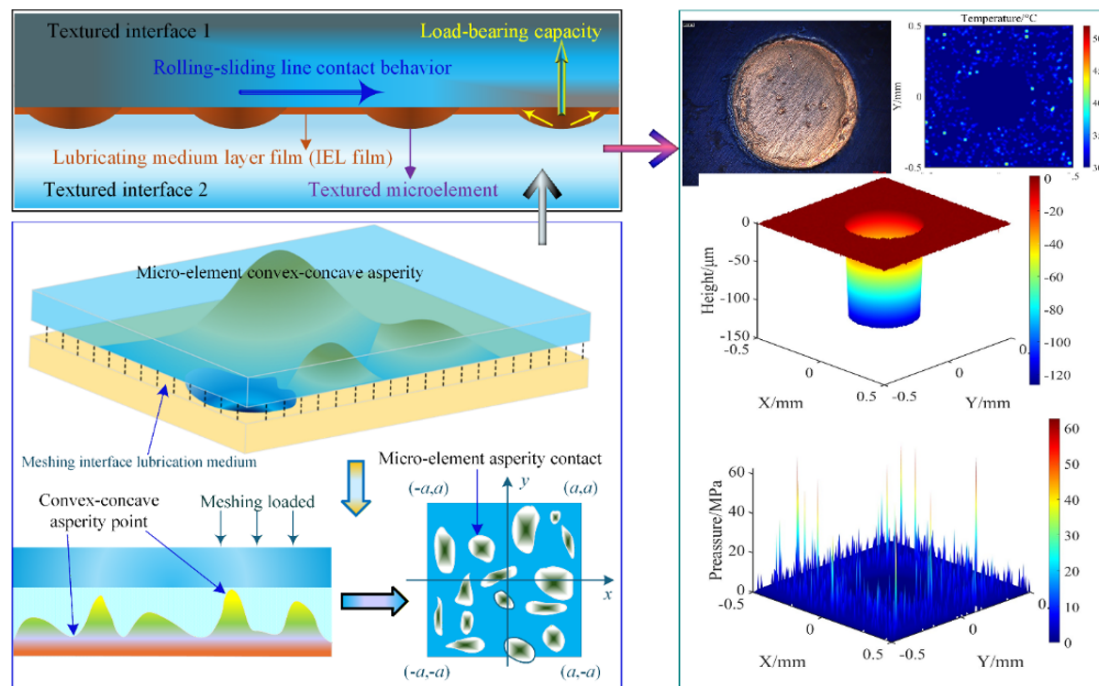


Figure 2. Boundary conditions for the lubricant domain of a micro-textured interface.

A sliding contact pair incorporating an MTMI oriented along the meshing direction under TEHL conditions is considered. The hydrodynamic lubrication model, based on the Navier–Stokes (N–S) equations [43], is formulated. The following fundamental assumptions are adopted in the present model: (1) the contacting bodies are treated as rigid solids, with elastic deformation effects neglected; (2) the lubricant is modeled as an incompressible Newtonian fluid with constant viscosity and density, and body forces are disregarded; (3) frictional heat generation is neglected, and the contact interface is maintained at ambient temperature; (4) the lubricant flow is assumed to be steady and laminar; (5) other classical assumptions associated with the Navier–Stokes equations are satisfied [44–46]. Under the foregoing assumptions, the governing equations are derived as follows:

$$\begin{cases} \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \eta \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) - \frac{\partial P}{\partial x} \text{ (in the } x \text{ - direction)} \\ \rho \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \eta \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) - \frac{\partial P}{\partial y} \text{ (in the } y \text{ - direction)} \\ \rho \left(u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \eta \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) - \frac{\partial P}{\partial z} \text{ (in the } z \text{ - direction)} \\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \end{cases} \quad (2)$$

where u , v , and w denote the velocity components of the lubricant bulk in the x , y , and z directions, respectively; ρ and η represent the density and dynamic viscosity of the lubricating medium, respectively; and P characterizes the lubricant bulk layer film pressure.

(I) Methodology and implementation of univariate sensitivity analysis

This study examines the critical design parameters governing MET performance, including feature dimension, area ratio, texture depth, and geometric pattern. The parametric investigation spans feature dimensions from 0 to 300 μm , area ratios from 0 to 65%, and depths from 0 to 15 μm , encompassing four geometric patterns: square, rectangular, circular, and elliptical configurations. A USA is conducted to evaluate interface MET morphologies, with 8, 4, and 6 levels assigned to feature dimension, area ratio, and depth, respectively, alongside 4 geometric patterns (refer to Table 2 for specific parameter combinations). Following the one-factor-at-a-time principle, each parameter level is varied individually while the other three parameters remain fixed at the reference levels.

Table 2. Geometric parameters of four micro-textured interface types for numerical simulations.

Geometry Configurations	Micro-Element Size (μm)	Area Ratio (%)	Micro-Element Depth (μm)
Non-textured	$a \times a$		
Square-MET	20, 100, 150, 200, 300, 400, 500, 600	20%, 30%, 40%, 50%	1, 3, 5, 7, 9, 11
Rectangular-MET	$c \times 1.5c$		
Circular-MET	r		
Transverse slit-MET	$L \times D$		

The hydrodynamic lubrication effect of the MTMI is predominantly localized at the peripheral region of the MET. As the lubricant flows into the MET, the clearance between friction pairs within the meshing interface increases due to the geometric configuration of the MET, thereby forming a divergent wedge-shaped flow channel that generates localized negative pressure in the divergent zone. When the lubricant flows out of the MET, the clearance between friction pairs rapidly decreases, establishing a convergent wedge-shaped flow channel where the positive pressure in the convergent zone increases.

The peak positive pressure typically exceeds the negative pressure in the valleys by a substantial margin, yielding an asymmetric pressure distribution across the MET edges and thereby generating additional hydrodynamic load-bearing capacity. The load-bearing capacity of the MTMI lubricant film is quantified by the area integral of positive pressure over the upper film interface, whereas the frictional resistance is determined by the area integral of shear stress along the lubricant film interface in the x -direction. The corresponding governing equations are formulated as follows:

$$\begin{cases} F_x = \iint \tau dx dy \\ F_z = \iint P dx dy \\ \mu = \frac{F_x}{F_z} \end{cases} \quad (3)$$

where F_x and F_z denote the load-bearing capacities of the lubricant bulk film along the x - and z -directions, respectively; P represents the contact pressure of the upper interface lubricant bulk film, τ is the shear stress of the lubricating medium, and μ denotes the friction coefficient at the meshing interface.

(II) Modeling and parameter optimization using multiple linear regression analysis

Considering the inherent limitations of conventional USA methods, including labor-intensive procedures, time-consuming computations, and insufficient efficacy for multi-parameter optimization, this study employs MLR to investigate the coupled influence mechanisms of MET geometric parameters on the tribological performance of meshing interfaces. Unlike classical statistical methods, MLR offers the significant advantage of not

requiring strict normality assumptions, thereby serving as an effective tool for preliminary sensitivity screening and baseline performance evaluation. The single-factor numerical simulation datasets are analyzed in depth via MLR using IBM SPSS Statistics 26.0 (Statistical Package for the Social Sciences). To ensure the reliability and predictive accuracy of the regression model, the Durbin–Watson (D-W) test is rigorously employed to detect residual autocorrelation [47–49]. The mapping relationships between key MET parameters and their tribological performance indicators are quantitatively characterized through multiple linear regression equations.

$$X = \delta_0 + \delta_1 Y_1 + \delta_2 Y_2 + \delta_3 Y_3 + \delta_4 Y_4 + \lambda \quad (4)$$

where X represents the key performance indicators of the meshing interface, such as load-bearing capacity or friction coefficient; Y_1, Y_2, Y_3 and Y_4 correspond to the MET dimensions, area ratio, depth, and geometric configuration, respectively; $\delta_1, \delta_2, \delta_3$, and δ_4 denote the regression coefficients for each variable; and λ represents the random error term.

For multiple candidate solutions generated through spatial stochastic simulation, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is employed for global optimal solution selection. This method is implemented via the Scientific Platform Serving for Statistics Professional (SPSSPRO). By calculating the Euclidean distances between each solution and both the positive ideal solution and negative ideal solution, a relative closeness index is constructed to objectively quantify and evaluate the superiority of multi-objective solution sets. The TOPSIS approach effectively eliminates subjective weighting biases, providing reliable decision-making support for multi-objective optimization of micro-texture parameters, and significantly enhancing the accuracy and engineering applicability of optimization results.

To evaluate the explanatory power of the regression model and the association characteristics of variables, this study proposes a dual statistical validation approach using the coefficient of determination (R^2) and the Pearson correlation coefficient (R). The R^2 quantifies the proportion of variance in the dependent variable explained by the MET independent variables, serving as the core metric for assessing model goodness-of-fit, while the correlation coefficient R characterizes the strength and directionality of the linear relationship between MET parameters and MTMI performance. The detailed analytical procedure is illustrated in Figure 3.

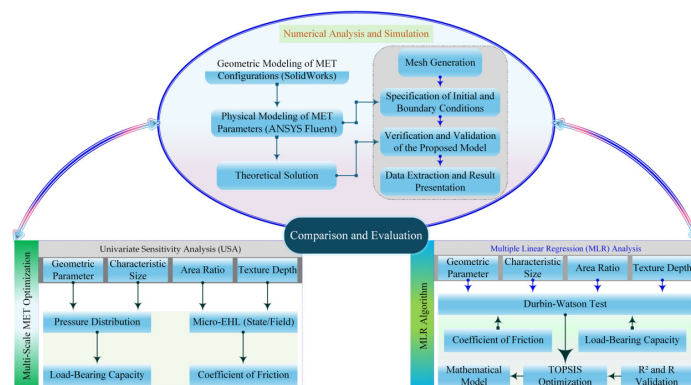


Figure 3. Detailed analytical procedure of multiple linear regression.

3. Simulation-Based Univariate Sensitivity Analysis and Discussion

In the model evaluation and validation phase, three benchmark cases of non-textured meshing interfaces with different characteristic lengths are selected. The computational domain lengths are determined as 1275.1 μm , 2540.9 μm , and 6338.2 μm based on the square

MET model, corresponding to micro-texture lengths of 100 μm , 300 μm , and 500 μm , respectively, with a fixed area ratio of 15%. Interface shear stresses are obtained through both numerical simulation and theoretical analysis for comparative validation. The theoretical shear stress for the non-textured interface is calculated using Equation (5).

