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Comparison of the thermophysical properties, microstructures, and frictional behavior of lining materials used in mine hoists

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ABSTRACT

Mine hoists for medium depth and deep mines in China rely on friction hoists. Proper function of the equipment involves controlled frictional contact between a rope and a lining. While there has been a lot of empirical testing of friction hoist materials, studies of the effects of their microstructure and basic properties on friction and wear have largely been neglected. Three commercial grade linings with similar compositions were investigated (trade names: K25, G30, and GM-3). Their thermo-physical properties were measured using XPS, FTIR and TGA. Their hardness and other properties were correlated with their microstructures and frictional behavior. The DTG curves of the three linings follow a similar pattern and their weight loss rate peaks occur in the second stage due to the cyclodehydration of phenolic hydroxyl and fracture of methylene. GM-3, which is highest content of inorganic filler, had the smallest weight loss. Reciprocating sliding friction and wear tests indicated that higher contents of methylene and filler improve the friction coefficient. Adhesive wear is observed when the friction material hardness is relatively low. When the sliding velocity increases, the friction coefficient of two of the linings (K25 and GM-3) increases, but that of G30 first rises then falls. The reasons for these differences in behavior are discussed.

1. Introduction

Hoist is important equipment used in the mining industry. This equipment transports mine materials, tools and workers, and connect the mineshaft and ground [1]. Medium-sized and deep mineshafts in China mostly use friction hoists. Friction hoist delivers power through the friction between steel rope and friction lining. Therefore, friction coefficients directly affect the performances of hoists such as their lifting capacity, efficiency and safety.

Friction lining, a typical viscoelastic material with good thermal stability, high coefficient of friction, low wear loss, oil resistance, water resistance, flame retardant and non-substances polluting the environment, harmful for human body and damaging wire rope, has been studied by many scholars. Most of these studies only focus on one particular friction property and its external influences [2,3]. However, only a few studies have been conducted to assess the relations between the microstructure and tribological properties of friction lining. Based on the study of the relationship between microstructures and tribological properties of friction linings and similar polymer materials, Guo et al. [4] found that the main wear mechanism of polyimide (PI) and acrylonitride butadiene styrene (ABS) is adhesive wear and the wear process products substantial friction heat due to its poor fluidity of internal molecular chain and huge intermolecular force; however, the main wear mechanism of high density polyethylene (HDPE) and ultra high molecular weight polyethylene (UHMWPE) is plastic flow and relatively small friction heat is produced in this wear process due to good flexibility of molecular chain and extremely small force among molecular chains. Dong et al. [5] discovered that under the effort of friction heat, the occurrence of the cyclic variation of softening, melting and flow at the friction interface of polyetheretherketone (PEEK) and low density polyethylene (LDPE) composite material results in the phenomenon of periodic fluctuation of friction coefficient. Yu et al. [6] indicated that the dependence relationship exists between friction coefficient of polytetrafluoroethylene (PTFE) materials and temperature; as sliding velocity increases, the contact surface temperature increases and friction coefficient decreases, however, when temperature resulting from friction heat reaches at a certain value, the rising temperature leads to the increase of friction coefficient; therefore, the lowest point exists in the curve of temperature and friction coefficient. Kim et al. [7] took phenolic resin as friction materials and proves that noise and friction vibration are more likely to be developed, and the stability of friction system would be gradually destroyed, as the hardness of friction linings increase. Moore et al. [8] introduced adhesion friction theory on rubbers

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and indicated that the friction mechanism of viscoelastic material is mainly adhesive and hysteresis frictions. Öztürk et al. [9] found that friction coefficient of ceramic and basalt fiber-reinforced hybrid friction material decreases as velocity and load increase and as temperature rises. Gopal et al. [10] studied the load, speed and temperature sensitivities of a carbon fiber-reinforced phenolic friction material and analyzed the effect of friction heat on its wear characteristics. Heinrich et al. [11] researched the dependence of the friction coefficient of tire rubber on load and velocity; during the process of tire friction, the occurrence of internal friction causes a huge quantity of friction heat to accumulate in the interface, this phenomenon consumes power and remarkably intensifies wear. Cong et al. [12] discovered that the wear of polyimide is a dynamic change process, meanwhile, friction heat and the status of friction interface present dynamic changes, and the molten layer on the surface of polyimide can reduce friction coefficient and wear loss. He et al. [13] and Fu et al. [14] found that because of small hardness, the primary friction mechanism of nitrile butadiene rubber (NBR) is adhesive friction, and friction coefficient is relatively large. Wan et al. [15] researched the relationship between hardness and tribological properties of high-hardness lining. Wang et al. [16] researched the thermal stability of lining, while the effect of the thermal stability on tribological properties is not tested.

