Role of titanium carbide and alumina on the friction increment for Cu-based metallic brake pads under different initial braking speeds

Tao PENG, Qingzhi YAN*, Xiaolu ZHANG, Yan ZHUANG

Laboratory of Special Ceramics and Powder Metallurgy, School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

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Abstract: To understand the effect of abrasives on increasing friction in Cu-based metallic pads under different braking speeds, pad materials with two typical abrasives, titanium carbide (TiC) and alumina (Al_2O_3), were produced and tested using a scale dynamometer under various initial braking speeds (IBS). The results showed that at IBS lower than 250 km/h, both TiC and Al_2O_3 particles acted as hard points and exhibited similar friction-increasing behavior, where the increase in friction was not only enhanced as IBS increased, but also enhanced by increasing the volume fraction of the abrasives. However, at higher IBS, the friction increase was limited by the bonding behavior between the matrix and abrasives. Under these conditions, the composite containing TiC showed a better friction-increasing effect and wear resistance than the composite containing Al_2O_3 because of its superior particle-matrix bonding and coefficient of thermal expansion (CTE) compatibility. Because of the poor interface bonding between the matrix and Al_2O_3 , a transition phenomenon exists in the Al_2O_3 -reinforced composite, in which the friction-increasing effect diminished when IBS exceeded a certain value.

Keywords: high-speed train; friction mechanisms; brake pads; abrasives

1 Introduction

Cu-based metallic brake pads are now commonly used for trains running over 250 km/h. They are designed to stop the train at a safe distance. To meet this goal, pad manufacturers usually add some abrasives to the materials because they believe that abrasives can prevent the buildup of friction films on brake surfaces, enhance bite or engagement, and improve brake efficiency [1]. Generally, the selection of abrasives is dependent on their hardness, fracture toughness, size, shape, content, and aggressiveness against the mated disks [2, 3]. However, the principles behind the selection of abrasives for brake pad materials are poorly understood owing to the difficulty in

determining the exact role of abrasives on the contact surfaces of multiphase inhomogeneous materials. According to Hu et al. [4], the effect of abrasives on the friction performance not only depends on intrinsic factors such as mechanical properties, but also on external factors such as the shape and size of the abrasive particles as well as the operating conditions.

In the past, many studies have focused on hardness, fracture toughness, stiffness [3, 5–7], size, shape, and volume fraction of the abrasive [5, 8–11], as well as the operating conditions [12–16]. Among these studies, the abrasive was often reported to be associated with the removal of the friction film on the sliding surface and the increase in torque variation during braking, and was sometimes found to be responsible

* Corresponding author: Qingzhi YAN, E-mail: qzyan@ustb.edu.cn

for high disc wear [17, 18]. The hardness of the abrasive determines the penetration depth of the abrasive to the counterface; therefore, a harder abrasive leads to stronger plowing during rubbing [19]. The fracture toughness determines the fragility of the abrasive particles. Brittle abrasives are inclined to break into smaller particles during rubbing, which is responsible for the low coefficient of friction (COF) at high loads [3]. Interface bonding plays a decisive role in determining the holding strength of the matrix to abrasives. A higher interfacial bond strength could prevent the extraction of abrasives from the matrix and result in better resistance to abrasion [9, 20]. The size effects of abrasives have a complex influence on the friction and wear behaviors. Cho et al. [18] and Lee et al. [21] found that fine abrasive particles tended to remove the friction film and produce friction instability, while the coarse particles provided better friction stability but led to severe disc wear. Prabhu et al. [5] found that large-sized and high-volume fractions of abrasives provided better wear resistance and brake performance under high sliding speed conditions (140–200 km/h) for Fe/silica composites and Fe/mullite composites. As a reinforcement, the increase in the volume fraction of the abrasive is often associated with the improvement in the wear resistance of metal matrix composites [22]. However, there are also some counter-examples [23].

