Wear 328-329 (2015) 270–276

Contents lists available at ScienceDirect

Wear

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

Wear map for a copper-based friction clutch material under oil lubrication

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ARTICLE INFO

Article history:
Received 12 November 2014
Received in revised form
12 February 2015
Accepted 20 February 2015
Available online 2 March 2015

Keywords:
Wear map
Metal–matrix composite
Clutches
Boundary lubrication
Ring-on-ring

ABSTRACT

Wear maps for specific material combinations can be used to depict dominant wear processes and their severity under a specified range of sliding conditions. Wet clutches are one application for which such maps can be used. In the current work, a copper-based friction material was slid against alloy steel in a ring-on-ring braking simulator. A wear map constructed from measured wear rates was partitioned into ultra-mild, mild and severe wear regimes. The dominant wear mechanisms that control these wear regimes are also discussed. Based on the data, linear equations were constructed to mark transition boundaries between wear regimes.

1. Introduction

Wet clutches are often used to transmit torque, bring about gear changes and prevent motion in vehicle drivetrains. For heavy-duty equipment applications such as tanks, wet clutches are always under high energy density friction conditions and are required to possess excellent friction and wear characteristics, smooth engagement (anti-shudder), high reliability and a long operating life. As critical components in the clutch system, friction materials strongly affect the force transmission, energy loss and lifetime of clutches, and they ultimately influence the dynamic behaviors of an entire vehicle. Therefore, friction materials should possess an adequate friction coefficient and moderately low wear rate over a broad range of contact pressures and sliding velocities under oil lubrication [1,2]. Copper-based friction materials manufactured by powder metallurgy have been widely applied to heavily-loaded wet clutches because of their excellent mechanical, thermal and tribological properties. These materials can also withstand higher stresses and temperatures compared with paper-based materials and are fairly cheap to manufacture when compared with carbon-fiber materials in wet clutch applications [3–5].

During wet clutch operation, friction materials will undergo a range of loading and sliding speed conditions, leading to changes in lubricating conditions and tribological factors including the friction coefficient, wear rate and worn surface topography. Many studies have investigated these factors. It was found that the friction coefficient of a paper friction material for wet clutch applications increased with decreasing apparent contact pressure and sliding speed, and the wear rate increased with increasing hardness [2]. Marklund and Larsson [6] described wet clutch friction characteristics of sintered bronze using a simplified pin on disc test under different loads and sliding speeds. Ingram et al. [7] analyzed the effect of contact pressure and sliding distance on contact properties of a wet clutch friction material. However, these investigations were mainly confined to a relatively narrow (localized) range or for moderate levels of sliding. Current studies are inadequate for comprehensively understanding the global tribological behaviors of wet clutch friction materials under different operating conditions, especially under high power conditions.

It is well known that repetition of clutch engagements causes wear of friction materials. As a crucial factor in tribological performance, wear property of friction materials needs to be considered because it can determine the lifetime of a wet clutch. A more complete approach is to link wear rates and wear mechanisms over a much wider range of sliding conditions in the form of a wear map. A wear map not only presents wear data in a multi-dimensional graphical manner but also provides an overall framework for wear behaviors of a particular sliding system, into which individual wear mechanisms observed under various operating conditions may be fitted [8]. It can further represent mechanistic changes on the worn material and the counterface under different operating conditions, indicating potential "safe" and "unsafe" operating conditions for materials [9,10].

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http://dx.doi.org/10.1016/j.wear.2015.02.055
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There has been extensive work performed on constructing wear maps for steels [11] and new tribological materials such as copper-based SiC_p reinforced composite [12], AA7010 aluminum matrix composite [13] and TiC composite coatings [14]. However, very few studies have been published on wear maps for copper-based friction materials in wet clutches, especially under high energy density conditions. This may be due to the complex composition of the material and the complicated working procedure of wet clutches.

Most wear maps are obtained using a pin-on-disc or block-on-ring wear tester for ease of sliding [11–16]. However, these wear tests cannot realistically simulate the actual working process of wet clutches and limit operating energy. Therefore, an alternative ring-on-ring braking test system is necessary. This system would be able to realistically simulate operation conditions at high energy densities of 385 W/cm^2 compared with typical values of 115～200 W/cm^2 [17] and achieve actual repetition of wet clutch engagement.

In this study, wear tests were performed for a copper-based friction material against alloy structural steel in a ring-on-ring braking simulator under varying loads (1.0～3.0 MPa) and braking speeds (6.7～20.1 m/s). This copper-based friction material has been applied to tank's wet clutch. Characteristics of ultra-mild, mild and severe wear regimes were identified after analysis of collected wear data, worn surfaces, subsurface and wear debris. A wear map was developed to explain the main wear mechanisms involved in each studied condition. The critical load and braking speed for wear mechanism transition were clearly identified. These results make it possible to forecast the service life of copper-based friction materials in wet clutches.

