Case Studies on Characterization of Brake Pad Surfaces Using Scanning Electron Microscope

Praveenkumar Babu and Darius Gnanaraj Solomon*

School of Mechanical Engineering, Vellore Institute of Technology, 632014 Vellore, Tamilnadu, India

Abstract

Scanning electron microscope (SEM) is the most important tool used for characterizing brake pad surfaces. Case studies on characterizing five different friction composite formulations are presented in this paper. Different features of SEM are related to explain the increase or decrease of friction and wear values. Different wear mechanisms operating at different temperatures are discussed. Special features in SEM results are highlighted for better understanding. Surface morphology, loose particles, friction films, primary and secondary plateaus are identified on worn surfaces. The case studies presented in this paper are expected to impart knowledge and skills to practicing R & D Engineers to characterize brake pad surfaces.

Keywords: Case studies, SEM, brake pads, characterization, surface analysis

Article Info

Received 3rd July 2020
Accepted 21st March 2021
Published 1st April 2021
*Corresponding author: Darius Gnanaraj Solomon; email: dariusgnanaraj.s@vit.ac.in
Copyright Malaysian Journal of Microscopy (2021). All rights reserved.
ISSN: 1823-7010, eISSN: 2600-7444

Introduction

In a world where lives depend on safety, Research and Development is the key and it is the driving force of any successful brake manufacturer. A manufacturer achieves new levels of performance and market acceptance using an extensive R&D facility located at its Bristol manufacturing plant. Once formulated, every Brake compound is subject to the conformity of production tests (to ensure compliance with R90 regulation) but is also fine-tuned within the R90 parameters to constantly ensure that the product performs to exacting standards. The R&D engineers are responsible for researching, testing, and homologation not just established production formulations but new elements and ingredients and production methods that can make pads more consistently and with higher quality thresholds. The R&D team is also responsible for factory troubleshooting and perfecting the production process which includes minimization of rejects and maximization of production efficiency. Every batch of brake pads made is subjected to rigorous testing including destructive sheer testing, density testing, sonar, and ultrasonic testing, compressibility testing, and friction level testing to ensure that every batch that leaves the factory is perfect. Whilst almost all other brake manufacturers still employ antiquated and cheap “Steel Fibre” based technology filled with dirty and dusty carbon and coke granules, R&D engineers lead the way in clean and advanced brake formulations. Blending with Aramid fibres gives endless flexibility in a formulation that is unheard of with cheap bulky steel fibre competitor products. The following challenges are met by R&D Engineers: pad lifetime, low disc/rotor abrasion, heat performance, reduction of brake dust, and protection of the environment. New products are now used by the majority of Police forces in the UK, ambulance forces and are original and aftermarket brake suppliers to London Taxi, Optare bus, Arriva bus group, Washington Metro in the USA, Chicago Rapid Transit, and numerous Motorcycle OEM builders.

MAT Friction Group in the Unites states develops the friction materials for electric vehicles. MAT Friction's R&D engineers develop friction materials for many leading European auto manufacturers that meet and surpass the OE specifications for pad durability and rotor cleaning (NAO), NVH requirements, cost, eco-friendly, and copper-free brake pads. The brake pads and rotor produce brake dust during braking. The MAT frictions group R& D engineers are concentrating to reduce pad wear and rotor wear. The R&D engineers need to focus on the material composition, particle size, and the right mix of raw materials and optimized manufacturing processes to ultimately reduce the brake dust by choosing the eco-friendly brake pad raw materials.

The braking system is the most critical part of automobile vehicles. In any vehicle, a brake pad is an important part. The main purpose of the friction pad is to stop the moving vehicle by producing friction force. Friction pads are used not only in light commercial vehicles but also used in heavy machinery and vehicles like trains. The friction pads utilize materials like asbestos, organic materials, non-asbestos organic materials, metallic and non-metallic materials, Asbestos friction pads produce carcinogenic problem and it is very harmful to human respiratory organs. A lot of researchers are working with non-asbestos materials. Darius et al. (2005) presented the characterization of brake friction materials used in Light Rail Transit (LRT) using Scanning Electron Microscopy (SEM) [1]. Darius and Berhan (2007) used Field emission SEM for characterizing brake pads and for comparing elemental distributions of commercial as well as new formulations [2]. Mohammadnejad et al. (2019) have provided a case study on the wear-induced failure of automotive brake pads. They used SEM for studying the details of fractured surfaces and EDS (energy dispersive spectrometer) for analysing the oxide particles [3]. Mutlu et al. (2015) studied the effect of porosity on the performance of

brake pads containing tire dust. They used SEM to study the behavior of friction layer and distribution of porosity [4]. Nagesh et al. (2014) studied the variation of friction material compositions and used SEM for analysing the worn surfaces of brake pads [5]. Laguna-Camacho et al. (2015) analysed the friction pads exposed to 40°C and 50°C high temperatures during real operating conditions for 8 months. This work was carried out in Poza Rica city in Mexico. In this extremely high temperature, brake pads experienced more rapid wear. Third body layers were formed due to heavy sliding and abrasion due to the deformation of the brake pad. The friction behaviour of brake pads was controlled by friction layers and films. Worn and Unworn surfaces were studied through SEM analysis. Rubbing surfaces have been analysed by SEM by many researchers working in different areas of Tribology. SEM helps to analyse the surface morphology, irregularities present in surface, conditions of the surfaces before and after conducting wear tests, identification of wear mechanisms, presence of wear debris, presence of loose particles, presence of foreign particles, friction films, back transfer, distribution of different elements, the formation of primary and secondary plateaus. This paper presents a few case studies on the uses of SEM in characterizing brake pad surfaces subjected to wear tests. SEM and EDS were used to analyze tribological surfaces.

