Study on the Influence of Surface Texture on the Lubrication Performance of Tribopairs under High-Temperature Environments

Lijia Yang*

Xi'AN MINGDE INSTITUTE OF TECHNOLOGY,College of Intelligent Manufacturing and Control Technology, Xi'an, 710124, China
**Corresponding author: yanglijia13@163.com*

Abstract: *Under high-temperature operating conditions, the deterioration of the physicochemical properties of lubricating oil films, the evolution of the surface state of tribopair materials, and the instability of interfacial behavior induced by thermal-mechanical coupling collectively constitute the core mechanisms responsible for the degradation or even failure of lubrication performance. To address this challenge, surface texture technology, which introduces regular microscopic morphologies onto tribopair surfaces, demonstrates the potential to actively regulate the interfacial lubrication state. This study aims to systematically investigate the influence mechanism of surface texture on the lubrication performance of tribopairs under high-temperature environments. This study first elucidates the multi-physics field coupling nature of lubrication failure induced by high temperatures. It then establishes a parametric design theory for texture geometry and a substrate stability criterion that incorporate thermodynamic effects. Finally, it reveals the intrinsic regulatory mechanisms by which surface texture enhances high-temperature lubrication performance through reconstructing the pressure and temperature distributions of the oil film, intensifying interfacial mass and heat transfer, and generating synergistic effects with the boundary lubrication film. This study provides a systematic theoretical basis for the development of high-performance surface texture designs tailored for extreme operating conditions.*

Key words: *High-Temperature Environment; Surface Texture; Tribopairs; Lubrication Performance; Regulatory Mechanism*

Introduction

In advanced equipment fields such as aerospace, energy, and power systems, tribopairs often operate under extreme high-temperature conditions, where the interfacial lubrication state directly determines system reliability, efficiency, and service life. High-temperature environments not only cause viscosity degradation and rapid oxidation of the lubricating medium but also induce thermal softening of materials and thermoelastic instability at the interface, causing traditional methods that rely on the intrinsic properties of lubricants and materials to face a bottleneck. Therefore, developing surface engineering techniques capable of actively adapting to and improving high-temperature interfacial behavior holds urgent theoretical value and engineering significance. As a method that regulates tribological performance by fabricating regular microscopic morphologies on the surface, surface texture provides a new approach to overcoming the bottleneck of high-temperature lubrication. However, existing research is mostly focused on normal or medium-temperature conditions, leaving the design principles of texture under high temperatures and its intervention mechanisms in complex failure mechanisms still unclear. This study aims to construct a systematic research framework that proceeds from failure mechanism analysis, to thermodynamic design of texture, and then to the elucidation of performance regulation mechanisms. It will deeply analyze the active regulation effect of textured surfaces on the multi-field coupled lubrication interfacial behavior under high temperatures, in order to fill the theoretical gap in this field and provide scientific guidance for the design of high-performance tribopairs.

1. Lubrication Failure Mechanisms of Tribopairs under High-Temperature Conditions

1.1 High-Temperature Induced Changes in the Physicochemical Properties of Lubricating Oil Films

The thermal effect induced by high-temperature environments first directly acts on the rheological properties of the lubricating medium. The viscosity of lubricating oil exhibits an exponential decline with rising temperature, and its viscosity-pressure coefficient also decreases simultaneously. This dual effect leads to a significant weakening of the hydrodynamic effect and a sharp reduction in the oil film thickness. In the elastohydrodynamic lubrication region, this change causes a drastic decrease in the film thickness ratio and a substantial reduction in the critical load at which the system transitions into the mixed lubrication regime. More critically, high temperatures may promote thermal cracking of the base oil molecular structure in certain synthetic lubricants, causing irreversible changes in their non-Newtonian fluid characteristics, such as an intensification of shear-thinning behavior, which further impairs the ability to maintain an effective film thickness under high-speed shear.