In studying the abrasives in the brake pads and their effects, Xu et al. [14] performed friction tests on polyimide-matrix composites with various silica powder contents of different sizes at various velocities (30–160 km/h). They found that the influence of silica content and powder size on the COF was directly related to the friction velocity, and reported that large silica (SiO_2) particles could effectively hinder the motion of the third body, contributing to a compact third body and the protection of the friction surface. Xiong et al. [16] investigated the effect of SiO_2 on the friction and wear behavior of Cu-based composites with rotating rates of 1,000–7,000 rpm (corresponding to 16–130 km/h) at a pressure of 0.5 MPa and a rotary inertia of $0.245 \text{ kg}\cdot\text{m}^2$. In their work, SiO_2 was reported to increase the COF and wear loss of friction materials at lower speeds, but the friction-increasing effect disappeared at higher speeds. They attributed the

results to the presence or absence of a friction film on the surface.

Although abrasives have attracted much attention, there is still a lack of knowledge on their effect on brake performance under high-speed braking. Currently, the running speed of high-speed rail has reached 350 km/h (corresponding to 65 m/s) in China, and higher operating speeds are likely in the future. Although the band-type brake is normally not activated until the train slows down to 200 km/h using electric braking, the brake pad is always required to have the ability to safely stop the train from its highest speed if the electric braking fails. The higher the running speed, the higher the braking energy and pad temperature. A large quantity of heat is consequently introduced into the brake system, and problems including matrix softening and fading have consequently occurred. At this point, the compatibility between the matrix and abrasives is an important concern that needs to be addressed before use in high-energy braking because interface debonding is usually the cause of delamination at high speeds. Therefore, exploring the role of abrasives at high braking speeds is important for solving the specific issues, such as fading, brought about by high-speed braking.

TiC and Al_2O_3 are widely used for manufacturing metallic friction composites, owing to their high hardness, high stiffness, good chemical stability, and excellent wear resistance. Both of them are superior to SiO_2 in terms of hardness and thermal conductivity, which can potentially provide increased performance in increasing friction and dissipating heat. They have been reported to play important roles in reinforcing composites or improving tribological performances [9, 15, 24–29]. However, there are some differences between them in terms of physical and frictional properties. In this study, pad materials with TiC or Al_2O_3 were produced and tested using a scale dynamometer to understand the effect on the friction increment of varying the type and volume fraction of abrasives under different braking speeds, especially when the speed is over 250 km/h. In addition, the relationship between the bonding of the particle-matrix and the frictional properties of the abrasives in the brake pad was particularly examined.

2 Experimental

2.1 Samples

Among the many abrasives used for commercial brake pad materials, TiC and Al₂O₃ were used to produce the pad materials. To highlight the effects of the abrasives, three groups of pad materials were designed (Table 1). The basic group (F0) in this experiment was produced based on a simple formulation with five ingredients, namely copper (Cu), iron (Fe), ferrochrome alloy (Cr–Fe), graphite, and molybdenum disulfide (MoS₂). Some parameters of the ingredients are given in Table 2. FTC and FAO were produced by keeping the formulation of the above five ingredients constant and using TiC and Al₂O₃ as abrasives, respectively. The specimens were prepared by powder metallurgy (PM). The ingredients were blended in a V-type mixer for 2 h. The blended powders were pressed into green bodies by a single uniaxial die compaction press under a pressure of 300 MPa. The green bodies were then sintered in a chamber furnace at 980 °C under a nitrogen–hydrogen (N₂:H₂ = 3:1 by volume) atmosphere for 1 h to avoid oxidation and ensure

full diffusion.

To characterize the compatibility between the matrix and abrasives, we also prepared specimens containing Cu, Fe, and abrasives using the same preparation process. The proportions of the three ingredients in these samples were identical to those in the corresponding pad materials. These samples were also divided into three groups: Basic (0), TC (TC-1, TC-2, TC-3), and AO (AO-1, AO-2, AO-3).

2.2 Braking tests

Braking tests were conducted on a single-ended inertial-type braking dynamometer (Fig. 1) under an ambient temperature of 30 °C and a relative humidity of 40% in the pad-on-disc configuration. More details about the test equipment can be found in Ref. [30]. The nominal contact surface area was 1,787 mm². The counter disc was 450 mm in diameter and 35 mm in thickness and made of forged steel (30CrSiMoVA) with a martensitic structure and 30–35 HRC hardness, which is one of the conventional materials in current high-speed trains in China.

Table 1 Compositions of the samples (by vol%).

