Analysis and Experimental Study on Friction and Wear Characteristics of Super High-Speed Mechanical Seal

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Abstract. Mechanical seal is the core component of the servo system. It’s sealing, reliability and wear resistance depend not only on the structural design of the seal, but also on the matching of friction pair materials on the end face of the seal. On the basis of the feasibility study of ion implantation on the surface of the seal ring, a comprehensive test scheme is proposed to verify the friction and wear characteristics of the seal pair. By selecting typical graphite and rotating metal ring pairs to test and test under dry grinding conditions, changing the linear velocity and the end face specific pressure, the friction and wear characteristics of paired friction pairs are compared and analyzed by using friction and wear testing machine, the influence of load and rotational speed on the pair friction coefficient of sealing pair is systematically studied, and the sealing tribological characteristics are revealed. This paper introduces mechanical-seal work reliability of temperature stress and system test performance based seal pair, the application of these plans will provide a reasonable and efficient technical way for the verification of life and reliability test of ultra-high speed mechanical seal.

1. Introduction
In the thrust vector servo system, the ultra-high speed hydraulic pump is the core power component to produce high-pressure medium, and the mechanical seal is the key component. Once serious failure occurs, the servo system will fail.

Hydraulic pump working process of the shaft system between one and two order critical speed, and with a special working condition of downtime, variable pressure and time-varying load, shafting vibration shape is complex, mechanical seal is working with aviation hydraulic oil as working medium, the seal face can increase to 400 °C temperature is even higher, so the mechanical seal on the extreme load conditions, its design is always a problem hard sealing field. The particularity of ultra-high speed mechanical seal graphite to the friction pair of high-temperature alloy and the severity of working conditions, coupled with the lack of relevant basic theory and experimental research, currently mainly rely on the experience of design, resulting in abnormal wear and leakage of mechanical seal occur from time to time. This paper mainly starts from the special working conditions of ultra-high speed mechanical seals, and conducts in-depth research on the characteristics of ion injection and friction and wear mechanism of the sealing pair, so as to provide the basis and support for the design and manufacture of high-speed hydraulic-pump mechanical seals.
2. Analysis of working principle of ultra-high speed mechanical seal

A high-speed hydraulic pump mechanical seal consists of a moving ring, a static ring, a sealed housing, etc. The utility model relates to a shaft sealing device which is held by a pair of opposite end faces which are relatively slidable relative to the shaft under the elastic force of the fluid pressure and the compensating mechanism to cooperate with the auxiliary sealing to achieve the leakage prevention[1].

3. Tribological properties of materials and their relationship with force / heat

3.1. influencing factors of friction and wear state

The state of friction and lubrication between seal faces has an important influence on seal performance and service life, so we use plint standard friction and wear testing machine to conduct exploratory friction and wear test, and study the influence of load, speed, material, medium and other factors on the state of friction and wear between seal faces. as shown in Figure 1.

3.2. friction and wear prediction of typical sealing pairs

Considering the thermal deformation, force deformation, end surface morphology and cavitation effect of the seal ring, a systematic study on the evolution of lubrication state, including modeling, numerical simulation and experimental analysis, was carried out for the lubricating oil film at the interface of friction pair[2]. Figure 2 shows the actual wear condition of the product seal moving ring.

On this basis, considering the rheological characteristics of the lubricating oil film under the ultra-high speed shear mode, the lubrication state and the corresponding sealing performance prediction model of the interface oil film under the multi field coupling effect of the thermal fluid structure are established, the influence law of the interface lubrication state under the conditions of variable temperature, pressure and ultra-high speed is studied, and the evolution law of the lubrication state of the friction pair interface of the mechanical seal end face under the high temperature condition is revealed, the relationship between mechanical seal performance and interface lubrication state at high temperature is obtained, and the design method of ultra-high speed mechanical seal is further improved.

A large number of tests have verified that the ion-implanted nitrogen moving ring can meet the requirements of mechanical dynamic sealing of a super-high-speed Hydraulic pump. In the process of product assembly and debugging, the product qualification rate is higher than the assembly qualification rate of the prototype moving ring. Under the same working conditions, the reliability of mechanical dynamic sealing work has been improved.

4. Study on Tribological Properties of Mechanical Sealing Materials

Aiming at the typical graphite material used in the mechanical seal of high-speed pump of servo system, the mechanical and thermal characteristics of the graphite material are systematically tested, and the actual operating conditions of the mechanical seal of turbine pump are simulated. Based on the systematic study of the tribological, mechanical, thermal and coupling mechanism of the friction pair
material of mechanical seal and the wear mechanism of the seal interface under the condition of pressure storage, and under the principle of ensuring that the PV value of the mechanical seal end face is not lower than the actual operation value[3], the experimental study on the friction and wear of graphite and superalloy pairing was carried out to reveal the typical seal end face pairing. The friction and wear characteristics of accessory materials provide theoretical basis and technical support for improving the reliability of super high speed mechanical seal and reducing its storage and maintenance workload.

