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Novel approach to studying the influence of surface structure on tribological properties of carbon fabric reinforced phenolic composites

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ABSTRACT

In order to make clear the engagement behavior, the numerical research is conducted to explore the influence of interface pressure on the tribological properties of carbon fabric reinforced phenolic composites. It is found that the dynamic friction torque is a linear function of interface pressure by curve fitting. And then the coefficient of dynamic friction is derived as an inverse proportional function of interface pressure. To demonstrate the results, the contact model is presented based on Gaussian surface asperity height distribution and the assumption of elastic deformation. Meanwhile, the asperity contact area is considered as the critical factor.

1. Introduction

With the amazing tribological properties, the composites have been widely used as friction components and the tribological properties have been largely studied. Davim JP et al. evaluated the tribological behaviors of three polymeric materials [1] and studied the tribological behaviors of the composites PEEK-CF30 at dry sliding against steel using statistical techniques [2,3]. Fei J et al. studied the effect of phenolic resin content on tribological properties of carbon fiber reinforced paper-based friction material under oil lubricated conditions [4].

As new fiber-reinforced composites, carbon fabric reinforced phenolic composites have been widely used for clutch of automatic transmissions because of their outstanding mechanical and tribological properties [5]. The tribological properties are influenced by friction material itself and the operating conditions such as interface pressure, rotating speed, rotational inertia and temperature etc. [6,7].

A significant amount of research has been conducted to better explore carbon fabric reinforced phenolic composites. Liu Pei et al. studied the influence of polytetrafluoroethylene (PTFE) contents on tribological properties [8]. Rattan Rekha et al. studied the influence of weave of carbon fabric on wear performance of polyetherimide composites [9]. Zhang Xinrui et al. investigated the effects of carbon fiber surface treatment on the tribological properties of 2D woven carbon fabric/phenolic composites [10]. However, the focus has mainly been on the effects of friction material itself on tribological properties.

It is important to make clear the relationship between tribological properties and operating conditions in analyzing the engagement behavior during engagement. Yang et al. discovered the relationship between friction coefficient and velocity was approximately close to an exponential function and presented two types of friction coefficient shapes, one increasing friction coefficient with velocity and the other making it fall [11]. In order to reproduce thermal effects in wet clutch engagement, Zagrodzki P et al. presented simplified models and analyzed the effects of speed, temperature and load on asperity contact torque [12,13]. Surface roughness, fluid viscosity, friction characteristics, material permeability, moment of inertia, groove area ratio and Young's modulus were considered as factors affecting the torque response by finite element modeling [14] and mathematical modeling [15]. But little numerical research on the relationship between tribological properties and interface pressure was reported.

The total pressure consists of hydrodynamic and asperity contact pressures during wet clutch engagement. The real contact pressure changes with location and time. Zhu D et al. studied the effect of surface roughness on pressure and gained the distribution function of asperity contact pressure based on the Gaussian distribution of asperity heights during engagement [16,17]. E. J. Berger et al. presented the asperity load sharing model based on the assumption that the deformation of a single engagement was elastic. And the

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elemental hydrodynamic pressure was also presented according to the finite element approach [14]. Coby L. Davis et al. developed the function link of applied load to time by curve fitting experimental load data [12]. Therefore, studying the connection of tribological properties with interface pressure is significant in that the wet clutch engagement can be made clear.

In the present work, the relationship between tribological properties and interface pressure is investigated and the function relationship is established. The determinant for the relationship is asperity contact area.

2. Experimental

2.1. Materials

The Cashew-modified phenolic resin (PF-6291 A) was provided by Shandong Shengquan chemical Co., Ltd., Jinan, China. The reinforcement is PAN-based unmodified carbon fabric (supplied by Weihai Guangwei Group Co. Ltd., China). The carbon fabric is plain weave and the tow of the carbon fabric is 12 K. The commercial carbon fabric was cut from the carbon fabric roll and was dipped in acetone for 24 h, and then cleaned ultrasonically in acetone for 1 h, finally, they were dried at 100 °C before used.

2.2. Preparation of carbon fabric reinforced phenolic composites

The dried carbon fabric was dipped into the cashew-modified phenolic resin solution (dissolved in the ethanol with the mass concentration of 30%) for 30 min, so that the Cashew-modified phenolic resin can be infiltrated into one layer of carbon fabric. After infiltration, the sample was dried at room temperature, followed by compression molding at 170 °C for about 5 min under the pressure of 5.0 MPa. Thus, the carbon fabric reinforced phenolic composite was obtained, whose thickness was 0.6 mm. The as-prepared composite contained 20 wt% of phenolic resin. The test specimens were cut from the composites with the help of the cutting mould according to the required standards for mechanical and tribological testing.

