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Toward a different aspect of polymer matrix friction composite worn surface structures

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Abstract

Brake friction composites are required to have a stable tribological behavior under moderate and severe braking conditions. To understand the factors that govern friction behavior, it is necessary to figure out the worn structure in the different conditions. The present study aims to enhance the comprehension of the evolution of pad surface's micro-structure at different braking applications. For this reason, a commercial copper-free polymer matrix brake pad was tested against a grey cast iron rotor based on the SAE J661 standard. Wear surface was studied by scanning electron microscopic (SEM) and an interferometer. Two main regions were observed upon wear surface named high land and low land. High land itself consists of three regions called contact plateaus (primary, secondary type one, and two) and low land which are introduced as micro-slot. The formation of the friction layer strongly depends on the variation of wear structure. A slight change in the worn structure led to variation in friction layer effective parameters which affect the friction coefficient.

Keywords brake pad, wear mechanism, polymer composite, friction layer, wear structure

Introduction

The friction behavior of the vehicle's brake system is dependent on three parts: pad surface, disc, and friction layer which is formed between the brake pad and disc [1]. From the historical point of view, friction surface was only investigated by the study of the disc's wear surface without any attention to the pad's surface, while the pad is composed of a variety of materials including polymers, minerals, metals, and ceramics [2][3][4].

Also, it has a complicated and special wear behavior. The aforementioned composition of brake pads is categorized into four main groups: binders, reinforcements, modifiers, and fillers [5].

Friction composites are divided into three types: metal matrix, ceramic matrix, and polymer matrix [6]. Researchers have mainly focused on the polymer matrix one due to its ease of processing [7]. On the other hand, for high-speed applications, racing cars, and aircraft, ceramic and metallic matrix composites are mainly used for the brake pad system.

Duo to The variety of raw materials in the composition of brake pads (that could reach up to 25 different materials) besides the affecting parameters on the process of brakings, such as temperature, pressure, and properties of the wear surfaces, make it complicated to be investigated [8][9][10][11][12].

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The surface of the brake pad is rough due to the existence of several materials with diverse mechanical properties.

The most important factors in evaluating the performance of brake pads are the friction characteristics of the worn surface and the friction layer which is formed between the worn surface and disc surface. Wear surfaces are comprised of two regions including CP (or high-land areas) and micro-slot (or low-land areas). CP is comprised of two surfaces, named primary contact plateaus and secondary contact plateaus [1]. The latter is classified into type I and type II secondary contact plateaus [13]. Primary contact plateaus include hard particles and fibers like steel fibers which are protruded from brake pads surface and act as a barrier opposed to wear debris [14]. Due to the impact of temperature and applied shear force, primary contact plateaus will be compressed over time and they will be changed to type I secondary contact plateaus. It is also possible for some secondary contact plateaus to be formed independently of primary contact plateaus, which are type II secondary contact plateaus [15]. Another important point that must be considered is that besides the contact plateaus, forming of friction layer on contact plateaus is vital for controlling the friction coefficient [16][17][18].

Dr. Österle et al [19], he has been claimed that wear properties are dependent on friction layers. It has been estimated that friction layers' particles are in the nanoscale and their size is in the range of 100 to 1000 nanometers. In order to investigate the characteristics of brake pads' wear structure with polymeric matrix in different conditions, it is necessary to evaluate the surface by non-destructive tests. For this reason, using scanning electron microscope for surface observation is a common method. Also, a white light interferometer is used to measure the brake pad's surface topography. Considering the mentioned above and the importance of wear structure during brake application and friction layer in friction performance of brake pads with polymeric matrix, the main objective of this research is to present a Comprehensive wear structure that governed the friction of coefficient characteristic of the brake pad with polymer matrix copper-free Low Metal composition.

