Tribology International 90 (2015) 502–508

Contents lists available at ScienceDirect

Tribology International

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

Simulation of the engagement of carbon fabric wet clutch: Analytical and experimental comparison

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

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

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
19 April 2015
Accepted 17 May 2015
Available online 3 June 2015

Keywords:
Carbon fabric reinforced phenolic composites
Engagement of wet clutch
Simulation
Analytical and experimental comparison

ABSTRACT

Studying the wet clutch engagement more efficiently makes it necessary to simulate the wet clutch behavior. So, based on the modified Reynolds equation and torque balance equation, the modified numerical model was developed by introducing the carbon fabric contact coefficient and the surface pattern parameter for the carbon fabric wet clutch. It was found that there was a good agreement between computational results and experimental measurements. And subsequently, the influences of the applied pressure, the permeability and the fluid viscosity on the engagement characteristics were explored with the proposed numerical model.

1. Introduction

Since the investigations of clutch engagement can help optimize the wet clutch, an accurate evaluation of their engagement characteristics becomes very important. On the one hand, the modeling and experimental investigations on the clutch engagement dynamics have been widely performed. Ompusunggu [1] achieved the condition monitoring and prognostics by developing the model of the engagement dynamics of a wet friction clutch system subjected to degradation. Galvagno et al. [2] studied the kinematic and dynamic analysis of a power-shift automated manual transmission characterized by a wet clutch, and subsequently confirmed the advantages in terms of gear shift quality and ride comfort of the analyzed transmission. Some design-objectives and design-guidelines for automotive friction clutch were presented by Tripathi et al. [3] based on clutch engagement dynamics in order to optimize the clutch design.

On the other hand, in an effort to provide insight into wet clutch engagement, numerous experiments including the composition and structure of friction materials were conducted. Fei et al. [4] studied the influence of the composition of friction materials on the dynamic friction torque during engagement. Marklund et al. [5] investigated the effect of the permeability on the temperature during engagement. It was found that the permeability can affect engagement time, temperature of the clutch and boundary lubrication friction coefficient. Nyman et al. [6,7] explored the influence of the surface topography and fluid on the friction characteristics during engagement. These researches make clear the importance of profoundly exploring the engagement for optimizing the wet clutch.

Meanwhile, the simulation of the engagement is also significant to investigating the frictional behavior of the wet clutch. Not easily measured in test rigs, the behaviors can be simulated. And the simulation can make the design process more efficient. The Reynolds equation was first used in the engagement of a paper-based wet clutch by Natsumeda and Miyoshi [8]. With the surface profile, permeability and groove geometry of paper-based friction materials taken into account, the modified Reynolds equation was presented by Berger et al. And the engagement was simulated by numerical and finite element methods [9,10]. Subsequently, the modified Reynolds equation was corrected by Yang et al. [11], Gao et al. [12,13] and Marklund [14] considering the correct average flow factors, fluid viscosity and asperity height distribution. And the effects of the surface roughness, fluid viscosity, friction characteristics, material permeability, moment of inertia, groove area and Young's modulus on the torque response were investigated with the modified Reynolds equation and the torque balance equation. However, these researches concentrate mainly on sintered bronze and paper-based friction materials, without adequate predictions of torque response validated by measured data.

As the important frictional components, the tribological properties of wet friction materials play a significant role in the wet clutch. Sintered bronze friction materials and paper-based friction materials have been widely applied to the wet clutches. Although

* Corresponding author. Tel./fax: +86 29 86168802.
E-mail address: huangjf@sust.edu.cn (H. Jianfeng).

http://dx.doi.org/10.1016/j.triboint.2015.05.018
0301-679X/© 2015 Published by Elsevier Ltd.

the sintered bronze friction materials exhibit the high mechanical strength, good thermal conductivity and excellent loading capacity, their application is limited due to the relatively low dynamic friction coefficient and inclination to seizure with the couple plate. With high friction coefficient, the paper-based friction materials are also limitedly applied in view of their comparatively low thermal conductivity and load-carrying capacity. Unlike them, carbon fabric reinforced phenolic composites are increasingly being used as frictional components in the civil engineering and aerospace industries, especially in the wet clutch of automatic transmissions owing to their unique combination of wear-resistance [15], good load-carrying capacity [16], self-lubricating [17] and thermal stability properties [18]. A significant amount of research works have been focused on the influence of particle reinforcement, fiber surface treatment and weave of carbon fabric on the tribological properties [15,19–22].

In order to study the wet clutch engagement more efficiently, the simulation was conducted on the engagement of a carbon fabric wet clutch in this paper. The modified Reynolds equation was used and improved according to the anisotropy of carbon fabric reinforced phenolic composites produced with reverse weave. To check the proposed model, experiments were also performed. Finally, the effects of the applied pressure, the permeability and the fluid viscosity on the torque response were investigated with the proposed numerical model.

2. Experimental

2.1. Sample preparation

The carbon fabric (CF) was provided by Weihai Guangwei Group Co. Ltd., China. The tow of the carbon fabric was 3 K. The adhesive resin (PF-6291A Cashew-modified phenolic resin) was provided by Shandong Shengquan chemical Co., Ltd., Jinan, China.

