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Friction and wear characteristics of natural bovine bone lubricated with water

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ABSTRACT

Natural bovine bone has the potential to act as a bearing surface for spool-in-sleeve servo valve of water hydraulics. To screen material combinations for that application, friction and wear tests were conducted on the following three pairs: 316 L stainless steel on natural bovine femoral cortical bone (NBFCB), carbon fibre reinforced polyetheretherketone (CFRPEEK) on NBFCB, and Al_2O_3 ceramic on BFCB. Tests were conducted on a face-loaded, annular ring-on-ring configuration with water lubrication. The worn surfaces were studied using an environmental scanning electron microscope (ESEM). The effects of normal pressure and sliding velocity on the friction and wear characteristics are discussed. Friction coefficients decreased with increasing velocity and pressure, and a running-in process was observed. The weight loss due to wear of the NBFCB was larger than that of the counterpart materials. Sharp reductions in both friction coefficient and wear rate were observed for NBFCB when sliding against Al_2O_3 compared to sliding against 316 L and CFRPEEK. The 316 L steel wore by micro-cutting, and the wear mechanism of the Al_2O_3 ceramic was fatigue wear. The wear mechanism of CFRPEEK was mainly adhesive wear. The wear mechanism of NBFCB was brittle fracturing when sliding with 316 L and the Al_2O_3 ceramic, and it was adhesive wear when sliding against CFRPEEK.

1. Introduction

Water hydraulics, which uses seawater or fresh water as the working medium instead of mineral oil, has various advantages, such as low cost, safety and environmental friendliness [1]. A water hydraulic servo valve shown in Fig. 1 is the core component of a water hydraulic servo control system. However, the low viscosity, strong corrosion and poor lubricating ability of water have introduced great challenges to the development and application of this component. Therefore, screening materials suitable for the water hydraulic servo valve becomes an urgent task, which is the purpose of this study.

Studies on the tribo-pairs of plastic/metal, plastic/ceramic and ceramic/ceramic materials used in water hydraulic components have been conducted over the last decade. Hua et al. [2] studied the friction and wear behaviour of SUS 304 stainless steel against an Al_2O_3 ceramic ball under relatively high load. The wear of SUS 304 stainless steel was determined to be a mixing mode of both adhesion and plough processes. Xiong and Ge [3] investigated the friction and wear properties of ultra-high molecular weight polyethylene (UHMWPE)/Al_2O_3 ceramic under different lubricating conditions. The friction behaviour of UHMWPE was considered to be very sensitive to its water absorption state. The fatigue-separated layers on the worn surface of UHMWPE had been produced with distilled water lubrication. Zhang et al. [4] found that the sliding velocity significantly affected the tribological characteristics via its effects on the contact surface temperature and strain rate of the polyetheretherketone (PEEK) surface layer. Davim et al. [5] investigated the influence of the surface roughness, sliding velocity and contact pressure on the tribological characteristics of PEEK under water lubrication. The study showed that the counterpart surface roughness had the greatest effect on the friction coefficient. The sliding velocity also strongly influenced the friction of the materials. Yamamoto and Takashima [6] discovered that the friction coefficient of PEEK under water lubrication was smaller than that under dry friction, whereas the wear increased.

The aforementioned literature demonstrates that PEEK/metal, PEEK/ceramic and ceramic/ceramic tribo-pairs show good tribological properties under the water lubricating condition, but certain limitations and shortcomings persist when these matching pairs were applied as the valve spool and sleeve materials of a water hydraulic servo valve. Ceramics have some advantages, such as good corrosion resistance and excellent mechanical properties, but they are difficult to drill and slot due to their brittleness and poor machinability [7,8]. When the friction pair is a combination of

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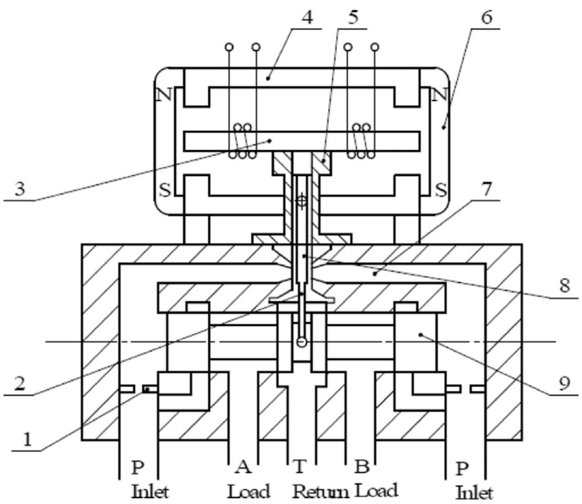

Fig. 1. Nozzle flapper electro-hydraulic servo valve. 1: Fixed throttle orifice, 2: feedback pole, 3: gag bit, 4: magnetiser, 5: spring pipe, 6: permanent magnet, 7: nozzles, 8: baffle, and 9: main valve.

ceramic and steel, wear and jam easily occur in the presence of abrasive. PEEK and other composites have been used in some water hydraulic components because of their excellent tribological characteristics [9–11]. However, plastics show high water absorption, dimensional instability and low resistance to abrasive wear, which make them not very suitable for acting as a bearing surface for spool-in-sleeve servo valve of water hydraulics.