2- Experimental methods

2-1: materials and sample preparation

Friction materials, which were used in this research, were Copper-free Low Metal ones, mainly including Phenol formaldehyde resin, steel fibers, Aramid fibers, Potassium titanite (K2TiO3), Alumina, Mica, Graphite, and Barite. Brake pads specimen are prepared based on these steps: mixing, primary shaping, final shaping (hot pressing), and thermal treatment (final baking). The mixing step was done by an electrical mixer (3600 rpm) with two choppers in 15 minutes. Then, friction materials were shaped (primary shaping) under the pressure of 30 bars for 10 seconds at room temperature. Considering that during the baking of Phenol formaldehyde resin, which is a polymerization and condensation reaction, water, will be one of the products of this chemical process. The water vapor must be evacuated from the system; otherwise, the final products will be inhomogeneous with different defects. Therefore, during the hot press of friction materials in the mold, pressure will be applied in a cyclic mode. In this way, materials will not experience any pressure at different intervals, and the water vapor and other undesirable gas products will be evacuated from the system. The high-temperature shaping cycle which was used in the research is based on the following:

Press cure time = (w+x).y+z

In this equation, "w" is the pressure time (s), "x" is the evacuation or not-applied pressure time (s), "y" is number of "(w+x)" repetitions, and "z" is the final pressure time which is different from "w".

2-2: Test equipment for friction properties and tribological characteristics

Friction properties of the evaluated composite were investigated based on the SAE J661 standard and by chase dynamometer (Figure 1).

Drum brake has been made of grey cast iron, like the brake discs of vehicles. In order to measure the temperature, a thermocouple is used at the back of the drum brake, and the test results including temperature, applied force, friction force, and the variations of friction coefficient by temperature could be observed on a computer's display which is connected to the test equipment. Different stages are included in this test for the evaluation of friction properties based on the SAE J661 standard, such as burnishing, first baseline, first fade, the first recovery, wear, second fade, second recovery, and second baseline. Details of this test on chase dynamometer equipment are mentioned in table 1.

2-4: Study of wear surfaces

In order to study the composite's wear surface after testing and characterize the contact plateaus' morphology and wear debris, SEM and EDX were used (TESCAN VEGA//XMU SEM). Also, to evaluate the topography of the wear surface, an interferometer was applied (MOZZA made by Fanavari Kahroba Company).

Table 1 Chase testing schedules according to SAE J661.

Stage	Speed (rpm)	Temperature(°C)		Load (N)	ON time (s)	OFF time (s)	application	On/Off
		Min	Max					
Burnishing	312		93	440	1200	-	1	
First baseline	417	82	93	667	10	20	20	
First fade	417	82	288	667	600	-	1	Heater
First recovery	417	260	93	667	10	rest	1	Blower
Wear	417	193	204	667	20	10	100	
Second fade	417	93	345	667	600	-	1	Heater
Second Recovery	417	317	93	667	10	rest	1	Blower
Second baseline	417	93	93	667	10	20	20	

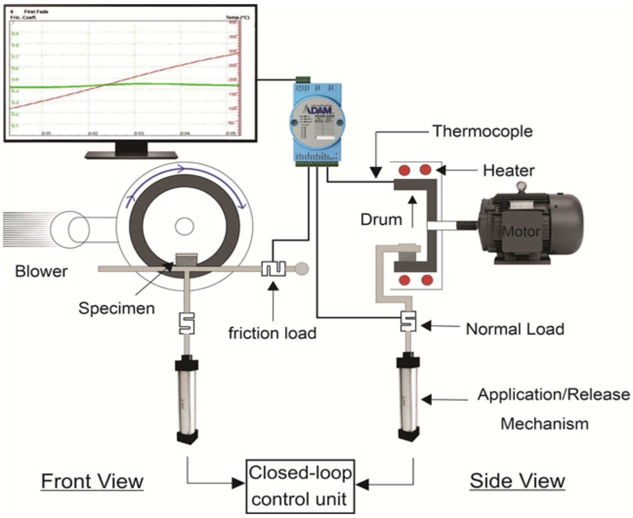

Fig. 1 Schematic representation of the friction test device (Chase dynamometer).

3- Results and Discussion

SEM image of the specimen's wear surface after performing the aforementioned stages of friction test based on SAE J661 standard is shown in Figure 2. Four regions could be observed in this image. Region A is attributed to primary CP, which is mainly comprised of protruded steel fibers and abrasion-resistant hard debris. Region B is ascribed to type (I) of secondary contact plateaus, region C is related to type (II) of secondary CP, and D is micro-slots or low lands regions. Generally, all brake pads composites with the polymeric matrix are comprised of the aforementioned regions and due to the variation in wear structure, such as area, type of distribution, number of CPs, and the mechanism of friction layer formation caused diversity in the friction propensity [20][21].

