Bio-inspired seal lip for application in electric vehicle coolant pumps

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Abstract
Power devices used for power control in electric vehicles have the drawback of high heat-generation, which can be effectively addressed by water-cooling. Their durability is affected by the performance of the seal lip in the coolant pump. The seal lip, in which a rotating shaft passes between liquid and gas phases, plays an important role in the separation of the two phases. To cool power devices, a specifically designed seal lip is required, as the seal lip is subjected to high pressure and temperatures of the water-based coolant and high-speed shaft rotation. A new type of seal lip has been developed by employing a biomimetic mechanism in which the hydrated lubrication mechanism found in natural articular cartilage is adopted. A fiber-reinforced PVF (polyvinyl formal) was employed as the hydrated and biomimetic seal lip material. The bio-inspired seal lip was attached to the shaft. Shaft rotation was controlled by a servomotor, which generated a speed of 5,000 rpm (revolutions per minute). An LLC (long-life coolant) was used as the coolant, which was diluted with distilled water at a concentration of 50%, heated to 75 °C, and pressurized to 0.3 MPa. Although the continuous leakage of LLC was observed, it was estimated that the bio-inspired seal lip might prevent the abrupt function failure in air-LLC separation. The frictional torque of the bio-inspired seal lip was lower than that of the conventional oil seal. These results suggest that the bio-inspired seal lip is a useful component in the water-cooling systems of high-power devices.

Keywords: Seal lip, Hydrated lubrication, Coolant pump, Electric vehicle, Power device, Friction, Tribology

1. Introduction

Electric vehicles require a high-power device, such as a semiconductor, in order to adjust the electric motor drive. However, a disadvantage of the power device is its high heat generation, which limits its performance. In order to improve the performance, a new type of power device with increased heat-tolerance must be developed. However, extensive research and development would be required to achieve this. A more practical solution is the adoption of a cooling system for the power device. At present, two types of representative cooling systems exist: air cooling systems and water cooling systems. The cooling capacity of water cooling systems is higher than that of air cooling systems; thus, the water-cooling technique is preferable for power devices.

Fig. 1 shows a schematic of an example semiconductor power device cooling system in an electric vehicle (Nakanishi et al., 2017). The basic configuration is similar to that of a vehicle with an internal combustion engine. A long-life coolant (LLC, a water-based liquid) absorbs the heat at the control device, which refers to the semiconductor power device acting as a thermal source, and promotes heat loss via a large radiator. The durability of the cooling system is influenced by the performance of the seal lip in the coolant pump. The seal lip, which encircles the rotating shaft that acts as the barrier between LLC and surrounding air, plays an important role in the separation of liquid-gas phases. This portion consists of a ring-shaped seal lip, and is attached to the rotating shaft. The dynamic seal face
between the seal lip and shaft, which is thought to assist in boundary lubrication, determines the LLC leakage trend and frictional behavior of the rotating shaft. To cool the power device, a specifically designed seal lip is required to offset the effects of the high pressure and temperature, which are generated from the water-based coolant and high-speed rotation of the shaft, on the shaft seal.

In this study, a new type of a seal lip was developed by implementing a biomimetic mechanism that employs a hydrated lubrication mechanism that is based on natural articular cartilage lubrication (Nakanishi et al., 2009, Furey et al., 1997).

2. Materials and methods

Fig. 2 illustrates the preparation process of the fibre-reinforced PVF, which was used as the hydrated seal lip material (Nakanishi et al., 2014). PVA (polyvinyl alcohol), which is one of only a few polymers with hydrophilic properties, was the base material of the PVF (Chang et al., 2017). A PVA solution was prepared by employing the method of agitation to mix partially hydrolyzed PVA, with a molecular weight of 1000, and distilled water for 48 h at 25 °C to hydrate the PVA. Following addition of H₂SO₄ as a catalyst, decompression of the solution was performed to remove any bubbles. In order to initiate condensation polymerization between the PVA molecules (i.e. cross-link formation), HCHO (formaldehyde) was added into the PVA mixture as a cross-linker. This chemical reaction facilitates improved mechanical strength and wear resistance of the PVA. The solution was then poured into a mound comprising PTFE (polytetrafluoroethylene) with embedded polyester fibers. After allowing the mound to set for 18 h at 25 °C, neutralization was performed using NaOH and water washing to remove the HCHO in the hydrated material. The resulting sheet of PVF was stamped, producing a hydrated seal lip with an internal and external diameter of 7 and 30 mm, respectively, and a thickness of 4 mm. Coating of PVF seal lip surface using 2-methacryloyloxyethyl

