Experimental Study on Frictional Characteristics of Scapharca Broughtonii under Dry Sliding Wear Conditions

You Lv, Wencui Xiu, Liqun Lei, Lina Sun and Xiufang Zhang

ABSTRACT

In this paper, the friction and wear properties of Scapharca broughtonii were investigated under low-speed (5-45 mm/s) and low-load (1.5N-6N) conditions by using a micro-tribological tester. The stereoscopic microscope and computer imaging analysis system was employed to test the abrasion slide size and calculate the wear volume of Scapharca broughtonii. The worn surface morphology of Scapharca broughtonii was observed by a scanning electron microscope (SEM), and the wear mechanism of Scapharca broughtonii was obtained. Experimental results show that the friction coefficient decreased rapidly with an increase in sliding speed under low-load and low-speed dry sliding conditions. When the load was below 6N, the influence of microstructure on the friction coefficient was very small. The wear rate of Scapharca broughtonii increased with an increase in sliding speed when the load was greater than 6N. When the speed increased, the influence of load on the friction coefficient occupied a dominant position. At the same time, the wear rate was increased with an increase in load. The main wear mechanisms of Scapharca broughtonii were stress fatigue wear and three-body abrasive wear, and mild adhesive wear and abrasion.

INTRODUCTION

After a long evolution, natural biological materials have obtained excellent performance compared with artificial materials[1]. The elastic modulus ratio ($E/\rho$) and tensile strength ratio ($\sigma_u/\rho$) of natural biological materials might be even higher than those of metal materials and ceramic materials[2].

The mollusk shell is a kind of natural biological material. It is subjected to various types of wear under natural conditions. The structure and function of mollusk shell materials have attracted worldwide attention[3,4]. The mollusk shell is composed of calcium carbonate (CaCO$_3$) and bio-polymer [5]. The rupture work of the nacreous layer is much higher than that of single-phase ceramics. This structural...
feature provides a bionics method for the design of new composite materials. This work explores dry sliding wear characteristics of *Scapharca broughtonii* under low-load and low-speed conditions.

**EXPERIMENTAL PROCEDURES**

*Scapharca broughtonii shell* consists of the horny layer, prismatic layer and nacreous layer outside in. The specimens were cut into the desired size (15mm×10mm×2mm), and cleaned by an ultrasonic cleaner. The dry sliding test was carried out on the friction test machine. The testing parameters were at a normal load of 1.5N-6N, a speed of 5-45 mm/s and the laboratory temperature was 23 degrees. Stainless steel ball (HRC62, 4mm in diameter) contacted with the shell samples, and made the straight reciprocating sliding motion on the sample, as shown in Fig.1.

The friction coefficient was recorded by an experimental machine. The stereoscopic microscope and computer image analysis system was used to measure the abrasion slide size. The formula for calculation of wear volume is shown in Eq. 1:

\[
\Delta v = l \left[ r^2 \arcsin \frac{d}{2r} - \frac{d}{2} \sqrt{r^2 - \left(\frac{d}{2}\right)^2} \right]
\]

\(l\) - reciprocating sliding distance, \(d\) - specimen surface wear scar width, \(r\) - stainless steel ball radius. The wear surface morphology was analyzed by a scanning electron microscope (SEM), and the wear mechanism was explored.

**RESULTS AND DISCUSSIONS**

**Surface Morphology**

The surface morphology of *Scapharca broughtonii* is shown in Fig.2. The striped feature of *Scapharca broughtonii* was evident. *Scapharca broughtonii* shell was 36 mm in height, 100 mm in length and 88 mm in width. It has a hard and thick texture, and expansive shape. The dimensions of the shells on the left and right sides were approximately equal. The back edge of the shell was straight, and both sides of the shell formed an obtuse angle. The front and abdominal edge of the shell was circular, and the rear end of the shell extended backward. There were 42 to 48 radiating ribs on the shell surface, with the majority of 43. The radiating rib was 900μm in height and 2500μm in width. The distance between the radiating ribs was generally 1000μm. The radiating rib was flat, and had no obvious nodule or bulge. The shell surface was white and was covered with brown hair. The radiating rib groove was dark brown. The inner surface of the shell was gray, and the edge of the shell had hair and sawteeth.
Microstructure

*Scapharca broughtonii* shell was cross-bedding in microstructure, as shown in Figs. 3(a) and (b). It can be seen that the porous and lath structures were connected to each other. It was apparent from the boundary of each structural unit that it had irregular shapes. The structural unit was developed for width ranges of several tens of microns to hundreds of microns. This kind of structure had significantly increased the complexity of the layered structure of *Scapharca broughtonii* shell, and had an important impact on its mechanical properties. Every structural unit had its own orientation, and all structural units were bonded together by organic matter. The organic matter had a positive effect on improving toughness of the shell.

As shown in Fig. 3(c), an irregular lamella stacking structure was exposed in the cross-bedding shell structure. These thin plates were usually several hundred nanometers in thickness, and were stacked in the same direction. Different thin plates had different lengths and thicknesses, and even the same plate had various length and width.

The thin plates were not aligned along the depth direction. Some excess little plates appeared between the thin plates. Moreover, there was a lack of plates in a stacked structure, which led to the existence of voids among lamellas. This type of structure will help to absorb tensile stress and reduce local stress concentrations. Thus, the microstructure of *Scapharca broughtonii* shell could improve its wear resistance and fatigue performance.

The EDS result of *Scapharca broughtonii* powder is shown in Fig. 4. It can be seen that the main elements are calcium, carbon and oxygen. From the XRD results in Fig. 5, we can know that the main chemical composition of *Scapharca broughtonii* is calcium carbonate (CaCO$_3$).