4.1. friction and wear test method

The main research object of this project is the metal moving ring and graphite static ring of the friction pair of the mechanical seal, which simulate the actual operation condition of the mechanical seal of the product, and carry out the research on the matching friction and wear characteristics of the alloy moving ring and the graphite of the seal. Different types of impregnated graphite and alloy steel were matched, in which graphite was the pin and stationary, and alloy moving ring was the test turntable. The working parameters collected by the friction and wear tester are speed and load. In order to compare with the actual operating conditions of the mechanical seal of the turbine pump, they are converted into equivalent linear speed and pressure. In this friction and wear test, three speed values and three load values are selected for orthogonal test, as shown in Table 1.

| End load /N | End pressure /MPa | Rotating speed/r/min | Average line speed /m/s |
|------------|------------------|----------------------|------------------------|
| 60         | 0.092            | 100                  | 0.482                  |
| 120        | 0.185            | 200                  | 0.963                  |
| 240        | 0.369            | 500                  | 2.409                  |
| 300        | 0.461            | 800                  | 3.854                  |

4.2. research on friction and wear of sealing pair materials

Taking alloy steel, carbon graphite and other common seal materials as the research object, the friction law of seal face under special working conditions is studied, the wear prediction model is established, and the mechanism and mechanism of seal face wear are revealed.

(1) Influence of different soft ring material load on friction coefficient

According to the test results, the influence of load on the friction coefficient of seal face can be studied. In the oil lubrication medium, the upper sample material is imported antimony impregnated graphite2 and domestic antimony impregnated graphite1, and the lower sample material is alloy steel 38CrMoAl. Under different rotating speeds, the change curve of friction coefficient with load is shown in Figure 3.

- Fig.3 Curve of Friction coefficient vs load
- Fig.4 Curve of Friction coefficient vs speed
As can be seen from the above figure, the friction coefficient between sealing rings decreases gradually with the increase of load. The reason may be: when there is a stable fluid film between the mechanical seal faces, the bearing capacity of the fluid film is relatively stable. With the steady increase of the load, the friction torque between the seal rings does not change much, resulting in the reduction of the friction coefficient between the seal faces.

(2) Effect of rotating speed on friction coefficient of different media
The influence of the friction coefficient of different media on the rotating speed is studied. In the two states of oil lubrication medium and dry friction[4], the upper sample material is antimony impregnated graphite made in China, and the lower sample material is alloy steel 38CrMoAl. Under different load conditions, the change curve of friction coefficient with rotation speed is shown in Figure 4.

As can be seen from the above figure, when the load is small, the friction coefficient increases gradually with the increase of rotating speed. When the load is high, the friction coefficient basically tends to be stable in both States. In the oil lubricated medium, the upper sample material is imported antimony impregnated graphite, and the lower sample material is alloy steel 38CrMoAl. The results show that the friction coefficient decreases with the increase of load. The possible reasons are: when the load is small, the fluid film formed between the seal faces is not stable, and the friction coefficient changes greatly; when the load is high, the stable fluid film is formed, and the friction coefficient is basically stable.

5. Reliability analysis of mechanical seal and test verification of the whole machine

5.1. Life distribution model of mechanical seal pair
In order to evaluate the life of the mechanical seal static ring assembly in the storage test, it is necessary to establish a life stress model, which links the failure rate or life with the given stress, so that the storage life at room temperature can be inferred from the measurement obtained in the accelerated test. In engineering, Weibull distribution is often used to analyze failure modes and regions. The Weibull distribution includes three types of early failure, accidental failure and loss failure in the life curve. The failure law of mechanical seal also obeys the Weibull distribution, as shown in formula (1). In the accelerated storage test of this project, it is first assumed that the storage life of the static ring assembly obeys the two parameter Weibull distribution[5] Among them, the parameter \( m \) is the shape parameter of Weibull distribution[5], the parameter \( \eta \) is the scale parameter, also known as the characteristic life of Weibull distribution. Under accelerated storage life, the parameters of the Weibull distribution under various temperature stresses can be estimated by maximum likelihood method.

\[
F(t) = 1 - \exp \left[ - \left( \frac{t}{\eta} \right)^{\beta} \right], \quad t > 0 \quad (1)
\]

\[
f(t) = \frac{\beta \eta^{\beta-1}}{\eta^{\beta}} \exp \left[ - \left( \frac{t}{\eta} \right)^{\beta} \right], \quad t > 0 \quad (2)
\]

In which, the parameter \( \beta \) is called the shape parameter of the Weibull distribution, and the parameter \( \eta \) is called the scale parameter, which is also called the Weibull distribution characteristic lifetime. Under the accelerated storage life, the parameters of the Weibull distribution under each temperature stress can be performed by the maximum likelihood estimation method[6]. According to the obtained experimental data, the static ring component distribution test \( m \) and \( \eta \) are obtained by inverse moment estimation or maximum likelihood estimation.