Fig. 1 Schematic of an example semiconductor power device cooling system in an electric vehicle. A long-life coolant (LLC) absorbs the heat at the thermal source and promotes heat loss via a large radiator. LLC flow is driven by a coolant (impeller) pump.
phosphorylcholine (MPC) was also performed, as it is well known that an MPC coating increases hydrophilicity and decreases friction torque (Moro et al., 2010). The average elastic modulus of the fibre-reinforced PVF with or without was estimated to 0.49 MPa through tensile tests by using a material tester (EZ-LX, Shimadzu Co., Japan) (Honda et al., 2018).

| Hydrophilic base: Polyvinyl alcohol (PVA) |
|-----------------------------------------|
| Agitation 25 °C 48 hours |
| PVA solution |
| Catalyst: H₂SO₄ |
| Agitation Cooling 5 minutes |
| Bubble removal Decompression 20 minutes |
| Cross-linker: HCHO |
| Agitation Room temperature 5 minutes |
| Moulding 25 °C 18 hours |
| Neutralizer: NaOH |
| Neutralization Room temperature 24 hours |
| Washing with fresh water |
| MPC coating |
| Solvent: Distilled water |

![Flowchart](image)

Fig. 2 Fibre-reinforced polyvinyl formal (PVF) preparation process used to fabricate the hydrated seal lip.

Fig. 3 shows an experimental set-up. The bio-inspired seal lip was attached to a rotary shaft and pressed by a holder jig for the fixation. The shaft was fabricated from stainless steel (SUS304-JIS), and had a diameter of 8 mm. The 0.02-µm surface roughness (Ra) of the rotating shaft was prepared by implementing a conventional lapping method (Thomas et al., 2005). The LLC was diluted to a concentration of 50% using distilled water, heated to 75 °C, and then pressurized to 0.3 MPa. An AC servomotor (NX-45, Oriental Motor Co. Ltd., Japan) was used to rotate the shaft at a
speed of 5,000 revolutions per minute (rpm). The frictional torque generated by the shaft seal was calculated according to the relationship between the rated torque of the motor and the power consumption. The leaked LLC was collected in a pan, and the total amount of LLC leaked during testing was calculated.

A conventional oil seal was also attached to the same shaft for comparison (AC0158A8, NOK Co. Ltd., Japan). The seal lip was made of a nitrile rubber (NBR) and its hardness of 70 by a durometer, type A. The oil seal had a diameter of 22 mm and a width of 7 mm, so that the shape of the holder jig was redesigned for the installation.

![Fig. 3 Experimental set-up.](image)

#### 3. Results and Discussion

The results are shown in figs. 4 and 5. As for the conventional oil seal (Fig. 4 (A)), a high frictional torque, which exceeded 100 N \( \cdot \) mm, was recorded at the initial stages of testing. Although intermittent peaks were subsequently recorded, the frictional torque was found to decrease with test duration. The mean frictional torque had been higher than 40 N \( \cdot \) mm. Obvious shaft vibration from the test rig was not confirmed. LLC leakage was at a low level during the test. However, because non-negligible leakage of LLC was observed at the 3744 h, the experiment was terminated. Aggregates with rubber particles of the oil seal and constituents of the LLC were detected with test duration (Fig. 5 (A)). Oil seals comprise a rubber seal lip that slides against the shaft surface. The seal lip of an oil seal is designed to have a pumping effect to form a fluid lubrication film derived from an asymmetric shape (Bock et al., 2003, Filtney, 2006, Watt, 1973). The surrounding air-LLC separation provided by an oil seal is not presumed to be ideal. The rubber seal lips in oil seals are hydrophobic so as to prevent promotion of the effective boundary lubricating film in the presence of a water-based liquid. Furthermore, when an excessive pressure by LLC is applied to the seal lip, the seal lip deforms, and the area of the contact surface increases. Consequently, an increase in seal lip wear leading to non-negligible LLC leakage was thought to be occurred (Fig. 6 (A) and (A')).