Group	Sample	Cu	Fe	Cr–Fe	Graphite	MoS ₂	TiC	Al ₂ O ₃
Basic	F0	38.0	18.0	10.0	30.0	4.0	—	—
	FTC-1	37.3	17.6	9.8	29.4	3.9	2.0	—
FTC	FTC-2	35.7	16.9	9.4	28.2	3.8	6.0	—
	FTC-3	33.5	15.8	8.8	26.4	3.5	12.0	—
	FAO-1	37.3	17.6	9.8	29.4	3.9	—	2.0
FAO	FAO-2	35.7	16.9	9.4	28.2	3.8	—	6.0
	FAO-3	33.5	15.8	8.8	26.4	3.5	—	12.0

Table 2 Parameters of the ingredients.

Ingredients	Particle size (μm)	Purity (%)	Theoretical density (g/cm ³)	Melting point (°C)
Cu	4–7	99.5	8.93	1,083
Fe	10–18	99	7.87	1,535
Cr–Fe	120–250	98	5.08	1,774
Graphite	250–500	97	2.25	3,652
MoS ₂	18–48	99	5.06	2,375
TiC	0.8–8	99	4.94	3,065
Al ₂ O ₃	1–10	99	3.96	2,054

Fig. 1 Schematic diagram of the single-ended inertial type braking dynamometer: (a) external diagram; (b) inside diagram; (c) pad-on-disc configuration; (d) worn pads.

The experimental conditions corresponded to nine emergency stop brakings for high-speed trains running at 80, 120, 160, 200, 250, 300, 320, 350, and 380 km/h. In all cases, the initial braking speed (IBS), brake inertia, and mean contact pressure was chosen in conformity with the scale-conversion rule [31]. The brake inertia was set as 27 kg·m², corresponding to 16 tons of mass to be stopped per disc in a real train, and the normal pressure was 1.27 MPa.

Braking tests were performed by accelerating the rotation shaft with the steel counterpart disc to the desired working speed. When the speed was reached, the motor power was switched off and two fixed metallic pads were simultaneously pressed against the steel counterpart at the desired normal pressure and a mean friction radius (R_m) of 155 mm until the rotation shaft completely stopped. The mean friction radius was determined using the equation $R_m = (R_1 + R_2)/2$, where R_1 and R_2 are the inner radius and outer radius of the friction track, as shown in Fig. 1(c). During each test, the

relevant parameters were measured as follows:

1) The transient COF and mean COF were automatically calculated by the computer system based on the friction force (F) and normal force (N), in which the friction force (F) was calculated by dividing the friction torque (T) by the mean friction radius (R_m). The friction torque was measured by the torque sensor, and the measurement accuracy and sampling frequency were 0.01 N·m and 100 Hz, respectively.

2) The subsurface temperature of the pad was measured using a thermocouple located 2 mm beneath the contact surface within the pad. The thermocouple was mounted into a prefabricated hole with a depth of 10 mm.

3) The pad wear was measured by checking its weight, M , before and after each test using an analytical balance with an accuracy of 0.01 g. Before each weighing, we used a banister brush to remove the debris from the pad surface. The data were then converted into wear volumes, V , using

the measured density of the pad. The specific wear rate, W_r , was determined from the wear volumes normalized by the dissipated energy E_s , using Eqs. (1) and (2):

$$E_s = \pi^2 J n^2 / 1,800 \quad (1)$$

$$W_r = V / E_s \quad (2)$$

where J and n are the rotational inertia and rotation speed, respectively.

Before each test, we conducted ten run-in brakings with an IBS of 160 km/h and a normal pressure of 1.27 MPa to ensure a favorable contact surface between the pad and disc. To ensure the reliability of the experimental data, the braking test at each IBS was repeated three times, and the mean value (mean COF, mean wear loss) of three is reported in this work.