5.2. Test Simulation of High Speed Mechanical Sealing Machine Test System
As shown in Figure 5, the test device is mainly composed of three parts, a high-speed drive electric spindle, an oil lubrication system and a test bench body. The test bed rotor is directly driven by an electric spindle to simulate the working life of the mechanical dynamic seal and the long-term stable operation reliability. The turbine bearing cavity lubricant is supplied by a special lubrication pump...
station (including impeller pump), and the lubricating oil is selected from No. 12 aviation hydraulic oil. It is completely feasible to excite the vibration test of the high-speed rotating shaft system on the vibration table according to the power spectrum, as shown in Figure 6.

![Fig.5 Structure of testing system](image1)
![Fig.6 the vibration test of the rotating shaft](image2)

The test process is as follows.

1. Under the condition of 20,000 rpm and high pressure and large flow oil supply, the oil loss is too large, and the motor current is as high as 15A.
2. Adjust the oil supply condition, and then operate normally at 52000 r/min, 58,000 r/min, and the motor current is 7A.
3. Adjust the pressure before the oil supply pipeline adjustment valve to 2MPa, and the oil return pipeline has oil and gas mixed reflux, run to 60,000 rpm, and keep it for 1 minute.
4. The conditions are the same as above, 90000 r/min, keep running for 5 minutes.

As shown in Figure 7 above, the on-site high-speed drag test is as follows.

1. The tester can be operated stably at 50000-60000r/min.
2. The mechanical seal has a single stable running time of 10 minutes and has the test condition for a single continuous operation for a longer period of time.

6. Conclusion

Mechanical seals are of paramount importance as a core component of ultra-high-speed Hydraulic pumps. The omni-directional ion implantation and deposition technology can provide reliable technical support for the surface strengthening treatment of the mechanical seal sub-rotating ring, which can effectively improve the performance and service life of the rotating ring, and further improve the friction and wear performance of the sealing moving ring and the graphite static ring.

Under the condition of ultra-high speed and high temperature, the abnormal wear failure of the mechanical seal end face of the ultra-high-speed Hydraulic pump is closely related to the material properties of the friction pair. It is helpful to explain the special work by revealing the correlation law and essence between the characteristics of the sealing material and the friction and wear of the end face. The failure law of mechanical seals provides an important basis for the selection of the matching materials. The ultra-high-speed mechanical dynamic seal test system is used to verify the reliability and working life of the mechanical seal by the frequent start and stop and long-time operation of the ultra-high-speed mechanical seal at different temperatures. The design of the whole system is reasonable and meets the requirements of technical indicators. In order to improve the reliability of the mechanical seal
of the servo system and reduce the storage and maintenance workload, it provides theoretical basis and technical support.

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References
[1] Chupp R E, Hendricks R C, Lattimore S B, et al. (2006) Sealing in turbo-machinery [J]. Journal of Propulsion and Power, 22 (2): 313-349.
[2] Green I. (2016) Robustness of modeling of out-of-service gas mechanical face seal [R]. In: Seal/Secondary Air System Workshop, Xi’an. 289-323.
[3] Zhang U, Zhao W. (2014) Design and experimental study on the controllable high-speed spiral groove face seals [J]. Tribology Letters, 53 (2): 497-509.
[4] CHEN H L, WANG Q, LI W Y, et al. (2012) Numerical simulation of 3-D flow in upstream pumping mechanical seals with spiral grooves based on Fluent [J]. Lubrication Engineering, 37 (2): 16-19.
[5] GU D S, SUN J J, MA C B, et al. (2015) Orthogonal test of elf-pumping mechanical seals based on numerical simulation [J]. CIESC Journal, 66 (7): 2464-2473.
[6] CAHN W, SONG P Y, MAO W Y, et al. (2015) Numerical analysis of temperature field of gas film in spiral groove dry gas seal [J]. Journal of Drainage and Irrigation Machinery Engineering, 33 (5): 422-427.