Preparation and properties of resin-based wet friction materials reinforced by SiCp/basalt fiber cloth

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Abstract. A new type of wet friction material was prepared by solution impregnation with phenolic resin as binder, SiC particles and basalt fiber cloth as reinforcement. The hardness, density, porosity, microstructure, tribological properties and surface roughness were analyzed. The results show that the coefficient of friction (COF) and COF stability of the prepared material is more than 0.11 and 90%, respectively, while the wear rate is $0.26 \times 10^{-7}$ cm$^3$/J. The main wear pattern of this wet friction material is resin shedding. There is no large-sized “third body” abrasive debris on the friction surface, resulting in low wear rate of friction material.

1. Introduction

The friction discs of wet clutch is used in the working environment of oil-immersed seal [1], offering the stable friction coefficient, high elastic modulus and good wear resistance. At present, the widely used wet friction materials are copper-based powder metallurgy friction materials as well as paper-based friction materials. Copper-based powder metallurgy friction material [2] has good thermal conductivity, large heat capacity and strong energy absorption capacity, but its dynamic COF is relatively low. Paper-based friction material [3] has high elastic modulus, high COF and uniformly distributed load on the whole friction surface. Its disadvantages are low heat capacity and poor heat transfer properties, which limits its application on the condition of high speed and heavy load.

Basalt fiber is a chain-like skeleton structure formed by SiO$_4$ connection and doped with oxides such as SiO$_2$, Al$_2$O$_3$, FeO, Fe$_2$O$_3$, CaO, MgO, TiO$_2$, Na$_2$O and K$_2$O [4]. It has good mechanical properties, green manufacturing process, wide working temperature range and stable chemical properties [5]. Lopresto et al. [6] found that the comprehensive mechanical properties of basalt fiber reinforced plastics are better than those of glass fiber reinforced plastics. SiC particles have the advantages of high melting point, good heat resistance [7], and can effectively improve the heat resistance of friction materials. It is well known that carbon fiber reinforced friction materials have excellent properties, but the high cost limits its usage amount [8]. In this letter, a new type of wet friction material coupled with SiCp/basalt fiber cloth was prepared and its comprehensive properties and wear mechanism were analyzed. Benefiting from the low-cost basalt fiber and hot pressing molding process, this friction material has a good application prospect in clutch disc.
2. Experimental

2.1. Raw materials
SiC particles (diameter of particles: 10-50μm, purchased from Yuhang metal materials Co., Hebei province, China), boron phenolic resin (decomposition temperature: 500 ℃, free phenol content: <7%, purchased from Tianyu high temperature resin material Co., Anhui province, China), basalt fiber cloth (diameter of fibers: 13μm, area density: 350g/m², purchased from GBF basalt fiber Co., Zhejiang province, China)

2.2 Preparation process of material
Firstly, 30 g boron phenolic resin and 0.6 g SiC particles were placed in 50 mL anhydrous ethanol and dispersed by ultrasonic stirring at 50 ℃ water bath. Then the impregnation solution was smeared on the positive and negative sides of the basalt fiber cloth (To achieve a resin content of 25 wt.%) and dried at 80 ℃ for 30 min by electrically heated drying oven (DHG-9146A, China). Next, the plate vulcanizer (XLB-d400×400, China) was used for hot-press forming, the temperature was 200 ℃, the pressure was 4.2 MPa, and kept for 13 min. Finally, the sample covered with graphite powder was put into muffle furnace (SX2-5-12, China) and kept at 340 ℃ for 3 h, then cooled in the furnace. SiCp/basalt fiber cloth coupling reinforced resin-based friction materials were prepared.

2.3 Characteristic method of material
The friction and wear properties were measured by using the friction and wear testing machine (MM1000-III, China). The temperature of hydraulic oil (L-HM 32, China) is 80 ℃, while the braking inertia is 0.1 Kg/m². The counter-pair is made of 45 carbon steel. Its’ average surface roughness is 0.32 μm and the hardness is 35 HRC. After 200 times braking, the change of thickness before and after friction was measured. The wear rate of the sample is calculated by the following formula:

\[ V = A \cdot \Delta h / 0.5 \cdot n \cdot I_0 \cdot \omega^2 \]

\( V \) is the wear rate, cm³/J; \( A \) is the apparent contact area, cm²; \( \Delta h \) is the thickness reduction, cm; \( n \) is the braking times; \( I_0 \) is the braking inertia; \( \omega \) is the braking angular velocity, rad/s.