The carbon fabric after pre-treatment (dipped in acetone for 24 h, cleaned with acetone in an ultrasonic bath for 1 h, and finally, dried at 100 °C) was immersed in the cashew-modified phenolic resin solution (dissolved in the ethanol with the mass concentration of 30%) for 30 min. Subsequently, the carbon fabric was dried at 60 °C and then fabricated by compression molding at 160 °C for about 5 min under the pressure of 5.0 MPa. The carbon fabric composite about 0.6 mm thickness was cut into preset sizes for the engagement tests.

2.2. Characterization

2.2.1. Surface roughness test

The surface roughness and the three-dimensional surface profile were obtained by an OPTELICS C130 real color confocal microscope, as shown in Fig. B1(a). The height data were extracted from Fig. B1(a) and used to study the surface asperity height distribution. Fig. B1(b) illustrated that the carbon fabric composites had nearly Gaussian surface profiles. Therefore, a Gaussian surface asperity height distribution was used in the analytical study. The surface pattern parameter was first introduced by Kubo and Peklenik [23] to describe the directional properties of roughness. It was defined as the ratio of x and y correlation lengths, as shown in Eq. (A.1).

$$\gamma = \frac{\lambda_{0.5x}}{\lambda_{0.5y}} \tag{A.1}$$

where γ is the surface pattern parameter; $\lambda_{0.5x}$ and $\lambda_{0.5y}$ are 0.5 correlation lengths of the x and y profiles.

2.2.2. Permeability test

The permeability test was conducted on the AutoPore IV 9500 based on Darcy's Law, as shown in Eq. (A.2)–(A.4).

$$K_{per} = \frac{ND_f}{8\tau^2}\left|\frac{1-\lambda^{5-D_f}}{\lambda^{-D_f}-1}\right|\frac{r_m^5}{5-D_f} \tag{A.2}$$

$$\lambda = r_0/r_m \tag{A.3}$$

$$\tau = L_c/L_m \tag{A.4}$$

where K_{per} is the permeability; D_f is the fractal dimension; r_m is the largest pore size; r_0 is the smallest pore size; N is the number of pores per unit volume. τ is the mean tortuosity of capillary; L_c is the radius of capillary; L_m is the length of capillary.

2.2.3. Young's modulus test

The Young's modulus tests were conducted on the CMT5304-30KN standing electromechanical universal testing machine at room temperature. The test sample dimensions were $10 \times 10 \times 0.6\ \text{mm}^3$.

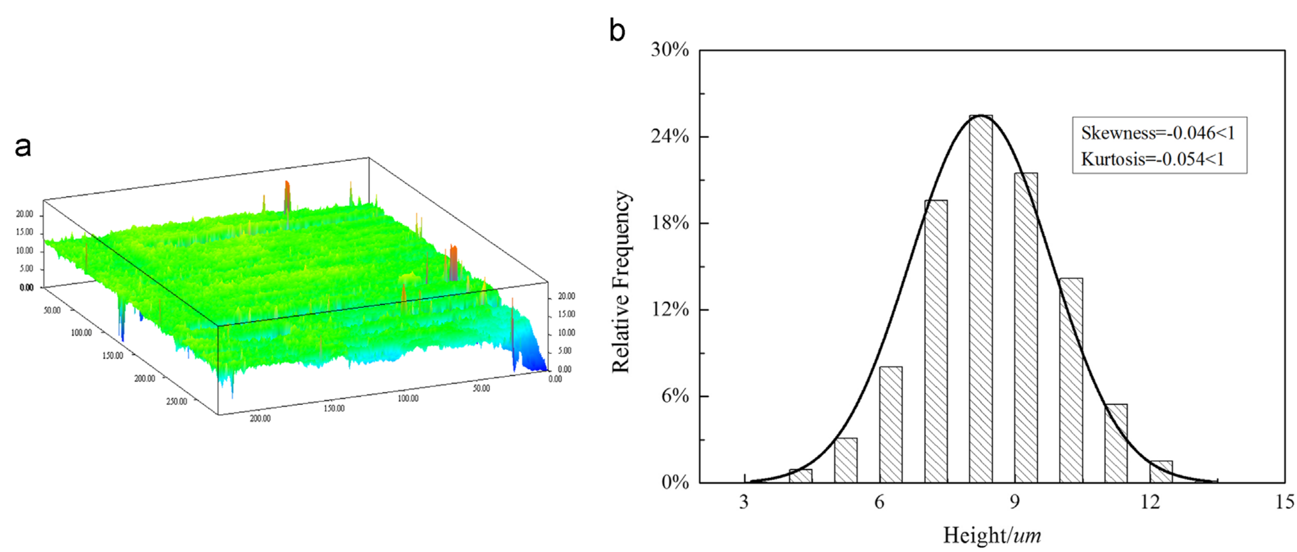

Fig. B1. (a) Three-dimensional real color surface profiles of the carbon fabric composites; (b) statistical analysis of the surface profiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)