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Experimental investigation on frictional behavior and sealing performance of different composites for seal application

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ABSTRACT

This study investigated the frictional behaviors and sealing performance of three seal polymer materials. Tests were conducted on a special test rig of the sealing ring. Polytetrafluoroethylene (PTFE), polyimide (PI), and polyetheretherketone (PEEK) composites were tested in the test rig with a sealing ring configuration against the steel counter surface. Investigations through scanning electron microscopy revealed the wear patterns of the sealing composites and the nature of the fillers. Results indicated that the surface temperature and leakage rate of the PTFE, PI, and PEEK composites increased with speed under oil-lubricated conditions. Moreover, friction coefficient initially decreased with increasing speed, reached a minimum, and then increased with speed. The PTFE and PEEK sealing composites had lower friction coefficients, less leakage during testing, and superior properties than the PI sealing composite.

1. Introduction

Sealing rings are found in transmissions of heavy vehicles and play crucial roles in the reliability and durability of the transmission. The performance of sealing rings is an important indicator of the general operation of the transmission. Seals are considered vulnerable parts of engineering devices [1]. Sealing rings are traditionally designed to operate in a full film regime with a thick oil film that separates sliding and stationary surfaces. In this regime, the sealing rings provide low friction and long service life. Metallic materials can provide acceptable performance. Some sealing rings are made of metallic materials, including wear-resistant cast iron and Cu-based powder metallurgy. However, transmissions continually require sealing rings to meet higher specifications (i.e., increased transmission power, increased fuel efficiency, and improved performance at low cost). The introduction of variable working environments has also resulted in frequent starts and stops of transmissions. Industrial applications and experimental investigations found that the metallic material currently used for this purpose was not optimal owing to the material's high potential damage and loss of power. New sealing materials, particularly composite ones, are needed to improve the sealing ability and durability of the original seals [2–4].

Consequently, researchers have devoted considerable attention to quantify the effects of surface friction and main sealing parameters by using experimental and analytical tools [5–8]. For example, Zhang et al. [9] built a seal test rig to analyze the sealing performance under different pressures and speeds. Lingerkar et al. [10] investigated the effects of sliding velocity and pressure differential across an O-ring seal by an experimental study. Yang et al. [11] analyzed the friction properties of PTFE matrix composite seals to determine the wear rules by experiments. In comparison with the seal experiment, the analytical method for the seal is common. Salant [12] discussed the contact problem of surface friction of the sealing system according to the corresponding elastic–plastic contact model. Frölich et al. [13] used a comprehensive approach for seals which took into consideration the interaction of temperature, friction and wear, and a macroscopic simulation model had been developed. Ilincic et al. [14] utilized the hybrid finite element method and boundary element method to calculate the contact pressure and the real area of contact for both normal and tangential loading between two rough surfaces. However, finding the underlying frictional phenomena and failure features that only use seal simulation is difficult. Hence, experimental research is important to understand the frictional behavior of sealing rings.

This study performed sealing ring experiments and scanning electron microscopy (SEM) analysis to reveal the influence of sealing materials on frictional behavior and sealing performance. A test rig was built for experiments on the sealing performance under oil-lubricated conditions. A series of test results was obtained, compared, and discussed to understand the effects of sealing materials on surface friction and sealing performance.

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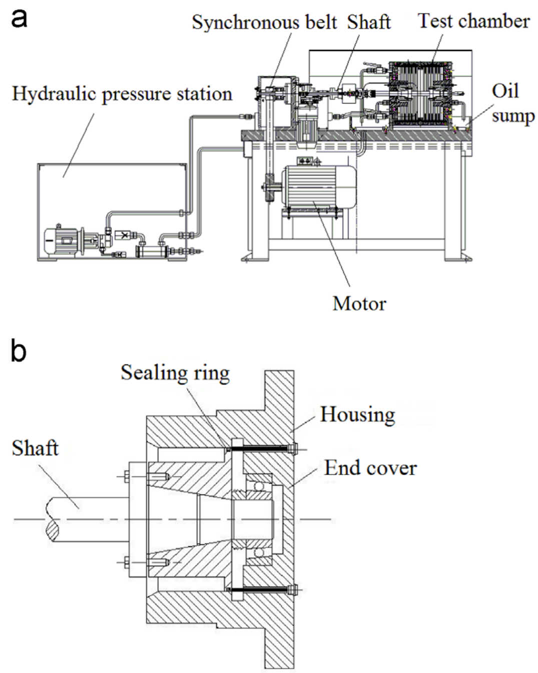

Fig. 1. The schematic illustration of the test rig. (a) The test rig. (b) The sealing ring in the test chamber.