The microhardness of the sample was measured by using a Vickers microhardness tester. Its’ density and porosity were measured by using an automatic densimeter (GH-128E, Japan). Sample’s wear surface was shown by scanning electron microscope (ZEISS EVO18, Germany). The surface roughness was observed by using a 3D laser microscope (OLYMPUS OLS5000, Japan).

3. Results and discussion
The porosity, Vickers hardness and density of the prepared wet friction material is 11.6 %, 74.2, and 1.97 g/cm³, respectively. In compression molding the resin as binder is heated, liquefied and then filled into the pores of each component. At the same time, B-O bonds with high binding energy made intermolecular structure of resin is hard to be destroyed, which improves the mechanical properties of the materials.

Fig. 1(a) shows the COF of the samples as a function of braking velocity. The COF is 0.12 at 1000 r/min, and drops to 0.11 at 3000 r/mins, the overall fluctuation is small. The main reason is that with the increase of braking velocity, the contact time between friction material and counter-pair is prolonged during the braking process, the friction surface temperature increases, lubricating oil viscosity decreases, leading to the decrease of COF. Fig. 1(b) shows the trend of COF as a function of braking pressure. The COF increases with the rise of braking pressure. The main reason is that the resin composition on the surface of the friction material is softened by the higher braking pressure, the contact area between the friction material and the counter-pair is increased, causes the COF to rise. At the same time, the higher braking pressure makes the oil film produced in the braking process more likely to be damaged, the time of mixed friction is shortened, this can also improve the COF to a certain extent. The COF stability of the samples are shown in Table 1, COF stability is characterized by the ratio of average COF to the
highest COF and all of the values are more than 90%. The high COF stability is due to the moderate resin content in the friction material. It can not only ensure the bond strength between the components, but also avoid the occurrence of serious thermal decay phenomenon. The effect of curing heat treatment temperature at 280 °C, 310 °C, 340 °C, 370 °C and 400 °C on the performance of material was measured. In this experiment, with the 340 °C curing heat treatment, the wet friction material shows good friction and wear performance. The test parameters of wear rate are as follows: braking pressure 1.0 MPa, braking velocity 2000 r/min, braking inertia 0.135 kg/m². Sample’s wear rate after 200 times braking is 0.26×10⁻⁷ cm³/J. As the result, good chemical properties [9] and resin Adhesion properties were shown by SiCp/basalt fiber cloth coupling reinforced resin-based friction material. SiC particles have special three-dimensional morphology [10], so they are not easy to fall off from resin matrix. The structure of the material is hard to be destroyed while braking, and the wear rate is reduced.

![Figure 1](image_url)  
Figure 1: Variation of COF(a) Braking pressure 1 mpa, braking velocity 1000 r/min, 2000 r/min, 3000 r/min; (b) Braking velocity 2000 r/min, braking pressure 0.5 MPa, 1 MPa, 2 MPa.

![Table 1](image_url)  
Table 1: Friction coefficient stability.

| Braking velocity (r/min) | 2000 | 1000 | 2000 | 3000 | 2000 |
|-------------------------|------|------|------|------|------|
| Braking pressure (MPa)  | 0.5  | 1    | 1    | 1    | 2    |
| COF stability (%)       | 90   | 95   | 92   | 91   | 95   |

