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: *At high temperatures, there will be changes in the physical and chemical properties of the lubricating oil film, changes in the surface condition of the tribopair material, and instability at the interface due to thermal-mechanical coupling; thus, the lubrication performance will decrease or fail. Therefore, to solve the problem of lubrication conditions, an organised microscopic structure can be formed at the surface of the tribological interface by employing the technology of surface texture. The purpose of this paper is to systematically study the effect of surface roughness on the lubrication performance of tribopairs at high temperatures. First, we will specify that the field-coupling nature of lubrication failure due to high temperature is complex. Then, the Parameter Design Theory for Texture Geometry and a Substrate Stability Criterion Based on Thermodynamics are developed. Finally, we can conclude that the internal regulation mechanism of how a rough surface improves the high-temperature lubrication performance of oil is to change the distribution of pressure and temperature in the oil film, increase interfacial mass and heat transfer, and create a synergistic effect with the boundary lubrication film. Organise the theoretical basis for the development of high-performance surface texture design in harsh environments in this paper.*

Keywords: *High-Temperature Environment, Surface Texture, Tribopairs, Lubrication Performance, Regulatory Mechanism*

Introduction

Most of the high-end equipment in aerospace and power systems has a relatively high operating temperature, so the tribopair needs to maintain the integrity and function of the lubricating film at high temperatures. High-temperature environments reduce the viscosity and accelerate the oxidation of the lubricating material; at the same time, they can cause thermal softening of materials and thermoelastic instability at the interface, so the traditional method of relying on the inherent properties of lubricants and materials is reaching its limit. Therefore, at present, many people have begun to study how to develop surface engineering technology that can actively adapt to and improve high-temperature interfaces. A regular microstructure has been added to the surface to change the tribological properties, and thus a new way to solve the problem of high-temperature lubrication has been achieved. Most of the previous research has focused on normal and moderate-temperature environments, so the design ideas for texture in high-temperature areas and all kinds of failure modes have not been well explored. The goal of this paper is to build an organized research system based on the analysis of failure modes and the thermodynamic design of texture, and then study the mechanism of performance regulation. Based on the above, the purpose of this paper is to carry out comprehensive research on the active regulation effect of textured surfaces on the behaviour of the multi-field coupled lubrication interface at high temperatures, identify the deficiencies in the related theoretical study, and provide a scientific basis for the design of high-performance tribopairs.

1. Lubrication Failure Mechanisms of Tribopairs at High Temperatures

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

The first effect of the high-temperature environment is on the rheological properties of the lubricant material itself. The viscosity of lubricating oil is lower at high temperatures, and thus, so is the viscosity-pressure coefficient. As a result of the two reasons mentioned above, both the hydrodynamic effect and the oil film thickness have decreased substantially. As a result of the above changes, the film thickness ratio in the elastohydrodynamic lubrication regime has decreased only slightly, and a considerable reduction has been achieved in the critical load for the system to enter mixed lubrication. More seriously, a high temperature can cause thermal cracking in the molecular structure of the base oil of some synthetic lubricants, leading to an irreversible change in their non-Newtonian fluid properties, such as an increase in shear-thinning behaviour; thus, it is difficult to maintain a sufficient film thickness at high shear rates.

At a high temperature, both the rate of thermal oxidation and the rate of catalytic oxidation for lubricating oil will be relatively high. A free-radical chain reaction is initiated on the surface of the metal to produce various oxidation products, such as alcohols, aldehydes and ketones, which then polymerise to form large molecules of varnish, sludge and acid. The products will directly pollute the lubrication system and, more seriously, change the boundary lubrication state at the interface. Zinc dialkyl dithiophosphate is a high-pressure anti-wear agent, but it has a low decomposition temperature. Therefore, the process of the reaction between the active sulfur and phosphorus elements and the metal surface to form a protective chemical reaction film is interrupted or prematurely exhausted, and an early breakdown of the boundary lubrication film occurs under the severe conditions for which it is supposed to operate[1].

1.2 Evolution of the Surface State in Tribopair Materials at High Temperatures

Due to a long period of high temperature and stress, the internal structure at the bottom of tribopair materials has been changed in several stages. Recover the material and then recrystallise it; at this time, the dislocation density will be reduced, the effect of work hardening will be eliminated, the yield strength will decrease, and a considerable thermal softening effect will be achieved. Soft materials have low hardness values and are more likely to undergo plastic deformation under load; thus, the contact asperities are more prone to plastic flow and material transfer, resulting in adhesive wear and changes in the microstructure of the surface layer due to tribological effects. At high temperatures, the strengthening phase in multiphase alloy materials may dissolve or coarsen; therefore, the original dispersion-strengthening effect will be lost and it will be more prone to wear.