Fig. 5 shows the XRD patterns of the inner layer, middle layer and outer layer. From the intensity and position of the peaks in the graph, it can be analyzed that *Scapharca broughtonii* shell was composed of aragonite calcium carbonate in the three layers. Although the XRD patterns of the three layers were different, calcium carbonate of the XRD characterizations of the three layers was mainly aragonite. The
results of the XRD analysis were in consonance with the microstructure of *Scapharca broughtonii* shell (Fig. 2).

![Figure 4. EDS analysis result of *Scapharca broughtonii.*](image)

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![Figure 5. XRD analysis result of *Scapharca broughtonii.*](image)

Figure 5. XRD analysis result of *Scapharca broughtonii.*

**Experimental Results**

Fig. 6 shows the relationships between the friction coefficients and the sliding velocities under four loading conditions. With an increase in sliding velocity, the friction coefficient decreased rapidly. When the sliding velocity reached 5 mm/s, the friction coefficient was stable at 0.06-0.08. There were many reasons for this phenomenon. When the sliding velocity was low, the degree of engagement between the asperities on the frictional interface was relatively large, and the frictional force was relatively high. With an increase in sliding velocity, a rise in the frictional surface temperature led to softening organic ingredients in the shell material, thus producing a certain degree of lubrication. It made the frictional surface become relatively smooth. The degree of engagement between the asperities on the frictional interface was reduced, and the friction force relatively decreased. In addition, during the tests, a part of shell material was transferred to the stainless steel balls, and the sliding contact between the frictional surfaces had been changed into sliding contacts between homogeneous materials. However, the friction between the shell materials had the self-lubricating effect, so the friction coefficient was reduced. The effect of load on the friction coefficient was relatively weak. When the load was 1.5-4.5 N, the friction coefficient was almost constant. When the load fetched 6 N, the friction coefficient fell off slightly.

![Figure 6. The relationships between the frictional coefficients and the sliding velocities.](image)

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Fig. 7 exhibits the relationships between the volume wear rate and the sliding velocity under four loading conditions. The higher the sliding velocity was, the higher volume wear rate was. When the load was low (1.5N and 3.0N), the relationship between the volume wear rate and the sliding velocity was linear. When the load was comparatively high, the effect of sliding velocity on the wear rate had a critical point. Under 4.5 N and 6N loading conditions, the critical speed altered from 5 to 10 mm/s. The results showed that the influence of the load on the volume wear rate was dominant in relatively high sliding velocities. The normal load and sliding velocity had a mutual effect on the volume wear rate. When the normal load and sliding velocity were relatively high, their combined effect led to a higher wear rate.

Fig. 8 demonstrates worn surface morphology of the *Scapharca broughtonii* shell. During the sliding contact test, the transferred material of shell had been adhered to the stainless steel ball surface, so adhesive wear occurred on the shell surface owing to homogeneous materials. Due to the characteristics of reciprocating sliding movement, the debris of the preceding wear process would become abrasive particles of the latter wear process, then there would be a certain degree of three-body abrasive wear, which directly led to the generation of scratches on the shell surface.

Because of the brick-and-mortar composite structure of *Scapharca broughtonii* shell, the shell surface was prone to crack at low load conditions, as shown in Fig. 8. These cracks were mainly initiated on the grain boundary. The sliding process of the
stainless steel ball against *Scapharca broughtonii* shell was a dynamic process and had a dynamic effect on the surface layer of *Scapharca broughtonii*, which could easily lead to the initiation of cracks in the surface layer. In the sliding process, the stainless steel ball was on the shell surface; the subsurface material of the shell withstood the maximum stress, and the dynamic stress concentrations generated. The front material was in compressive stress states, while the rear material was in tension stress states. Under the action of the stainless steel ball, the material of surface layer withstood the alternation of compressive stress and tensile stress. This kind of alternating stress not only accelerated the cracking of shell surface along the grain boundary and the secondary crack initiation, but also resulted in subsurface crack initiation. The surface and subsurface cracks continued to expand and connected with another, and the flake-like wear products were generated under the action of the adhesive force. The spall pits could be seen on the worn surface of *Scapharca broughtonii* shell. However, under the action of the reciprocating sliding, the flake-like wear particles would also be further crushed into smaller fragments, so that the flake-like wear particles could not be seen in the wear products. This kind of tiny wear products existed in the sliding interface, which led to three-body abrasive wear of the shell surface. In consideration of the low plasticity of *Scapharca broughtonii* shell, stress fatigue wear took place due to alternating stress.

**CONCLUSIONS**

This paper has investigated the microstructure and friction-wear behavior of *Scapharca broughtonii*. According to the analyses, the following conclusions are drawn:

1. Under low normal load (1.5N-6N) and low sliding speed (5-45 mm/s) conditions, the reciprocating friction and wear performance of *Scapharca broughtonii* shell was a function of normal loads and sliding speeds.
2. The friction coefficient decreased rapidly with an increase in sliding velocity. When the normal load was below 6N, the effect of load on the friction coefficient was small. When the normal load reached 6N, the effect of load on the friction coefficient slightly increased. The volumetric wear rate increased with an increase in the sliding speed.
3. The influence of normal loads on friction and wear performance of shell was dominant in conditions of higher speeds. The volumetric wear rate was increased with an increase in normal loads. The wear mechanisms of *Scapharca broughtonii* shell were mainly stress fatigue wear and three-body abrasive wear, accompanied by mild adhesive wear and abrasion.

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