The SEM-EDS is the tool for conducting the following analyses:

- analysis of wear debris and deposits
- characterization and particle sizing
- Failure analysis
- Metallurgical analysis
- Contaminants analysis

Characterization of Brake Pads using SEM

This section presents the case studies on the procedures, results, and characterization using SEM reported by a few researchers working in the areas related to the tribology of brake pads.

Case Study-1: Organic brake pads

Oktem and Uygur (2018) [6] analysed friction and wear properties of organic brake pad samples under various speeds, Pressures, and temperature conditions. Friction pads were tested by the hot and cold test conditions under the constant pressure of 15 bar at various speeds: 450 rev/min, 750 revs/min,1050 rev/min, under temperatures of 30°C, 90°C, 95°C & 180°C and braking cycles of 100,500,1000 applications to find the friction coefficient and wear rate values. Braking tests were repeated three times. In cold conditions, the friction coefficient was measured at a braking temperature between 30°C and 90°C. In hot conditions, the friction coefficient was measured at a braking temperature between 95°C and 180°C. In cold braking cycles, the friction coefficient values change from 0.48 to 0.56. The results of 1000 braking cycles exhibit a higher coefficient of friction compared to 100-500 braking cycles. During 500 and 1000 braking cycles, the friction value is increasing rapidly up to a disc speed of 750 rev/min and beyond this point, friction value increases gradually up to 1050°. The friction coefficient is more stable at 1000 braking cycles when compared to 100 and 500 Braking cycles. The wear rate increases gradually with temperature from 30°C to 70°C. The wear rate is affected due to the following: 1) The increase in the coefficient of friction due to lower thermal fade, 2) The organic dust which causes secondary plateaus. 3) The formation of metallic particles like brass and steel fibres.

Organic friction pads are analysed by SEM after braking and shown in figures 1(a) to 1(d). The wear mechanism of the friction pad is shown by the surface morphology. Wear debris particles are scattered on the surface. The formation of the wear debris is promoted by steel and brass fibres present in the friction materials. Hard particles are seen in many locations. A friction layer formation is seen. Many voids and scratches caused by hard particles are present [6]. EDS analysis was carried out to find the uniform distribution of friction dust within the matrix of the brake pad samples.

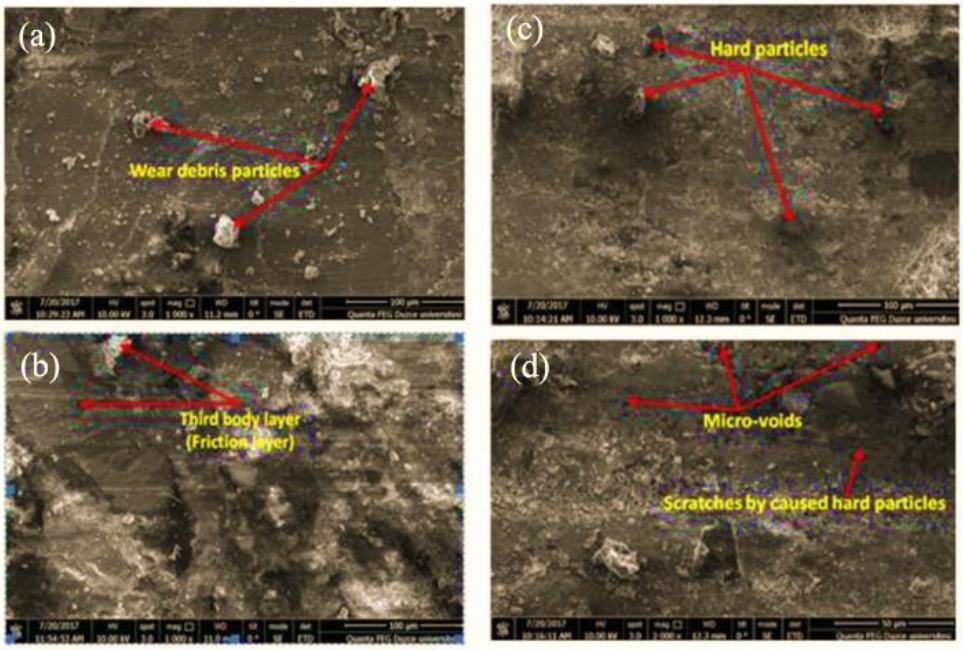


Fig. 1 The worn surface of the organic friction pad [6]