2.3 Characterization methods

The physical properties and mechanical properties of the pad samples, including the density, relative density, and hardness, were tested. The density was determined using Archimedes' principle, and the relative density was calculated from the density divided by the theoretical density. The Brinell hardness of the initial pad was tested on a hardness tester in accordance with GB/T 231.1-2009. A high-temperature three-point bend test setup was used to assess the compatibility between the matrix and abrasives. This method has been widely reported in the field of diamond grinding tools, in which the bending strength was used to indirectly represent the holding force of the matrix to diamond [32–34]. This test was conducted on a universal testing machine at 600 ± 3 °C based on GB/T 14390-2008. The size of the specimens for the bending strength testing was 3 mm × 4 mm × 36 mm and the crosshead speed was 0.5 mm/min. The average value of the high-temperature bending strength (HTBS) for five specimens is reported.

A scanning electron microscope (SEM) with energy dispersive X-ray spectrometry (EDS) was applied to examine the particle-matrix interface bonding, the surface morphologies of the friction pads, and the wear debris after the friction tests. The acceleration voltage, electron beam diameter, and beam current used in these experiments were 20 kV, 10 nm, and

80 μ A, respectively. The estimated depth of the X-ray penetration for different elements was between 0.5 and 2 μ m based on the Win X-ray Monte Carlo software. X-ray diffraction (XRD) measurements were carried out to identify the crystalline phases in the friction surface.

3 Results and discussion

3.1 Physical and mechanical properties

The typical physical and mechanical properties of the abrasive particles used in this investigation are listed in Table 3. TiC is superior to Al_2O_3 in terms of modulus of elasticity and fracture toughness, while the Mohs hardness of the two compounds is comparable [35, 36]. The coefficient of thermal expansion (CTE) of TiC is higher than that of Al_2O_3 , and the ratio of the CTE of the TiC/matrix is lower than that of the Al_2O_3 /matrix, which means that the thermal stress at the interface of the TiC/matrix is less than that at the interface of the Al_2O_3 /matrix at elevated temperatures. Based on the contact angle data (Table 3), it is observed that both abrasives exhibit poor wettability by Cu [37, 38]; TiC shows better wettability by Fe than Al_2O_3 [37, 39] because there is a reciprocal transport of atoms between the molten Fe and TiC, which is not the case for molten Fe and Al_2O_3 [37].

Figure 2 shows the backscattered electron image (BSE) of the sintered samples, in which the components are indicated based on the EDS identification. Note that some components, such as graphite, Cr-Fe particles, and Al_2O_3 , preserved the original appearance of the particles. The abrasives are dispersed within the matrix, as shown in the bottom insert pictures.

Table 4 shows the physical and mechanical properties, including density, theoretical density, relative density, porosity, and Brinell hardness, of the samples in this investigation. The relative density and porosity decreased and increased, respectively, with the increase in abrasive content, which can be attributed to the increase of particle-matrix interface. For a given abrasive content, the FTC samples possessed a higher relative density and lower porosity than the FAO samples, which may be associated with the

Table 3 Physical parameters of the abrasives investigated in this study [35–39].

Type	Density (g/cm ³)	Modulus of elasticity (GPa)	Mohs	Fracture toughness (MPa·m ^{1/2})	CTE, linear (10 ⁻⁶ /K)	Contact angle by Cu (°)	Contact angle by Fe (°)
TiC [35]	4.94	448–451	9.0–9.5	4.5	7.7 (25 °C)	127 [37]	40 [37]
Al ₂ O ₃ [36]	3.96	370	9.0	2.2	5.5 (25 °C)	130 [38]	128 [39]

Fig. 2 Back scattered electron image (BSE) of starting samples: (a) F0; (b) FTC-1; (c) FTC-2; (d) FTC-3; (e) FAO-1; (f) FAO-2; (g) FAO-3. The bottom left inset shows a high magnification image of the matrix.**Table 4** Physical and mechanical properties of braking pads.

Group	Sample	Density (g/cm ³)	Theoretical density (g/cm ³)	Relative density (%)	Porosity (%)	Brinell hardness (HB)
Basic	F0	4.57	6.37	71.7	16.3±0.2	12.7±0.7
	FTC-1	4.52	6.34	71.3	16.3±0.6	11.0±0.8
FTC	FTC-2	4.37	6.28	69.6	17.4±0.7	13.1±1.8
	FTC-3	4.26	6.19	68.8	18.9±0.5	13.1±0.6
	FAO-1	4.42	6.32	69.9	16.9±0.7	12.1±1.5
FAO	FAO-2	4.18	6.21	67.3	18.3±0.5	12.8±1.0
	FAO-3	3.90	6.06	64.4	20.1±0.8	12.0±0.1

relatively poor interface bonding between the matrix and Al_2O_3 . This will be discussed further in a later section. The Brinell hardness was very low and nearly identical for all the samples.