The comparison results are presented in Table 3. The theoretical shear stress remains constant at 8457.68 Pa across all three cases, while the numerical simulation results are 8556.48 Pa, 8534.29 Pa, and 8486.31 Pa, yielding relative deviations of 1.18%, 0.91%, and 0.33%, respectively. The maximum deviation is controlled within 1.18%, which falls within the acceptable engineering tolerance range, thereby effectively validating the accuracy and reliability of the numerical model.

$$\tau_s = \eta_{dv} \frac{dv}{dz} = \eta_{dv} \frac{V}{h_{fm}} \quad (5)$$

where τ_s denotes the interface shear stress, η_{dv} represents the dynamic viscosity of the lubricating medium, dv/dz is the velocity gradient across the lubricant bulk layer film thickness, V signifies the entrainment velocity, and h_{fm} indicates the lubricant film thickness.

Table 3. Shear stress on micro-textured interfaces: theory vs. simulation and error analysis.

Micro-Texture Length (μm)	Theoretical Shear Stress (Pa)	Simulated Shear Stress (Pa)	Deviation (%)
1275.1	8457.68	8556.48	1.18%
2540.9		8534.29	0.91%
6338.2		8486.31	0.33%

A progressive meshing strategy is adopted to balance computational accuracy and efficiency. The bulk fluid domain is discretized with a baseline hexahedral element size of 0.1 mm, while adaptive local refinement is implemented in critical regions, particularly the gear meshing contact zones, where the element size is reduced to 0.02 mm. Structured hexahedral grids are employed to accurately capture boundary layer flow characteristics. Five prismatic inflation layers are generated adjacent to the gear meshing interfaces, featuring a first-layer thickness of 0.001 mm and a growth ratio of 1.2, thereby satisfying wall-resolved requirements ($y^+ < 1$). This hierarchical meshing approach ensures high-fidelity resolution of near-wall phenomena while maintaining computational tractability.

A comparative analysis is conducted between square MTMIs with a MET depth of 5.0 μm and an area ratio of 50%, and non-textured interfaces. Figure 4 illustrates the lubricant bulk layer film pressure distribution characteristics of square MTMIs with varying MET dimensions. The results demonstrate that the peak pressure of the lubricant bulk layer film exhibits an increasing trend with enlarging MET size. Based on numerical computations, the influence of MET dimensions on the load-bearing capacity of the MTMI is elucidated, as depicted in Figure 5a. The abscissa represents the side length of the square METs, while the equivalent characteristic dimension of the non-textured interface is determined according to Equation (1). The evolution of the friction coefficient with respect to MET size is illustrated in Figure 5b. Similar to the variation trend observed for the load-bearing capacity, the friction coefficients of both meshing interfaces exhibit comparable behaviors within a certain range of characteristic lengths.

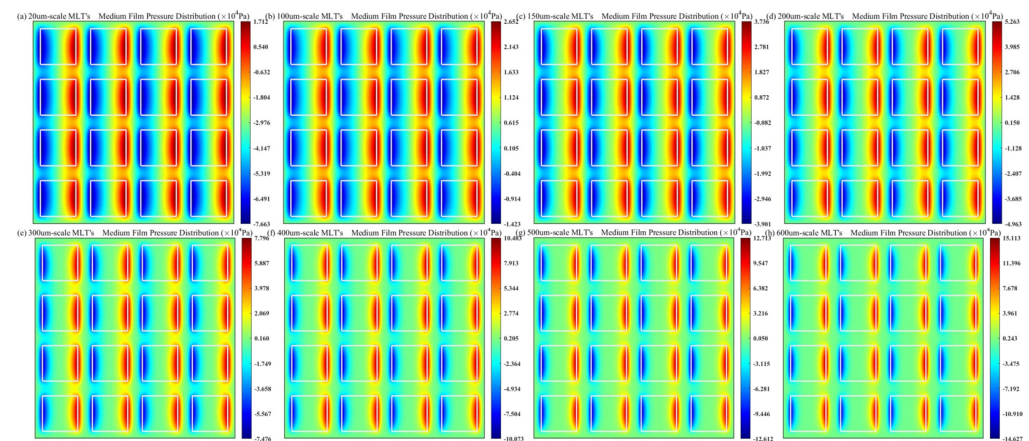


Figure 4. Effect of MET feature size on medium film pressure distribution. The pressure field evolution of square-patterned MTMIs is analyzed over a dimensional span of 20–600 μm , with prescribed texture depth (5.0 μm) and areal density (50%).

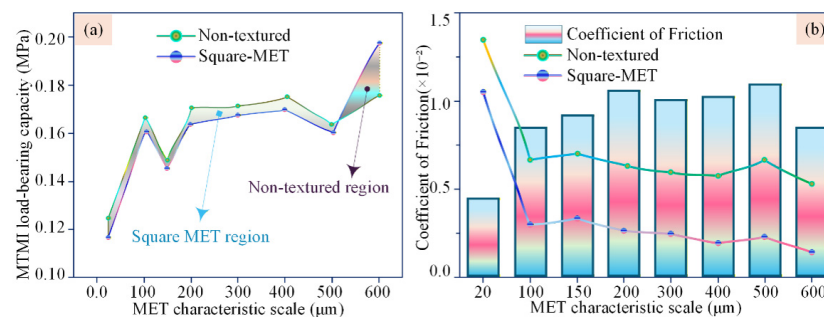


Figure 5. (a) Evolution of load-bearing capacity for MTMI; (b) Comparison of friction coefficients between non-textured interface and square MTMI with varying MET characteristic dimensions under conditions of 5.0 μm MET depth and 50% area density.

The maximum and minimum friction coefficients are observed at 600 μm and 20 μm , respectively. The friction coefficients of the square-patterned MTMI are consistently lower than those of the untextured interface, indicating that the square MTMI with a MET size of 500 μm delivers optimal tribological performance and load-bearing capacity. In Figure 4, under constrained conditions of MET depth (5.0 μm) and area density (50%), the evolution of lubricant pressure fields is analyzed for square-patterned MTMIs across a characteristic dimension range of 20–600 μm .

The aforementioned phenomena are mechanistically interpreted as follows. When relative sliding motion occurs at the gear MTMI, the viscous shear forces of the lubricant bulk drive fluid flow within the micro-textured interface, thereby forming wedge-shaped clearances. This flow behavior generates micro-hydrodynamic pressure effects, which enhance the load-bearing capacity of the meshing interface while reducing the interface friction coefficient. As the MET size increases, the lubricant bulk retention capacity of the meshing interface correspondingly increases, thereby intensifying the hydrodynamic pressure effect. This is likely the primary mechanism responsible for the improved load-bearing capacity and reduced friction coefficient observed with increasing MET dimensions. Notably, abrupt declines in the load-bearing capacity of the micro-textured interface are observed at MET sizes of 150 μm and 500 μm (see Figure 5a). This mechanism may be attributed to scale-effect-induced alterations in local micro-elastohydrodynamic flow behavior, leading to lubricant bulk layer film rupture. At smaller MET sizes, scale effects are pronounced, resulting in unstable local micro-elastohydrodynamic flow behavior; consequently, the load-bearing capacity may deteriorate under certain operating conditions.

As the MET size increases, scale effects diminish, and micro-elastohydrodynamic flow behavior stabilizes, explaining why the magnitude of reduction at 500 μm is less severe than that at 150 μm .

3.1. Influence of MET Area Fraction on IEL Load-Bearing Capacity

Given that square METs with a side length of 500 μm have demonstrated optimal load-bearing capacity and tribological performance, this section further investigates the influence of area ratio (area density) on MTMI lubrication characteristics. The geometric parameters of the square METs are specified as follows: a depth of 5.0 μm , a side length of 500 μm , with the area ratio varying in the range of 20–50%. Figure 6 presents the pressure distribution characteristics of the lubricant bulk layer film for square METs under varying area ratios. The results indicate that the peak pressure of the bulk lubricant film varies non-monotonically with increasing areal density of square METs, first ascending and then descending. As the micro-texture size increases, the hydrodynamic effects induced by surface texturing and the associated film load-bearing mechanisms exhibit distinct scale-dependent behavior. The pressure distribution morphology evolves markedly across scales, shifting from localized high-pressure concentrations at the micro-scale to smoothly distributed profiles at the macroscopic scale. This scale-dependent transition elucidates the evolutionary shift in lubrication mechanisms operating across multiple scales.

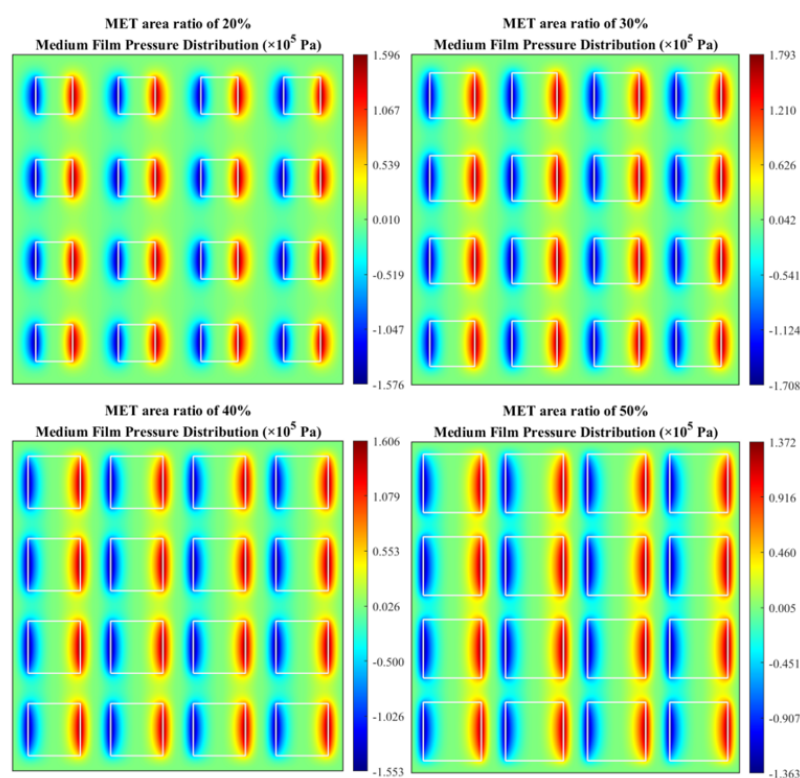


Figure 6. Lubricant bulk layer film pressure distribution of square MTMI at varying area ratios (20–50%), with MET depth of 5.0 μm and side length of 500 μm .

Figure 7a illustrates the influence of area ratio on the load-bearing capacity of the lubricant bulk layer film for square-patterned MTMIs compared with untextured counterparts. For square MTMIs, the load-bearing capacity exhibits a parabolic trend with increasing area ratio as follows: it increases significantly as the area ratio rises from 20% to 40%, reaching its peak at 40%; however, further increasing the area ratio to 50% results in a decline in load-bearing capacity, with the minimum value observed at 20%. In contrast, the

untextured interface demonstrates a more complex fluctuation pattern, presenting local maxima and minima at area ratios of 30% and 40%, respectively.