High temperatures will also change the shape of the ground and harm the environment in other ways. Oxygen-containing groups on the surface or in the cracks of the lower-layer material can react with the metal to form an oxide layer. The formation rate, thickness, shape and mechanical properties of this oxide film are determined by the alloy composition of the material and the environment. The brittle oxide film will be cracked and spalled due to repeated contact stress, and the hard particles that break away during spalling will act as third bodies at the friction interface and cause serious abrasive wear. A high temperature can also cause an unfavorable phase change or selective diffusion of elements at the surface to form a soft layer; thus, there will be a difference in mechanical properties between the surface layer and the substrate, and this will be 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 combined effect of heat and force is not the sum of the two; there are many other irregular interactions at the interface. The local flash temperature at the contact zone and the bulk temperature of the system are combined to form a non-uniform temperature field; thus, there will be variations in the viscosity of the lubricating oil, elastic modulus of the material and coefficient of thermal expansion. Thermal-mechanical coupling causes the failure of the prediction by the classical isothermal elastohydrodynamic lubrication theory, leads to a distortion in the oil film pressure distribution, may shift the position of the minimum oil film thickness, and it is also possible that the secondary pressure peak will be attenuated or migrate. Thermal deformation of the material due to non-uniform thermal expansion is large enough to change the geometric convergence shape of the contact zone, and thus it will affect the generation mechanism of hydrodynamic pressure.

Due to the continuous action of coupled loads, the lubrication condition is often forced to be in the range of mixed lubrication or even boundary lubrication. Therefore, the friction and wear behaviour at the interface are jointly determined by the very thin fluid film, the adsorbed molecular film, the chemical reaction film and the properties of the solid surface itself. High temperatures increase the molecular thermal motion energy of the components in the boundary lubricant, raise the desorption rate of the physically adsorbed film, and accelerate the dynamic competition process between the growth and wear of the chemical reaction film. If the rate of wear is higher than the formation rate, the protective film layer will not be formed, and there will be direct contact between the metal substrates. The contact will have a high flash temperature and be subjected to a large shear force; therefore, there may be local micro-welding and tearing, a considerable drop in the friction coefficient will occur, and it will enter a high-energy-consumption, high-wear precursor state of instability.

2. Geometric Characteristics and Thermodynamic Design Principles of Surface Texture

2.1 Parametric Model Method for Texture Geometry Orientation in High-Temperature Lubrication

The first step in the Design of the surface texture for high-temperature lubrication is to build a parameter system that can accurately describe the shape features of the texture and link them to tribological performance. The two levels of this system are generally the distribution parameters for the macroscopic shape and the local shape parameters. The Parameters of the large-scale distribution are the area density of the texture, the arrangement pattern (e.g., a square or hexagonal array), and the spatial orientation with respect to the sliding direction. The above parameters will together determine the whole path of the lubricant in the joint area and the pressure distribution. Local Geometry Parameters are the shapes of small sections. Most dimple-type patterns have a first parameter that is the ratio of the depth of the dimple to the opening diameter. The Parameters of a groove-type texture are the width-to-depth ratio, cross-section shape and longitudinal profile. The local parameters mentioned above will directly affect the micro-hydrodynamic effect of a single texture unit and the lubricant storage capacity.

Since it is a hot area, the thermodynamic data can be taken as given or set as the objective function in parametric models. The optimisation goals for the geometry parameters in the old isothermal condition may no longer be suitable; thus, we need to consider the dynamic changes in the actual geometric dimensions of the texture due to material thermal expansion during operation, as well as the effect of lubricant viscosity at different temperatures on the fluid in the texture. Therefore, the improved parametric model is no longer a fixed geometric description but a set of parameters that link thermoelastic deformation and nonlinear rheological behaviour. Introduce a dimensionless parameter group, such as the ratio of the thermal film thickness to the texture Reynolds number, to combine the geometric parameters, operating conditions and high-temperature lubrication performance; thus, a theoretical foundation will be laid for the following numerical simulations and optimisation Design.

