Tribology International 99 (2016) 29–37

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Variation of the tribological properties of carbon fabric composites in their whole service life

Fei Jie [a], Li Wenbin [a], Huang Jianfeng [a,*], Cao Liyun [a], Yao Chunyan [b]

[a] School of Materials Science & Engineering, Shaanxi University of Science and Technology, Xi'an, Shaanxi 710021, PR China
[b] Culture and Communication School, Shaanxi University of Science and Technology, Xi'an, Shaanxi 710021, PR China

ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form
7 March 2016
Accepted 9 March 2016
Available online 16 March 2016

Keywords:
Carbon fabric reinforced phenolic composites
Tribological properties
Wear mechanisms
Service life

ABSTRACT

To make clear the changes of the service ability of carbon fabric wet clutch in their whole service life, the tribological properties were investigated under oil lubricated condition. Results show that the torque transmission ability firstly increases and then decreases as the engagement cycle increases. The friction stability and pedal feel become gradually poor and the shudder phenomenon becomes serious. Carbon fabric composites exhibit a combination of adhesive wear, abrasive wear and thermal degradation mechanism and the worn surface shows different wear characteristics in different directions. To prolong their service life, the excellent interfacial adhesion and heat-resistant matrix are necessary.

1. Introduction

Wet clutches are frequently used to distribute torque in vehicle drive-trains of automatic transmissions and limited slip differentials. Friction plays an important role in these vehicle drive-trains, which can make separator disc and friction lining in relative motion strive against a zero relative velocity by applying a normal force under oil lubricated condition [1]. Paper-based friction materials have been widely used as friction lining, whose tribological properties have also been systematically studied in previous researches [2–4]. However, the comparatively low thermal conductivity and load-carrying capacity limit their applications [5]. Compared with paper-based friction materials, carbon fabric composites exhibit the unique combination of wear-resistance [6], good load-carrying capacity [7], self-lubricating [8] and thermal stability properties [9] because of their orderly aligned structure. Thus, the increasing investigations on their tribological properties are performed, such as carbon fiber surface treatment [10,11], phenolic content [12], micro- or nano-particles modification [13,14], fabrication process [15] and weave of carbon fabric [16,17].

The friction lining (especially surface structure) experiences complicatedly physical and chemical changes during its whole service life, which leads to the constant change of tribological properties. The further affected torque transmission ability and friction stability will largely affect the safety and comfort of shift gear. The wear behaviors of carbon fabric composites play an important role in their service life and greatly influence their surface structure [18]. Zhang et al. explored the wear behavior of 2D woven carbon fabric/phenolic composites (CFRP) [19]. It was found that the wear mechanisms of CFRP are shifted from adhesive wear to abrasive wear. Bijwe et al. investigated the abrasive wear performance of carbon fabric reinforced polyetherimide composites and elaborated the fiber damage mechanisms [20]. Kumaresan et al. studied the dry sliding wear behavior of carbon fabric–reinforced epoxy composites (C–E) and found that the abrasive wear mechanism governs the interaction between the surfaces at higher sliding velocity [21]. Thus, it is concluded that the different carbon fabric composites show different wear mechanisms and the abrasive wear is the main wear mechanism for above carbon fabric composites. Moreover, most of carbon fabric composites used as friction components generally exhibit a combination of two or more wear mechanisms. Although the wear behaviors of carbon fabric composites are mainly studied under dry condition, they can provide evidence for the wear mechanisms of carbon fabric composites in their whole service life.

In conclusion, few studies were performed on the tribological properties of carbon fabric composites in their whole service life under oil lubricated condition. The time of sliding friction is usually shorter in most papers mentioned above and the real working conditions are rarely simulated in these researches. Therefore, making clear the changes of friction performances and

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* Corresponding author. Tel./Fax: +86 029 86168802.
E-mail address: huangjf@sust.edu.cn (H. Jianfeng).

http://dx.doi.org/10.1016/j.triboint.2016.03.006

wear mechanisms under oil lubricated condition in the whole service life is very significant in material ratio, process optimization and enriching wet tribology theory of carbon fabric composites. Subsequently, the carbon fabric wet clutch with more safe and comfortable shift gear can be designed and manufactured to prolong the service life. The carbon fabric composites need to be replaced because of their serious wear and obviously unstable torque transmission performance when the mileage is more than 100,000 km. The engagement cycles are 10,000, when the shift gear is done per 10 km. Thus, in order to better reflect the changes of friction performances and wear mechanisms in different service periods, the 10,000 continuous engagement cycles are selected.

