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# TRIBOLOGICAL AND THERMAL BEHAVIOR OF WAGON BRAKE SHOES SLIDING AGAINST WHEEL MATERIAL

**Adler Armelini Furlan**

**Rubson Mação Camporez**

Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 – Vitória, Espírito Santo  
[adler.furlan@edu.ufes.br](mailto:adler.furlan@edu.ufes.br), [rubsonmc@gmail.com](mailto:rubsonmc@gmail.com)

**Manuelle Curbani Romero**

Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 – Vitória, Espírito Santo  
[manu.curbani@gmail.com](mailto:manu.curbani@gmail.com)

**Cherlio Scandian**

Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514 – Vitória, Espírito Santo  
[cherlio@gmail.com](mailto:cherlio@gmail.com)

**Abstract.** Metal pickup (MPU) is a phenomenon commonly observed in braking systems of railway wagons. The sliding between the wheel and the brake shoe causing friction heating can often lead to the formation of an iron layer on the shoe surface reducing the friction coefficient and accelerating wear. This paper aims to investigate the effect of this metallic layer adhered to the surface of the brake shoe on the wear, friction and contact temperature of the shoes when sliding against the wheel. Pin-on-disc sliding wear tests were carried out in Plint TE67 tribometer. Pins made from brake shoes with and without adhered metallic film were tested with discs made from steel wheels. The contact temperature was measured during the test using an infrared thermographic camera. The metallic film was characterized by optical microscopy (OM) and microhardness. The identification of the different constituents of the shoe pads and its composition were obtained using energy dispersive X-ray spectroscopy (EDX) and OM. Wear mechanisms were determined using OM. An analytical method for the calculation of contact temperature was developed using the test contact geometry. Experimental temperature results were compared to those obtained from the analytical method. The metallic film decreased the friction coefficient and affected contact temperature. The analytical model results presented a good agreement with the experimental values.

**Keywords:** brake shoe, sliding wear, contact temperature, wheel-rail contact, friction.

## 1. INTRODUCTION

Shoe braking is widely used on railway systems due to its low cost, simple configuration and easy maintenance. During braking, the brake shoe is in directly contact with the wheel, dissipating the high kinetic energy of the vehicle mainly through frictional heat (Mazzu *et al.*, 2019, Lyu *et al.*, 2018).

Brake shoes used to be made of cast iron due to its high thermal conductivity that allowed to rapidly dissipate frictional heating. However, this materials disadvantages include high noise levels and high occasional friction coefficients, justifying its substitution with organic composite materials, which overcome these drawbacks (Lyu *et al.*, 2018). Basically, this composite is made of binders, such as rubber and phenolic resins, reinforcing fibers, friction modifiers, which can be lubricants or abrasives, curing agents and fillers (Day, 2014, Wasilevski, 2017).

The wear of brake shoes should not go along with a decrease of performance triggered by a change of materials properties or contact surface during service. However, it is frequently observed the formation of a metallic layer adhered to the brake shoe surface resulting in brake shoes end of service life. According to Blau and Meyer (2003), this film has a complex and heterogeneous structure.

The formation of this metallic film during braking is known as metal pick-up (MPU). According to Lange and Ostermeyer (2011), debris that are generated, participate in the contact, contributing to friction coefficient, but later leave the contact. In this case, debris can help to establish a mild wear regime in which a positive regeneration of sliding surface occur. However, when those debris particles are metallic, their beneficial effect is minor, given that they firmly adhere to the surface and do not leave the contact, increasing friction coefficient.

Lewis and Olofsson (2009) pointed out that with the sliding, the metal adhered to brake shoe surface become reddish and hot, resulting in composite burning and microscopic melt wear of the wheel tread.

Kalousek *et al.* (1995) proposed that the metallic particles are originated previously to braking, in the wheel-rail contact. Wheel-rail wear is oxidative, generating iron oxides as debris. This wear particles, when entering the wheel-shoe

contact are subjected to high temperatures and abundant carbon sources, enabling the reduction of oxide particles and the adherence of metallic particles to the brake surface. When this metallic film is finally removed, it results in large craters in shoes surface.