To reduce leakage, the clearance between the spool and the sleeve of a water hydraulic servo valve should be smaller than that of an oil hydraulic servo valve because of the low viscosity of water. The smaller clearance and the relatively poor lubrication ability of water hinder complete liquid lubrication between the spool and the sleeve. Therefore, stick-slip is a common kinematics phenomenon of the servo valve spool, which leads to the adhesive wear of the friction surface and reduces the control precision of servo valve. Once the spool is jammed due to stick-slip, the servo valve will be invalidated.

Animal bone, a kind of natural biological material, is composed of both organic and inorganic constituents. The toughness of bone is attributed to the organic parts which mainly consist of collagen and non-collagen proteins. The hardness of bone is attributed to the inorganic parts such as hydroxyapatite crystals [12]. Based on its microstructure, bone is macroscopically distinguished as cortical bone and cancellous bone. The mass density and hardness of the cortical bone in the outer layer are high. The structure of the cancellous bone in the inner surface is loose and spongy. Cortical bone mainly exists in the diaphysis of long bones and the surface layer of other types of bone. Cortical bone resists stress and tension well because of its thick bone bed and high hardness [13–15]. The main physical and mechanical properties of bovine bone and other specimen material are listed in Table 1.

Natural bone can be regarded as a type of biological ceramic, with certain characteristics, such as dimensional stability and compressive strength approximate to those of engineering plastics [15]. Moreover, the internal flowing tissue of bone forms tiny cavities and pore space, which results in a number of natural small puddles in the processed bone surface. The puddle can improve the effect of water lubrication, and contain the solid particles in the working medium to reduce abrasive wear. In addition, the remaining cellular material in the dry bone tissue contains fat that can reduce the friction. All of these properties make it possible to be used in water hydraulic servo valve. Therefore, natural bone is naturally resistant to corrosion in water or seawater.

Table 1
Main physical and mechanical properties of the natural bovine femoral cortical bone.

Material properties	Test method	Units	Value
Hardness[a]		HV	51.3
Density[a]		g cm^{-3}	2.06
Melting point		–	–
Thermal conductivity[a]	25 °C	W m^{-1} K^{-1}	0.521
Tensile modulus[b]		GPa	1.01 ± 0.18
Compressive modulus[b]		GPa	5.67 ± 0.67
Compressive strength[c]	0° with the Femur shaft	MPa	254
	30° with the Femur shaft	MPa	190
	60° with the Femur shaft	MPa	148
	90° with the Femur shaft	MPa	146
Tensile strength[c]	0° with the Femur shaft	MPa	144
	30° with the Femur shaft	MPa	99
	60° with the Femur shaft	MPa	60
	90° with the Femur shaft	MPa	46

[a] Mensurated by authors.
[b] Data from [19] by Le et al.
[c] Data from [20] by Cowin (1981).

Davim and Marques [16] investigated the friction and wear behaviour of bovine cancellous bone sliding against a metallic counterface in the water lubricated environment. The obtained results showed that the friction coefficient is independent of experimental variables. The sliding distance exerts a greater effect on the wear of cancellous bone. The interactions between selected variables are statistically insignificant on the wear of cancellous bone. Yu et al. [17] studied the fretting behaviour of cortical bone against titanium and its alloy. The friction logs were revealed to transform from partial slip directly to gross slip without a mixed regime. The wear depths of bone generally increase with the friction coefficient. The abrasive wear and delamination (microcracks) related to the microstructure of bone characterise the wear mechanism of cortical bone. Qing-liang and Shi-rong [18] studied the tribological behaviour of the swine femoral bone against UHMWPE with dry friction, physiological water and human plasma lubrication. The experimental results demonstrated that both the friction coefficient and wear rate of UHMWPE were the lowest when human plasma lubrication was used. The wear mechanism of the compact bone is mainly fatigue wear with dry friction, corrosive wear under physiological water lubrication and abrasive wear with human plasma lubrication.

However, research on the friction and wear characteristics of natural bovine cortical bone in the water-lubricated environment has not been conducted. The authors selected natural bovine femoral cortical bone (NBFCB), which shows excellent mechanical properties in terms of hardness and strength, as the research subject. This study examined the basic tribological characteristics of NBFCB separately sliding against 316 L stainless steel, carbon fibre reinforced polyetheretherketone (CFRPEEK) and Al_2O_3 ceramic on a face-loaded, annular ring-on-ring test rig. The friction and wear mechanism were analysed by examining the worn surface morphology. The exploratory research will provide an experimental basis for the application of NBFCB in water hydraulic servo valves and other water hydraulic components.

2. Experiment

2.1. Principle of the test rig

The tribological behaviours were investigated on a MMU-10F type face-loaded, annular ring-on-ring test rig produced by Jinan Gold Group Corporation, China. The working principle of the test rig is shown in Fig. 2. The upper specimen rotates with the shaft