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Study on tribological properties as a function of operating conditions for carbon fabric wet clutch

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ABSTRACT

Carbon fabric/phenolic composites with the filaments counts of 12,000 were prepared by dip-coating and hot-press techniques. The effects of operating conditions on the tribological properties were investigated. Results show that the dynamic friction coefficient (u) firstly increases and then decreases as the rotating speed and total inertia increase. However, the friction stability and shudder phenomenon become gradually poor. The influence of braking pressure on u is the largest, followed by the total inertia among the above three operating conditions. The adhesive wear and abrasive wear are the main wear mechanisms during 1000 continuous braking cycles.

1. Introduction

As automobile develops to high speed and heavy load, there has been an increasing demand for safer and more stable wet transmission systems. So far, paper-based friction materials have been widely applied to the wet clutch of automatic transmissions, because they possess high friction coefficient and stable torque transmission ability. However, the comparatively low thermal conductivity and load-carrying capacity limit their development and application. Owing to the unique combination of excellent load-carrying capacity [1], self-lubricating [2] and thermal stability properties [3], carbon fabric composites are increasingly studied and used as frictional components [4–8]. The tribological properties of carbon fabric composites mainly depend on the inherent material properties, such as carbon fiber surface treatment, phenolic content, micro- or nano-particles modification, fabrication process and weave of carbon fabric [5,9–12]. Additionally, the operating conditions such as pressure, speed, inertia and temperature have a very significant effect on the tribological properties [13–15] of friction materials. The effect has been explored from two aspects: experiment and simulation.

A large number of experiments have been conducted in order to understand the effect of operating conditions on the tribological properties. Mäki et al. investigated the influences of temperature, normal force and velocity on anti-shudder properties. It was concluded that the friction coefficient decreases with the increase of temperature and the normal load has a very small influence on the friction coefficient at all temperatures above 30 °C [16]. Holgerson et al. optimized the smoothness and temperature by reducing normal force [17]. Gopal et al. illustrated the load, speed and temperature sensitivities of a carbon-fiber-reinforced phenolic friction material and found that the dynamic friction coefficient is the most sensitive to applied load [18]. Satapathy et al. studied the sensitivity of friction and wear of composite friction materials based on organic fiber and revealed that operating parameters are more sensitive compared with the individual organic fiber variation [19].

In order to further make clear the effect of operating conditions on the tribological properties, the computer simulations were conducted and their focus was on the torque response during engagement. Gao et al. developed a numerical model to study the effects of friction material and moment of inertia on the torque response, and found that the torque amplitude is less affected by the moment of inertia compared with the braking time [20]. Berger et al. established a finite element model to investigate the influences of applied load and groove on the torque response, and found that the high facing pressure increases the peak torque and shortens the engagement time [21]. Davis et al. presented a simplified approach to model the effects of thermal on the torque response and found that the high temperature increases the peak torque and shortens the engagement time [22]. However, these

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researches mainly focus on paper based friction materials and little research is reported on carbon fabric composites.

The carbon fabric composites (especially surface structure) undergo complicated physical and chemical changes under different operating conditions of wet clutch, which would affect the tribological properties. So, the torque transmission ability and friction stability may produce larger changes, which would make the reliability and comfort of shift gear worse. Thus, making clear the effect of operating conditions on the tribological properties is very significant in the material ratio and process optimization and hence can make shift gear more safe and comfortable. Besides, it is very significant in enriching wet tribology theory of carbon fabric composites. Therefore, in order to take full advantage of carbon fabric composites, it is necessary to study the effect of operating conditions on the tribological properties.

In the present study, MM1000-II wet friction performance tester was used in order to more really reflect the tribological properties and wear mechanisms of the carbon fabric composites in real working conditions. The effect of operating conditions (braking pressure, rotating speed and total inertia) on the tribological properties (dynamic friction coefficient and dynamic friction torque) of the carbon fabric/phenolic composites (CFPC) were explored. The program was designed to assess the relative significance of each factor in determining the tribological properties. Finally, the wear performance during 1000 continuous braking cycles was investigated based on the analysis of the micrographs and three-dimensional surface profiles of worn surfaces of CFPC and separator plate.