Case Study-2: Brake pads having five different cashew friction dust

Singaravelu et al. (2019) [7] developed compositions of brake pads using five different cashew friction dust: Boron modified, Furfural modified, Cardanol, CNSL (Cashew Nutshell Liquid), and Boron graphite modified. These five brake pads were analysed for fade, recovery, and wear of the composites. The composite pads were tested for coefficient of friction at different speeds and pressure values. When the speed and pressure values increased the friction values decreased. The reasons for the decrease in friction are: increased contact areas due to high pressures, increased friction heating due to increased speeds, the formation of plateaus from the damage of asperities resulting from mechanical and thermal overloading. The tested friction pads have a friction coefficient in the range of 0.30 to 0.54. The friction fade level values are always within the range of advisable limits. Friction fade is the most significant parameter that reflects the worsening of friction values under elevated conditions. As per the industrial standardss, 0 to 20 % is the acceptable limit for fade rate. A friction pad is cooled by using an air blower to get the recovery of friction material. The formation of the viscous layer becomes solid at high temperatures. The third body abrasion takes place because of hard abrasives formed due to the loosening of wear debris during fade cycles. Friction fade is always greater than friction recovery. The major deciding factor in friction value is the Recovery rate. The range for a better recovery rate is 75 to 100%. The results showed that the surface of the friction material containing plateaus affected friction coefficient and wear rate [7].

The tribological properties of friction composites are analysed by scanning electron microscope as shown in figures 2(a) and 2(b). In these compositions, the major role is played by plateaus in changing the behaviour of friction pads. Primary plateaus formed by fibres have the load-bearing capacity and increase friction values while the load-bearing capacity is reduced by secondary plateaus. It is appropriate if a friction pad has more primary plateaus and fewer secondary plateaus. In boron modified friction composite, more de-bonded materials are present as shown in SEM micrograph Fig. 2(a). To visualize the back-transfer, the elemental mapping is done in the secondary plateau regions in Fig 2a. The level of back transfer is comparatively more due to excessive wear.

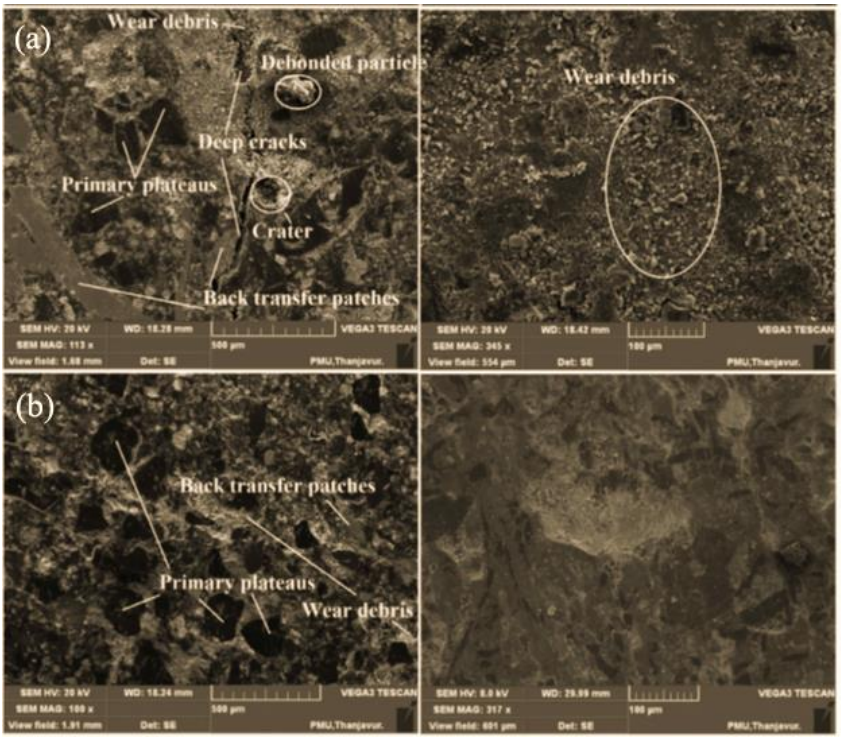


Fig. 2 (a) Boron Modified (b) Boron-Graphite modified friction pad surface [7]

Due to the de-bonding of material, it forms craters so that the furrow effect causes the plastic to flow and ploughing of the softer matrix. More friction causes increased temperature which leads to more wear and cracks in the boron modified friction brake pad. In boron-graphite composites, as shown in figure 2(b), back transfer patches are less compared to primary plateaus. In this composite, wear debris is less, and also wear is less when compared to other friction pads since the ironing mechanism is most important in boron-graphite brake pads. The graphite and boron-modified friction brake composite have more thermal stability. Graphite acts as a lubricant by its nature. The protective layer is formed by an ironing mechanism [7].

