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A statistical model for evaluating the tribological properties of paper-based friction materials

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ABSTRACT

In order to synthetically evaluate the tribological properties of friction materials, fuzzy comprehensive evaluation model was developed. The analytic hierarchy process was introduced into the model to establish weight function. The paper-based friction materials with different CNTs content were chosen as the six projects. It is found that the comprehensive evaluation indexes are increased by 126–307% for the samples with 4–15 wt% of CNTs compared with the sample without CNTs. The judgment matrix has high consistency by consistency checking. And the evaluation results are also in accordance with the results obtained through the friction torque, surface structure and temperature.

1. Introduction

As a kind of important fiber-reinforced composites, paper-based friction materials have been widely used for the wet clutches of automatic transmissions because of their outstanding mechanical and tribological properties. A large number of researches have been conducted to better explore paper-based friction materials. Yi et al. investigated the mechanical properties of phenolic resin-based friction composites and found that the bending strength and hardness increase with the rise of calcined petroleum coke content [1]. Fujii et al. studied the fatigue strength of aramid fiber reinforced paper-based friction materials under shear-compressive loading and found that the fatigue strength is remarkably high under the compressive-dominant stress condition [2]. Wang et al. explored the wear performance of carbon fiber reinforced nylon 1010 composites from the perspective of filler and got the finding that MoS_2 filler increases their wear [3]. Hwang et al. investigated the friction performance of paper-based friction materials containing carbon nanotubes (CNT) from the perspective of friction modifier, finding that CNT modifier increases the fade resistance and friction stability [4]. Patnaik et al. studied the fade resistance and recovery properties of fiber reinforced hybrid phenolic composites from the perspective of reinforcement and found that the fade resistance and recovery increase with the increase of aramid fiber and decrease of ceramic fiber [5]. Fei et al. explored the tribological properties of carbon fiber reinforced paper-based friction materials from the perspective of binder and discovered that the samples with lower resin content (ranging from 35 wt% to 40 wt%) exhibit high friction coefficient, excellent friction stability, good heat-resistance and reasonable strength [6]. Regarded as a kind of important properties of paper-based friction materials, tribological properties have been widely studied, such as dynamic friction coefficient, the ratio of dynamic and static friction coefficient, static friction coefficient, variation coefficient, wear rate and friction torque.

The dynamic friction coefficient can well reflect the torque transmission ability and braking efficiency of paper-based friction materials [7]. The static friction coefficient mainly exhibits the torque transmissions ability in the later stage of shifting/joint and the high static friction coefficient easily leads to serious shudder phenomenon. The ratio of dynamic and static friction coefficient can demonstrate the potential for friction-induced vibrations and the large ratio indicates excellent anti-shudder performance [8]. The variation coefficient can reflect the friction stability and the lower variation coefficient indicates better friction stability [9]. The wear rate is the key index characterizing the life of paper-based friction materials and the small wear rate means long service life. Therefore, the above five indexes are very important to evaluate the tribological properties of paper-based friction materials. However, these indexes are usually inconsistent and show the complex nonlinear interaction, which makes it difficult to determine whether a friction material that has excellent tribological properties.

Kim et al. studied the friction stability and wear resistance of friction materials containing two different phenolic resins [10]. It was found that the friction materials with the modified novolac resin show improved friction stability while reducing wear resistance. Fei et al. investigated the effects of carbon fiber length (100, 400, 600 and 800 μm) on the tribological properties of paper-

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based friction materials. It was found that bigger porosity and more covering of resin make the friction material with 600 μm carbon fibers exhibit greater dynamic friction coefficient, but the wear rate is also greater [11]. Kim et al. studied the friction and wear performances of chopped glass fibers reinforced friction materials [12]. It was found that the chopped glass fibers decrease the wear rate at 100 °C, but the friction coefficient and friction stability are also decreased. Zhang et al. explored the influences of compound mineral fiber content (0, 5, 10, 15 and 20 wt%) on the tribological properties of paper-based friction materials [9]. As was found, the friction material with 15 wt% of compound mineral fiber has the smallest wear rate and variable coefficient, but the dynamic friction coefficient is not the largest. Thus, in order to settle the above inconsistency problems of multiple indexes, comprehensive evaluation model is very necessary in that it can unite multiple evaluation indexes into one index.

A number of evaluation methods have been employed in the evaluation of friction materials. Mustafa et al. accomplished the selection of friction materials with cambridge engineering selector edupack software based on eco-aware lightweight, cost effective and non-toxic [13]. However, the tribological properties were not considered. Dadkar et al. conducted the tribo-evaluation of flyash-filled and aramid fibre reinforced hybrid polymer matrix composites by linear polynomial approach and modified Rhee equation [14]. However, the evaluation method is only suitable for the situation where independent variable and dependent variable can be measured. The selection and verification of kenaf fibers as an alternative friction material were conducted using weighted decision matrix method by Mustafa et al. [15]. However, the determination of weight factor is subjective relatively and the verification of evaluation result is not abundant relatively. In order to comprehensively evaluate the anti-shudder performance of ATFs, oil absorption ability of the post-test friction material surface was proposed to be an important parameter [16]. Mortazavi et al. developed a global statistical approach for the evaluation of mechanical properties of silica/epoxy nanocomposite [17]. However, the global statistical approach cannot unite multiple evaluation indexes into one index. Therefore, few good approaches in previous researches were found to be suitable for the evaluation of tribological properties.