2.2 Correlation Analysis of Texture Morphology and Microscopic Hydrodynamic Effects

Different Shapes of Textures at various Relative Positions can change the flow regime of the lubricant at the interface and thus result in all kinds of micro-hydrodynamic phenomena. There are regularly spaced small dimples or grooves on the surface of the bearing area, and at different times during sliding, they periodically change the convergence shape of the clearance at the friction pair. Occasionally, there will be two kinds of changes in the lubricating oil film. First of all, there is a local hydrodynamic effect, and an additional pressure rise occurs at the bottom of the groove to increase the whole load-bearing capacity of the oil film. Second, there are also micro-vortices or secondary flows. Micro-vortices can improve the distribution of lubricant in the core and at the periphery of the interface, introduce new, cool lubricant to the contact area, and at the same time remove old lubricant that has been heated by shear stress[3].

Different Textures have different shapes at the micro level, so they will behave differently in fluid flow. Dimple-type structures have a certain depth-to-diameter ratio, are used as microscopic lubricant reservoirs, and thus generate squeeze-film lubrication and microcirculation in the sliding process. Grooves running in one direction are better at carrying lubricant in that direction, and the extent of the hydrodynamic effect is highly dependent on the angle between the orientation of the groove and the direction of sliding. The above are also true at high temperatures. Microcirculation of the lubricant in the textured area will increase the supply of lubricant and improve convective heat transfer at the contact place; thus, the local flash temperature will be reduced. At the same time, the extra space in the texture can also accommodate some of the fine solid particles produced by high-temperature oxidation and thus reduce damage caused by three-body abrasion and maintain a good state of interfacial lubrication under extreme conditions.

2.3 Design Criteria for Texture Substrate Stability Based on Thermoelasticity Theory

Given that the environment is very hot and frequently exposed to all kinds of stress, the structure of the surface texture should not change over time in use. Texture is usually a small change in the shape of the surface of a material. The discontinuous part is probably a stress concentration point, especially at the ends and bottoms of dimples or grooves. Due to the thermal expansion of the material and the temperature gradient at the surface and the bottom under a thermal load, an extra thermal stress field is formed in the texture. In addition to the stress from an external mechanical load, there is also a thermal stress field; thus, the local stress may exceed either the yield strength or the fatigue limit of the material, causing plastic deformation, tearing at the texture edge, or the initiation and spread of fatigue cracks.

Based on the theory of thermoelasticity, the aim of the Design is to maintain the long-term stability of the texture sublayer under a large combined thermal and mechanical load. Therefore, we need to change the geometry of the texture to reduce the stress concentration factor. A dimple with an elliptical or spherical shape and a small slope can be used to reduce stress, and it is not a prismatic dimple. A Selection of the Depth-to-Diameter Ratio is Necessary. Although it is relatively deep and suitable for an oil tank, both the local bending stiffness and the thermal conductivity of the material will be reduced; thus, there will be high stress concentration and heat accumulation. Therefore, the optimisation function should be set up to have the geometry of the texture as the variable, and the aim is to improve the structure and reduce stress concentration. The function should be able to list the mechanical property parameters of the material at high temperatures, such as creep strength, thermal fatigue resistance and coefficient of thermal expansion. According to the theoretical calculation and finite element analysis mentioned above, a safe range for the geometric parameters of the texture has been determined to ensure good lubrication performance and good mechanical stability at high temperatures[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 Microstructure

Microstructures are present at the interface of the tribopair, so the shape and boundary conditions are changed, and thus the pressure and temperature distribution of the lubricant film are affected. When the sliding surface is in contact with a rough surface, a few small holes are formed irregularly in the flow of the lubricant oil, and thus a considerable local pressure increase occurs at the rear end or the lower side of the rough part; this is known as the micro-hydrodynamic effect. An extra pressure peak will increase the load-bearing capacity of the oil film, but since the viscosity of the oil at high temperatures is lower, this effect has been reduced and separation at the interface will occur. At the same time, the local convergent and divergent clearances in the texture units change the shear flow path of the lubricating oil and thus modify the distribution of internal heat generation due to viscous shear. Therefore, the area of the highest flash temperature may no longer be a continuous strip on a smooth surface but rather discrete or periodic according to the texture array.