From the perspective of physicochemical processes, high temperatures greatly accelerate the reaction kinetics of thermal oxidation and catalytic oxidation of lubricating oils. The free radical chain reaction, catalyzed by the metal surface, generates intermediate oxidation products such as alcohols, aldehydes, and ketones, which ultimately polymerize to form large molecular varnish, sludge, and acidic substances. These products not only directly contaminate the lubrication system but, more importantly, alter the boundary lubrication state at the interface. Additive molecules, particularly extreme pressure and anti-wear agents such as zinc dialkyldithiophosphate, are prone to decomposition under high temperatures. The process of their active sulfur and phosphorus elements reacting with the metal surface to form a protective chemical reaction film is thereby disrupted or excessively depleted, leading to premature failure of the boundary lubrication film under the extreme conditions where its function is required[1].

1.2 Surface State Evolution of Tribopair Materials under Extreme Temperature Conditions

Under the coupled effects of sustained high temperature and stress, the subsurface microstructure of tribopair materials undergoes a series of dynamic evolution processes. The material undergoes recovery and recrystallization, accompanied by the redistribution of dislocation density, which leads to the elimination of work hardening effects and a decrease in yield strength, resulting in a significant thermal softening phenomenon. This softening reduces the material's resistance to plastic deformation, making the contact asperities more susceptible to plastic flow and material migration under load, thereby creating conditions for adhesive wear and tribologically induced microstructural transformations in the surface layer. For multiphase alloy materials, high temperatures may promote the dissolution or coarsening of the strengthening phases, disrupting their original dispersion strengthening effect and consequently accelerating the wear process.

High temperature simultaneously serves as a powerful driving force for the interaction between the surface and the environmental media. Oxygen elements diffuse through the surface or penetrate into the subsurface layer via cracks, reacting with metal elements to form an oxide layer. The formation rate, thickness, morphology, and mechanical properties of this oxide film depend on the alloy composition of the material and the environmental atmosphere. The brittle oxide film is prone to cracking and spalling under cyclic contact stress, and the hard particles after spalling enter the friction interface as a third body, causing severe abrasive wear. Furthermore, high temperatures may induce harmful phase transformations or the selective diffusion of elements to the surface to form a soft layer, resulting in a mismatch in mechanical properties between the surface layer and the substrate, which becomes a source of crack initiation under thermomechanical fatigue loading[2].

1.3 Interfacial Lubrication Behavior under the Coupling of Thermal Load and Mechanical Load

The coupling of thermal load and mechanical load is not a simple linear superposition; rather, it induces a series of complex nonlinear interfacial responses. The local flash temperature generated within the contact zone and the bulk temperature of the system collectively constitute a non-uniform temperature field, which in turn profoundly influences the viscosity distribution of the lubricating oil, the elastic modulus of the material, and the coefficient of thermal expansion. This thermal-mechanical coupling effect leads to the failure of the classical isothermal elastohydrodynamic lubrication theory in its predictions, causes distortion in the oil film pressure distribution, may shift the location of the minimum oil film thickness, and even results in the attenuation or migration of the secondary pressure peak. The thermal deformation of the material due to non-uniform thermal expansion is sufficient to alter the geometric convergence shape of the contact zone, thereby fundamentally affecting the generation mechanism of hydrodynamic pressure.

Under the continuous action of coupled loads, the lubrication state is often forcibly confined to the mixed lubrication or even the boundary lubrication regime. Under such conditions, the frictional and wear behavior at the interface is jointly determined by the extremely thin fluid film, the adsorbed molecular film, the chemical reaction film, and the properties of the solid surface itself. High temperatures significantly increase the molecular thermal motion energy of the boundary lubrication components, accelerate the desorption rate of the physically adsorbed film, and simultaneously accelerate the dynamic competition process between the growth and wear of the chemical reaction film. When the wear rate exceeds the formation rate, the protective film layer fails to be maintained, leading to direct contact between the metal substrates. This contact, accompanied by instantaneous high flash temperatures and intense shear, may induce local micro-welding and tearing, causing the friction coefficient to exhibit severe fluctuations and the system to enter a high-energy-consumption, high-wear precursor state of instability.