Furthermore, Crosa and Baumvol (1993) highlighted that wear mechanism of the brake shoe-wheel pair also has an important thermal contribution, which involves chemical and physical reactions occurring in the surface. The high temperatures that take place at the asperities, which form the real contact area, can lead to the decomposition of the shoe's organic components, as well as transforming microregions of the pearlitic wheel into hard and brittle martensite. This later phenomenon is known as hot spots.

When braking occurs and the kinetic energy is transformed, the heat is portioned between the brake and the wheel according to the partition factor. Determining the heat partition factor, i.e., the division of heat between the stationary body (brake shoe) and the sliding body (wheel), as well as the resultant temperature field is vital to the comprehension of this pair wear process (Tudor and Khonrashi, 2006).

Heat partition and the flash temperature concept have been investigated by many authors (Block, 1937, Newcomb, 1960). The flash temperature is associated with the very high temperatures (superior to 1000°C) that takes place at the asperities during contact, which can last microseconds. This temperature increase during sliding depends on the boundary conditions applied to the Fourier's law for heat conduction, which allows to calculate flash temperature increase of bodies with uniform heat distribution and with several contact geometries (Bushan, 2001).

Besides, nominal temperature also increases. During the first braking cycle, the surface temperature increases, but there is no enough time to cool before the second braking cycle, thus increasing the nominal temperature. The heat is then transferred by conduction through the nominal contact area or is dissipated by convection in the wheel case. For the shoe, which is stationary, the nominal temperature increase is determined by unidirectional heat conduction to the interior of the body (Bushan, 2001, Kennedy, Lu and Baker, 2015). It is also important to considered time scale. How long it takes for the pair shoe-wheel reach thermal equilibrium once heat partition factor is a transient function (Vernesson, 2007).

Analytical solutions have been used to determine temperature distribution and indicated that the brake shoe can act as a thermal insulator, thus the heat is entirely transferred to the wheel. Other experiments showed that 3 to 5% of the heat is transferred to the organic composite brake shoes (Tudor and Khonrashi, 2006).

A literature gap was identified with respect to the experimental effect of the metallic layer on the friction and wear of the shoes and how it influences the contact temperature increase. Therefore, this paper aims to examine the effect of the metallic adhered layer on the friction, wear and temperature distribution of the brake shoe-wheel pair. Sliding wear tests were carried out in shoes with and without metallic adhered film and the temperature was monitoring through a thermographic camera. An analytical temperature model was developed and its results were compared to the experimental measurements.

## 2. EXPERIMENTAL

### 2.1 Materials

Pins were obtained from commercial wagon brake shoes. Two different conditions were studied: without metallic film adhered, made from new brake shoes, and samples with metallic film adhered to the brake shoe surface, acquired from brake shoes at the end of service life. Brake shoe's composition was determined by energy-dispersive x-ray spectroscopy (EDS).

Disc were machined from wagons wheel. The wheel's composition is presented in Table 1.

Table 1. Wheel (disc) chemical composition. Adapted from Association of American Railways.

Chemical composition (%wt.)	Elements												
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Al	Ti	Nb
	0.67-0.77	0.6-0.9	0.03 max.	0.005-0.04	0.15-1	0.25 max.	0.25 max.	0.1 max.	0.04 max.	0.35 max.	0.06 max.	0.03 max.	0.05 max.

### 2.2 Methods

Pin-on-disc friction and wear tests using pin-on-disk configuration were performed on a PLINT TE67 tribometer (Phoenix Tribology, Kingsclere, England). Tests were carried out at 0.8 MPa, sliding speed of 0.9 m/s and dry environment to simulate in-service conditions (Almeida *et al.*, 2016). The sample rate was 10 Hz. Surface temperature was monitored using an infrared thermographic camera with an acquisition rate of 20 Hz.

