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Investigating relationship between deformation behaviours and stick-slip phenomena of polymer material

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ABSTRACT

Deformation behaviours of polymer materials on a wear surface affect stick-slip phenomena. This study aimed to investigate the relationship between the deformation behaviours and stick-slip phenomena of plastic materials under water-lubricated and low speed conditions on a UMT-3 tribo-tester. The characteristics of the deformation behaviours and stick-slip phenomena were analysed and compared, and their relationships were revealed. The results showed that the velocity changed the deformation behaviours to influence the stick-slip phenomena. The deformation behaviours for large heights and lengths caused larger fluctuation amplitudes and fluctuation periods of stick-slip phenomena. The knowledge gained herein provides a better understanding of stick-slip phenomena and the deformation of plastic materials, which is useful for controlling or decreasing the deformation behaviours to control or decrease stick-slip phenomena.

1. Introduction

Many polymeric materials are usually green and pollution-free materials, highly resistant to fatigue and wear. Moreover, they can absorb vibrations and have excellent chemical stability to resist corrosion [1,2]. Therefore, engineering plastics, synthetic rubbers, and fibre resins have been widely used in water-lubricated polymer stern tube bearings for marine equipment [3–7]. Water-lubricated polymer stern tube bearings are important supporting parts of the propulsion systems of underwater vehicles. However, when the underwater vehicles are in states of low speed, heavy load, starting or stopping modes, it is very difficult to form an effective water-lubricated film layer between the polymer stern tube bearings and stern shafts. Hence, mixed lubrication, boundary lubrication, or dry friction conditions occur. In these cases, the friction and wear between the stern shafts and polymer bearings increase severely [8–10]. The stick-slip phenomenon is easily generated and eventually results in frictional vibration and radiating noise, severely undermining the survival and concealment performance of underwater vehicles [11–13]. Therefore, solving this problem is very important for improving the survival of underwater vehicles and to reduce environmental noise pollution.

Reducing the stick-slip of polymer materials is a very effective method for decreasing and controlling frictional noise [14–16]. Many scholars have investigated the stick-slip phenomenon of viscoelastic materials using coefficient of friction (COF) and friction force [17–19]. However, COF and friction force are an indirect representation of the stick-slip phenomenon. In fact, the adhesion and deformation of a material on a wear surface directly determine the stick-slip phenomenon [20,21]. Therefore, it is necessary to study the deformation behaviours of materials at the wear interface. Plastic materials have good viscoelasticity and plasticity [22–24], and their deformations cannot recover to the original morphology after being subjected to the wear process. The residual plastic deformation is a measure of deformation behaviour and can reflect the stick-slip phenomenon to some extent [25,26]. Therefore, in this study, plastic materials were chosen to investigate the relationship between deformation behaviours and stick-slip phenomena under the water-lubricated, heavy load, and low velocity conditions. The objective is to comprehensively understand the stick-slip phenomena, control the deformation behaviours to reduce the stick-slip phenomenon of the plastic stern tube bearing, and increase the survival and concealment performance of underwater vehicles.

2. Methods and experiments

2.1. Experimental materials

Plastic approved for marine application was commercially available and used as square pin specimens in this study (see Fig. 1). The

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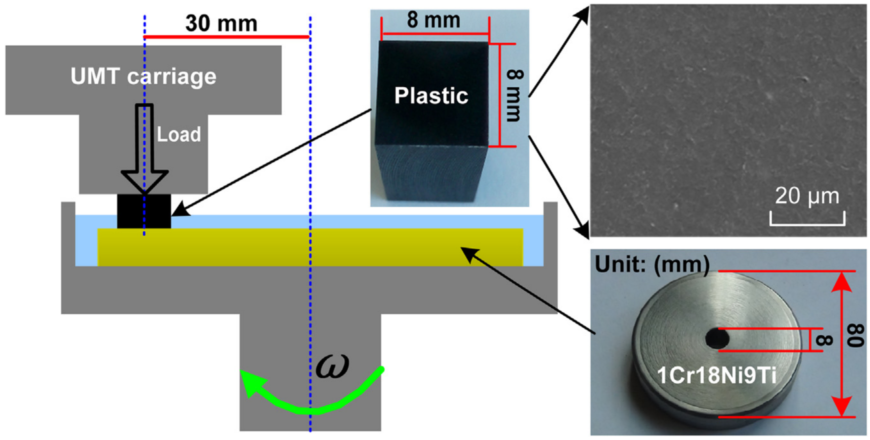

Fig. 1. Schematic of UMT-3 tribo-tester, plastic pin, and1Cr18Ni9Ti stainless steel plate specimens used in this study.