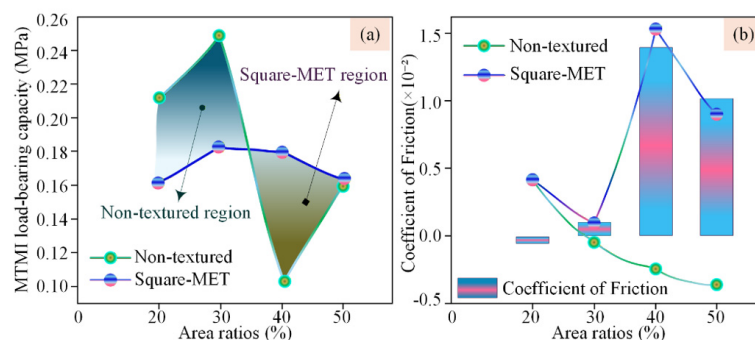


Figure 7. (a) MTMI load-bearing capacity; (b) Friction coefficient variation of non-textured interface and square-patterned MTMI under varying area ratios (fixed depth: 5.0 μm , length: 500 μm).

As depicted in Figure 7b, the variation trend of the friction coefficient with respect to the area ratio exhibits a marked discrepancy from that of the ASLBC. For the untextured interface, the friction coefficient demonstrates a fluctuating characteristic of initial decrease, subsequent increase, and final decrease, whereas for the square MTMI, the friction coefficient exhibits a monotonically decreasing trend as the area ratio increases. The extreme values of the friction coefficient for two interfaces occur at area ratios of 20%, 50%, 40%, and 30%, respectively. The maximum divergence between the friction coefficients of the two interfaces is observed at the 40% area ratio, indicating that the micro-texturing achieves its most pronounced friction reduction effect under the operating condition.

The underlying mechanisms governing these phenomena can be elucidated from the following two aspects. On one hand, with increasing area ratio, the distribution density of METs increases, thereby enhancing the micro-elastohydrodynamic pressure effect and contributing to improved interface load-bearing capacity. On the other hand, the densified MET distribution enhances the continuity of the lubricant film, effectively suppressing direct solid-to-solid contact between meshing components and consequently reducing the friction coefficient. However, when the micro-texture distribution becomes excessively dense (area ratio > 40%), the flow interference of the lubricant bulk between adjacent textures intensifies, leading to a deterioration in film stability and, paradoxically, a degradation in load-bearing capacity of the MTMI.

3.2. Influence of Microtexture Depth on Interfacial Load-Bearing Capacity

This study investigates the lubrication characteristics of square-shaped METs with an area density of 40% and a side length of 500 μm , and presents an analysis of meshing interfaces with and without micro-texturing. Figure 8 illustrates the hydrodynamic pressure distribution characteristics of square-textured interfaces at various MET depths. The lubricant bulk film pressure reaches its peak at the outlet edge of the micro-texture and drops to its minimum at the inlet edge. The maximum medium film pressure exhibits a non-monotonic trend, initially increasing and subsequently decreasing as the MET depth increases. The tribological behaviors are attributed to the increased lubricant enrichment within the METs resulting from the augmented texture depth, which provides sufficient lubrication supply for the meshing pairs and enhances the hydrodynamic effects. When the MET depth exceeds a critical threshold, the lubricant shear effect progressively dominates the tribological process, inducing micro-flow vortex phenomena within the MET cavities and consequently attenuating the hydrodynamic pressure generation. This leads to a degradation in interface load-bearing capacity and an elevation in the friction coefficient.

of the meshing pairs. Comparative analysis demonstrates that the square-MTMs exhibit superior lubrication performance compared to their non-textured counterparts.

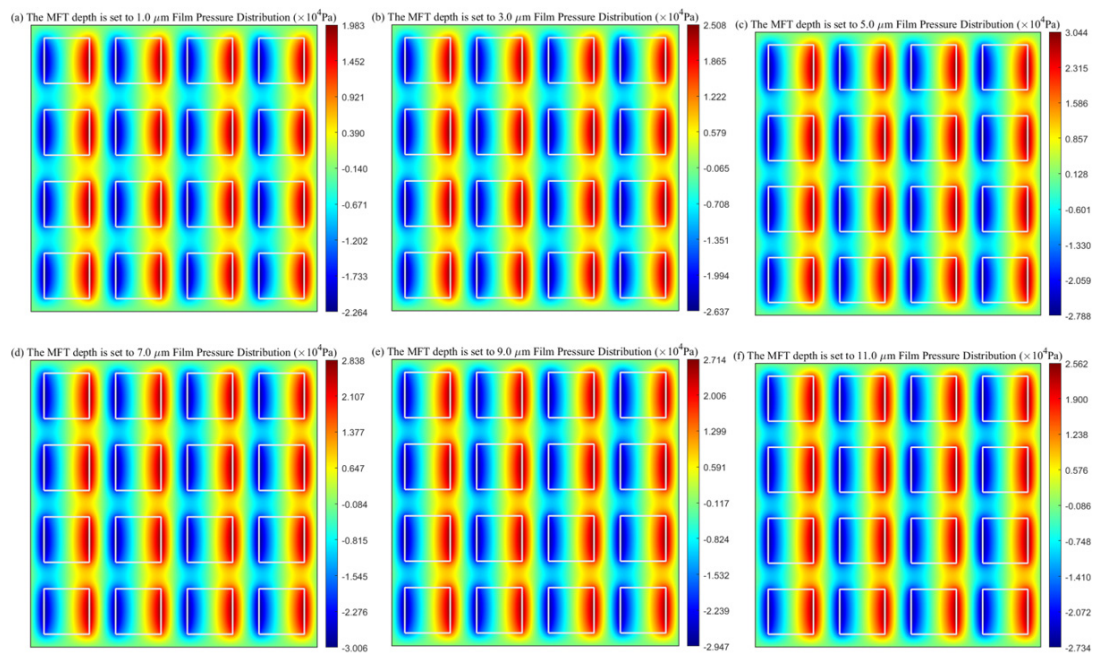


Figure 8. Pressure distribution characteristics of lubricant film in square-textured interfaces with MET depth varying from 1.0 to 11.0 μm (side length: 500 μm , area ratio: 40%).

This section examines the pressure distribution characteristics of the lubricant film within square-textured interfaces. The MET is parametrically configured with depths spanning 1.0–11.0 μm , a characteristic side length of 500 μm , and a fixed area ratio of 40%. The analysis specifically focuses on elucidating how MET depth variations govern the interface pressure field distribution and modulate lubrication characteristics.

Figure 9a,b depicts the evolutionary patterns of load-bearing capacity and friction coefficient with respect to MET depth for interfaces with and without micro-textures, respectively. For square-textured interfaces, the load-bearing capacity initially rises and then declines with increasing depth, whereas the friction coefficient demonstrates an inverse trend, decreasing first and then increasing.

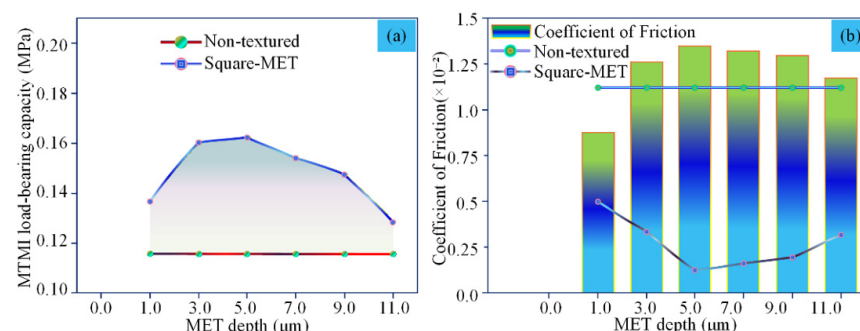


Figure 9. Variations of (a) load-bearing capacity and (b) coefficient of friction with respect to different MET depths, where the micro-texture area ratio is 40%, and the side length is 500 μm .

The maximum load-bearing capacity is achieved at a depth of 5.0 μm , while the minimum capacity corresponds to a depth of 11.0 μm . The extreme values of the friction coefficient occur at depths of 1.0 μm (maximum) and 5.0 μm (minimum). Within the depth range of 2.83–7.26 μm , the friction coefficient decreases monotonically with increasing

depth. The tribological characteristics of MTMIs across a MET depth range of 1.0–11.0 μm are analyzed. The observed non-monotonic variation of the friction coefficient with depth, initially decreasing and subsequently increasing, is attributed to the limited parameter range examined and the absence of consideration regarding the coupling effects among multiscale MET parameters.

3.3. Influence of Geometric Configurations on the Meshing Characteristics of Micro-Textured Interfaces

Four MTMI configurations with distinct MET geometries are proposed, where the depth is 5.0 μm , the length is 500 μm , and the area ratio is 40%. For the square and circular MET configurations, the lubricant bulk film pressure difference in the central MET region of the MTMI is significantly reduced, as shown by the medium film pressure distribution characteristics in Figure 10a–d. This is primarily attributed to the larger flow space within the MET, which leads to insufficient medium filling in the central part of the micro-texture, thereby weakening the hydrodynamic effect of the lubricant bulk layer in the MET domain. In contrast, the rectangular and slit micro-texture configurations exhibit a favorable guiding effect on the lubricating medium, enhancing the meshing IEL. The smaller outlet area intensifies the hydrodynamic modulating behavior, and the medium layer film pressure distribution around the high-pressure region becomes more uniform due to the gear transmission characteristics of the hydrodynamic pressure generation mechanism.

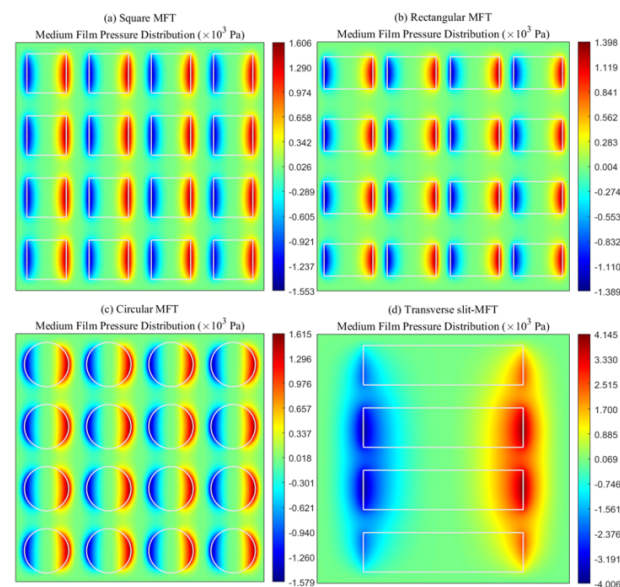


Figure 10. Lubricant bulk film pressure distribution contours of MTMIs with various MET geometric configurations. Subfigures (a–d) present the film pressure distributions for square, rectangular, circular, and transverse slit-patterned METs, respectively, with a MET depth of 5.0 μm , characteristic length of 500 μm , and area ratio of 40%.