Case Study-3: Brake pads having high molecular weight binder resin

Jara and Jang (2019) [8] found that friction materials with high molecular weight binder resin produced a high level of coefficient friction at a temperature below 350°C with improved fade resistance. Before thermal decomposition, the wear rate increases at a slow rate with temperature. The degradation of the binder at a temperature above 350°C increases the wear rate. High molecular weight resin has less amount of wear compared to lower (Mw) molecular

weight resin. Potassium-titanate of whisker type has more amount of wear compared to potassium-titanate of platy type. The bonding strength of phenolic resin is lost due to the thermal decomposition of resin which increases wear rate. When the friction temperature is above 350°C, the wear is rapidly increasing. Finally wear mechanism suggest that: a) at temperatures below 350°C, the wear process is depending on the wear resistance of each ingredient. b) high molecular resin binder resin and potassium-titanate cause the formation of secondary plateaus at high temperature contributing to a wear mechanism. The results show that the wear resistance is improved by platelet potassium-titanate at low temperature and whisker potassium-titanate at high temperature.

Plateaus growing on the surface take an important role in brake performance such as noise vibration, service life, fade resistance, and friction level. In figures 3 and 4, the worn surface of the friction pad is shown after conducting sliding tests at temperatures 180°C and 450°C. These friction pads contain various resins and reinforcements. The specimens were examined to understand the temperature-dependent tribological properties. Figure 3(a) shows the worn surface of low-whisker composite; it has secondary plateaus at 180°C. Secondary plateaus may cause low friction, high wear and make the friction film unstable. Fibrous potassium titanate reinforced friction material has yielded mostly primary contact plateau and it has low friction value and high wear rate. At that temperature Figure, 3(b) shows that a high-whisker composite with higher molecular weight resin increases the size of secondary plateaus. Improved mechanical property may be the cause for the formation of secondary plateaus in the composite having high-Mw resin and a similar trend is noticed in platy potassium titanate composite matrix. In figures 3(c) and 3(d), reinforcement composite with whisker potassium titanate has smaller secondary plateaus compared to potassium-titanate of platy type. When the temperature is above the thermal decomposition temperature it destroys the friction film formed on the brake pad. During sliding, the shear force damages the friction film and plateaus [8].

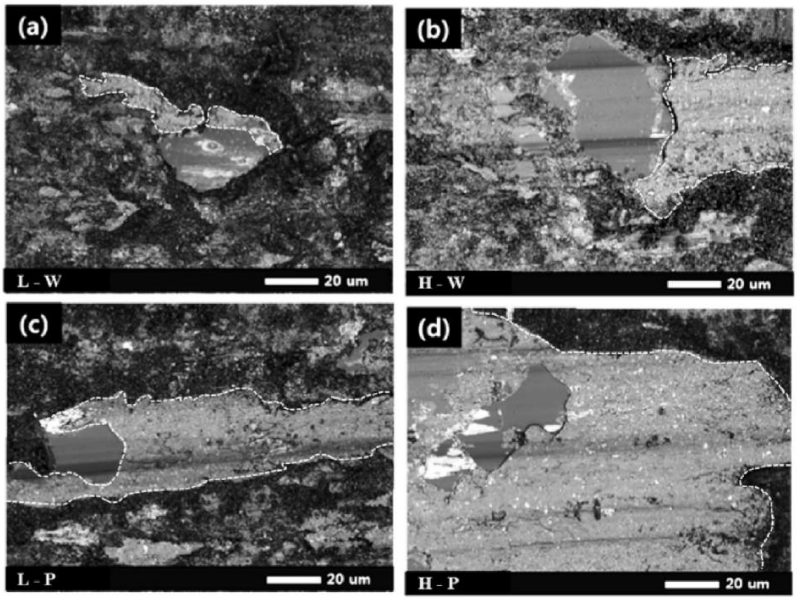


Fig. 3 Brake pad – worn surface at 180°C [8]

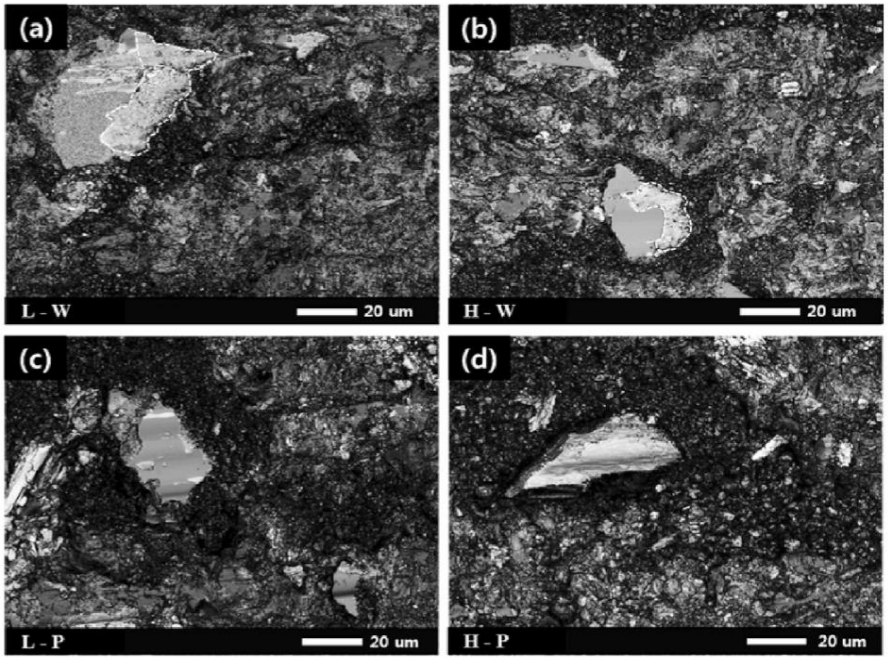


Fig. 4 Brake pad – worn surface at 450°C [8]
(a) Low whisker (b) High whisker (c) Low Platy potassium (d) High platy potassium titanate