Table 1
Important mechanical properties of the plastic at room temperature.

Elongation at break (%)	Tear strength ($kN\ m^{-1}$)	Tensile strength (MPa)	Shore Hardness (A)	Initial temperature of thermal decomposition (°C)
185	26	44.1	83	100

length, width, and height of the specimens were 8, 8, and 20 mm, respectively. The polymer surfaces were polished before testing to obtain a mean surface roughness (S_a) of about 0.02 ± 0.01 μm (white light interferometer, Micro Xam, ADEP Hase Shift, Inc., Tucson, AZ, USA). The basic physical properties of the polymer are given in Table 1. The counterpart of the polymer was a 1Cr18Ni9Ti stainless steel plate with a diameter of 80 mm and a thickness of 10 mm as shown in Fig. 1. Its surface roughness (S_a) was 0.02 ± 0.01 μm, measured using the same white light interferometer mentioned above. The important mechanical properties of the 1Cr18Ni9Ti steel are given in Table 2.

2.2. *Experimental apparatus and sliding wear tests*

All the friction tests were conducted on a commercial pin-on-disc friction testing machine (UMT-3 tribo-tester, Center for Tribology, Inc.) as illustrated in Fig. 1. The upper polymer pin specimen was kept stationary, while the lower 1Cr18Ni9Ti plate specimen slid against the lower surface of the upper pin specimen with a rotational motion under water lubrication.

In the tests, the applied nominal pressure was 3 MPa. The radius of the sliding track was 30 mm. The rotational speeds were set to be 1, 5, 10, 15, 20, and 25 r/min, corresponding to sliding velocities of 3.14, 15.7, 31.4, 47.1, 62.8, and 78.5 mm/s, respectively. The duration of each test was 3 min. All tests were repeated several times to check the repeatability of the experiments. The friction force was measured every 0.01 s during the tests.

2.3. *Measurement techniques and procedures*

The surface topographies of the tested polymer pins were examined using a JSM-6701F scanning electron microscope (JEOL, Japan) and an atomic force microscope (MFP-3D Classic, Asylum Research, Santa Barbara, CA, USA).

3. Results and discussion

Fig. 2 shows the stick-slip phenomena between the plastic pins and 1Cr18Ni9Ti plates with water lubrication and under 3 MPa at different velocities. The frictional force and COF behaviours at a velocity of 3.14 mm/s during all wear processes are shown in Fig. 2a as an example. They undulated obviously, and their fluctuation amplitudes were stable. Fig. 2b–g shows the details of COF behaviours at 4 s for different velocities. Generally, COFs fluctuated as the sliding time increased and resembled a saw tooth. Obviously, the plastic pins and 1Cr18Ni9Ti plates were in contact with each other at the beginning, and COFs increased almost linearly during the sticking process as shown in Fig. 2b. When the friction force reached the maximum value and sliding continued, the COFs decreased sharply during the slipping process. These phenomena suggested that the stick-slip phenomena were generated between the plastic pins and 1Cr18Ni9Ti plates at low velocities. Moreover, the velocities had significant influences on the stick-slip phenomena. At the lowest velocity (3.14 mm/s), the average value of COF was 0.47, and was the greatest as shown in Fig. 2a. Its fluctuation amplitude of 0.25 was the biggest. Moreover, its fluctuation period was the longest at 2.7 s. With increasing velocity, the average value, fluctuation amplitude, and fluctuation period of COF decreased gradually as shown in Fig. 2c–f. When the velocity increased to 78.5 mm/s, the average value, fluctuation amplitude, and fluctuation period decreased observably, and were 0.256, 0.07, and 0.32 s respectively and were at the lowest levels as viewed in Fig. 2g. The stick-slip phenomena weakened as the velocity increased.

As is well known, the deformation of a viscoelastic material on a wear surface has a significant effect on the stick-slip phenomenon. For further insight into the wear process, the surface topographies of the tested plastic pins at different velocities were examined by scanning electron microscopy (SEM), and the results are shown in Fig. 3. Generally, many deformed fringes, perpendicular to sliding

Table 2
Important mechanical properties of 1Cr18Ni9Ti stainless steel.

Hardness HRA[a] (MPa)	Young's modulus E (MPa)	Mass density ρ (g/cm^3)	Tensile strength (MPa)	Yield strength (MPa)	Elongation at break (%)
38	198	7.85	≥ 550	≥ 210	≥ 40

[a] Rockwell A-Scale Hardness, Brale indenter, 60 kg load.