The variation in meshing load-bearing capacity and interface friction coefficient for different MET geometric configurations is shown in Figure 11a. Among the four MET morphologies, the Transverse Slit MET (TSI-MET) exhibits the highest load-bearing capacity, followed by Square MET (Sq-MET), Circular MET (Ci-MET), and Rectangular MET (Re-MET). In terms of friction coefficient, the order from low to high is TSI-MET, Sq-MET, Re-MET, and Ci-MET. It is worth emphasizing that the most notable observation is that the load-bearing capacity of all MTMIs is higher than that of non-textured interfaces, and their friction coefficients are lower than those of non-textured interfaces.

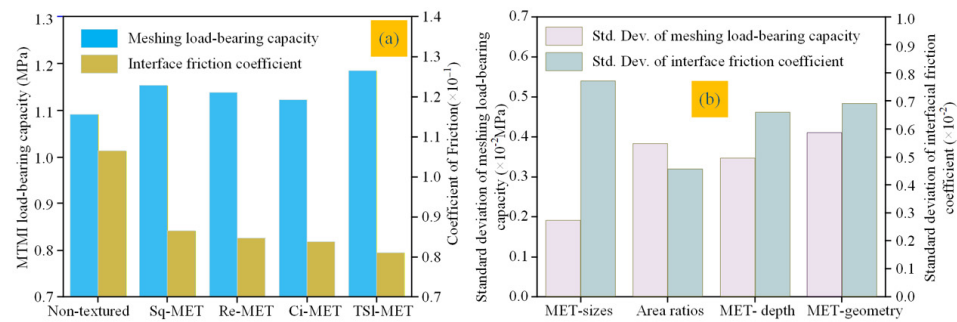


Figure 11. (a) The influence of different MET geometric configurations on load-bearing capacity and friction coefficient; (b) The standard deviation distribution characteristics of load-bearing capacity and friction coefficient under various MET parameter combinations. The MET depth is set to 5.0 μm , the characteristic length to 500 μm , and the area ratio to 40%.

Existing studies have compared circular, square, and annular micro-textures and concluded that the Ci-MET micro-textured interface exhibits superior friction-reducing performance [50,51]. However, under the same MET parameter conditions, this study further reveals that the TSI-MET micro-textured interface outperforms the Ci-MET micro-textured interface in terms of meshing load-bearing capacity and interface friction performance. Figure 11b illustrates the distribution of the standard deviations of load-bearing capacity and friction coefficient for the four types of MET geometric configuration parameters, reflecting the sensitivity of meshing load-bearing performance and friction characteristics to MET geometric configuration parameters. In terms of meshing load-bearing capacity, the standard deviations of each parameter are as follows: MET size 0.0023, area ratio 0.0041, depth 0.0037, and geometric configuration 0.0046, indicating that MET geometric configuration has the most significant influence on load-bearing capacity. Regarding the interface friction coefficient, the standard deviations of each parameter are MET size 0.0082, area ratio 0.0051, depth 0.0069, and geometric configuration 0.0073, suggesting that MET size is the dominant factor affecting the interface friction coefficient.

For the transverse slit micro-texture configuration, an optimized design is implemented using a MET depth of 5.0 μm , a characteristic length of 500 μm , and an area fraction of 40%. The optimization analysis yields an optimal interface friction coefficient of 0.0686, representing an 11.6% reduction compared to the non-textured interface under identical operating conditions. Under the same conditions, the load-bearing capacity of the meshing interface reached 1.163 MPa, which falls short of the theoretical optimal value. This shortfall is primarily attributed to the difficulty in achieving a balanced matching between the shear stress and normal stress distributions at the meshing interface.

4. Optimized MLR Algorithm with Parameter Correlation

The D-W statistics for Data Model 1 (with meshing load-bearing capacity as the dependent variable) and Data Model 2 (with interface friction coefficient as the dependent variable) are 1.902 and 1.243, respectively, indicating the absence of autocorrelation in both linear regression models. The results presented in Table 4 are derived from the Durbin–Watson (D–W) test analysis. Further analysis reveals that MET parameters exhibit a relatively weak influence on the meshing load-bearing capacity, whereas their impact on the interface friction coefficient is considerably more pronounced. Specifically, the coefficients of determination (R^2) for Data Model 1 and Data Model 2 are approximately 0.069 and 0.531, respectively, with approximate standard deviations of 3372.61 and 0.0054.

Table 4. Results of Durbin–Watson autocorrelation test.

Data Model	R ²	R	Adjusted (R ²)	Deviation	D-W Test
Model 1	0.069	0.252a	0.067	3372.61	1.902
Model 2	0.531	0.658a	0.529	0.0054	1.243

The multi-dimensional dataset encompassing MET parameter combinations, meshing load-bearing capacity, and interface friction coefficients is imported into the SPSSPRO analytics platform, wherein the TOPSIS method is employed for multi-objective decision analysis. The meshing load-bearing capacity is designated as a positive indicator (benefit-type criterion), while the interface friction coefficient is designated as a negative indicator (cost-type criterion). The weights for each evaluation index are objectively determined through the entropy weight method. Based on the aforementioned analytical outcomes, the regression coefficients for the MLR equations are obtained, as presented in Table 5. The mathematical expressions for Data Model 1 and Data Model 2 are formulated as follows:

$$\begin{cases} X_1 = 1.138 \times 10^5 - 30.40Y_1 + 3.586Y_2 - 2.274 \times 10^3Y_3 + 0.357 \times 10^3Y_4 \\ X_2 = 0.103 - 3.302 \times 10^{-4}Y_1 - 1.458 \times 10^{-5}Y_2 - 1.210 \times 10^{-2}Y_3 - 1.031 \times 10^{-3}Y_4 \end{cases} \quad (6)$$

where X_1 and X_2 represent the gear meshing load-bearing capacity and interface friction coefficient characteristics, respectively, whereas Y_1 , Y_2 , Y_3 , and Y_4 correspond sequentially to the MET dimension, area ratio, depth, and geometric configuration.

Table 5. Parameter estimation in multiple linear regression model.

Data Model		Unstandardized Coefficient (USC)		Standardized Coefficient (SC)	t-Statistic	Significance (S)	Covariance Statistic (CS)	
		Coefficient (B)	Standard Deviation (SD)	Delta (δ)			Tolerances (T)	Variance Inflation Factor (VIF)
Model-1	Constant term	1.138×10^5	352.106	-	289.739	0.000	-	1.005
	MET Depth	-30.40	32.438	-0.027	-0.898	0.367	0.993	1.000
	MET Size	3.568	0.573	0.197	6.985	0.000	1.000	1.000
	Area ratio	2.274×10^3	647.658	-0.092	-3.416	0.001	1.000	1.005
	MET Geometry	0.357×10^3	76.752	0.096	3.548	0.001	0.993	
Model-2	Constant term	0.103	0.000	-	229.483	0.000		1.005
	MET Depth	-3.302×10^{-4}	0.000	-0.193	-7.918	0.000	0.993	1.000
	MET Size	-1.458×10^{-5}	0.000	-0.624	-25.289	0.000	1.000	1.000
	Area ratio	-1.210×10^{-2}	0.001	-0.298	-13.891	0.000	1.000	1.005
	MET Geometry	-1.031×10^{-3}	0.000	-0.161	-6.864	0.000	0.993	1.005

The significance value of MET depth in Data Model 1 is 0.367 (greater than 0.05), indicating that MET depth is not a statistically significant factor, as presented in Table 5. Considering the parameter importance across Data Models 1 and 2, the sensitivity ranking of meshing load-bearing capacity to MET parameters follows the order: dimension, area ratio, geometric configuration, and depth. Similarly, the sensitivity ranking of the interface friction coefficient to MET parameters is dimension, area ratio, depth, and geometric configuration. The parameter sensitivity of the interface friction coefficient obtained in this

study aligns with the findings, demonstrating that MET depth exerts a less pronounced influence on the interface friction coefficient compared to area ratio [52–54]. This ranking differs from the results derived through the USA standard deviation method, which may be attributed to the limited dataset employed in the USA. Following TOPSIS optimization, the optimal meshing load-bearing capacity and interface friction performance are achieved under the following conditions: characteristic dimension of 500 μm , area ratio of 40%, MET depth of 5.0 μm , and geometric configuration of Transverse Slit MET (TSI-MET). The optimized performance metrics are meshing load-bearing capacity of 1.106 MPa and an interface friction coefficient of 0.0679. Compared with the untextured interface, the friction coefficient is reduced by 13.7%. Furthermore, relative to the results obtained via the USA method, the friction coefficient exhibited an additional reduction of 4.58%.

5. Experimental Validation and Result Analysis of the Proposed Model

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 analyze the temperature field and friction characteristics of textured meshing interfaces, with experimental validation of the proposed theoretical model. This section presents a comprehensive TEHL model incorporating thermal effects, elastic deformation, and temperature-dependent material properties, serving as a counterpart to the simplified model discussed in Section 2. This study investigates the microtexturing treatment of phosphor bronze alloy (ZCuSn10Pb1) substrates using a micro-element configuration with a 200 μm mask diameter. Material etching removal performance was evaluated through three methods: immersion, oscillation, and Mask-Guided Microbial Jet Machining (MGMJM). The Material Etching Amount (MEA) and Material Etching Rate (MER) under various microbial chemical etching conditions are presented in Figure 12, where “NT” (Non-Terminated) indicates algorithm failure to converge within the 12-hour threshold.