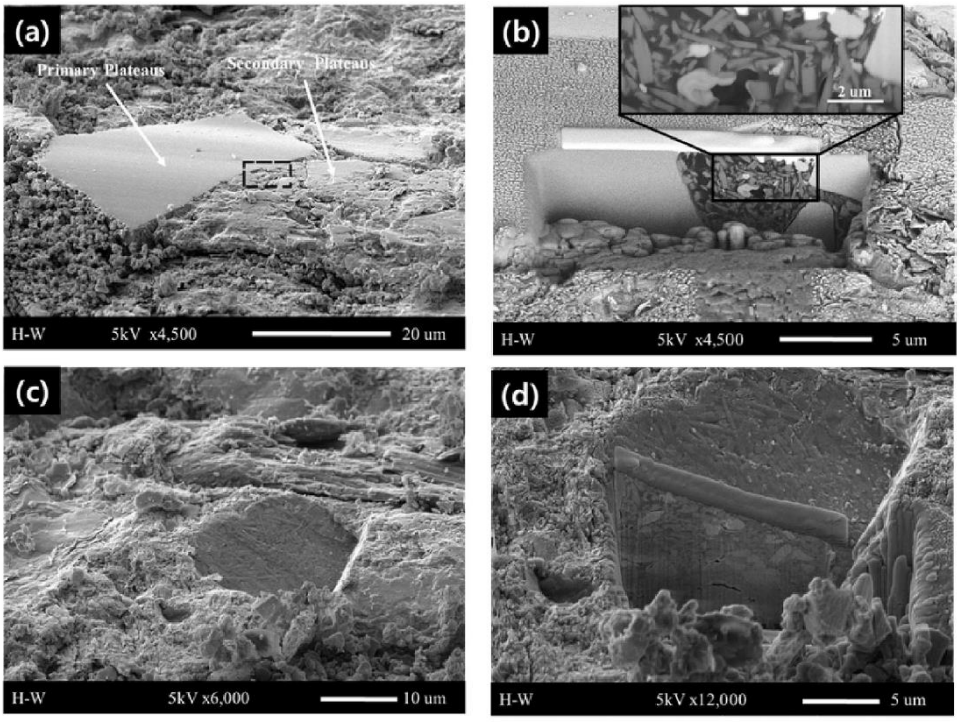


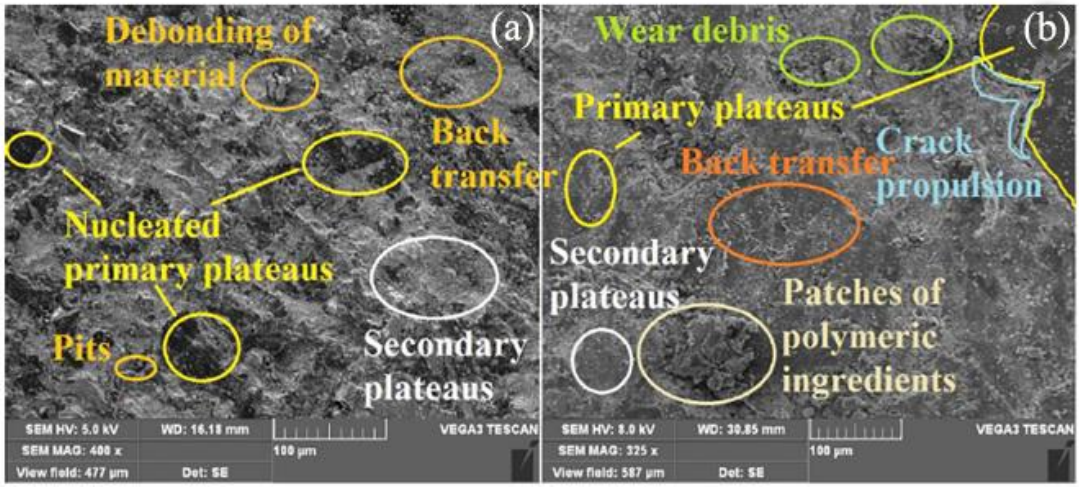
Fig. 5 High whisker surface after drag test 450°C [8] (a) primary and secondary plateaus on worn surface (b) Potassium titanate whisker mixed with other ingredients in the cross-section beneath the secondary contact plateau. (c) and (d) Potassium titanate whisker beneath the secondary contact plateaus.

Figure 5 shows that Whisker potassium-titanate improved the high temperature wear resistance and it facilitates the formation of secondary contact plateaus having improved capabilities as seen in SEM pictures of the surface underneath the secondary plateaus [8].

