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The effect of axial position of contact zone on the performance of radial lip seals with a texturing shaft surface

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ABSTRACT

On the basis of elastohydrodynamic model established by the present authors in advance, the present study numerically analyzes the influence of the axial position of contact zone on the sealing performances of lip seals with different micro-dimple texture shapes (circle, square and triangle) on the shaft surface, assuming a smooth elastomer and that the contact zone spans only a few rows of texture. It is found that the triangle micro-dimple texture shape that can always produce positive pumping rate no matter where the contact zone locates on the shaft surface. According to the determined texture shape, parameter analysis is conducted to select the optimal shape parameter that is less sensitive to the axial position of contact zone and produces more pumping rate and less friction torque.

1. Introduction

Radial lip seals are widely used in the lubrication area of rotating machinery to prevent leakage and exclude contamination. This tribological seal system consists of three major components: shaft, seal ring and lubricant, as shown in Fig. 1. It is the narrow sealing zone between seal ring and shaft, only 0.1–0.2 mm in width (see Fig. 2), that prevents lubricant from leaking. Under the action of interference and the garter spring force, the elastic deformation of the seal ring generates a contact pressure distribution with an unsymmetrical triangle-like profile in the narrow sealing zone, combining with the circumferential deformation of asperities on the lip surface when the shaft is rotating, which leads to generate a reverse pumping action from the air-side toward the liquid-side [1–3]. So, the reverse pumping rate is the most important performance characteristic for the success of lip seals. If the pumping rate is too small, the seal will leak.

Theory and experiment have shown that the reverse pumping action can also be produced by the shaft itself [4–6]. Thus the reverse pumping is a combined action that takes both the seal and the shaft into consideration. Surface texturing technology as a method to improve tribological performances of mechanical components has been paid more and more attention. There are many research reports and successful application cases in mechanical seals and thrust bearings fields [7–11]. It is only during the last few years that the surface texturing technology for the application in the lip seal system has been studied. Jia et al. [12,13] have used elastohydrodynamic analysis to study the pumping rate of radial lip seals with a variety of oblique groove patterns on the shaft surfaces, which are fabricated by laser surface texturing techniques. Theoretical and experimental results show that shafts with oblique grooves can create more reverse pumping rate than the conventional lip seal containing no groove on the shaft surface. But, the directionality of oblique grooves inevitably leads to the shaft rotation is unidirectional, meaning reverse rotation will result in leakage instead of pumping action. So, the application of this kind of texture form is very limited. According to the above elastohydrodynamic analysis model of Jia et al., Stephens and coworkers [14–18] have studied various micro-bulge and micro-dimple texture shapes on the shaft surface how affect the performance of lip seals. They also demonstrate that the existence of suitable texture on the shaft can enhance load capacity and cause more reverse pumping. And there is no requirement for the direction of rotation of the texturing shaft. Stephens and coworkers' research findings lay a good foundation for the application of the surface texturing in the lip seal system.

From Fig. 2, it is seen that the sealing behavior i.e. pumping action only occurs in the narrow contact zone. A little change of the contact zone characteristic will cause a large change of lip seal's performance [19,20]. So, different texture numbers in the contact zone must cause different effects due to the difference of

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NOMENCLATURE

a	bottom length of non-circle texture
b	height of non-circle texture
h_{ref}	reference film thickness, μm
D	diameter of shaft, mm
F	cavitation index
H	dimensionless film thickness, h/h_{ref}
K	aspect ratio, L_x/L_y
I	influence coefficient for normal (radial) deformation
L_x	length of solution domain in circumferential (x) direction
L_y	width of solution domain in axial (y) direction
P	dimensionless fluid pressure, p/p_{ref}
p_a	ambient pressure, MPa
p_{avg}	fluid pressure averaged over on cycle in the x direction, MPa
p_{sc}	static contact pressure, MPa
Q	volumetric pumping rate, m^3/s
V	surface speed of shaft, m/s
y_c	distance between the edge of texture and contact boundary
$\hat{V}$	dimensionless surface speed of shaft, $\frac{6\mu L_x}{p_{ref} h_{ref}^2} V$
$\hat{x}$	dimensionless circumferential coordinate, x/L_x
$\hat{y}$	dimensionless axial coordinate, y/L_y
γ	shape parameter
μ	viscosity of fluid, Pa s
$\hat{\rho}$	dimensionless density, ρ/ρ_0
ρ_0	liquid density, $\mathrm{kg/m}^3$
Φ	pressure/density function
τ	shear stress on shaft surface
ω	angular speed of shaft

flowing characteristic of lubricant. Considering manufacturing precision and economy, for the only 0.1–0.2 mm contact width the scale of the texture belonging to tens of micron range is suitable. Based on laser surface texturing techniques, the smaller the texture dimension is, the greater the manufacturing difficulty is. So, it is not practical to have many rows of texture along the axial direction (y direction in Fig. 1) in the narrow contact zone. However, in the research of Stephens and his coworkers [17,18], there were many rows of texture in the sealing zone. It is because they analyzed a worn seal, leading to a larger contact width. The shaft texture should firstly guarantee the improvement effectiveness at the initial stage, and then guarantee the effectiveness after wear.