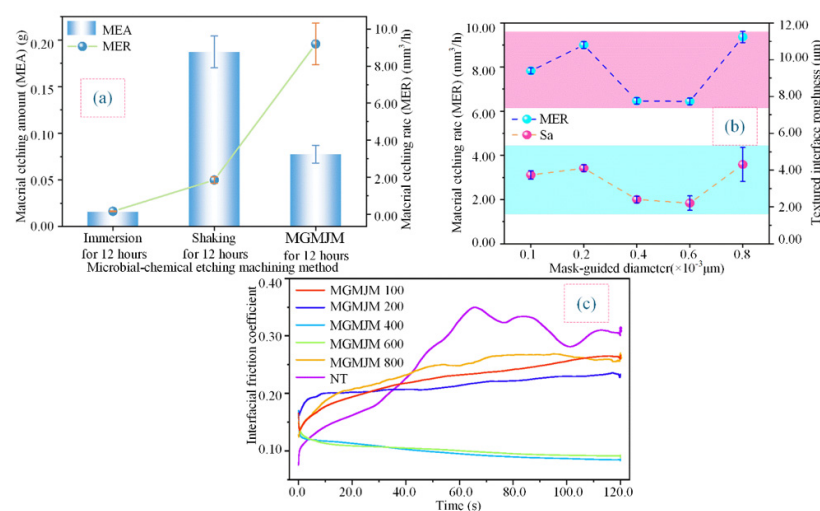


Figure 12. Evaluation of the processing characteristics of microbial chemical etching and the performance of MET contact interfaces; (a) Comparison of MEA and MER for different processing methods (immersion method, shaking method, and MGMJM); (b) Influence of mask aperture diameter on MER and the roughness of micro-textured interfaces; (c) Variation patterns of the contact friction coefficient curves for micro-textured interfaces with different MET diameters.

Results demonstrate that MGMJM enables precise selective etching of phosphor bronze alloy via mask guidance. Under comparable 12-h conditions (1.0 h for MGMJM), the MEA values were 0.014 g (immersion), 0.152 g (oscillation), and 0.063 g (MGMJM), with average MERs of 0.118 mm^3/h , 1.396 mm^3/h , and 6.927 mm^3/h , respectively. Notably,

MGMJM achieved MER values $\sim 59\times$ higher than immersion and $\sim 5\times$ higher than oscillation. Compared to literature-reported copper oscillation machining MER of ~ 11.3 mg/h at 200 rpm [55–57], MGMJM attained 64 mg/h under similar conditions, representing a 4.7-fold improvement.

These findings highlight MGMJM's substantial efficiency advantages and its potential as a promising approach for high-efficiency micro-machining of phosphor bronze alloy micro-element configurations. The experimental specimens feature circular MET interfaces fabricated by Mask-Guided Microbial Jet Machining (MGMJM), as reported in our previous work [58]. Preliminary investigation of roughness parameters for micro-textured interfaces fabricated by MGMJM technology [59]. Conventional statistical roughness parameters are scale-dependent and non-unique, failing to capture topographical scale invariance. A fractal-based, scale-independent parameter system enables quantitative 3D morphology characterization, while a progressive deformation theory spanning elastic, elastoplastic, and plastic regimes is proposed for fractal gear line contacts. Integrating micro-texture optimization with multiphysics contact behavior, this study provides theoretical foundations and numerical pathways for high-precision thermo-mechanical analysis of micro-textured interfaces. The experimental platform setup and multi-condition testing scheme are illustrated in Figure 13. The operating conditions and structural parameters of the gear test rig are listed in Table 6.

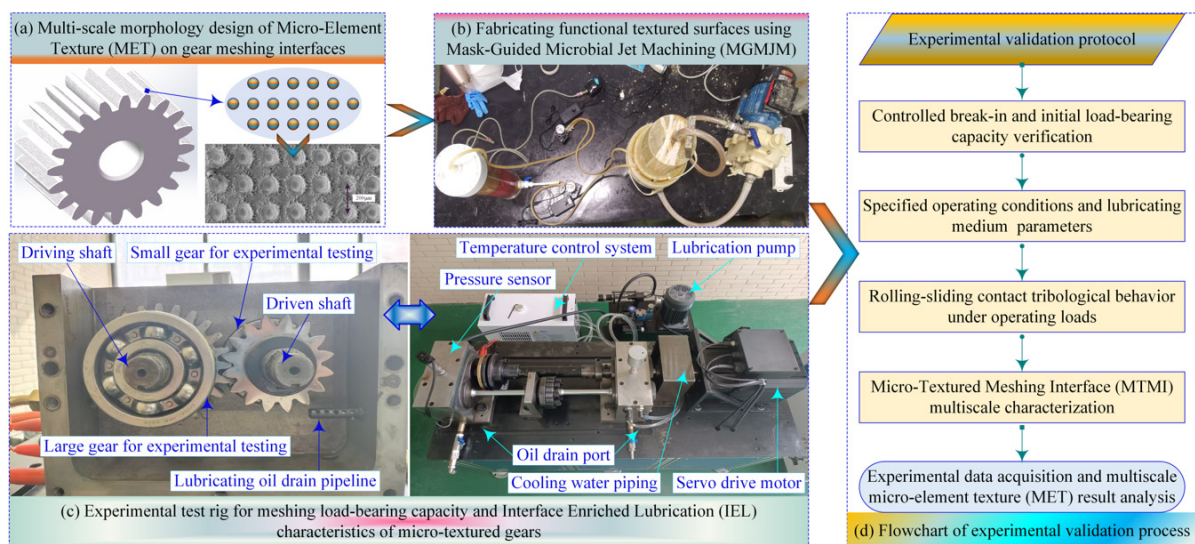


Figure 13. Experimental platform development and test protocol design. (a) Multiscale morphology design of Micro-Element Texture (MET) on gear meshing interfaces; (b) Fabricating functional textured surfaces using Mask-Guided Microbial Jet Machining (MGMJM); (c) Experimental test rig for meshing load-bearing capacity and Interface Enriched Lubrication (IEL) characteristics of micro-textured gears; (d) Flowchart of experimental validation process.

Through numerical simulation, the pressure and temperature distribution characteristics within 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.

Table 6. Operating conditions and design parameters of the gear test rig.

Category	Parameter	Symbol	Value	Unit	Remarks
Operating Environment	Ambient Temperature	—	25 ± 2	°C	Constant-temperature laboratory
	Relative Humidity	RH	45–65	%	Non-condensing
	Lubricant	—	ISO VG 68	—	Mineral-based oil
	Oil Supply Temperature	—	40 ± 1	°C	Thermostatic control
	Oil Supply Pressure	—	0.3 ± 0.02	MPa	Pressurized lubrication
Geometric Parameters	Module	m	4	mm	Standard involute profile
	Number of Teeth	z	25/50	—	Gear ratio 2:1
	Pressure Angle	α	20	°	—
	Face Width	b	30	mm	—
	Material	—	20CrMnTi	—	Carburized and quenched
Operating Conditions	Input Speed	n	1500 ± 10	rpm	Variable frequency drive
	Output Torque	T	500 ± 5	N·m	Magnetic powder brake loading
	Test Duration	—	72	h	Continuous operation

5.1. Effect of MET Radius on Lubrication Characteristics

The simulation experimental conditions are set as follows: the mean interface pressure of 2.0 MPa, the sliding velocity of 1.0 m/s, the lubricant bulk temperature of 30 °C, the MET depth of 120 μm , and the MET radii of 150 μm , 200 μm , and 300 μm , respectively. A comparative analysis of the MET radius variation is conducted to elucidate the influence of the mechanism on the meshing load-bearing capacity of interface lubrication characteristics, as illustrated in Figure 14. The simulation results reveal that with increasing MET radius, the local maximum contact pressure rises from approximately 121 MPa to 148 MPa, representing an increase of 22.31%. The temperature rise distribution exhibits a consistent evolution trend with the pressure field; the temperature rise within the MET contact area is significantly lower than that in the surrounding regions, manifesting a pronounced thermal barrier effect.

The synergistic enhancement mechanism induced by the geometric features of micro-textures is further revealed. (1) Geometric spatial effects of MET on lubricant bulk storage capacity and film thickness uniformity: As the MET radius increases, its absolute volume expands proportionally, providing enhanced storage and circulation space for the lubricant bulk. The larger MET radius reduces the geometric curvature of the texture configuration, significantly attenuating capillary resistance and micro-scale turbulence effects as the lubricant bulk flows within the dimple during relative interface motion. This facilitates the transport of lubricant bulk from the reservoir area toward the contact interface, resulting in the formation of a more continuous, thicker, and uniformly distributed hydrodynamic lubricating medium film. The uniform film thickness serves as the foundation for efficient heat conduction, effectively preventing localized overheating at the MTMI caused by dry friction. (2) Contact stress homogenization and hot spot suppression: According to Hertzian contact theory, actual contact between rough interfaces occurs at the asperity tips (the MCCA). When the MET radius is small (i.e., small MCCA tip radius with sharp geometry), the real contact area becomes extremely limited, leading to excessively high contact stresses. Increasing the MET radius effectively blunts the MCCA tips, transforming the contact mode from point contact (sharp tip) toward a more distributed interface-like contact state. Under constant total load conditions, the enlarged contact radius reduces the mean interface pressure and flattens the contact pressure distribution curve. Localized high pressure constitutes the direct trigger for surging frictional heat flux density and lubricant bulk film rupture; by eliminating pressure spikes through radius enlargement,

the instantaneous generation of localized high temperatures (hot spots) at the interface can be effectively suppressed, thereby enhancing the thermal stability of the gear transmission system. (3) Enhanced hydrodynamic lubrication effect and friction coefficient reduction: During relative interface motion, the convergent wedge-shaped gap constitutes the critical geometric condition for generating hydrodynamic load-bearing capacity. A larger MET radius implies more gradual curvature variation, which facilitates the construction of a hydrodynamically optimized convergent wedge structure in the meshing inlet area.