However, the advantages of being concise, practical, systematic and quantitative have enabled analytic hierarchy process (AHP) to be widely used in consensus building [18] and ranking insurance firms [19] and so on, but not in the evaluation of tribological properties. Moreover, AHP can unite multiple evaluation indexes into one index. Thus, AHP is suitable for evaluating the tribological properties of paper-based friction materials based on the above analysis.

In the paper, the fuzzy comprehensive evaluation model was developed based on AHP and weight function. Subsequently, it was applied to the evaluation of the tribological properties of the paper-based friction materials with different CNTs content and the validity was checked by the friction torque, surface structure and temperature. The model can be well applied to the evaluation of the tribological properties of paper-based friction materials, because it can well unite multiple inconsistent evaluation indexes into one index. Moreover, the model can help the designer more effectively, accurately and comprehensively investigate paper-based friction materials and then select the friction materials possessing excellent tribological properties. The model can also provide evidence for material ratio and process optimization.

2. Methods and materials

2.1. Materials

The mixture of PAN short carbon fibers (75–150 μm length, supplied by Anshan Sinocarb Carbon Fibers Co., Ltd., Anshan, China) and bamboo fibers (90°SR freeness, supplied by paper making engineering department of Shaanxi University of Science & Technology) was used as reinforcement. The friction modifier was CNTs (dispersed in water with styrene–maleic anhydride copolymer (SMA), provided by the reaction engineering laboratory of Tsinghua University). The PF-6291A cashew-modified phenolic resin (provided by Shandong Shengquan chemical Co., Ltd., Jinan, China) was used as binder. The ingredients used in this study are listed in Table C1.

2.2. Fabrication of composites

The stable suspensions were obtained by mixing the carbon fibers, bamboo fibers and CNTs in water and stirring for about 30 min. Then the preform sheets were shaped by pouring the suspension into paper making machine. Afterwards, the preform sheets were rolled and dried at 110 °C for 10 min. After that, the dried preform sheets were dipped into the cashew-modified phenolic resin solution (dissolved in the ethanol with the mass concentration of 30%) for 30 min. After infiltration, the preform sheets were dried at room temperature, followed by compression molding at 160 °C for about 5 min under the pressure of 5.0 MPa. Thus, the paper-based friction materials were obtained, whose thicknesses were 0.6–0.7 mm. The as-prepared composites containing 0, 2, 4, 8, 12 and 15 wt% of CNTs were designated as C1, C2, C3, C4 and C5, respectively (Table C1). Finally, the test specimens were cut from the as-prepared composites with the help of the cutting mould according to the required standard (GB/T 13826-2008) for tribological properties test, whose schematic diagram is shown in Fig. B1. And subsequently, the facings were adhesively bonded to the supporting metal member under heat and pressure in order to obtain the desired paper-based friction plate samples.

2.3. Tribological properties test

The tribological properties of the specimens were obtained by the QM1000-II wet friction performance tester with plate-on-plate configuration. Fig. B2 shows a schematic diagram of the equipment. The as-prepared composites have an outside radius of 51.5 mm and inner radius of 36.5 mm. The temperature and flow rate of lubrication oil (No. N32 engine oil) were kept at 40 °C and 90 ml/min in all tribological properties tests. The temperatures of mating plate were measured by thermometer (Fig. B2(12)) during each engagement and then the data were transferred to the controller (Fig. B2(14)) where there was a temperature indicator. Afterwards, the highest temperature was recorded by manual method. The measurements of dynamic friction coefficient and static friction coefficient were repeated for six times. And then an average value was calculated as the result.

The change of sample thickness was measured after 500 engagement cycles under interface pressure of 1.0 MPa, initial rotating speed of 2000 rpm and total inertia of 0.1294 Kg m^2, respectively. The wear rate was obtained from Eq. (A.1), which was defined as wear volume per work and used for further analysis, where V is wear rate, mm^3/J; A is the apparent contact area, mm^2; Δh is the change of sample thickness, mm; n is the number of engagement cycles; I_0 is the total inertia, Kg m^2; ω is the relative angular velocity, rad/s.

In this work, the variation coefficient was used to reflect the friction stability of the dynamic friction coefficient during 500 engagement cycles under interface pressure of 1.0 MPa, initial rotating speed of 2000 rpm and total inertia of 0.1294 Kg m^2, respectively. The variation coefficients of the samples were calculated by Eq. (A.2), where $C.V$ is the variable coefficient; σ is the standard deviation; μ_m is the average value of the dynamic friction coefficient of 500 engagement cycles.