2. Methods and materials

2.1. Materials

The Cashew-modified phenolic resins (PF-6291A) were supplied by Shandong Shengquan chemical Co., Ltd., Jinan, China. The plain weave carbon fabrics (supplied by Weihai Guangwei Group Co. Ltd., China) were balanced geometrically because of the same crimp ratio between the warp and weft direction. The carbon fabrics were dipped in acetone for 24 h, and then cleaned ultrasonically in acetone for 1 h, and finally dried at 100 °C. The dried carbon fabrics were dipped into the cashew-modified phenolic resin solution (dissolved in the ethanol with the mass concentration of 30%) for 30 min to get the preform sheets. After infiltration, the preform sheets were 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/phenolic composites (CFPC) containing 40 wt% of phenolic resins were obtained, whose properties were shown in Table 1.

2.2. Characterization

2.2.1. Tribological properties test

MM1000-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 friction and wear performances of CFPC, whose maximum braking pressure, rotating speed and total inertia were 2.0 MPa, 4000 rpm and 0.22 kg m^2, respectively. Fig. 1(a) shows a schematic diagram of the equipment. When the AC motor reaches the setting speed, a normal force is applied to the separator plate by hydraulic cylinder and thus a friction force makes two surfaces in relative motion strive against a zero relative velocity, which is very close to the real working conditions of wet clutch. The separator plate is made of 45# steel with a hardness of HRC35, which is the quality carbon structural steel with 0.42–0.50% carbon. The temperature and flow rate of lubrication oil (no. N32 engine oil) are kept at 40 °C and 80 ml/min. The as-prepared friction materials have an outside radius of 51.5 mm and inner radius of 36.5 mm, as shown in Fig. 1(b). With the actual working conditions (service speed: 1000–3000 rpm, service pressure: 0.5–1.5 MPa, service inertia: 0.05–0.15 kg m^2), GB/T 13,826-2008 (braking pressure of 0.5–2.0 MPa and rotating speed of 1000–3000 rpm) and measuring range of MM1000-II taken into account, the braking pressure of 0.2–1.6 MPa, rotating speed of 200–3000 rpm, and total inertia of 0.05–0.22 kg m^2 were selected.

According to GB/T 13,826-2008, in order to establish nearly complete contact between the separator plate and friction lining, the running-in (120 min, once every 1 min) was conducted under the braking pressure of 1.0 MPa, rotating speed of 1000 rpm and total inertia of 0.13 kg m^2, respectively. The friction torques could be obtained by a torque transducer and transmitted to a computer. Meanwhile, the torque curves were recorded and an average of dynamic friction torques during mixed asperity contact phase was used to calculate the dynamic friction coefficient by a computer according to Eq. (1).

$$u = \frac{3M_d}{2\pi p(R_o^3 - R_i^3)} \tag{1}$$

where u is the dynamic friction coefficient; M_d is the mean dynamic friction torque of three tests, N; p is the braking pressure, MPa; R_o is the outside radius, m; R_i is the inner radius, m.

In the present work, the variation coefficient (C.V.D) was used to reflect the friction stability of the dynamic friction coefficient in operating conditions, which was obtained by Eq. (2).

$$C.V.D = \frac{\sigma}{u_m} \times 100\% \tag{2}$$

where $C.V.D$ is the variation coefficient; σ is the standard deviation; u_m is the average value of dynamic friction coefficient of different operating conditions.

2.2.2. Worn surface test

Scanning electron microscope (SEM, JEOL 6460) was used at 3 keV to obtain the morphologies of new surface and worn surface. Gold coating was applied on specimen surface to improve its conductivity.

Real color confocal microscope (OPTELICS C130, Japan) was used to evaluate the optical micrographs and three-dimensional surface profile of sample. The 3D amplitude parameter S_q (surface quadratic mean), S_a (surface arithmetic mean), S_{sk} (surface skewness) and S_{ku} (surface kurtosis) were used as 3D surface roughness.

3. Results and discussion

3.1. Effect of operating conditions on the tribological properties

Friction torque curve can be usually divided into three phases, which corresponds to the squeeze film phase, mixed asperity contact phase and consolidating contact phase of engagement [23]. μ_i, μ_d, and μ_o are the friction coefficients near the initial stage of engagement, during sliding and near the final stage of engagement, respectively, as shown in Fig. 2. The torque jump

Table 1
Properties of the specimens used in the experiments.

Material	Thickness (mm)	Filaments count	Filament diameter (μm)	Skeletal density (g/cm^3)	Shear strength (MPa)
CFPC	0.6	12,000	7	1.045	0.86