3.2 Bonding between the matrix and abrasives

As mentioned in Section 2.1, specimens containing only Cu, Fe, and the abrasives were prepared. Line profile analysis was used to identify the element distribution in the particle-matrix interface and to assess the interface bonding between them, as shown in Fig. 3. In the case of FTC, there was an obvious gradient transitional layer with a thickness of $2.65\text{ }\mu\text{m}$ at the Fe/TiC interface, within which the concentrations of Fe and Ti varied gradually. However, the Cu/TiC interface was abrupt, as can be seen with the sharp increase/decrease of the distributions of Cu and Ti (Fig. 3(a)). For FAO, the elemental concentrations displayed obvious saltation at the Cu/ Al_2O_3 and Fe/ Al_2O_3 interfaces with a thickness of about $1.32\text{ }\mu\text{m}$ (Fig. 3(b)). Considering the detection precision of the EDS instrument (about $0.5\text{--}2\text{ }\mu\text{m}$ estimated by Win X-ray Monte Carlo software in our work), these phenomena indicated that the interfaces of the TiC/matrix were hybrid mechanical-diffusional bonds, while the interfaces of the Al_2O_3 /matrix were merely mechanical bonds. This was in agreement with the investigation of Ref. [37] and the wettability behaviors, as reported in Table 3.

To further investigate the bonding between the matrix and abrasives and to satisfy the service conditions (high temperature induced by high-speed braking) as much as possible, high-temperature ($600\pm 3\text{ }^\circ\text{C}$) bend tests were performed on the specimens

containing Cu, Fe, and abrasives. The results are shown in Fig. 4. Note that the point corresponding to 0% represents the HTBS of the basic sample (containing only Cu and Fe). The tests suggested that the HTBS of TC was higher than that of AO. The HTBS of TC with different TiC volume fractions showed little difference, while the HTBS of AO decreased with an increase in the volume fraction of Al_2O_3 . We also found that the gap between the HTBS of TC and AO expanded gradually with the volume fraction. Based on the results, it was concluded that the interface bonding of the TiC/matrix was superior to that of the Al_2O_3 /matrix. In addition, because of the weak interface of the Al_2O_3 /matrix, the decline in the HTBS of AO with the increasing volume fraction of Al_2O_3 resulted from the increased interfacial contact.

3.3 Braking behaviors

Figure 5 demonstrates the mean COF as a function of IBS at the same pressure and inertia for different samples. It was noted that the mean COF increased after the addition of abrasives, suggesting the friction-increasing effect of both TiC and Al_2O_3 in the composite pads. Nevertheless, the two types of abrasives contributed to distinct friction and wear performances under different IBS values. Additionally, with the increase in IBS, the COFs of all the samples increased initially, followed by a decrease until the IBS exceeded a certain value. This decline at high braking speed is commonly called “fading”.

To highlight the effects of abrasives on friction, the COF increments derived from adding abrasives

Fig. 3 Line profile analysis of composite showing distribution of different elements: (a) TC-1; (b) AO-1.

Fig. 4 High temperature bending strength (HTBS) as a function of volume fraction for the specimens containing only Cu, Fe, and abrasives.

Fig. 5 Mean COF as a function of initial braking speed (IBS) for different samples.

were calculated based on the subtraction of F0 from FTC and FAO in the COFs, and the results (Δ COFs) are shown in Fig. 6. In the case of FTC, the Δ COFs generally increased with increasing IBS, except for a slight decrease from 320 to 380 km/h for FTC-3. The Δ COFs increased with an increase in the volume fraction of TiC. Moreover, in most cases, the higher the volume fraction of TiC, the higher the growth rates of Δ COF versus IBS. For FAO samples, there were some turning points in the Δ COF versus IBS curves, where the Δ COFs increased first and then decreased with the increase in IBS. In addition, the turning point was lower for samples with a higher volume fraction of Al_2O_3 . Specifically, there was no turning point in the

Δ COF vs. IBS curve with regard to FAO-1. However, when the volume fraction of Al_2O_3 increased to 6% (for FAO-2), the curve appeared as a turning point at 300 km/h, and for FAO-3, the turning point appeared at 250 km/h. When IBS was less than the turning points, FAO exhibited similar Δ COF behaviors with FTC in the magnitudes and growth rates, irrespective of the volume fraction. However, when IBS exceeded these points, the higher the volume fraction of Al_2O_3 , the greater the fading rate of Δ COF. The Δ COFs decreased with the volume fraction of Al_2O_3 when IBS was higher than 350 km/h.