Before each test, pin and disc were cleaned with soap and water, ethanol on ultrasound for 10 min, then weighed (Sartorius CP 225D analytical balance, resolution: 0.01 mg). The mass loss was converted to volumetric loss through density of the materials. Worn surfaces were characterized by optical microscopy (OM, Nikon Eclipse MA200).

The microstructure of the pin, disc and metallic film were analyzed using a Nikon Eclipse MA200 microscope. Brinell hardness of the disc and Vickers microhardness of the metallic film were carried out.

### 2.3 Temperature analytical model

Based on Kennedy et al. (2015) work, the contact temperature ( $T_c$ ) has three contributions and can be calculated by the following equation:

$$T_c = T_{amb} + \Delta T_{ss} + \Delta T_f \quad (1)$$

Where  $T_{amb}$  is the ambient temperature,  $\Delta T_{ss}$  is the nominal temperature rise in steady state and  $\Delta T_f$  is the flash temperature rise.

The heat generated per unit of area of contact by the sliding of surfaces,  $q_{total}$ , is calculated as follows:

$$q_{total} = \mu p v \quad (2)$$

Where  $\mu$  is the friction coefficient,  $p$  is the contact pressure and  $v$  is the sliding speed. In this model, it is assumed that all the friction energy is dissipated as heat. A portion of this total heat is transferred to the pin ( $q_{pin}$ ) and the rest to the disc ( $q_{disc}$ ).

$$q_{total} = q_{pin} + q_{disc} \quad (3)$$

The rectangular contact was approximated to a circular contact with  $R_{pin}$  radius as follows:

$$R_{pin} = \sqrt{\frac{A_{pin}}{\pi}} \quad (4)$$

Thus, the radius of the contact area ( $a$ ) was calculated:

$$a = \left( \frac{3WR_{pin}}{4E^*} \right)^{1/3} \quad (5)$$

$$\frac{1}{E^*} = \frac{1 - \nu_{pin}^2}{E_{pin}} + \frac{1 - \nu_{disc}^2}{E_{disc}} \quad (6)$$

Where  $W$  is the normal load,  $E$  is the young's modulus and  $\nu$  is poisson coefficient. The Hertz contact pressure ( $P$ ) is calculated:

$$P = \frac{3W}{2\pi a^2} \quad (7)$$

Using Fourier's law for heat conduction and the applied boundary conditions (sample geometry, stationary or movement sample), flash temperature rise for the pin (rectangular shape approximated to a circular contact) ( $\Delta T_{f-pin}$ ) and for the disc ( $\Delta T_{f-disc}$ ), nominal temperature rise for the pin ( $\Delta T_{ss-pin}$ ) and for the disc ( $\Delta T_{ss-disc}$ ):

$$\Delta T_{f-pin} = 3\pi q_{pin} a / 8k_{pin} \quad (8)$$

$$\Delta T_{f-disc} = 2.32 q_{disc} a / k_{disc} \sqrt{\pi(1.234 + Pe)} \quad (9)$$

$$\Delta T_{ss-pin} = q_{pin} l_p 4a^2 / k_{pin} d^2 \quad (10)$$

$$\Delta T_{ss-disc} = \frac{q_{disc} a^2}{h * r^2} \quad (11)$$

Where  $a$  is the radius of the real contact area of the pin,  $k$  is the thermal conductivity,  $l$  is the thickness,  $Pe$  is the Peclet number,  $r$  is the radius disc radius and  $h$  is the heat convection coefficient.