2. Geometric Characteristics and Thermodynamic Design Principles of Surface Texture

2.1 Parametric Modeling Method for Texture Geometry Oriented Toward High-Temperature Lubrication

For the design of surface texture tailored to high-temperature lubrication conditions, the core lies in establishing a parametric system that can accurately characterize the geometric features of the texture and correlate them with its tribological functions. This system typically encompasses two levels: the macroscopic distribution parameters of the microscopic morphology and the local geometric parameters. The macroscopic distribution parameters include the area density of the texture, the arrangement pattern (such as square or hexagonal arrays), and the spatial orientation relative to the sliding direction. These parameters collectively determine the overall flow path of the lubricating medium within the interface and the pressure distribution framework. The local geometric parameters define the characteristics of individual microscopic features. For common dimple-type textures, the primary parameter is the depth-to-diameter ratio, which is the ratio of the dimple depth to the opening diameter. For groove-type textures, these parameters include the width-to-depth ratio, the cross-sectional shape, and the longitudinal profile. These local parameters directly influence the microscopic hydrodynamic effect generated by a single texture unit and the lubricant storage capacity.

Under the specific constraints of high-temperature conditions, parametric modeling must incorporate thermodynamic variables as key boundary conditions or optimization objectives. The optimization criteria for geometric parameters under traditional isothermal conditions may become invalid, and the modeling needs to account for the dynamic changes in the actual geometric dimensions of the texture during operation caused by material thermal expansion, as well as the influence of the lubricant's viscosity-temperature characteristics on the fluid behavior within the texture. Therefore, an advanced parametric model is no longer a static geometric description but a parameter set that couples thermoelastic deformation and nonlinear rheological properties. By introducing dimensionless parameter groups, such as the thermal film thickness ratio and the texture Reynolds number, the correlation between geometric parameters, operating conditions, and high-temperature lubrication performance can be established, thereby providing a theoretical framework for subsequent numerical simulation and optimization design.

2.2 Correlation Analysis Between Texture Morphology and Microscopic Hydrodynamic Effects

Specific texture morphologies, under relative motion, can actively intervene in the flow state of the lubricant within the interface, generating a series of microscopic hydrodynamic effects. When regularly distributed microscopic dimples or grooves exist on the surface of the bearing area, they periodically alter the convergence shape of the clearance between the friction pairs during the sliding process. This periodic variation produces two main effects on the lubricating oil film. First, it generates local hydrodynamic effects, creating an additional pressure increment at the downstream edge of the texture, which helps to enhance the overall load-carrying capacity of the oil film. Second, it induces microscale vortices or secondary flows. These microscopic vortices can promote the exchange of lubricant between the central zone of the interface and the edge regions, facilitating the introduction of fresh, cooled lubricant into the contact area while simultaneously expelling lubricant that has been heated by shear stress and has aged[3].

The difference in texture morphology directly determines the intensity and mode of the microscopic hydrodynamic effects. For example, dimple-type textures with a certain depth-to-diameter ratio primarily serve as microscopic lubricant reservoirs, generating squeeze film effects and microcirculation during the sliding process. In contrast, groove-type textures with a certain orientation are more inclined to guide the lubricant for transport along a specific direction, and their hydrodynamic effects strongly depend on the angle between the groove orientation and the sliding direction. Under high-temperature conditions, these effects acquire new significance. The lubricant microcirculation induced by the texture not only replenishes the lubricant but also enhances convective heat transfer in the contact area, contributing to the reduction of local flash temperatures. Meanwhile, the additional space provided by the texture can accommodate some of the fine solid particles generated by high-temperature oxidation, delaying the detrimental effects of three-body abrasion, thereby improving the interfacial lubrication state under extreme conditions.