These findings suggest that TiC and Al_2O_3 possessed a similar friction-increasing effect when the sliding condition was moderate, while they played different roles in the composites when the sliding condition exceeded certain limits. This will be discussed in a section below.

Figure 7 shows the maximum subsurface temperature (T_{max}) as a function of IBS. The T_{max} increased linearly with the IBS for all samples. However, it was difficult to reach any conclusions regarding the influence of the type and content of abrasives on the T_{max} , since there are only small differences between the T_{max} –IBS curves of different samples.

Two distinct wear behaviors versus IBS with regard to FTC and FAO are shown in Fig. 8. The wear rates of the samples with different TiC contents were nearly equal, and they were approximately the same as that of F0, suggesting similar wear mechanisms between FTC and F0. The wear rates of FAO were higher than those of FTC and F0 for all IBS. With

Fig. 6 Friction increments (Δ COFs) of abrasives as a function of IBS for different samples.

Fig. 7 Maximum subsurface temperatures ($T_{\max}$) of the pad as a function of IBS for different samples.

Fig. 8 Wear rate as a function of IBS for different sample.

the increase in Al_2O_3 content, the wear rate slightly increased when the IBS was < 250 km/h and sharply increased when the IBS was > 250 km/h.

3.4 Frictional surface characterization

Figure 9 shows representative morphologies of the friction surfaces at 380 km/h. It should be noted that the corresponding area of each component is marked in the graph based on EDS identification. For all the samples, the smooth plane was a tribo-oxide film, which was formed by mechanical mixing and compaction of the oxides during friction. In addition, peeling pits, furrows, and graphite particles can be clearly seen on the surface. Other components such as Cr-Fe particles were difficult to recognize because of the coverage of the tribo-oxide film. All of the samples displayed typical delamination wear, although there were also many furrows on the

surfaces of the FTC. The delamination was of two distinct types with regard to FTC and FAO. FTC showed a relatively mild delamination characterized mainly by small peeling pits (Figs. 9(b)–9(d)), while FAO showed a serious delamination characterized by a large fracture zone (Figs. 9(e)–9(g)). Note that FTC and F0 seemed to exhibit a similar failure mode, where the graphite/matrix interface acted as the source of the delamination fracture (Figs. 9(a)–9(d)), as we described in Ref. [40]. The similar failure mode may be responsible for their nearly equal wear rates. However, the source of the delamination fracture may be generated within the Al_2O_3 /matrix interface, which can be demonstrated by the fact that numerous Al_2O_3 particles were distributed around the edge of the fracture zones based on the EDS identification (Figs. 9(f)–9(g)). This phenomenon was probably related to the poor interface bonding between the matrix and Al_2O_3 , as stated in Section 3.2.

With the increase in abrasive content, the amount of furrows increased on the surface of the FTC (Figs. 9(b)–9(d)), suggesting enhanced plowing effects resulting from third-body abrasives. For FAO, the fracture zone expanded with increasing Al_2O_3 content, manifesting as an increased wear rate (Fig. 8).

In our previous work [30], the wear regime of pad composites subjected to different IBS was divided into three levels: mild wear ($W_r \leq 10^{-5} \text{ mm}^3/\text{J}$), moderate wear ($10^{-5} \text{ mm}^3/\text{J} < W_r < 10^{-4} \text{ mm}^3/\text{J}$), and severe wear ($W_r \geq 10^{-4} \text{ mm}^3/\text{J}$) based on the wear rate. Abrasive, plow, and oxidative wear were the key wear mechanisms when IBS was less than 250 km/h. The main wear mechanism was transformed to delamination as IBS exceeded 250 km/h. In this study, the previous conclusions are also applicable to F0, FTC, and FAO because of their similar compositions and test conditions. Thus, the main wear mechanisms of F0 and FTC might be abrasive wear and delamination when $\text{IBS} \leq 300$ km/h and > 300 km/h, respectively, while the division between the two wear mechanisms was at 250 km/h with respect to FAO (Fig. 8).