According to Block's postulate,  $T_c$  is assumed to be the same for the pin and the disc ( $T_{c-pin} = T_{c-disc}$ ), thus heat partition factor can be calculated as follows:

$$\alpha = q_{pin}/q_{disc} \quad (12)$$

Therefore:

$$q_{pin} = \frac{\alpha}{1 + \alpha} q_{disc} \quad (13)$$

### 3. RESULTS AND DISCUSSION

Brake shoe semi-quantitative chemical composition result is presented in Table 2. Calcium content is probably due to the presence of calcium silicate as reported by several authors (Lyu, 2018, Blau, 2002, McIntyre and Holinski, 2003). According to McIntyre and Holinski (2003), fibers like calcium silicate are used as substitutive of asbestos, reducing noise levels while maintaining the same performance. Barium and Sulphur contents can be attributed to the presence of barium sulphate that are used to reduce cost and improve manufacturability (Eriksson and Jacobson, 2000). Oxides can also be present to maintain a constant friction coefficient (McIntyre and Holinski, 2003) and to act as abrasives to offer better rubbing surfaces by removing iron oxides films that could eventually be formed (Blau, 2002), this could account for the presence of Zr and Zn. Iron content can be attributed to the presence of steel fibers that improves thermal conductivity or to metal sulfides that have a lubricant role (Crosa, 1993, McIntyre and Holinski, 2003).

Table 2. Brake shoe (pin) chemical composition.

Chemical composition (% wt.)	Elements						
	Ca	Ba	Fe	Zr	S	Zn	K
	34.49	28.96	21.62	7.86	4.37	1.87	0.39

Brake shoe surface is shown in Figure 1. It can be observed the different phases present. Brighter particles are seen and probably metallic particles. The darker phase is the binder, possibly constituted of phenolic resin and rubber.

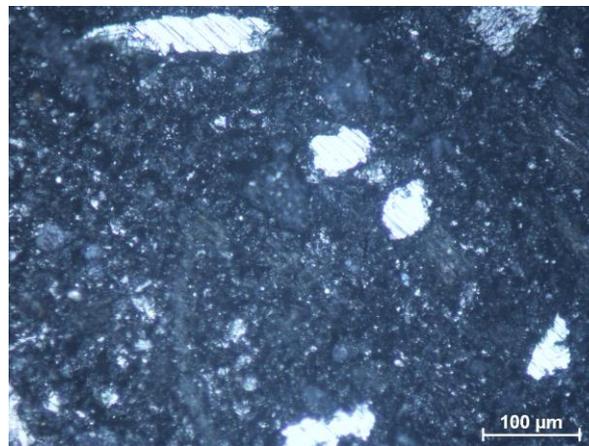


Figure 1. Brake shoe surface image obtained by OM.

Figure 2 (a) shows the microstructure of the metallic film adhered to the brake shoe surface. It can be observed that the grain size is smaller than 5  $\mu\text{m}$ . This film is highly deformed during the several braking cycles and together with the high temperature that take place during the contact, grain refinement occurred. The film has a pearlitic structure and proeutectoid ferrite grains are also seen. Figure 2 (b) shows the microstructure of the wheel (disc). The material contains pearlite, proeutectoid ferrite and upper bainite, which is in accordance with what was previously reported by other authors for railway wheel materials (Rezende *et al.*, 2020, Li *et al.*, 2019, Zhang *et al.*, 2020).