As for the bio-inspired seal lip (PVF) Fig. 4 (B)), a high frictional torque of 70 N \( \cdot \) mm was also recorded throughout the early stages of testing. However, the frictional torque value was lower than that observed when a conventional oil seal was employed (Fig. 4 (A)); furthermore, the value was found to immediately decrease. The mean frictional torque of the bio-inspired seal lip was recorded less than 40 N \( \cdot \) mm, the value was also lower than that of the oil seal. Obvious shaft vibration from the test rig was not confirmed. The continuous leakage of LLC was observed.
throughout the test. Tarnishing of the seal lip was observed because of LLC penetration into PVF (Fig. 5 (B)), and plastic deformation of the seal lip was observed. The plastic deformation might promote the clearance flow of LLC between dynamic seal faces (Fig. 6 (B) and (B’)). In order to reduce frictional loss and reduce wear of seal lip, a hydrophilic sliding material should be used, because promotion of the effective hydrated lubricating film at a dynamic seal face is expected in the presence of a water-based liquid. Viewed as a sliding material, articular cartilage is a type of hydrated material. The most commonly used material able to approximate the behavior of articular cartilage is a PVA-hydrogel. However, because the PVA-hydrogel exhibits no wear resistance, in this study, PVF was implemented as the hydrated seal-lip material; this is because PVF is a cross-linked polymer of PVA, and is thus able to compensate for the unfavorable characteristic of PVA-hydrogel. Although PVF fiber reinforcing was implemented in order to prevent seal lip deformation as due to an excessive pressure by LLC, plastic deformation was observed. Because the polyester fibers exhibit hydrophilicity, a non-woven textile composed of polyester fibers was selected as a fibrous reinforcing material. Adjustments of fiber orientation, diameter, and density are required in order to prevent plastic deformation of the seal lip, which contributes to low LLC leakage.

The MPC coating may reduce friction throughout the early stages of testing, because the decrease in friction from 70 N ∙ mm (Fig. 4 (B)) to 55 N ∙ mm (Fig. 4 (C)) was recorded. However, the effectiveness was not significant in terms of steady-state friction. The higher LLC penetration into PVF was thought to be occurred, because the higher tarnishing of the seal lip was observed (Fig. 5 (C)). Large deformation of the PVF seal lip was observed. The MPC coated-process might promote the PVF to adsorb more LLC, which might make the PVF more hydrophilic and softer material. The change of material characteristics during the test might lead to reduce friction in the early stages and deteriorate
Fig. 5 Seal lips before and after the test.

Fig. 6 Mechanism for leakage of LLC in each seal lip. A high pressure condition was applied for the experiments.

steady-state leakage of LLC.

Although the continuous leakage of LLC was observed, it was estimated that the bio-inspired seal lip might prevent the abrupt function failure in air-LLC separation. The seal lip also exhibited low frictional torque, suggesting that its use is advantageous in the water-cooling system of high-power devices. The cost of manufacture of the shaft seal with the bio-inspired seal lip is estimated to be lower than that of conventional shaft seals. As the raw materials, such as PVA, are inexpensive, and the housing required for the installation of the hydrated seal lip can be relatively simply
constructed.

In this study, a rectangle and ring-like seal lip was designed and implemented. However, further investigation is required in order to optimize the design of the hydrated seal lip. Firstly, appropriate hydration and Young's modulus (hardness) of the seal lip should be explored. Secondary, optimization of the contact conditions between the seal lip and surface of the rotating shaft require further investigation.

4. Conclusion

A novel bio-inspired seal lip, which was designed for suitability with electric vehicle coolant pumps, was proposed. A fiber-reinforced PVF (polyvinyl formal) was employed as the hydrated and biomimetic seal lip material. Although the continuous leakage of LLC was observed, it was estimated that the bio-inspired seal lip might prevent the abrupt function failure in air-LLC separation.

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