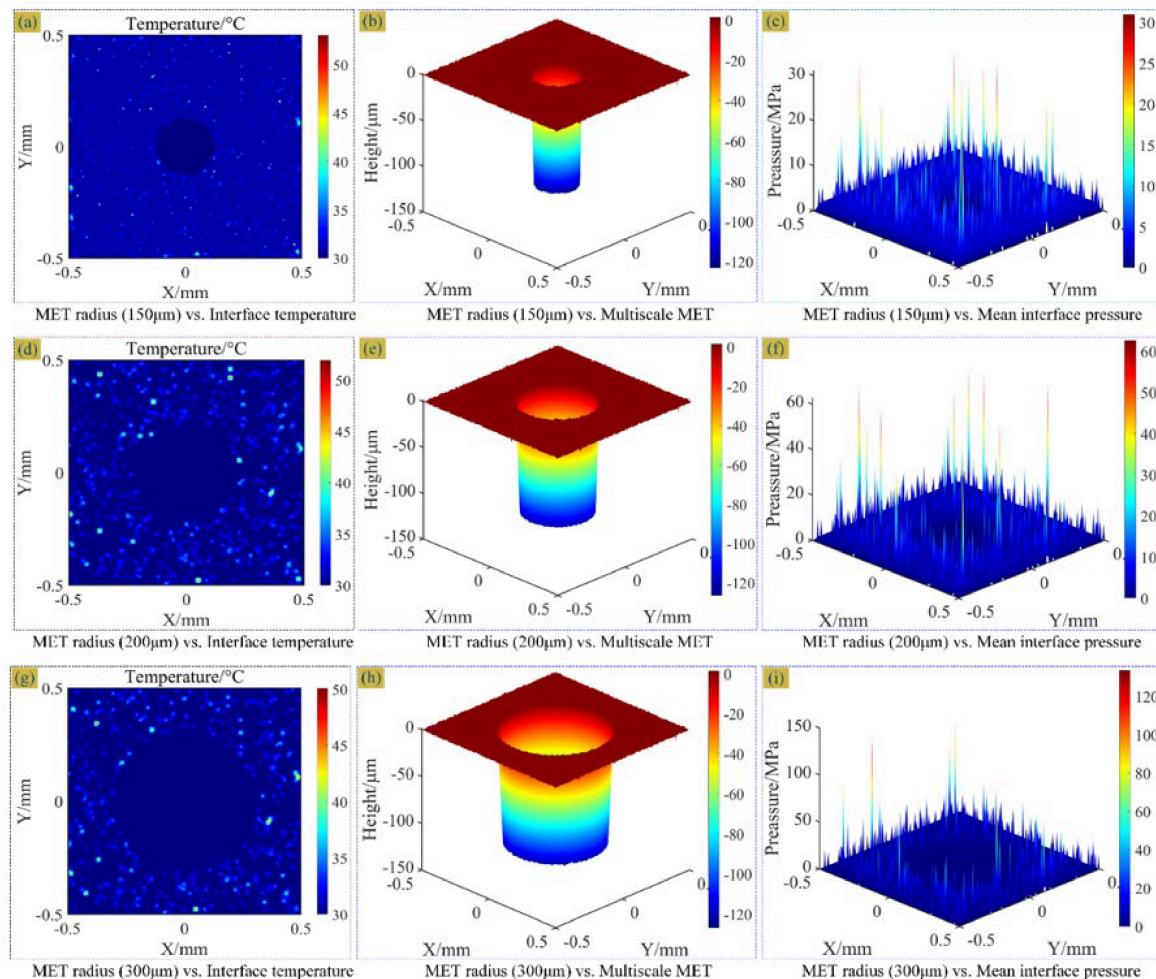


Figure 14. Regulating mechanisms of MET radius on multiphysics interface behaviors.

The gently tapered wedge region enables more efficient entrainment of lubricants, generating higher hydrodynamic pressure and thereby achieving complete separation of the two metallic interfaces. Once a full hydrodynamic lubricant bulk film is established, the frictional resistance becomes dominated by the internal friction (viscous shear) of the lubricant rather than external friction between metals (adhesive wear/plowing wear). This directly leads to a reduction in the friction coefficient, consequently decreasing the generation of thermal flux density loading.

5.2. Effect of MET Depth on Lubrication Characteristics

The simulation experiments are conducted under the following operating conditions: a mean interface contact pressure of 2.0 MPa, a sliding velocity of 1.0 m/s, and a lubricant bulk temperature of 30 °C, with a MET radius of 260 μm. The MET depths are selected as 50 μm, 150 μm, and 200 μm to investigate the influence of MET depth variation on micro-textured interface lubrication characteristics and meshing load-bearing capacity, as

illustrated in Figure 15. The simulation results reveal that with increasing MET depth, the local maximum contact pressure at the MTMI rises from approximately 106 MPa to 114 MPa, representing an increment of up to 7.55%.

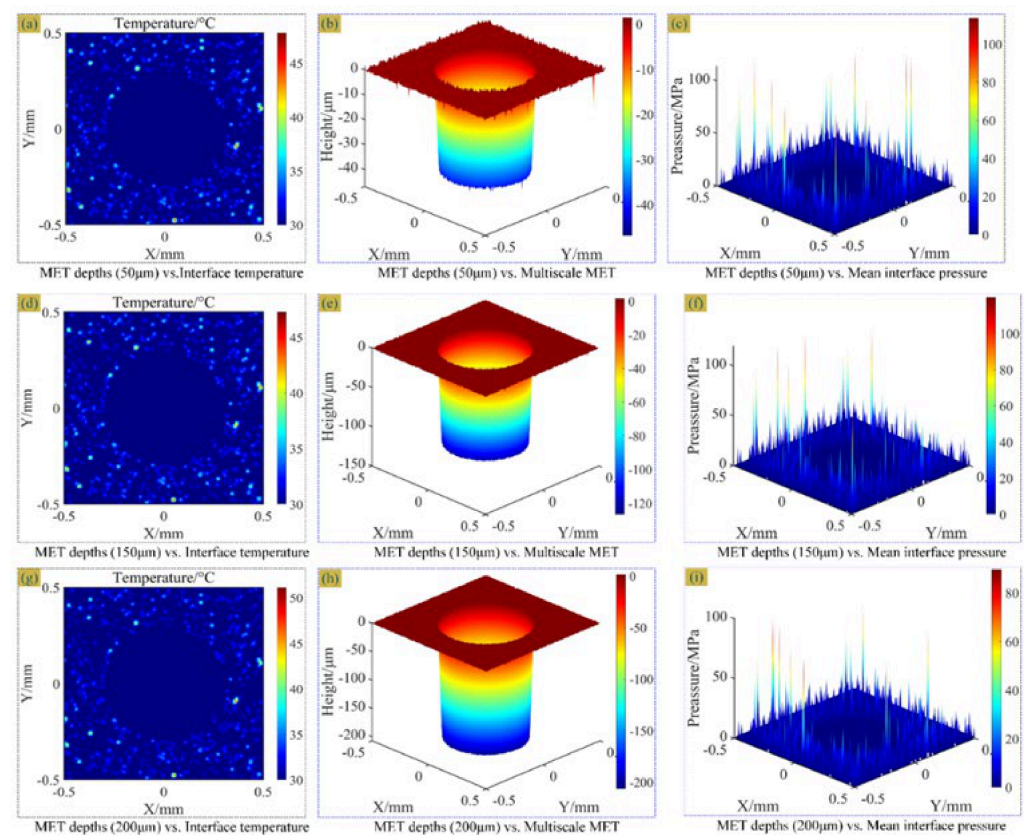


Figure 15. Regulating mechanisms of MET depths on multiphysics interface behaviors.

Further analysis reveals that with increasing MET depth, the interface contact temperature exhibits a consistent variation trend; however, the magnitude of mean interface temperature rise remains limited, and the rate of temperature increase gradually decelerates. Specifically, at a MET depth of 200 μm , the maximum interface contact temperature reaches 48.56 $^{\circ}\text{C}$, representing merely a 0.38% increase relative to the baseline condition. The mean and minimum interface temperatures rise by 0.28% and 0.19%, respectively, indicating that the influence of MET depth on interface contact temperature is considerably less pronounced than that of MET radius. Analogous to the effect of increasing MET radius, greater MET depth enhances lubricant enrichment and storage capacity while intensifying the hydrodynamic pressure effect at the MTMI.

Although deeper METs lead to elevated local contact pressure, the mean interface temperature rise remains at a relatively low level. This phenomenon is primarily attributed to the formation of a thicker lubricant film at the MTMI, facilitated by deeper METs, which effectively reduces the direct contact area of the MCCA, thereby decreasing frictional heat flux density and improving interface heat dissipation conditions.

5.3. Effect of Mean Contact Pressure on Lubrication Characteristics

Simulated experimental conditions: The sliding velocity is set to 1.0 m/s, with the lubricant bulk temperature maintained at 30 $^{\circ}\text{C}$. The MET geometric parameters are configured with a radius of 120 μm and a depth of 80 μm . Three representative nominal contact pressure conditions, 2.0 MPa, 3.0 MPa, and 4.0 MPa, are selected to comparatively analyze the interface contact pressure distribution and temperature rise evolution under varying

pressure conditions, thereby elucidating the influence of mechanisms of micro-texture parameters on MTMI lubrication characteristics and meshing load-bearing capacity, as illustrated in Figure 16.

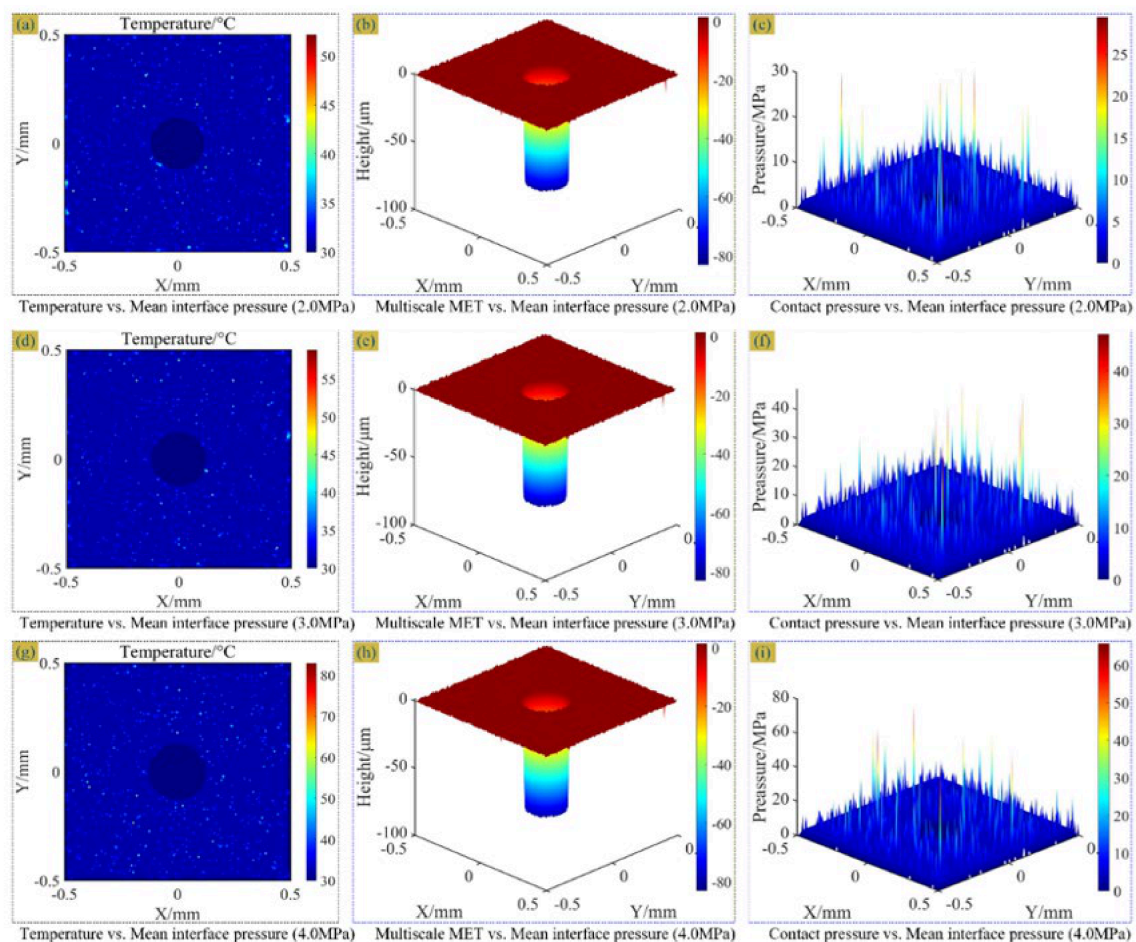


Figure 16. Regulating mechanisms of mean contact pressure on multiphysics MTMI behaviors.