Redistribution of pressure and temperature will change the stability of the high-temperature lubrication state. A peak in the local pressure will increase the bearing capacity of the whole body, and due to the distribution in space, a relatively stable structure can be formed for the lubricating oil film that is less prone to damage from thermal and mechanical disturbances. The peak and gradient of the reconstructed temperature field are relatively small; therefore, it is believed that the textured cavities are microscopic heat sinks that increase the path for heat dissipation. Joint reconstruction of the pressure field and the temperature field can be carried out to reduce the deterioration of the lubrication condition, form a mixed-lubrication and boundary-lubrication state, and thus extend the safe working range of full-film lubrication at high temperatures.

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

In the small region between the relatively moving surfaces and the fine details of the micro-texture, many kinds of secondary flows are produced by the main shear flow, such as micro-vortices and Taylor vortices. Secondary flows are formed in the textured cavities and at the boundaries of the cavities, and they break the restriction of the laminar sublayer for mass and heat transfer. An increase in the density of the microcirculation will improve the convection of the lubricating material from the centre of contact to the outside. At the same time, aged lubricant with high-temperature shear and additive depletion is continuously carried away from the core contact area, and at the same time, fresh lubricant enriched with additives and in good condition is introduced to maintain the chemical and physical properties of the lubricating oil at a certain level and prevent lubrication failure caused by oil degradation[5].

Secondary flow increases the rate of convective heat transfer in the direction of heat transfer. A smooth surface conducts heat only in the solid material, so the fluid microcirculation caused by texture is employed as a lubricating oil to carry away frictional heat and shear heat from the heat-generating surface by means of forced convection. Increase the heat dissipation to reduce both the general temperature and the maximum temperature at the interface, break the chain of harmful effects caused by high temperatures, such as increased lubricant oxidation, thermal softening of materials and thermoelastic instability. Therefore, in order to improve the thermodynamic and kinetic stability of the tribopair system at high temperatures, one can increase the mass and heat transfer in the confined space.

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

At high temperatures, if the thickness of the oil film reaches the nanometre scale or if there is a local rupture, the boundary lubrication film will be the main cause of friction and wear. There are many degrees of synergy between the surface texture and the boundary lubrication film. Small cavities in the texture can be employed to store and release the active substances of boundary lubrication, such as adsorbed molecules and decomposed additive products. Due to the high stress at the contact, the material in the cavity is gradually released at the friction interface to form a boundary film; this film has been depleted by high-temperature desorption or mechanical wear and is thus no longer effective. The other is that it will not be harmed by high temperatures.

The Geometry of the Texture can also affect how the boundary film is formed and supported at a physical level. The extra surface area at the edge of the texture can be regarded as an ideal place for the start of the chemical reaction in the boundary film. More importantly, in the mixed-lubrication stage at the point of asperity contact, the textured area also bears some of the load along with the stored lubricating medium and the micro-hydrodynamic effect generated there; thus, both the actual contact pressure and the flash temperature at the asperity contact are reduced. Load sharing can create a good condition for the formation and stability of the boundary lubrication film at a lower load and reduce the risk of its premature failure. Therefore, texture alone is not enough; in order to achieve this end, a boundary-lubrication film will also be added. That is to say, it can form a material reserve, modify the environment at the interface, distribute mechanical loads, etc., to build a more stable high-temperature tribological defence line.

Conclusion

Organise the laws and reasons for the effect of surface texture on the lubrication performance of tribopairs at high temperatures systematically in this paper. Research has shown that lubrication failure caused by high temperature is due to the systematic deterioration of the rheological properties of the oil film, changes in the state of the material at the surface, and thermal-mechanical coupling at the interface. Based on the general ideas of thermoelasticity and fluid mechanics, parametric Design and stability evaluation indices for high-temperature textures are put forward in this paper. According to the above theory, a rougher surface can reduce the local concentration of stress and temperature at the contact point, suppress micro-hydrodynamic phenomena, increase the load-bearing capacity of the oil film, and thus avoid localised high-temperature flash. Secondary flow and microcirculation increase both the mass and heat transfer in this small area at the interface, so the chemical decomposition and thermal accumulation of lubricating oil are reduced. Change the shape of the texture to create a high-temperature boundary lubrication film, reduce the release of substances, distribute the load evenly, form a good film-forming environment, and thus improve the tribological stability at the interface. Therefore, the first reason for the drop in high-temperature lubrication performance is a loss of surface roughness. In the future, we will learn to dynamically adjust the texture parameters according to the strong coupling of all these fields, what happens to the long-term stability of textures after exposure to material creep and fatigue at high temperatures, and how to design intelligent lubrication systems based on adaptive textures.

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