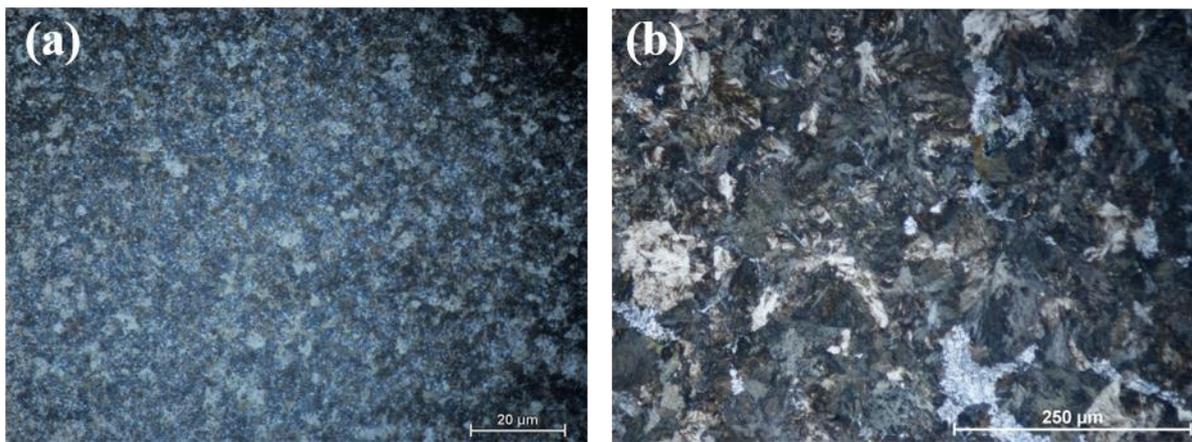


Figure 2. (a) Metallic film microstructure and (b) wheel microstructure.

The Brinell hardness of the disc was  $338.2 \pm 20.8$  HB and the microhardness of the metallic film was  $389.9 \pm 25.9$  HV<sub>0.1</sub>.

Figure 3 shows the friction coefficient evolution and measured temperature with test time for the brake shoe samples without metallic film adhered. It can be observed a long running-in period in which the friction coefficient increases with test time, reaching around 1.2. Later, the friction decreases until reaching steady state value around 0.7. Measured temperature also increased with test time during running-in and later stabilized. It should be underlined that running-in period ended when occurred a temperature stabilization. A similar behavior was observed by Cho et al. (2008) when investigating potassium titanate filler effect on the tribological response of organic composite brake shoes. The authors showed a friction stabilization in high temperatures. At temperature higher than 200 °C, organic phenolic resin shows glass transition, increasing chain mobility and weakening chemical bonds between polymeric chains, which can weaken the bonding between matrix and fillers, facilitating fillers removal. Thus, the brake shoe turns into an inorganic, less sensitive to sliding temperature material (Cho et al., 2008). Besides, rubber is also an additive used in brakes. It is known that with temperature increase, rubber is more prone to elastic deformation, increasing friction coefficient, but at higher temperatures it decomposes, decreasing the friction (Antonyraj and Singaravelu, 2020). Even though, the measured temperature is lower than the necessary for rubber and phenolic resin decomposition, it should be considered that this temperature is measured a few millimeters (around 5 mm) away from the contact.

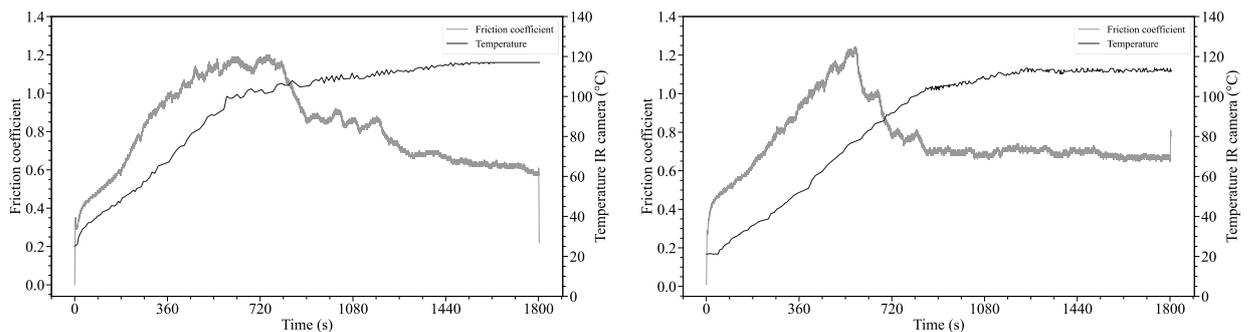


Figure 3. Friction coefficient and measured temperature as function of time – Brake shoe without metallic film adhered (a) sample 01 (b) sample 02.