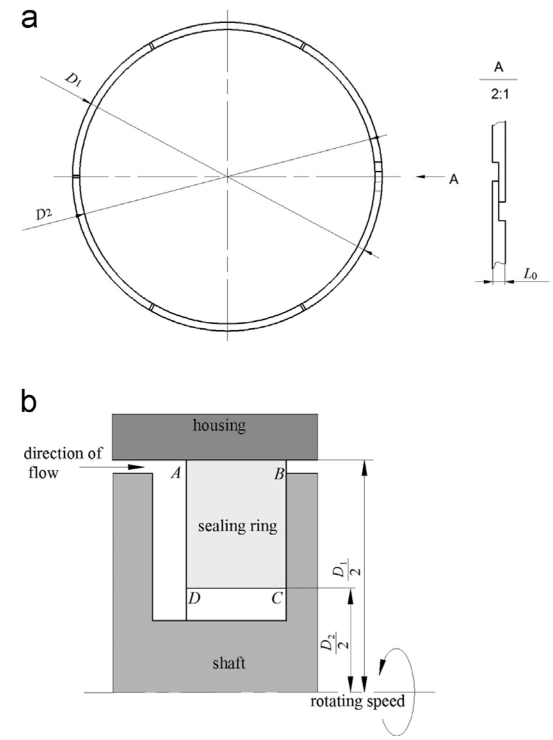

Fig. 2. The sealing ring in the transmission. (a) The structure of the sealing ring. (b) The sealing principle.

2. Experimental details

2.1. Experimental device

A special test rig was built and used for the experiments on dynamic sealing performance under high pressure and high speed, which is shown in Fig. 1. This test rig was composed of a transmission system, a seal test system, and a control and data acquisition system. The transmission system consisted of a variable frequency motor, a shaft, a synchronous belt, and other ancillary equipment. The seal test system included a test chamber, a hydraulic pressure station, an oil recovery device, and other components. The control and data acquisition system involved sensors in the test rig, test software, and other electronic devices.

The shaft passed through the test chamber, and the other end of the shaft connected the motor. A torque/speed sensor, which measured torque and speed, was connected to the shaft as a whole. Oil pressure was supplied by the special hydraulic pressure station. The temperature measurement and adjustment system in the test chamber was composed of oil temperature sensors, heaters, and controllers. The DRFL series torque sensor, which was made by ETH Company, was selected for the test rig to measure torque and speed simultaneously. The rated torque was 30 N m, and the rated speed was 6000 r/min. The maximum torque measurement error was 0.1% of the full scale, and speed measurement accuracy was ± 1 r/min. Pressure was measured by the pressure sensors produced by Hydrotechnik Company. The sensor's measurement ranged from 0 MPa to 6 MPa, and the sensor's maximum pressure measurement error was 0.5% of the full scale. Oil leakage was measured by an ultrasonic fluid meter made by Dynasonics Company. The sensor's measurement ranged from 0 L/min to 40 L/min, and the sensor's maximum flow measurement error was 0.1% of the full scale. The meter was installed on an oil inlet pipe. The leakage amount in the test chamber was the same as the amount of oil supplied. Therefore, the meter could measure the leakage rate of the sealing ring in the test chamber. A Pt100 series temperature sensor made by Jumo Company was chosen to measure the temperature of the sealing rings. The sensor's measurement ranged from -30 °C to 250 °C, and the maximum measurement error was 1% of the full scale.

2.2. Material and specimen

The sealing ring was located between the groove in the rotating shaft and the housing in the test rig. The sealing rings maintained the oil pressure between the stationary housing and the rotating shaft. The sealing ring employed in this study had a joint. The design of the sealing ring was quite similar to that of the piston ring. However, the sealing ring rotated instead of performing a reciprocating motion. The schematic of a sealing ring is shown in Fig. 2(a). The sealing principle of the sealing rings in the transmission of a heavy vehicle is presented in Fig. 2(b). The sealing principle indicated that the end surface "BC" was the main sealing face, and the cylindrical surface "AB" was the auxiliary sealing face. Under working conditions, the shaft rotated, whereas the sealing ring remained at rest. That is, the sealing ring did not rotate with the shaft.

The main parameters of the sealing ring were the outer diameter D_1, inner diameter D_2, and thickness L_0. The outer diameter of the sealing ring corresponded to the rotating shaft diameter. The parameters of the sealing ring used in this study were as follows: outer diameter D_1 was 125 mm, inner diameter D_2 was 119.2 mm, and thickness L_0 was 2.6 mm. Several sealing rings worked together in the transmissions of heavy vehicles. The appropriate surface roughness should be established to reduce power loss and enhance transmission efficiency. Therefore, the average surface roughness (Ra) of the sealing ring was set at 1.6 µm. The average surface roughnesses of the shaft and that of the sealing ring were the same.

The practical experiences and references explained that polytetrafluoroethylene (PTFE), polyimide (PI), and polyetheretherketone (PEEK) matrix materials were chosen because of their excellent material properties. Prior to the present study, the three matrix materials abovementioned were studied with different filler materials. The most suitable of the three sealing composite materials from the various filler materials of the three matrix materials was selected