The three-dimensional image of the wear surface's topography obtained by the interferometer is shown in Figure 3. Micro-slots in this image is due to difference in the height of contact and non-contact areas were formed which let wear debris enter to and exit from the worn structure. Also, it is worth mentioning that such micro-slots make gas products, which are produced by the decomposition of organic materials, enter the atmosphere and leave the system. In Figure 4a, a schematic of the mentioned process is illustrated. On the other hand, the lower thermal resistance of friction composite led to faster decomposition of phenolic resin which caused increasing wear debris detachment of worn surface. Over detach causes agglomeration of debris in the micro-slots due to the pressure and friction heat that is blocking the micro-slots (fig-

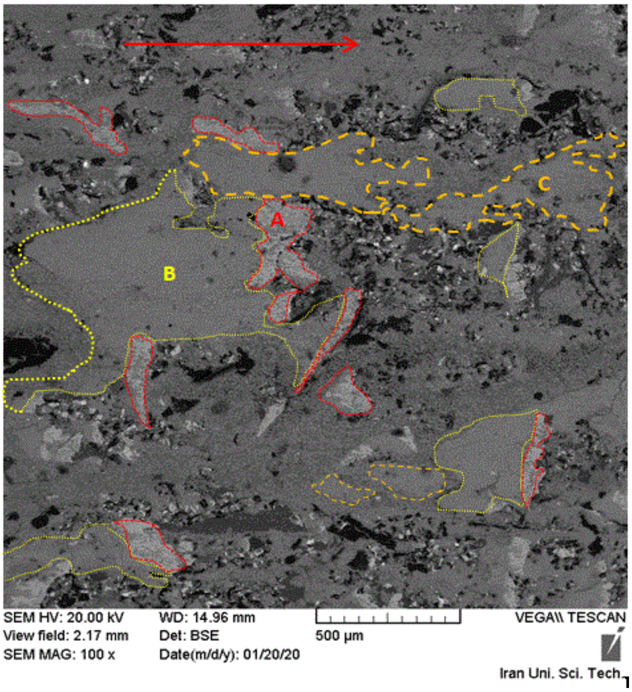

Fig. 2 wear structure of pad's worn surface.

ure 4b). Blocked micro-slots turn to the contact area (secondary) and decrease the low lands that less generated heat by friction can dissipate from the wear surface which increased the decomposition rate of organic ingredients and led to friction coefficient deterioration.

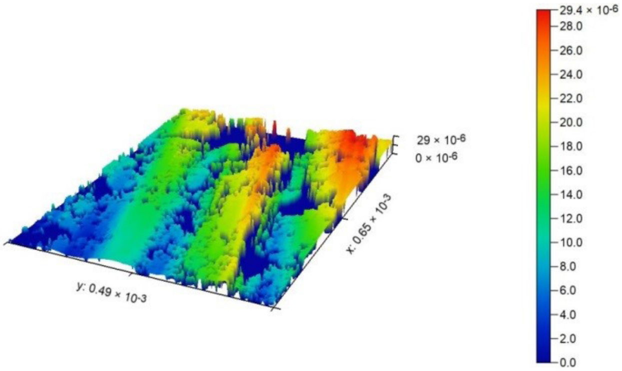

Fig. 3 3D image of pad's worn surface (The axes are in meters).

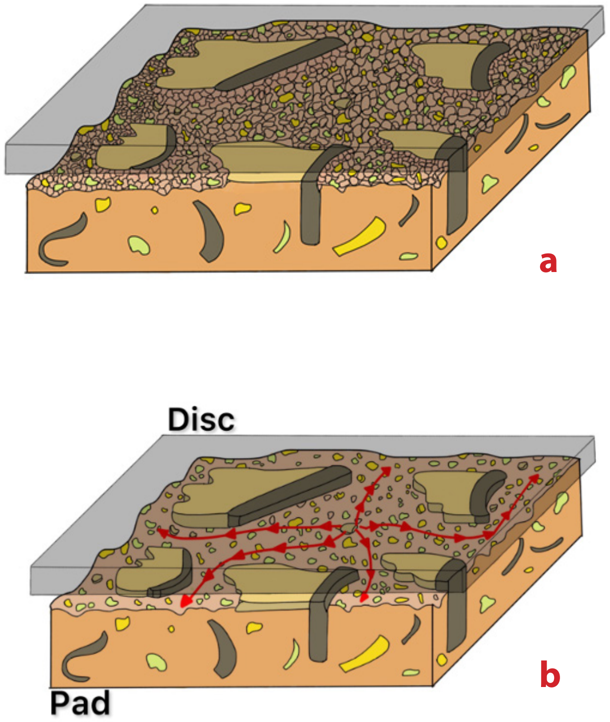

Fig. 4 Wear structure of pad's surface a) moderate condition and b) severe condition (high temperature).