In the present study, QM1000-II wet friction performance tester was used to obtain the tribological properties in real working conditions. Moreover, in order to better make clear the changes of friction performances and wear mechanisms in the whole service life of carbon fabric composites, their tribological properties were investigated under oil lubricated condition during the continuous engagement process. Meanwhile, the worn surfaces, TG–DTG (thermogravimetry–differential thermogravimetry) curves and mechanical properties were also analyzed. Finally, the wear mechanisms were presented.

2. Experimental

2.1. Materials

Cashew-modified phenolic resin (PF-6291A, provided by Shandong Shengquan chemical Co., Ltd., Jinan, China) was used as matrix. PAN-based unmodified carbon fabrics (supplied by Weihai Guangwei Group Co. Ltd., China) were used as reinforcement. The carbon fabrics are plain weave and the tows (filaments count per fiber bundle) are 3 K, whose schematic overview and characteristics have been presented in our previous research [22]. The commercial carbon fabrics were cut from carbon fabric roll and were 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 fabrics were put into phenolic solution (dissolved in the ethanol with the mass concentration of 30%) and dipped for 30 min, then the carbon fabrics were put into an oven to evaporate solvent at 100 °C. A series of repetitive immersing of the carbon fabrics in the phenolic solution were done to generate composite consolidation, followed by compression molding at 170 °C for about 5 min under the pressure of 5.0 MPa. The weight percent of carbon fabric was 80% in the carbon fabric composites. The laminates were cut into annulus (outside radius of 51.5 mm and inner radius of 36.5 mm) with the help of cutting mould according to the required standards (GB/T 13826-2008) for friction and wear tests. Finally, the samples were cooled and the facings were adhesively bonded to the supporting metal member under heat and pressure in order to obtain the desired carbon fabric friction plate samples. Notably, in order to better investigate the worn surfaces and tensile strengths after different engagement cycles, three same samples were prepared under the same condition and hence they were used to the friction and wear tests under 0, 5000 and 10,000 continuous engagement cycles, respectively.

2.3. Characterization

2.3.1. Microstructure test

Scanning electron microscope (SEM, JEOL 6460) was operated at 3 keV to observe the morphologies of worn surfaces during the continuous engagement process. Gold coating was applied on the sample surface to improve the conductivity.

2.3.2. Surface roughness test

Real color confocal microscope (OPTELICS C130, Japan) was used to explore the three-dimensional surface profiles and surface roughness of the samples. The 3D surface roughness was obtained by Eq. (1) [23,24].

$$S_q = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^2(x_i, y_j)} \tag{1}$$

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; $\eta\ (x_i,\ y_j)$ is the height of points.

2.3.3. Thermal property test

Thermo gravimetric analyzer (STA 409C, NETZSCH, Germany) was used to analyze the degradation characteristics of the samples. The measurement was carried out in nitrogen at a flow rate of 50 ml/min. TG–DTG curves were obtained from 100 °C to 800 °C at a heating rate of 10 °C/min.

2.3.4. Mechanical properties test

The mechanical properties tests were performed on standing electromechanical universal testing machine (CMT5304-30KN) under dry condition at room temperature. The specimen dimension of compressibility/recovery test was 10 × 10 mm^2. The single strip specimen of tensile test was shown in Fig. 1. A controlled displacement rate of 5 mm/min was constantly applied to pull the samples until tensile failure occurred. In order to reduce joint failure and slippage while tested, the end tabs of the specimens were used. The mechanical properties tests were conducted for five same specimens and then the experimental results were obtained from the average of three specimens, the highest and lowest responses omitted.

2.3.5. Tribological properties test

The friction and wear tests were carried out on an inertia-type friction tester (QM1000-II, Xian Shun Tong Institute of Electromechanical Application, Xi'an China) under oil-lubricated condition. Fig. 2 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. Meanwhile, the lubrication oil is pumped from oil tank (i) to friction interface by DC motor (j) and then it is discharged from friction interface. The oil temperature can be well controlled by pyrogenation installation (k), thermometer (l) and controller (n) and the flow rate can be well controlled by a control valve (h). Because the new oil is continuously pumped to friction interface and the old lubrication oil is continuously discharged during engagement, the oil characteristics are same during whole test.

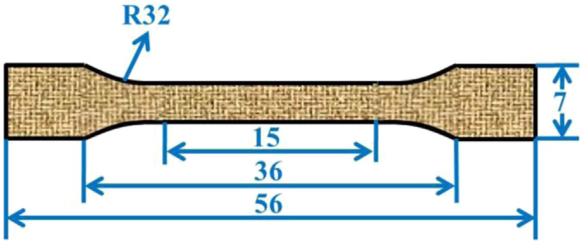

Fig. 1. Specimen dimensions of tensile test (all dimensions in millimeters).