Figure 4 shows the evolution of friction coefficient and measured temperature as a function of test time for the brake shoe with metallic film adhered samples. Differently from what was observed for the brake shoes, this condition has a short running-in period. Recorded temperature rapidly stabilized and were lower than in the other studied condition. Friction coefficient was around 0.6. Despite the difference between steady state friction coefficients were not that different for the two studied conditions, they show a large difference during the first 1080 s. Regarding the real in-service condition, this behavior is important since the brake shoe operates in an intermittent manner. Hence, every time it is activated, it goes through a new running-in period. The metallic film adhered changes brake shoe tribological response.

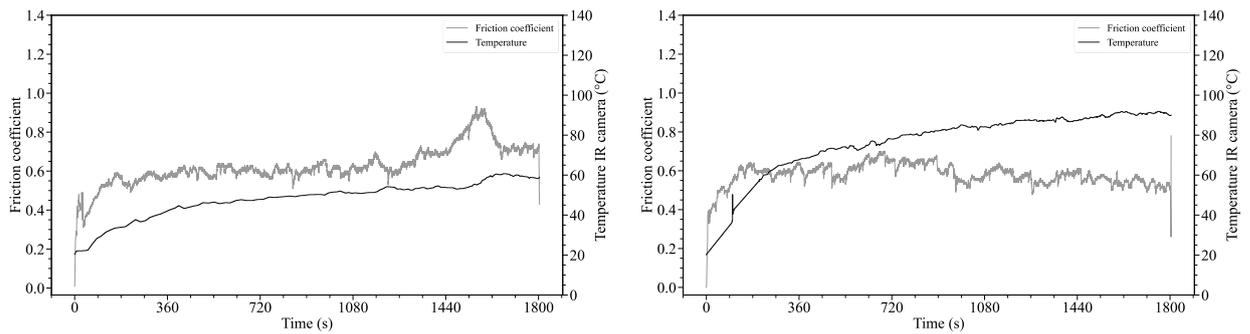


Figure 4. Friction coefficient and measured temperature as function of time – Brake shoe with metallic film adhered (a) sample 01 (b) sample 02.

It is possible to approximate the contact temperature using the analytical temperature model proposed by Kennedy et al. (2015) described previously. As can be seen in Figure 05, calculated contact temperature for the brake shoe samples is higher than with the metallic film, following the same tendency that the nominal temperature observed in experimental tests. When the metallic film is present, the thermal conductivity of the pin is increased, enabling a rapid heat dissipation. Contact temperature of the brake shoe is superior to 380 °C, which could explain the friction behavior due to phenolic resin and rubber decomposition.

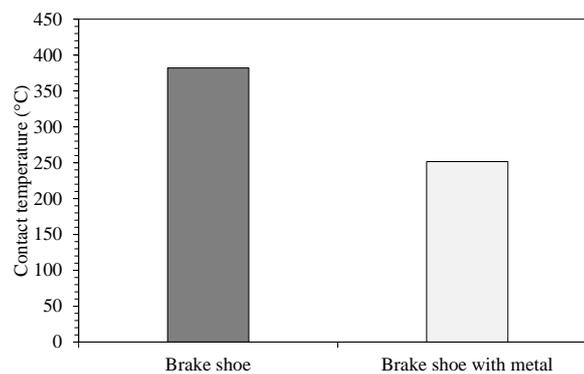


Figure 5. Analytical contact temperature model results.

The wear rate is presented in Figure 06. It can be observed that when the metallic adhered film was present, the wear rate was 6 times higher. The metallic film is worn out in the form of large particles composed not only of the metal but also of the polymeric bulk. A similar behavior was reported by Lange and Ostermeyer (2011). Figure 07 shows the wear micro mechanisms that took place during the test. In both images, it can be seen the presence of abrasion grooves possibly due to the action of metallic debris and abrasive fillers in the contact. It could be possible to observe in the brake shoe surface that the matrix was preferably worn, thus the fillers were in a different depth, making different to focus the MO imaging.