Results indicate that with increasing MET depth, the local maximum contact pressure escalates significantly from approximately 37 MPa to 81 MPa, representing a substantial increase of 118.92%. The high-pressure areas and localized high-temperature spots within the meshing domain exhibit a synchronized growth pattern. The underlying physical mechanism can be attributed to the fact that elevated contact pressures promote the expansion of the local real contact area, intensifying contact stress concentration and, consequently, inducing more severe frictional heat flux density. Under thermo-mechanical coupling effects, the local interface temperature rises markedly, establishing a high-pressure–high-temperature synergistic reinforcement nonlinear feedback effect that exerts a decisive influence on the lubrication failure risk and load-bearing durability of the MTMI.

Further analysis reveals that as the contact pressure increases, the maximum interface temperature demonstrates a pronounced upward trend. When the contact pressure increases from 2.0 MPa to 4.0 MPa, the maximum temperature surges from 34.79 °C to 96.57 °C, corresponding to an increase of 177.58%. In contrast, the mean and minimum temperatures exhibit relatively moderate increases. The mean interface temperature rises from 29.93 °C to 62.76 °C (109.69% increase), while the minimum contact temperature increases from 29.48 °C to 51.68 °C (75.31% increase). These data demonstrate that the maximum temperature exhibits significantly higher sensitivity to contact pressure compared to the mean and minimum temperatures. Under high-pressure operating conditions, the lubricant

film thickness undergoes substantial reduction, leading to increased direct contact area at the MTMI and, consequently, exacerbating frictional heat generation, thereby forming a positive feedback effect of temperature rise. Notably, as the mean interface pressure elevates, the temperature differential between the maximum contact temperature and the mean/minimum contact temperatures expands dramatically. This pronounced intensification of temperature distribution non-uniformity portends potential risks of non-uniform thermal stress damage and localized wear at the MTMI.

5.4. Effect of Sliding Velocity on Lubrication Characteristics

The simulation parameters are configured as follows: the mean contact pressure of 2.0 MPa, the lubricant bulk temperature of 30 °C, and the MET depth and radius of 80 μm and 120 μm , respectively. Three sliding velocity conditions (1.0 m/s, 1.5 m/s, and 2.0 m/s) are selected to comparatively analyze the influence of sliding velocity variations on local pressure and temperature distributions at the MTMI, thereby elucidating the underlying mechanisms governing interface lubrication characteristics and meshing load-bearing capacity, as illustrated in Figure 17.

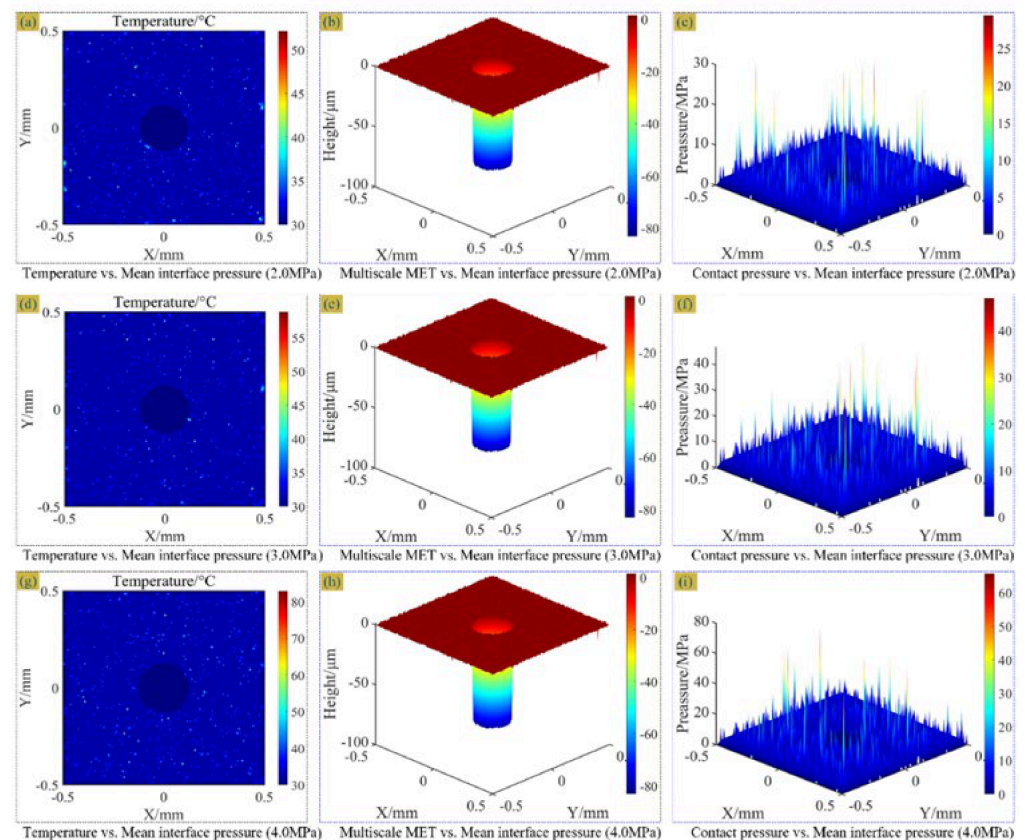


Figure 17. Regulating mechanisms of sliding velocity on multiphysics MTMI behaviors.

The simulation results indicate that with increasing sliding velocity at the MTMI, the local contact pressure gradually decreases from approximately 81.36 MPa to 42.78 MPa, while the number of high-pressure regions remains relatively stable. The local temperature distribution exhibits a characteristic pattern, with the MTMI center serving as the heat source and a gradient decrease toward the periphery, with no significant change in the number of high-temperature spots. This suggests that the enhancement of sliding velocity exerts a more pronounced promotional effect on the heat dissipation process of the MTMI than its direct impact on the quantity of high-temperature areas.

As depicted in Figure 17, the MTMI contact temperature rise rate demonstrates a decelerating trend with increasing sliding velocity. When the sliding velocity increases from 1.0 m/s to 2.0 m/s, the maximum contact temperature rises from 41.26 °C to 50.73 °C (an increase of 22.95%); the mean internal ambient temperature of the gearbox increases from 32.48 °C to 37.69 °C (an increase of 16.04%), and the minimum temperature rises from 31.54 °C to 34.87 °C (an increase of 10.56%). The aforementioned temperature rise phenomena are primarily attributed to the increased frictional heat flux density loading at the meshing interface caused by higher sliding velocities. Owing to the thermal diffusion and convective heat dissipation effects of the lubricating medium, the interface contact temperature rise rate is effectively suppressed. This demonstrates that although the elevated sliding velocity increases the frictional heat flux loading on the MTMI, its temperature rise effect is significantly mitigated by the heat dissipation mechanisms.

5.5. Effect of Lubricant Bulk Temperature on Lubrication Characteristics

The numerical simulation conditions are selected as follows: a mean interface contact pressure of 2.0 MPa, a sliding velocity of 1.0 m/s, a micro-texture depth of 80 µm, and a texture radius of 120 µm. The lubricant temperature is set at three levels: 30 °C, 60 °C, and 90 °C. An analysis is conducted to investigate the influence of temperature variation on the local pressure and contact temperature distributions at the meshing interface, thereby elucidating the underlying mechanisms by which temperature affects interface lubrication characteristics and ASLBC. To isolate the thermal effect of lubricant properties, the gear body is modeled as an isothermal heat sink maintained at the measured steady-state bulk temperature. Convective heat transfer induced by gear rotation is omitted in the present tooth-level TEHL model; instead, its global thermal influence is equivalently accounted for via the prescribed inlet oil temperature, which is calibrated against system-level thermal network simulations and/or experimental data. The simulation results indicate that the MTMI contact temperature exhibits a linear increasing trend with rising lubricant temperature, accompanied by a significant expansion of high-temperature regions; the local pressure distribution does not demonstrate any discernible regular variation.

As illustrated in Figure 18, the maximum, mean, and minimum temperatures at the meshing interface all increase linearly with lubricant temperature, suggesting that the lubricant temperature exerts a substantially greater influence on the lubrication characteristics and load-bearing capacity of MTMI compared to other parameters. Specifically, when the lubricant temperature increases from 30 °C to 90 °C, the maximum MTMI contact temperature rises from 53.73 °C to 148.68 °C, representing an increase of 176.72%. Compared to the mean interface temperature (52.96 °C) and the minimum MTMI contact temperature (51.89 °C), the increases amount to 180.74% and 186.53%, respectively. The primary mechanisms underlying these phenomena are as follows: elevated lubricant temperature leads to a reduction in dynamic viscosity, which consequently causes a decrease in lubricant film thickness and attenuates the IEL effect.

As the proportion of frictional heat flux generated by the MCCA at the meshing interface increases, elevated lubricant temperatures enhance thermal conductivity and fluidity, yet the reduced film thickness impedes heat dissipation from the MTMI, exacerbating localized hot spots. Investigating the mechanical contact and thermal transfer mechanisms is, therefore, critical across engineering domains. A rigorous multiscale framework is required, synergistically integrating fractal geometry, for realistic, scale-invariant interfacial micro-contact characterization, with a hybrid analytical–numerical approach employing asperity-level constitutive models. This methodology is indispensable for cross-scale contact analysis and directly governs optimal micro-textured element design for rolling–sliding

line-contact meshing interfaces, thereby determining the operational efficiency of marine power rear transmission systems.