In this paper, the microstructure and tribological properties of three friction linings commonly used in coal mines (K25, G30 and GM-3), are tested and compared. Meanwhile, the effects of the microstructure on the tribological properties are analyzed. The objective of this study is to select an excellent friction lining for hoist.

2. Experiments

2.1. Materials

The current experiment investigates three commercial friction linings, namely, K25, G30 and GM-3(Luoyang, China). These linings are widely used in mineshaft hoist in China.

Friction lining is a typical composite material composed of matrix, fillers and functional additives. At present, the matrix of friction linings in China is mainly phenolic resin modified by NBR. The fillers are montmorillonite, SiO_2 and other space fillers. Meanwhile, the functional additives are rubber additives, including cross-linkers, plasticiser, accelerator and antioxidant agent [17]. The XPS spectra of K25, G30 and GM-3 are similar (Fig. 1), which indicates that the element composition of three linings is similar, mainly C, N and O. The added inorganic fillers result in a few metallic element peaks. The results in Table 1 illustrate that G30 has relatively higher C element (72.91%). GM-3 has only 58.98% of C element and contains more Si, O and Cl than G30 and K25. It indicates that GM-3 has the largest amount of inorganic fillers (montmorillonite and SiO_2).

2.2. Methods

2.2.1. X-ray photoelectron spectroscopy (XPS) analysis

Electron spectrometer Escalab 250Xi (US) is used to analyse the element content on the surface of the linings. The X-ray excitation source is Al Kα ray, and the beam spot size is about 900 μm. The dimensions of the samples for this experimental analysis are 5 mm × 8 mm × 4 mm with a smooth surface.

2.2.2. Fourier transform infrared spectroscopy (FTIR) characterization

German Bruker's Vertex 80v FTIR-ATR is used to study the internal structure, organic functional groups and types of chemical bonds. The incident light scope of the tested spectrum varies between 3800 and 600 cm^{-1}. The resolution rate is 0.1 cm^{-1}, and the scan is repeated 32 times. The sample is a solid block.

2.2.3. Thermogravimetric (TG) test

TG of the three friction linings is performed in a Netzsch STA409C analyzer. The sample is powder and reference material is empty crucible. The experimental conditions are shown in Table 2. DTG records the TG curve and performs the first order difference calculation, acquiring the functional relationship between mass change and temperature.

2.2.4. Hardness test

The hardness of three linings is taken on a Shore durometer (D) with the standard GB/T2411-2008 (in China). The dimensions of the samples are 25 mm × 25 mm × 25 mm with a smooth surface. Measurements on bent or rough surfaces were avoided. Three samples of each lining were tested a minimum of five times with individual testing points spaced at least 6 mm apart.

2.2.5. Microstructure analysis

Hitachi S-3000N scanning electron microscopy is used to observe the internal microstructure of friction linings. This experiment also studies the effect of the filler on hardness and tribological properties.

2.2.6. Friction and wear test methods

The friction and wear of three linings are tested with UMT-II multi-functional micro-friction test machine according to coal industry standard MT/T248-91 and mechanical industry standard JB/T10347-2002 (in China). The experimental device principle is shown in Fig. 2. The lower sample is a friction lining material of 30 mm × 30 mm × 5 mm. The friction pair is a hemisphere indenter made of 0.45 wt% C steel (Baosteel Co., Ltd., Shanghai), and the movement mode is reciprocating sliding with in 10 mm. Each experiment is performed three times. After the test, a super-depth 3D microscope and JB-4C precision roughness tester are adopted to observe the wear surface and wear depth of friction linings and analyse wear mechanism. The experimental parameters are shown in Table 3.

3. Results and discussion

3.1. Chemical bond of linings

The FTIR spectra of three linings are shown in Fig. 3. The spectrograms show that K25 and G30 have more infrared absorption bands than GM-3, particularly when the wavelength is below 910 cm^{-1}. It indicates that K25 and G30 contain more group species, and thus the internal component is more complex. This is because K25 and G30 have less filler. In the spectra of the three linings, wide and blunt absorption band appears around 3330 cm^{-1}. Meanwhile, a strong C–O stretching vibration absorption band can be observed from 1250 to 1050 cm^{-1}. So the absorption band around 3330 cm^{-1} is association hydroxyl (O–H). The matrixes of three friction linings are mainly phenolic resin modified by NBR. Therefore, K25, G30 and GM-3 have benzene ring framework vibration absorption bands at 1595 cm^{-1}, 1610 cm^{-1} and 1609 cm^{-1}, respectively. Moreover, K25, G30 and GM-3 in 2921 cm^{-1} and 2851 cm^{-1}, 2918 cm^{-1} and 2850 cm^{-1} and 2920 $cm^{-1}$and 2850 cm^{-1} displayed anti- and symmetric stretching vibration absorption bands of methylene