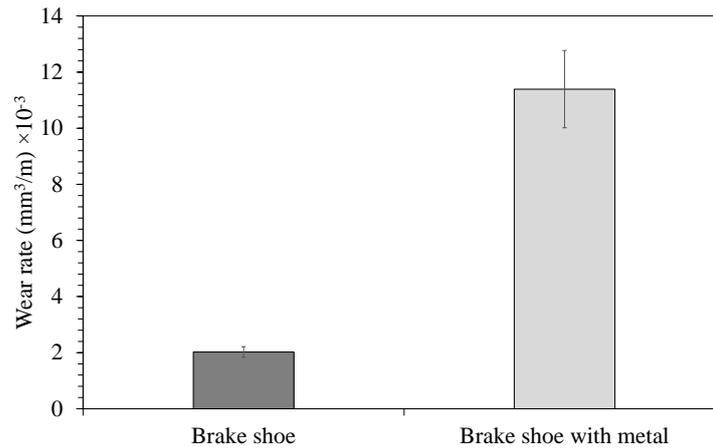


Figure 6. Wear rate for both studied conditions.

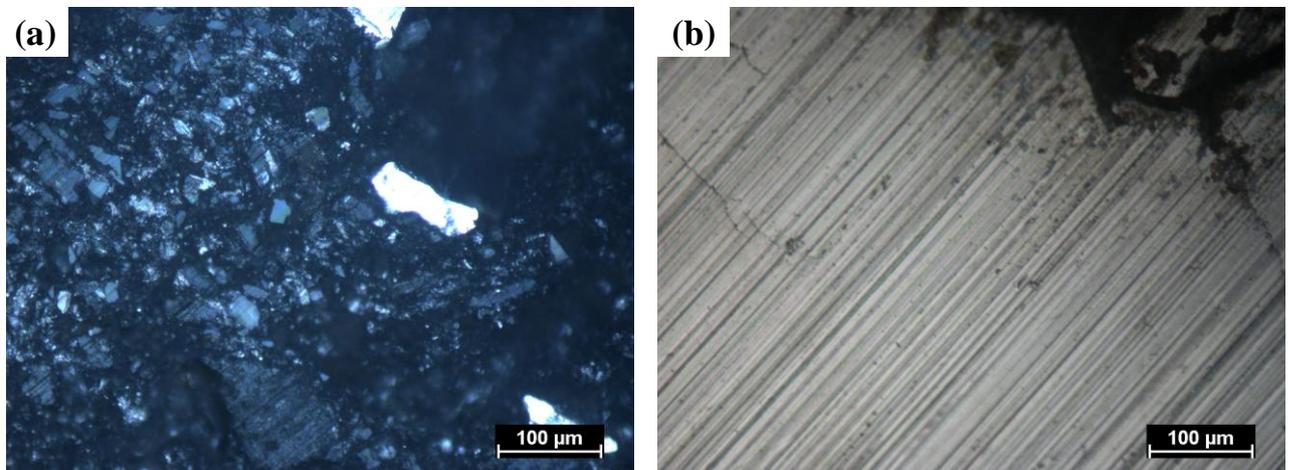


Figure 7. Wear micro mechanisms (a) brake shoe and (b) brake shoe with metallic film adhered.

#### 4. CONCLUSIONS

The adherence of metallic film in the brake shoe surface modified the friction and wear behavior. In the absence of the metallic film, a long running-in period is observed in which the friction coefficient reached 1.2, however, when this film was present, the friction coefficient rapidly stabilized around 0.6. Besides, the film led to a higher wear of the brake shoe and to large particles removal. Using the analytical contact temperature model, it was possible to identify that the temperature reached at the contact was superior to the measured by the IR camera and was high enough to result in rubber and phenolic resin decomposition.

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