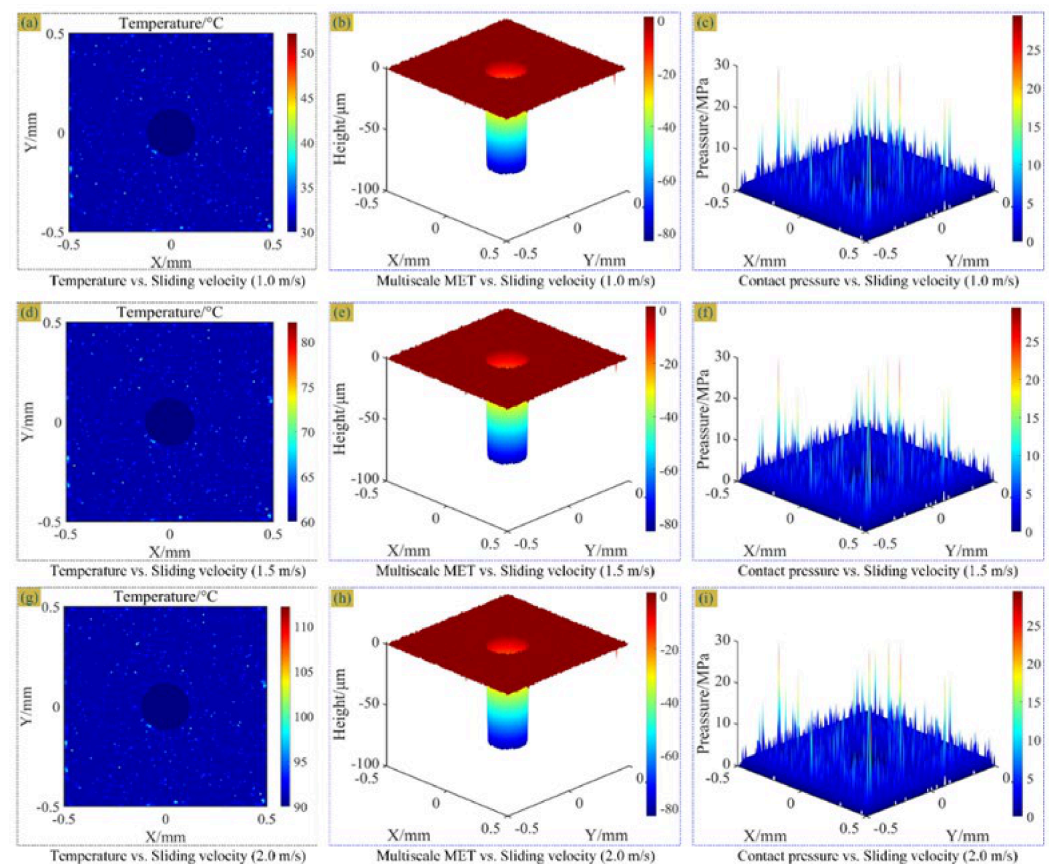


Figure 18. Regulating mechanisms of lubricant bulk temperature on multiphysics MTMI behaviors.

6. Conclusions

This study proposes a multiscale textured interface contact model incorporating MCCA characteristics to elucidate the synergistic modulation mechanism between IEL performance and the ASLBC of MTMI under transient TEHL conditions. The model employs homogenization theory to evaluate the effects of areal density and depth-to-diameter ratio on IEL characteristics. A time-resolved micro-elastohydrodynamic lubrication model is developed through dimensionless discretization and multi-level mesh refinement, enabling investigation into the influences of autocorrelation length and MCCA amplitude on interfacial behavior. A correlation model linking MET geometric features to meshing ASLBC is established to identify optimal parameters for simultaneously enhancing IEL and ASLBC. Experimental validation, combined with analysis of temperature field evolution and dynamic friction coefficient variations at the MTMI, substantiates the predictive accuracy and effectiveness of the proposed model. USA and MLR methods are employed to explore the effects of MET sizes, area ratio, and configuration on meshing ASLBC and friction coefficients, thereby optimizing microtexture parameters. The principal conclusions drawn from this research are as follows.

(1) The MET significantly influences the thermal characteristics of the MTMI. As the MET radius and depth increase, the maximum interfacial contact temperature rises by 9.72% and 0.38%, respectively. However, compared with macroscopic operating parameters such as mean contact pressure, sliding velocity, and lubricant bulk temperature, these temperature increments are substantially smaller. The contact temperature within the MTMI region remains significantly lower than that in the surrounding areas, indicating that

the MET exerts dual effects of lubrication enrichment, enhancement, and cooling dissipation on the MTMI. This phenomenon is primarily attributed to the fact that increasing MET geometric dimensions enhances the lubricant storage capacity and meshing hydrodynamic pressure effect, thereby effectively reducing the real contact area.

(2) As the mean contact pressure increases, the maximum and minimum interface temperatures rise by 177.58% and 75.31%, respectively. This significant amplification of temperature differential primarily stems from the exacerbated non-uniformity of contact pressure distribution within the MTMI. When the lubricant temperature elevates, the maximum and mean interface temperatures increase by 180.74% and 186.53%, respectively, attributable to the viscosity reduction induced by medium heating, which consequently leads to a diminution of the lubricating film thickness. Furthermore, as the sliding velocity increases, the rising rate of interfacial contact temperature exhibits a progressively decelerating trend; this phenomenon arises because the frictional heat flux density remains relatively low under low-speed operating conditions, maintaining the overall temperature rise of MTMI at a comparatively moderate level.

(3) The optimal TSI-MET parameters (dimension: 500 μm , area ratio: 40%, depth: 5.0 μm) identified via USA yield a meshing load-bearing capacity of 1.163 MPa and a friction coefficient of 0.0686, an 11.6% friction reduction versus untextured counterparts. MLR analysis refines these findings as follows: for load-bearing capacity, parameter sensitivity ranks as MET size > area ratio > geometric configuration > depth (dimension and configuration positively correlated; depth and area ratio negatively correlated); for friction coefficient, the ranking is MET size > area ratio > depth > geometric configuration (all negatively correlated). MLR optimization yields identical parameters but superior performance: 1.106 MPa load-bearing capacity and 0.0679 friction coefficient, representing a 13.7% friction reduction versus untextured interfaces and 4.58% improvement over USA-optimized configurations.

While the 500 μm square-MET (40% area ratio) delivers optimal tribological performance under the present TEHL regime, its industrial cost-effectiveness requires scrutiny. Smaller textures (200–300 μm) are preferable for mass production. Laser interface texturing (LST) scales nearly linearly with texture coverage, and halving the feature size reduces scanning path and processing time by 30–40%, significantly lowering unit costs. Finer textures also relax beam focusing and positioning tolerances, improving consistency across large gear blanks and reducing scrap. Complementary methods (ECM, micro-milling) likewise exhibit improved pattern fidelity and prolonged tool life for finer features. However, our parametric analysis reveals a critical trade-off: below 300 μm , load-bearing capacity drops by 8–12% relative to the 500 μm optimum, and friction-reduction benefits attenuate. Thus, for high-power-density systems where tribological performance is paramount, the 500 μm design remains preferred despite higher processing costs. For general industrial gearboxes, a 300 μm texture with a 35–45% area ratio offers a pragmatic compromise, achieving approximately 85–90% of optimal lubrication improvement at substantially lower manufacturing cost. Future work will explore hybrid strategies, such as selective laser texturing on heavily loaded flanks paired with untextured lightly loaded regions, to optimize the overall cost/performance ratio.

With escalating demands for high power density, elevated operating speeds, and enhanced reliability in warship PRTS, anti-scuffing failure induced by inadequate lubrication during gear meshing has emerged as a predominant concern, exposing critical deficiencies in interface reliability and load-bearing safety. Consequently, improving the IEL performance and ASLBC of heavily loaded line-contact interfaces has become a widely recognized challenge. The performance enhancement of micro-textured IEL has garnered substantial attention, yielding advanced theories that enhance real-time synergistic regulation of interfacial lubrication while presenting formidable theoretical and practical challenges. To

address these issues, the MLR framework enables systematic interrogation of multiscale phenomena across expansive design spaces, elucidating parametric coupling mechanisms inherent to MTMIs. Looking forward, advanced machine learning architectures, including Random Forest ensembles, deep neural networks, and multimodal learning paradigms, offer substantial potential for augmenting micro-texture performance prediction, particularly when integrated with multiscale homogenization techniques. Nevertheless, data-intensive methodologies demand extensive high-fidelity datasets and impose significant computational burdens. In this context, the omission of thermoelastic effects results in a substantial underestimation of peak pressure and minimum film thickness, substantiating the indispensable role of TEHL modeling, and physics-based mathematical modeling retains its viability as a computationally efficient and economically advantageous approach for tribological performance forecasting. The prediction results based on TOPSIS combined with multiple regression analysis indicate that transverse groove textures exhibit the highest comprehensive performance potential and are therefore recommended as the priority candidate for subsequent experimental validation.

Considering that friction experiments in different orientations would entail additional efforts in test protocol design, specimen preparation, and data analysis, the anisotropic tribological performance of transverse slit micro-textures is designated as a key focus for subsequent research to maintain the present study's coherence and completeness. Future work will involve (i) comparative friction and wear tests under sliding directions parallel and perpendicular to the texture orientation; (ii) finite element simulations to elucidate the directional dependence of contact stress fields and lubricant flow behavior; and (iii) a systematic investigation into the influence of micro-texture geometric parameters (width, depth, spacing) on anisotropic friction characteristics.

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Abbreviations

MTMI	Micro-Textured Meshing Interface
MET	Micro-Element Texture
IEL	Interface Enriched Lubrication
ASLBC	Anti-Scuffing Load-Bearing Capacity
TEHL	Thermo-Elastohydrodynamic Lubrication
USA	Univariate Sensitivity Analysis
MLR	Multiple Linear Regression
MGMJM	Mask-Guided Microbial Jet Machining
MEA	Material Etching Amount
MER	Material Etching Rate

Nomenclature

b	Each with lateral dimension (edge length)
L	Longitudinal dimension of the transverse
c	Side lengths (rectangular-MET)
r	Radius(circular-MET)
d	Width(transverse slit-MET)
a	Side length of the square-arrayed
S	Area ratio
u	Velocity components of the lubricant bulk in the x direction
v	Velocity components of the lubricant bulk in the y direction
w	Velocity components of the lubricant bulk in the z direction
ρ	Density of the lubricating medium
η	Dynamic viscosity of the lubricating medium
P	Lubricant bulk layer film pressure
F_x	Load-bearing capacities of the lubricant bulk film along the x direction
F_z	Load-bearing capacities of the lubricant bulk film along the z direction
τ	Shear stress of the lubricating medium
μ	Friction coefficient at the meshing interface
x	Key performance indicators of the meshing interface, such as load-bearing capacity or friction coefficient
Y_1	MET dimensions
Y_2	MET area ratio
Y_3	MET depth
Y_4	MET geometric configuration
$\delta_1, \delta_2, \delta_3, \delta_4$	Regression coefficients for each variable
λ	Random error term
τ_s	Interface shear stress
η_{dv}	Dynamic viscosity of the lubricating medium
dv/dz	Velocity gradient across the lubricant bulk layer film thickness
V	Entrainment velocity
h_{fm}	Lubricant film thickness

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