To further explore the compositional variation of friction surfaces after the 380 km/h braking test for different samples, XRD measurements were carried out, and the patterns are shown in Fig. 10. Con-

Fig. 9 Representative morphologies of the friction surfaces at 380 km/h: (a) F0; (b) FTC-1; (c) FTC-2; (d) FTC-3; (e) FAO-1; (f) FAO-2; (g) FAO-3 (the bar scale is the same for all the images).

sidering the delamination wear at 380 km/h, XRD patterns mainly represented the region exposed on the surface, such as tribo-films, peeling areas, and protruding abrasives. In the case of FTC, Cu and graphite were the major phases, followed by Fe_3O_4 and Cu_2O . The minor phases were Fe, FeO, TiC, $\text{Cu}_2\text{V}_2\text{O}_7$, and CuFeS_2 (Fig. 10(a)). The presence of $\text{Cu}_2\text{V}_2\text{O}_7$ indicated material transfer from the disc to the pad surface because there was no V in the composition of the pad. There seemed to be no

difference in the peak intensities of any of these phases in samples with different TiC contents, except for a slight increase in the intensity of the TiC peak with increasing TiC content. In addition, the phase compositions of FTC were similar to those of F0. Combined with the friction surface morphologies (Figs. 9(a)–9(d)), it can be concluded that the wear mechanism of FTC was similar to that of F0 at 380 km/h, both of which showed a similar failure source for delamination fracture. In

Fig. 10 XRD patterns of the friction surfaces at IBS of 380 km/h: (a) FTC; (b) FAO.

comparison to the phase composition of F0, Cu and Fe peaks were prominent in FAO, while the oxides and graphite peaks were inconspicuous. In addition, the intensity of the Al_2O_3 peak slightly increased with increasing Al_2O_3 content.

Based on the above results, we speculated that, in the cases of FTC and F0, the graphite/matrix interface acted as the source of delamination fracture, resulting in the exposure of graphite particles on their worn surfaces, which may be the cause for the conspicuous graphite peak in their patterns. However, in FAO, the weaker peak intensity of graphite as well as numerous Al_2O_3 particles at the edge of the fracture zones (Figs. 9(f)–9(g)) suggest that the Al_2O_3 /matrix interface, rather than the graphite/matrix interface, acted as the preferential site for delamination fracture with regard to FAO.

3.5 Role of abrasives under different IBS

According to the above results, the role of abrasives can be elucidated as follows: with the increase of IBS, the matrix became ductile owing to the rise in surface temperature above the softening temperature of copper (approximately 190 °C) [41], while TiC and Al_2O_3 were still tough and acted as hard points to provide additional friction force. Thus, the friction-increasing effect became more significant as the sliding speed increased, characterized by an increase in ΔCOF with increasing IBS (Fig. 6). Moreover, with a higher volume fraction of abrasives, the increase in friction was greater because of the increasing number of hard points. TiC and Al_2O_3 exhibited similar friction-increasing behaviors before the turning points (Fig. 6), which may be attributed

to their similar hardness.

This tendency disappeared when IBS exceeded a certain threshold, represented by the turning points in the ΔCOF –IBS curves with regard to FAO (Fig. 6). At higher braking speeds, a number of issues, such as the softening of Fe, plastic flow, adiabatic shearing, thermal mismatch, and heat fatigue cracking, become more significant. These have a negative influence on the holding capacity of the matrix to the abrasive, which restricts the effect of the abrasives in enhancing friction. At high IBS, the primary wear mechanism was delamination (Fig. 9), which resulted from crack initiation and propagation on the particle–matrix interfaces through stress concentration and interface debonding, as shown in Fig. 9, Section 3.4. The addition of abrasive particles inevitably introduces additional particle–matrix interfaces, which facilitates the formation of delamination damage. Therefore, both friction and wear performance are closely related to the particle–matrix interface bonding at high IBS.