Case Study-4: Brake pads having solid lubricants

Antonyraj and Singaravelu (2020) [9] developed friction pads using solid lubricants like tungsten-disulfide, tin-disulfide, molybdenum-disulfide, and graphite to study the tribological characteristics and the physical, mechanical, thermal properties. The coefficient of friction values were found for four composites under two different load conditions. When the applied load is increased, it reduced the coefficient of friction values. Due to an increase in load, the gap between the pin and surface is reduced which leads to the clustering of wear debris and reduced coefficient of friction values. The friction value is decreased because the increase in load enlarges the contact area. When the pin is forced on the disk, the frictional heating increases, which promotes the thermo-mechanical overload resulting in the breakage of asperities. Plateaus are exposed due to a drastic change in the coefficient of friction.

In the mating interface, metal oxides are formed in the third body layer by metal-sulfide due to thermochemical reaction. Micro-hardness is increased due to the formation of WO_3 by the oxidation of WS_2 increasing friction lubricants, and reduces wear rate and friction rate. De-bonding of fibres and powdery ingredients from molten resin causes an increase in friction coefficient and they act as third body particles. When the speed increases, it reduces the friction level due to the reduction in the contact area. Friction films were formed due to resin pyrolysis at high temperatures. Materials de-bonded due to thermal softening and plastic deformation caused by heat developed in interface. Loss of wear is due to increase in contact area in materials caused by higher loads [9].



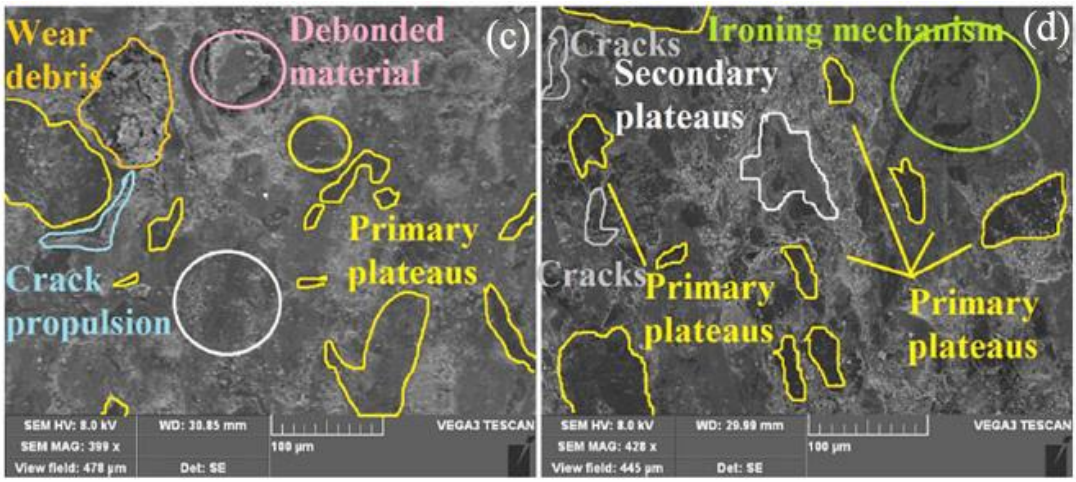


Fig. 6 (a) Synthetic graphite (b) Tin disulphide (c) Tungsten disulphide & (d) Molybdenum disulphide composite worn surface SEM at higher load conditions [9]

Figures 6(a) and (b) show SEM micrographs of Synthetic graphite and Tin-disulfide composites which are subjected to higher load conditions. It is noticed that a large number of primary and secondary plateaus nucleated by back transfer of polymer ingredients took place in synthetic graphite composites. Ploughing action by the counter face promotes debonding of materials and the resulting pits are observed by SEM in figure 6(a). Figures 6(a) and (b) show that wear resistance is poor due to poor lubrication and due to higher back transfer. Back transfer from the mating surface causes additional particles of polymeric ingredients and a high wear rate due to improper lubrication. More propulsion and crack formation are seen in figure 6(b) due to wear resistance. Some of the wear debris is present as third bodies and they do not form patches. Friction levels are increased by large-sized primary plateaus in Tin-disulfide composites as seen in figure 6(c). The lubrication offered by the tungsten disulfide reduced back transfer and secondary plateaus. The debonded material is adhering to the surface in figure 6(c). Due to the higher d-spacing of MoS_2, the lubrication is very effective in Molybdenum-disulfide composites. Secondary plateaus are less than primary plateaus as shown in figure 6(d). Friction values are consistent since the contacts between plateaus are increased. The wear resistance is increased in Molybdenum-disulfide due to less back transfer. Plateaus are improved in Tungsten-disulfide and Molybdenum-disulfide composites [9].

Case Study-5: Brake pads exposed to real operating conditions

Laguna-Camacho et al. (2015) [10] analysed the friction pads exposed to 40°C and 50°C high temperatures during real operating conditions for 8 months. This work was carried out in Poza Rica city in Mexico. In high temperatures, brake pads experienced more rapid wear. Differences in wear mode and surface characteristics of brake pads were identified. Third body layers were formed due to high sliding, abrasion wear, and the deformation of brake pad surfaces. The friction behaviour of brake pads was controlled by friction layers and films. Worn and unworn brake pad surfaces were analysed by SEM [10].