For the manufactured shaft containing texture on the surface, different axial positions of the contact zone along the axial direction must bring about different boundary conditions in elastohydrodynamic analysis, leading to different pumping rates [12,13]. Unfortunately, the axial position of contact zone cannot be obtained exactly before and/or after assembly process, which is approximately calculated from the finite element analysis. So, the exact boundary location on the axial direction is also unknown. It is known that the sealing performance for the contact boundary locating at a smooth non-texturing zone is very different from that for the contact boundary locating at the texture zone. If the change of boundary location for some kinds of texture on shaft surface causes the pumping action to change greatly, even results in the opposite effect i.e. leakage, these kinds of texturing shafts are not applicable to lip seals. Thus, it is necessary to analyze the influence of any axial position of contact zone on the sealing performances of lip seals, to find a kind of micro-dimple texture shape that can always produce positive pumping rate no matter where the contact zone locates, which is the purpose of this paper. The elastohydrodynamic model established from our previous researches [12,13,23] is used in this paper, for the micro-dimple texturing shafts with different shapes including circle, square and triangle. Further, according to the determined texture shape, parameter analysis is conducted to select the optimal shape parameter that is less sensitive to the axial position of contact zone and produces more pumping rate and less friction torque.

2. Texturing shaft

For the lubricant oil film thickness is much smaller than the seal radius, the effect of curvature can be neglected; so a Cartesian coordinate system is used, and it is fixed to the shaft in order to make the problem steady. In Fig. 3, the x direction represents the circumferential direction, i.e. the shaft rotation direction; while the y direction represents the axial direction, i.e. the direction of contact zone between the seal and shaft. And the axial coordinate $y=0$ denotes the air-side of the lip seal, while $y=1$ denotes the oil-side. L_y represents the axial width of contact zone, only 0.1–0.2 mm generally. According to the elaboration in Introduction, it is reasonable that there are two to three rows of texture on the shaft surface in the contact zone. So, the scale of texture belongs to tens of micron, which can be relatively easily obtained in practical manufacturing.

Six different texturing shafts with three micro-dimple shapes: circle, square and isosceles triangle are numerically analyzed in the present study, as shown in Fig. 3. The characteristics of these

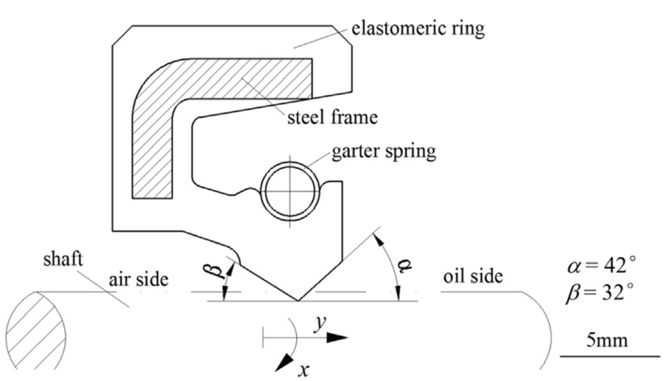

Fig. 1. Cross section of a radial lip seal.

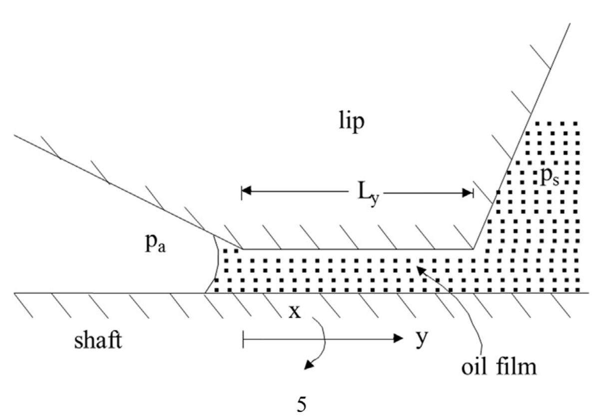

Fig. 2. Schematic of enlarged sealing zone.