As mentioned in the earlier sections, the wear mechanism of brake pads composites is complicated due to the impact of a plethora of parameters on the final friction properties. In Figure 5, the SEM images of primary CPs and secondary type I CPs are depicted. Yellow lines show friction layer which is formed on the primary CPs. Chemical analysis of A and B regions, which are respectively related to friction layer and primary CP, are mentioned in Table 2. Region A is the residue of the friction layer which is formed on the primary CP (region B). According to Table 2, differences between some elements like Mg, Si, S, Fe, Ti, and O are totally sensible. These elements are representing the materials that are affecting the formation and stability of the friction layer. For example, Ti is the representative of Potassium titanite, which is mainly used as an alternative for copper in the composition of friction composites materials [22]. Potassium titanite acts as a friction modifier agent in elevated temperatures [23]. Also, S in chemical analysis indicates that metal sulfide exists in the composition and it is responsible for lubrication improvement in high temperatures stabilization of friction coefficient. In order to achieve a stabilized friction coefficient, it is necessary to make a balance between solid lubricant materials and abrasive debris. The process of friction layer formation on CPs is dynamic and it includes nucleation, growth, and deterioration stages. CPs and friction layers could be destroyed through different mechanisms like third body abrasion and erosion with hard debris or could be destroyed by collision into the disc's rough surface [8]. The structure of wear surfaces is influenced directly by friction force, normal load, abrasion rate, and surface temperature.

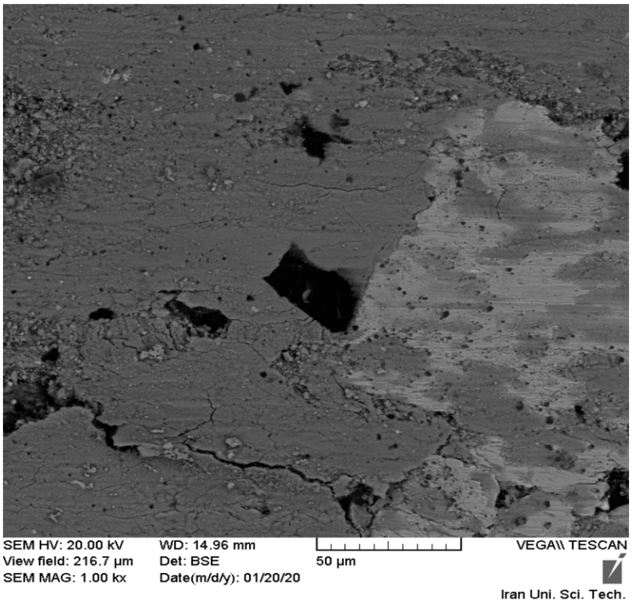

Fig. 5 Wear mechanism of pad's worn surface

In our previous study, the impact of friction layer formation on CPs in different stages of wear test was investigated [24]. Other important points which must be studied are the structure of the worn surface and the mechanism of its impact on the friction layer and friction properties. CPs and disc surface never directly in touch with each other on the microscopic scale.

Table 1 EDS analysis performed at different points.

Elements	A (Wt. %)	B (Wt. %)
C	6.87	5.98
O	29.68	2.94
Mg	1.31	0.15
Al	0.86	0.45
Si	1.62	0.09
S	1.57	0.23
K	0.98	0.17
Ca	1.04	0
Ti	1.77	0
Fe	51.86	88.26
Sb	0.62	0.22
Ba	1.81	0.34