Fig. 2(a) and (b) show the surface SEM morphologies of the sample after 200 times braking. It can be seen from Fig. 2(a) that the sample’s surface is smooth, the basalt fiber bundles appear to be laminated and interlaced. Such a feature makes the rough peak on the surface of the friction material take the lead to mechanical contact with the counter-pair during the braking process, while the concave part is fully impregnated with lubricating oil. At the same time, due to the high compressive strength and good high temperature resistance of basalt fiber, the friction material can make the load distribution even when subjected to load, thus improving the COF stability. According to Fig. 2(b), the basalt fiber on the surface of the friction material is closely arranged and less fractured, and it has good binding effect with the resin binder, which is one of the reasons for the low wear rate of the friction material. At the same time, a small amount of resin shedding can be observed on the friction material surface, but there is no large-sized “third body” abrasive debris, which effectively avoids the occurrence of such serious wear behavior as furrow action. This is also a reason for the low wear rate of friction material. Due to the high hardness of basalt fiber and its good self-lubrication performance, it is not easy to be ground in the friction process, so the surface roughness peak of the friction material is still composed of basalt fiber after two hundred times of braking. The existence of rough peak can release the friction heat generated in the friction process by using the heat exchange effect of the oil, reduce the decomposition of resin, and keep the friction material with high COF and COF stability.
Figure 2 SEM images of specimen surface (a) SEM images under 50 times magnification; (b) SEM images under 600 times magnification:

Fig. 3 shows the 3D profile of the sample surface before braking. Its’ roughness is only 3.39 μm, lower than some carbon fiber reinforced paper-based friction materials [11]. The low surface roughness leads to a good fit between the sample and the counter-pair. When the sample subjected to the shearing action of the counter-pair, the stress concentration is reduced, and the friction material is not easy to fail.

Figure 3 3D profile of sample surface.

4. Conclusion
The resin-based friction material reinforced by SiCp/basalt fiber cloth was prepared by solution impregnation. The friction material shows good mechanical properties. After curing heat treatment at 340°C, materials’ surface roughness is only 3.39 μm and the basalt fiber bundles appear to be laminated and interlaced, which makes the COF stable and the wear rate low. The COF reached 0.11-0.13 under all test parameters. After 200 times of braking, the wear rate of the sample is 0.26×10^{-7} cm^3/J. SiCp/basalt fiber cloth coupling reinforced resin-based friction material shows good friction and wear performance. Resin shedding is the main wear pattern on the worn surface.

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References:
[1] M. Li, M.M. Khonsari, D.M.C. McCarthy, J. Lundin. (2015) On the wear prediction of the paper-based friction material in a wet clutch. J. Wear., 334-335: 56-66.
[2] A.M. Kovalchenko, O.I. Fushchich, S. Danyluk. (2012) The tribological properties and
mechanism of wear of Cu-based sintered powder materials containing molybdenum disulfide and molybdenum diselenite under unlubricated sliding against copper. J. Wear., 290-291: 106-123.

[3] X. Zhang, K.Z. Li, H.J. Li, Y.W. Fu, J. Fei. (2014) Tribological and mechanical properties of glass fiber reinforced paper-based composite friction material. J. Tribol. Int. 69: 156-167.

[4] J. Militky, V. Kovacic. (2007) Ultimate mechanical properties of basalt filaments. J. Text. Res. J. 66 (4): 225-229.

[5] O.V. Gogoleva, P.N. Petrova, S.N. Popov, A.A. Okhlopkova, J. Frict. (2015) Wear-resistant composite materials based on ultrahigh molecular weight polyethylene and basalt fiber. J. Wear. 36 (4): 301-305.

[6] V. Lopresto, C. Leone, I. De Iorio. (2011) Mechanical characterisation of basalt fibre reinforced plastic. J. Compos. Part B-Eng. 42 (4): 717-723.

[7] H.J. Zhan, N. Zhang, D. Wu, Z.Q. Wu, S.X. Bi, B.J. Ma, W.Y. Liu. (2019) Controlled synthesis of β-SiC with a novel microwave sintering method. J. Mater. Lett. 255: 126586.

[8] V. Dhand, G. Mittal, K.Y. Rhee, D. Hui. (2014) A short review on basalt fiber reinforced polymer composites. J. Compos. Part B-Eng. 73: 166-180.

[9] H. Jamshaid, R. Mishra. (2016) A green material from rock: basalt fiber – a review. J. J. Text. I. 107 (7): 923-937.

[10] N. Chawla, V.V. Ganesh, B. Wunsch. (2004) Three-dimensional (3D) microstructure visualization and finite element modeling of the mechanical behavior of SiC particle reinforced aluminum composites. J. Scripta. Mater. 51 (2): 161-165.

[11] J.H. Lu, Y.F. Li, Y. Wang, Y.W. Fu. (1993) Analysis of surface roughness using confocal microscopy. J. J. Tribol. T. 28 (14): 3879-3884.