2.3. Characterization

2.3.1. Surface roughness test

The three-dimensional surface profile of the sample was also gained by an OPTELICS C130 real color confocal microscope (Japan). The 3D amplitude parameter S_q was used as 3D surface roughness [18]. It was defined as Eq. (A1).

Where S_q is the quadratic mean of the deviations from the mean; M and N are the number of sample points in the x and y directions, respectively; $\eta\ (x_i, y_i)$ is the height of points.

2.3.2. Compressibility and recovery test

The compressibility and recovery tests were carried out on the CMT5304-30KN Standing Electromechanical Universal Testing Machine (Shenzhen SANS Testing Machine Co., Ltd., China) under dry conditions at room temperature. The test carbon fabric composites sample dimensions were $10 \times 10 \times 0.6\ mm^3$. The test specimen was placed in the center of the anvil, and a preload 5 N was then applied and maintained for a period of 10 s, meanwhile, the preloaded thickness was recorded. Subsequently, the major load was employed at a speed of 0.2 mm/min and maintained for a period of 10 s while reaching the set value and the thickness of the specimen was recorded. After that, the major load was unloaded to the preload 5 N, and the thickness of the sample was then recorded when the original preload was maintained for a period of 10 s. This loading–unloading process of one specimen was repeated by four cycles for each major load. Five kinds of major load, 25 N, 50 N, 75 N, 100 N and 150 N, were used for each sample. The compressibility (ψ) and recovery (ξ) were given by ASTM F36-99 (2009), as shown in Eqs. (A2) and (A3).

Where h_0 is thickness under preload, mm; h_1 is thickness under major load, mm; h_2 is recovered thickness, mm.

2.3.3. Tribological properties test

The QM1000-II wet friction performance tester (Xian Shun Tong Institute of Electromechanical Application, Xi'an China) with plate-on-plate configuration was used to examine the tribological properties of the specimens. The as-prepared composite had an outside radius of 51.5 mm and inner radius of 36.5 mm. The measurements of μ_d (The coefficient of dynamic friction) and M_d (the dynamic friction torque) were repeated for six times, and an average of the experimental data was taken as the result. The temperature and flow rate of lubrication oil were kept at 40 °C and 90 ml/min during all the tribological property tests. The coefficient of dynamic friction of the specimen was calculated by Eq. (A4) according to GB/T 13826-2008.

Where p is the interface pressure; R_o is the outside radius; R_i is the inner radius.

3. Results and discussion

3.1. The connection of interface pressure to surface topography

Carbon fabric is weaved from twill and satin with carbon fiber [9]. Hence, the unique surface topography characteristics appear, such as a large number of micro-pores and grooves, fiber protrusion and exposing [18,19]. According to the three-dimensional surface profiles of the sample shown in Fig. B1, the surface topography is anisotropic. In contrast with the surface topography of specimen before friction test (Fig. B1a), the surface topography of specimen after friction test (Fig. B1b) has little changed, except that some higher asperity summits are worn out.

The 3D measurement method that could take all points into account in the measured area was used to comprehensively evaluate the characteristics of surface profiles [20]. It is found that the distribution of height is relatively organized. The values of S_q are 1.274 um before friction test and 1.265 um after friction test.

Surface parameters used in the analysis were obtained by measuring the surface profiles. Fig. B2a illustrates that the composites have nearly Gaussian surface profiles. Therefore, a Gaussian surface asperity height distribution was used in the analytical study. The height distribution obeys a Gaussian summit distribution function, as shown in Eq. (A5). In order to get the probability of $\eta(x_i, y_i) \le h$, error function erf(h) was used, as shown in Eq. (A7). Fig. B2b shows the $P(h)$ increases with the increase of $\eta*$ between -2 and 2, and is close to the linear growth between −1 and 1 [21].

Where m is the arithmetic average; σ is the standard deviation; η *is the random variable; $P\ (h)$ is Gaussian cumulative distribution function.

3.2. The link of interface pressure to compressibility and recovery properties

In practice, all engineering surfaces are rough, especially on microscopic scale [21]. Thus, contact only occurs at asperity summits with small contact area compared to the nominal area. Deformation which might be elastic, plastic or elasticplastic depends on the nominal pressure, surface roughness and material properties [22–24]. In general, the deformation of friction surface was always assumed as elastic deformation [14,16].