2.3 Design Criteria for Texture Substrate Stability Based on Thermoelasticity Theory

In the harsh environment characterized by the combined action of high temperature and cyclic mechanical stress, the structural integrity of the surface texture itself serves as the prerequisite for its sustained functionality. The introduction of a texture essentially creates microscopic geometric discontinuities on the material surface. These discontinuous regions, particularly the edges and bottoms of dimples or grooves, are prone to becoming stress concentration points. Under thermal loading, due to material thermal expansion and the temperature gradient between the surface layer and the substrate, an additional thermal stress field is generated around the texture. This thermal stress field, when superimposed with the stress field induced by external mechanical loads, may cause local stresses to far exceed the material's yield strength or fatigue limit, leading to plastic deformation, tearing at the texture edges, or the initiation and propagation of fatigue cracks.

Based on the theory of thermoelasticity, the design criteria aim to ensure the long-term stability of the texture substrate under high thermal-mechanical coupled loads. This requires optimizing the geometric shape of the texture to minimize its stress concentration factor. For example, using elliptical or spherical dimples with smooth transitions to replace prismatic dimples with sharp edges can significantly improve the stress distribution. The selection of the depth-to-diameter ratio is crucial. While an excessively large depth-to-diameter ratio is beneficial for oil storage, it severely weakens the local bending stiffness and thermal conductivity of the material, exacerbating stress concentration and heat accumulation. Therefore, it is necessary to establish an optimization function that takes the geometric parameters of the texture as variables and aims to maximize structural stability while minimizing stress concentration. This function must incorporate the mechanical property parameters of the material under high temperatures, such as creep strength, thermal fatigue resistance, and the coefficient of thermal expansion. By combining theoretical calculations with finite element analysis, a safe boundary for the geometric parameters of the texture can be determined, ensuring both favorable lubrication functionality and excellent mechanical stability under specific high-temperature operating conditions[4].

3. Regulation Mechanisms of Textured Surfaces on High-Temperature Lubrication Performance

3.1 Reconstruction of Local Oil Film Pressure and Temperature Distribution Induced by Micro-Textures

The presence of micro-textures substantially alters the geometric morphology and boundary conditions of the tribopair interface, thereby actively reconstructing the pressure field and temperature field within the lubricating oil film. When the sliding surface traverses the textured area, the flow of the lubricating oil is periodically disturbed by the micro-cavities, generating a significant local pressure increase in the trailing edge or downstream edge region of the texture, which is known as the micro-hydrodynamic effect. This additional pressure peak directly enhances the load-carrying capacity of the oil film, which is attenuated by the decrease in viscosity at high temperatures, helping to separate the contacting surfaces. Simultaneously, the local convergent and divergent clearances formed by the texture units alter the shear flow path of the lubricating oil, thereby affecting the distribution of internal heat generation dominated by viscous shear. Consequently, the region of maximum flash temperature may shift from a uniform band-like distribution on a smooth surface to a discretized or periodically distributed pattern associated with the texture array.

This reconstruction of pressure and temperature distribution is crucial for the stability of the high-temperature lubrication state. The presence of local pressure peaks not only enhances the overall load support but also, through their spatial distribution characteristics, helps to form a more stable lubricating oil film configuration, inhibiting film rupture induced by thermal disturbances or mechanical vibrations. The reconstructed temperature field exhibits lower peak values and gentler gradients, as the textured cavities, to some extent, act as microscopic heat sinks, increasing the pathways for heat dissipation. The coupled reconstruction of the pressure field and the temperature field jointly delays the degradation of the lubrication state toward mixed lubrication and boundary lubrication, thereby expanding the safe operating range for full-film lubrication under high-temperature environments.

3.2 Enhancement Effect of Secondary Flow and Microcirculation on Mass and Heat Transfer in Confined Spaces

Within the confined space formed by the relatively moving surfaces and the micro-textures, the mainstream shear flow induces the generation of complex secondary flow structures, such as micro-vortices and Taylor vortices. These secondary flows, generated inside or at the edges of the textured cavities, break through the limitations imposed by the laminar sublayer on mass and heat transfer. From the perspective of mass transfer, the intense microcirculation promotes convective exchange of the lubricating medium between the central contact region and the peripheral areas. This process continuously carries the lubricant that has aged due to high-temperature shear and additive depletion away from the core contact zone, while simultaneously transporting fresh lubricant rich in additives and with a favorable cooling state into the zone, thereby maintaining the chemical and physical properties of the lubricating oil at a dynamic level and mitigating lubrication failure caused by oil degradation[5].