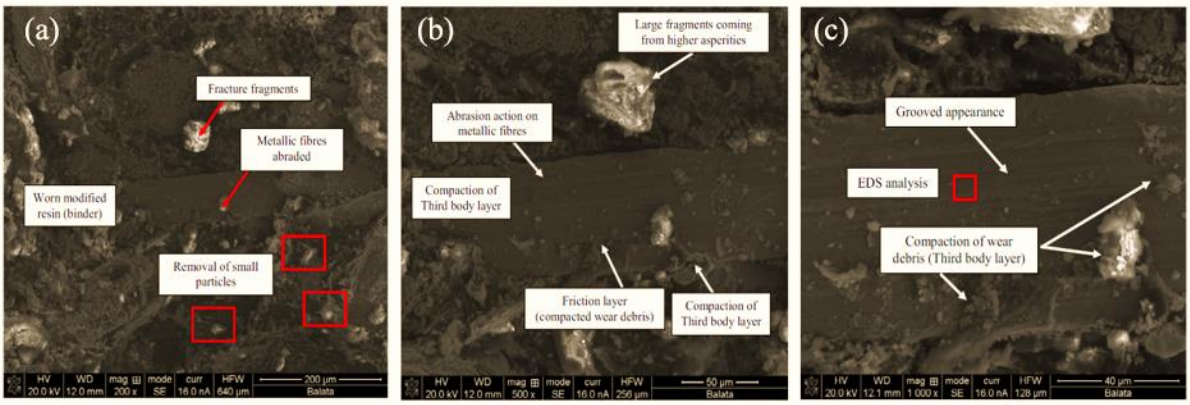


Fig. 7 (a) to (c) Micrograph image of worn surface brake pad [10]

Figure 7 shows the SEM images of worn surfaces of brake pads. It is noticed that debris got smeared on the brake pad surface which was in contact with the disk. Due to abrasion action, small filler particles like Al_2O_3 and SiC were removed on the worn surface. After the real services underwent by the brake pads, metallic particles were seen on brake pad surfaces. The fracture fragments of metallic surfaces and fillers constitute the third body surface layer. High sliding action played a major role in causing grooves (parallel lines) on the metallic fibers in the direction of sliding as shown in figure 7 (a) to (c). The chemical elements found in the EDS analysis were (O) 45.48%, magnesium (Mg) 21.81%, and silicon (Si) 32.7% which well correlated to the elements that are commonly found.

Frictional additives silicon carbide and alumina particles increased the resistance to wear and stabilize the friction coefficient. Thermally-induced deformation decreased due to the addition of these hard particles. Removed metallic fibres, particles, and iron oxide probably constitute the friction layer or third body layer. After real service, this layer was identified clearly. Wear debris deposited in grooves or material included and described as friction films were present on the worn surfaces. Wear increased in a few zones and the coefficient of friction values reduced. This could be due to the action of the steel disc which had tiny particles of the friction material. Figure 8d shows black particles, probably graphite present on the friction pad surface were polished because of abrasive and sliding action [10]. Abrasive action and melting action probably produced loose wear particles due to high abrasive action on the surface [10].