2. Materials and experimental methods

2.1. Material preparation

Powder metallurgy was used to fabricate the copper-based friction material with the composition shown in Table 1. A high proportion of graphite (17～22 wt%) as lubricant were used to reduce wear in order to prolong the service life of this material. Low SiO_2 content (4～7 wt%) in the copper matrix was utilized to enhance the friction coefficient so that the friction material could transmit torque effectively. Table 2 shows the physical and mechanical properties of the copper-based friction material, which were relatively low due to the high mass fraction of ductile graphite. Microstructure of the copper-based friction material was observed by a Leica-Q550 metallurgical microscope as shown in Fig. 1, in which graphite (light black strips) and SiO_2 particles (dark black and angular particles) were uniformly dispersed in the copper matrix (light gold color). Graphite strips were distributed over the composite in layers, parallel to the vertical direction of compaction.

Table 1
Composition of the copper-based friction material (wt%).

Cu	Graphite	Zn	Sn	SiO_2	Others
54～70	17～22	3～5	3～6	4～7	3～6

Table 2
Physical and mechanical properties of the copper-based friction material.

Density (g/cm^3)	Brinell hardness	Compressive strength (MPa)	Elasticity modulus (GPa)	Transverse rupture strength (MPa)
4.05	16	30.89	3.75	10.98

2.2. Experimental methods

Wear tests were carried out under oil lubrication using a ring-on-ring braking test system (Fig. 2) with a load range of 1.0～3.0 MPa, a braking speed range of 6.7～20.1 m/s and a constant moment of inertia (0.1 Kg m^2). Energy density was able to reach the highest value of 385 W/cm^2. CD15W-40 diesel engine oil (Changcheng, China) was used for lubrication and flowed out from an oil outlet pipe installed above the contact face between friction pairs. As friction pairs engaged, the lubricating oil spread on the contact surface. The temperature of oil was controlled to be within 50～80 °C and the flow rate was 20 ml/ (min cm^2). The friction pairs of the copper-based friction material with alloy structural steel (0.27～0.35% C, 1.0～1.3% Cr, 0.5～0.8% Mn, 0.5～0.8% Si, 0.4～0.5% Mo, 0.3～0.4% V, $\leq$0.035% P, $\leq$0.03% S and Fe rest, HRC 40$\pm$2) as the counterpart were machined into rings with dimensions as shown in Fig. 3. A narrow contact area of the copper-based friction material was maintained by controlling the outer radius (R33.6 mm) and inner radius (R30.4 mm) (Fig. 3a) to keep each part of the contact surface with a desired constant sliding speed and pressure and realistically imitate a wet clutch. The surfaces of the friction material ring and steel counterpart ring were ground and polished before wear testing until surface roughness values (R_a) of 1.2 and 0.6 μm were obtained, respectively.

Wear testing was performed by accelerating the rotation shaft with the steel counterpart ring to the desired working speed. When the speed was reached, motor power was switched off and

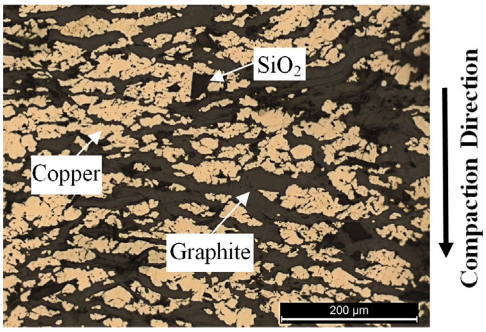

Fig. 1. Microstructure of the cross section of the copper-based friction material.

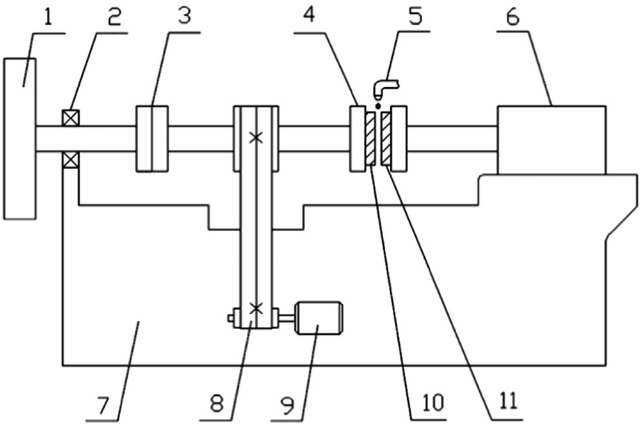

Fig. 2. A schematic diagram of the ring-on-ring braking test system�1 – flywheel; 2 – bearing; 3 – clutch; 4 – rotation shaft; 5 – oil outlet pipe; 6 – air cylinder; 7 – concrete base; 8 – feed belt; 9 – motor; 10 – steel counterpart ring; 11 – copper-based friction ring.