CPs and disc surface make indirect contact through friction layer which is known with other names as tribofilm, third body layer, transfer layer or film, tribo-layer, and friction film [25]. The friction layer is placed between the disc surface and brake pad or more precisely, between the disc and CPs. The friction layer is dynamic and will be altered due to the impact of different parameters such as temperature, pressure, friction force, and composition. Abrasive particles are embedded in the friction layer with a specific thickness between two bodies (pad surface and disc surface). This model was introduced by Williams et al [8]. However, this model hasn't illustrated the exact mechanism of contact between embedded abrasive particles and wear surfaces (CPs and disc surfaces). The friction layer is a mixture of the soft matrix (solid lubricant and decomposed organic materials) and abrasive particles. The soft matrix prevents direct contact of abrasive particles to the CPs and disc surface which is illustrated in figure 6. Therefore, a stable friction layer requires a perfect balance between friction modifiers (solid lubricants and abrasives) to prevent less damage to the wear surface.

Microscopic evolution of wear structure and friction layer is the main reason for friction coefficient oscillation. Figure 7 shows the friction coefficient variation at the second fade stage according to the SAE J661 standard test procedure. At the begging of the test, the friction layer starts to nucleate and growth.

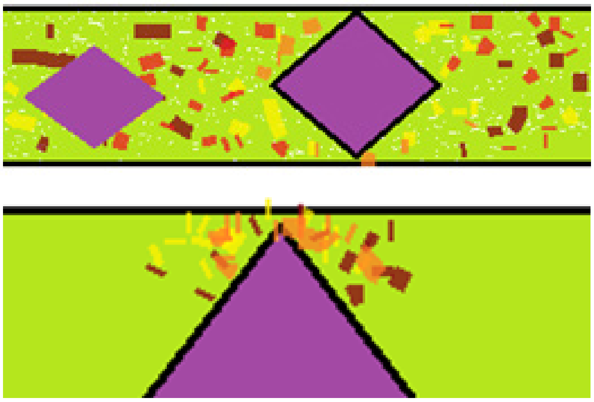

Fig. 6 Contact mechanism of abrasive particle embedded in friction layer.

In the following by increasing the temperature, polymer matrix starts to decompose which led to detachment of wear debris from pad surface and caused increasing friction layer thickness. Thickening of friction layer brings out abrasive particles without effective contact with wear surface just float in the soft matrix that led to a dramatic drop in friction coefficient at the elevated temperature which is known as a fade phenomenon. In the recovery process, by reducing the temperature and removing most of the wear debris through the micro-slots and the pad surface friction layer thickness is reduced and a relative balance is established between the friction modifiers in the friction layer that bring about an increase in friction coefficient.

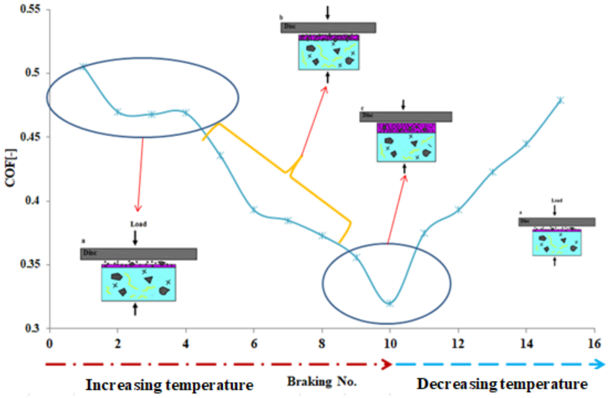

Fig. 7 Relationship between micro-evolution of friction layer and variation of friction coefficient.

4- Conclusion

The wear structure and friction layer evolution of polymer matrix friction composite were investigated. Where different temperature conditions during friction test were applied on the brake pad specimens. Variation of wear structure during brake application governs the effective parameters on friction layer which led to diversity in friction coefficient. Micro-slots as a low land that help to air circulate through the worn surface during brake service and also help to remove wear debris from the pad surface. Over detachment of wear, debris blocked the micro-slots and brings out generated heat by friction trapped in the worn surface which increases the decomposition rate of organic ingredients. Over decomposition of organic materials mainly resin phenolic led to more detachment of wear debris from the worn surface (sudden increase in wear rate) increased the CPs area and also increment the thickness of friction layer. Thickening of friction layer has a negative impact on effective contact between abrasive particles and wear surface which causes fading of frictioncoefficient.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: Feb. 2022 Accepted: Mar. 2023
Published online: Apr. 2023

DOI: 10.22034/ASAS.2023.401033.1022

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