From the perspective of heat transfer, secondary flows greatly enhance the convective heat transfer mechanism. Compared with a smooth surface that relies solely on heat conduction through the solid material, the fluid microcirculation induced by the texture utilizes the lubricating oil itself as an efficient heat transport medium, carrying frictional heat and shear heat away from the heat-generating surface through forced convection. This enhanced heat dissipation capability directly acts to reduce the bulk temperature and local flash temperature at the interface, effectively inhibiting the chain of negative effects triggered by high temperatures, such as accelerated lubricant oxidation, material thermal softening, and thermoelastic instability. Therefore, by enhancing the mass and heat transfer processes within the confined space, the texture improves the robustness of the tribopair system in high-temperature environments from both the thermodynamic and chemical kinetic dimensions.

3.3 Synergistic Mechanism Between Surface Texture and High-Temperature Boundary Lubrication Film

Under high-temperature conditions, when the oil film thickness decreases to the nanometer scale or local rupture occurs, the boundary lubrication film becomes the dominant factor controlling frictional and wear behavior. A multi-layered synergistic mechanism exists between the surface texture and the boundary lubrication film. The microscopic cavities of the texture can serve as reservoirs and supply sources for boundary lubrication active substances, such as adsorbed molecules and decomposed additive products. Under contact stress, the substances stored in the cavities can be slowly released into the friction interface, continuously replenishing the boundary film depleted by high-temperature desorption or mechanical wear, thereby extending its effective duration. This "controlled-release" effect is crucial for maintaining the high-temperature boundary lubrication state.

The geometric morphology of the texture can also physically alter the formation and load-bearing process of the boundary film. The additional surface area provided by the texture edges may serve as preferential nucleation sites for chemical reactions within the boundary film. More importantly, during the mixed lubrication stage when asperity contact occurs, the textured regions share a portion of the load through the stored lubricating medium and the generated micro-hydrodynamic effects, thereby reducing the actual contact pressure and flash temperature at the asperity contacts. This load-sharing effect creates an opportunity for the boundary lubrication film to form and be maintained under relatively mild conditions, reducing the risk of its instantaneous breakdown. Therefore, the texture does not function independently of the boundary lubrication film; instead, it forms a functional complementarity and synergy with the boundary lubrication film by providing material reserves, altering interfacial conditions, and sharing mechanical loads, collectively constructing a more robust high-temperature tribological defense line.

Conclusion

This study systematically elucidates the influence laws and mechanisms of surface texture on the lubrication performance of tribopairs under high-temperature environments. The research reveals that lubrication failure induced by high temperatures originates from the systematic degradation of the rheological properties of the oil film, the evolution of the material surface state, and the thermal-mechanically coupled interfacial behavior. To address this challenge, this study proposes parametric design and stability evaluation criteria for high-temperature textures that must integrate thermoelasticity and fluid dynamics. Theoretical analysis demonstrates that optimized surface textures can effectively reconstruct the pressure and temperature distributions in the contact zone by inducing microscopic hydrodynamic effects, thereby enhancing the load-carrying capacity of the oil film and reducing local flash temperatures. The secondary flows and microcirculation excited by the textures significantly intensify the mass and heat transfer processes within the confined interfacial space, delaying the chemical degradation of the lubricating oil and thermal accumulation. Furthermore, the texture forms a synergistic and complementary mechanism with the high-temperature boundary lubrication film, collectively enhancing the tribological robustness of the interface by providing controlled substance release, sharing the load, and optimizing the film-forming environment. In summary, surface texture constitutes an effective approach for the active regulation of high-temperature lubrication performance. Future research can further focus on the dynamic optimization of texture parameters under multi-field strong coupling conditions, the long-term service behavior of textures considering material creep and fatigue at high temperatures, and the design of adaptive texture systems oriented toward intelligent lubrication.

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