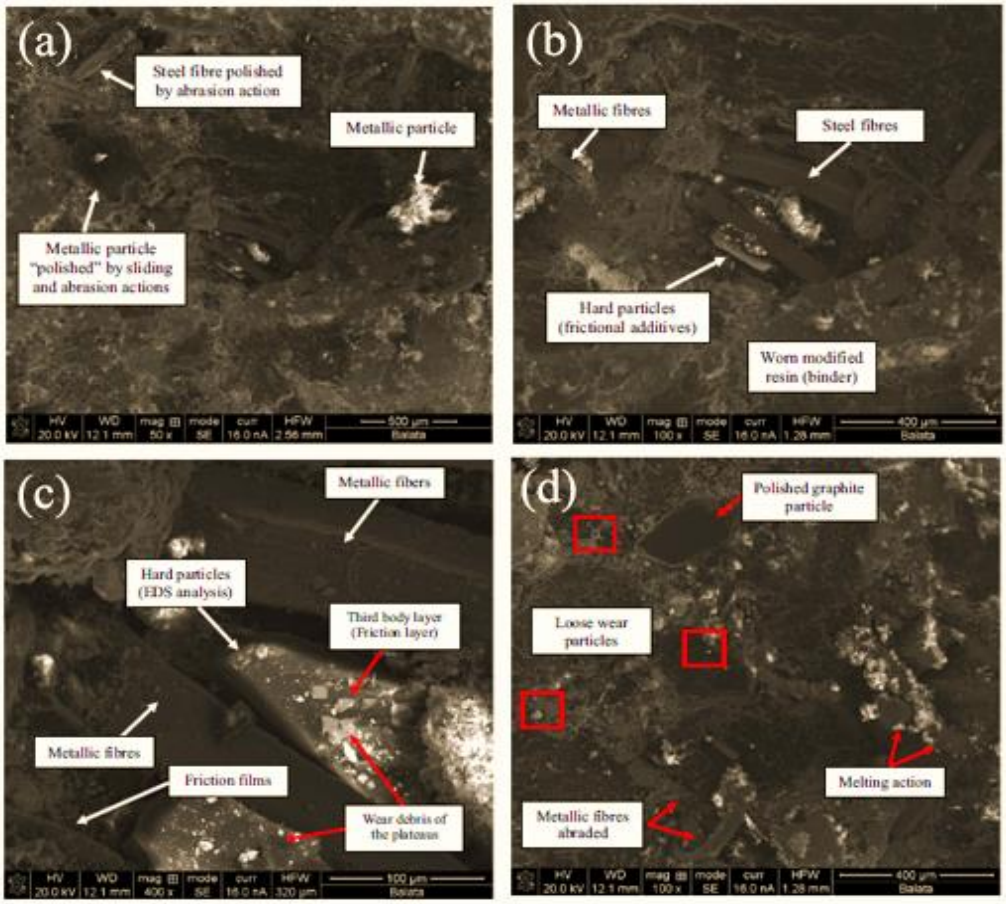


Fig.8 (a) to (d) SEM micrograph of worn surface of brake pad [10]

Conclusion

Case studies on characterizing brake pad surfaces using a scanning electron microscope are presented. Case studies on the following brake pads are presented: (a) organic brake pads, (b) brake pads having five different cashew friction dust, (c) brake pads having high molecular weight binder resin, (d) Brake pads having solid lubricants and (e) brake pads exposed to real operating conditions. The following features present in SEM analysis are explained: micro-voids, scratches, deep cracks, pits, crack propagation, fracture fragments, wear debris particles, hard particles, debonded particles, metallic particles polished by abrasion, third body friction film, patches of polymeric ingredients, back transfer patches, primary plateaus, and secondary plateaus. The contents of this paper would help R&D Engineers to understand how to characterize brake pad surfaces using SEM.

Acknowledgements

The authors are thankful to the management and administration of VIT Vellore for extending infrastructure, support and cooperation in carrying out this work.

Author Contributions

All authors contributed toward data analysis, drafting, and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

References

[1] Darius G.S., Berhan, M.N., David, N.V., Shahrul, A.A., Zaki, M.B. (2005). Characterization of Brake Pad Friction Materials. Computational Methods and Experiments in Materials Characterisation II, WIT Transactions on Engineering Sciences. 51:43-50.

[2] Darius G.S., Berhan, M.N. (2007). Characterization of Friction Material Formulations for Brake Pads. Lecture Notes in Engineering and Computer Science. 2166.

[3] Mohammadnejad, A., Bahrami, A., Goli, M., Dehbashi Nia, H., & Taheri, P. (2019). Wear Induced Failure of Automotive Disc Brakes—A Case Study. *Materials*, *12*(24), 4214. https://doi.org/10.3390/ma12244214

[4] Mutlu, İ., Sugözü, İ., & Keskin, A. (2015). The effects of porosity in friction performance of brake pad using waste tire dust. *Polímeros*, *25*(5), 440–446. https://doi.org/10.1590/0104-1428.1860

[5] Nagesh, S. N., Siddaraju, C., Prakash, S. V., & Ramesh, M. R. (2014). Characterization of Brake Pads by Variation in Composition of Friction Materials. *Procedia Materials Science*, *5*, 295–302. https://doi.org/10.1016/j.mspro.2014.07.270

[6] Öktem, H., & Uygur, I. (2018). Advanced Friction–Wear Behavior of Organic Brake Pads Using a Newly Developed System. *Tribology Transactions*, *62*(1), 51–61. https://doi.org/10.1080/10402004.2018.1478054

[7] Singaravelu, D. L., Vijay, R., & Filip, P. (2019). Influence of various cashew friction dusts on the fade and recovery characteristics of non-asbestos copper-free brake friction composites. *Wear*, *426–427*, 1129–1141. https://doi.org/10.1016/j.wear.2018.12.036

[8] Jara, D. C., & Jang, H. (2019). Synergistic effects of the ingredients of brake friction materials on friction and wear: A case study on phenolic resin and potassium titanate. *Wear*, *430–431*, 222–232. https://doi.org/10.1016/j.wear.2019.05.011

[9] Antonyraj, I. J., & Singaravelu, D. L. (2020). Tribological characterization of various solid lubricants based on copper-free brake friction materials – A comprehensive study. *Materials Today: Proceedings*, *27*, 2650–2656. https://doi.org/10.1016/j.matpr.2019.11.088

[10] Laguna-Camacho, J. R., Juárez-Morales, G., Calderón-Ramón, C., Velázquez-Martínez, V., Hernández-Romero, I., Méndez-Méndez, J. V., & Vite-Torres, M. (2015). A study of the wear mechanisms of disk and shoe brake pads. *Engineering Failure Analysis*, *56*, 348–359. https://doi.org/10.1016/j.engfailanal.2015.01.004