In the case of FTC, which possessed a good particle–matrix interface bonding, the holding capacity of the matrix to TiC was better, and TiC particles were difficult to eject from the braking system during friction. Therefore, the friction-increasing effect of TiC can be maintained even at higher IBS values (Fig. 6). In addition, owing to the good TiC/matrix bonding, cracks were difficult to initiate and propagate within the TiC/matrix interface (Figs. 9(b)–9(d)). In this case, FTC and F0 presented a similar crack propagation path during high-speed braking, as supported by Figs. 9 and 10(a) and illustrated by a schematic diagram (Fig. 11(a)), which may be

Fig. 11 Schematic of wear damage within the subsurface for different samples during high speed braking: (a) FTC; (b) FAO.

responsible for their low and comparable wear rates.

For FAO, however, owing to the poor interface bonding and thermal mismatch of the Al_2O_3 /matrix, the cracks were more inclined to propagate along with the Al_2O_3 /matrix interface, leading to the easy removal of Al_2O_3 particles from the matrix (Figs. 9(f)–9(g)). Thus, when subjected to high-speed braking, there were numerous defects within the near-surface region of the composite. At the point when IBS exceeded the turning points, the weak subsurface neither retained Al_2O_3 particles nor withstood intensive sliding contact. Energy, therefore, was easily dissipated by crack propagation and delamination (producing a new interface) [42], leading to the decline of ΔCOF (Fig. 6). The transition to this phase took place at lower IBS in the composites with a higher volume fraction of Al_2O_3 , although the decline in ΔCOF was not obvious in FAO-1. This is because the higher volume fraction of the abrasive introduced a higher amount of particle-matrix interface, providing more paths for crack nucleation, propagation, and delamination (Fig. 11(b)). It was also responsible for the sharply increased wear rates with the increase in volume fractions of Al_2O_3 when IBS was higher than 300 km/h (Fig. 8).

4 Conclusions

The effect of the abrasives on the friction and wear performances was affected by the combination of

the type, volume fraction, and IBS.

When IBS was no more than 250 km/h, owing to lower friction heat, both TiC and Al_2O_3 acted as hard points and exhibited similar behaviors in increasing friction, where the friction-increasing effect was not only enhanced as IBS increased, but also increased by increasing the volume fraction of the abrasives.

When IBS exceeded 250 km/h, because of the matrix softening and deformation caused by high temperature and stress, FTC showed a better friction-increasing effect and wear resistance than FAO owing to its superior particle-matrix bonding and CTE compatibility. In the case of FTC, the friction-increasing effect and a relatively low wear level were maintained even at higher IBS. For FAO, there were turning points in the ΔCOF versus IBS curves, after which the friction-increasing effect of Al_2O_3 diminished with the increase in IBS.

The volume fraction of abrasives affected the friction and wear behaviors mainly by controlling the number of hard points and particle-matrix interfaces in the composites. Before the turning points, the friction-increasing effect was increased by increasing the volume fraction of the abrasives; after these points, particle-matrix bonding behavior was predominant. The IBS corresponding to the turning point was lower in the composites with higher volume fractions of Al_2O_3 .

Under different IBS, two wear regimes, that is,

moderate wear and severe wear, were found in FTC and FAO with dividing points of 300 km/h and 250 km/h, respectively. The wear rates of FTC were comparable to those of F0 and lower than that of FAO for any IBS. On the other hand, the wear rate was not affected by the volume fraction of TiC for FTC, while it increased with the volume fraction of Al₂O₃ for FAO, especially in the severe wear regime.

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Tao PENG. He received his Ph.D. degree in materials science and engineering from University of Science and Technology Beijing,

China, in 2020. His research is focused on the friction and wear mechanisms of Cu-based friction materials.

Qingzhi YAN. She received her Ph.D. degree in materials science and engineering from University of Science and Technology Beijing, China, in 2005. After then, she joined the Laboratory of Special

Ceramics and Powder Metallurgy at University of Science and Technology Beijing. Her current position is a professor. Her research is focused on the high-performance Cu-based friction materials and metal-matrix and ceramic-matrix materials used in nuclear power.