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Wear Mechanism and Modelling for Automotive Brakes with Influence of Pressure, Temperature and Sliding Velocity: A Review Article

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ABSTRACT
Brakes are the automobile component plays an important role respect to safety and in performance of automobile. According to the crash report of automobiles about 22 % of crash occurred due to the failure in brakes. This Paper discusses the wear mechanisms and wear modelling techniques in brake surface for increasing the effectiveness and preciseness with the influence of different operating conditions. The surface topography of brake pad interface at various stages and wear mechanisms of brake is studied and summarized. The wear models analysed for studying the numerical modelling techniques of brakes contact surface interaction, which was beneficial to improve life and performance of brake. The influence of operating parameters like contact temperature, pressure and sliding velocity on surface interface behaviour of different brake materials were summarized and analysed. Studies conclude that there was rapid process of wear with increasing temperature and formation of new layer on the brake surface due to heat which changes the tribological surface behavior and slow process wear with increase in pressure. The braking performance have complicated influence of wear due to that the perfect prediction of brake surface interaction and operating parameter influence is necessary to minimize the effect and improves the life, safety, reliability and performance of braking system.

Key words: wear mechanism, wear modelling, brake pad, braking condition, sliding velocity.

INTRODUCTION

Brakes are the crucial and important components in today's car because of safety considerations of lives those who riding in the vehicle. The safety of vehicle strongly influenced by proper braking operation which depends on interface of contact between pad-to-drum or disk. Brake system ensure that to stop the vehicle within shortest period of time and distance during emergency conditions [1]. It should also maintain the vehicle speed on climbing and holds stationary at grades [2]. Drum and disc brakes are the two types of mechanism that were implemented in present automobiles. Braking operation starts with the application of foot pressure on brake pedal by the driver, which slows down speed and stop a vehicle after some time due to squeezing of pads into contact with the disc. The forces of friction at the interface on sliding between pads and the disk decelerate the rotational movement of the disk and the axle on which it is mounted. The friction between dry sliding contacts of brake causes wear of surface materials. Wear is a system property commonly related to progressive loss or removal of unwanted material from one or more operating solid surfaces caused due to the mechanical action. The solid surfaces having rolling, sliding, or impact motion relative to each other. The wear of surface makes brake pad thinner and clearance between the contact of pad-to-disk or drum bigger, which decreases braking performance due to direct effect on time and torque [3]. The brake related problems when arises, blames always goes to the pads because of vulnerable nature due to various conditions such as vehicle velocity, pedal pressure, temperature, environmental conditions and durability. Simultaneously disk also responsible for brake failure causes such as judder, noise and fade [4]. The investigations on the wear behaviors of brake's friction materials must be valuable for reducing wear, developing new fine friction materials, and improving braking reliability. Therefore, a great deal of researches on this field had been carried out in the past years. The relationship between various braking conditions were complex. If they can be properly modelled then wear rate predicted easily based on the conditions. Brake wear modeling involves the proposing of theories, ideally ending with mathematical expressions of those theories. It begin with the observation of a wearing system. Every wearing system is complicated, but typically only a fraction of the wearing phenomena is actually observed. Wear modelers propose theories to explain the observed phenomena and derive mathematical expressions to predict wear processes based on the proposed theories.

In this paper, our attention was focused on study done by different researchers on the dynamic wear behavior of brake contact surfaces interaction at various operating parameters during a braking cycle and investigating the possibilities of modelling the brake contact surfaces interaction, which can be reliable for improving braking performance.

WEAR MECHANISM AND MODELLING IN AUTOMOTIVE BRAKES

Wear Mechanism in Automotive Brakes

The braking behaviors and its tribological mechanisms of automobiles were studied by a series of tribological experiments [5]. Eriksson et al. described contact surface variation of automotive brakes in disc pads, which was vary with respect to properties, size and composition. The nature of contact in brakes was multiple and intricate. It also analyze the wear mechanisms produced by the contact surface variations causing rapid deterioration processes, affected by braking force changes, vibrations and wave motions in the brake pad and cast iron disk, and slow degradation processes where the thermally induced deformation, shape adaptation and contamination and cleaning played an important role [6]. Osterle et al. conducted a study of the chemical and microstructural changes occurring during braking simulation. In this work, a series of reciprocating tests on the surface of a conventional disk brake pad material, were performed. Characterization techniques such as scanning electron microscope and energy-dispersive X-ray spectroscopy (SEM/EDS), selected area diffraction (SAD) and transmission electron microscopy (TEM) were used to know the chemical changes, before and after testing [7]. The wear debris produced by three-body abrasive wear was analyzed. The major wear mechanism was delamination of filler particles from the organic binder, supported by local degradation of the phenolic resin during asperity heating. Quartz crystals preserved thereby adopting the function of primary contact areas. Mikael et al. pointed out that the braking tribological performance of automobiles is generally defined as the friction coefficient, wear rate, noise and vibration of its brake lining under the influences of different velocity, pressure and temperature [8]. Mutlu et al. contrasted the influences of surroundings (fresh water, salt water and oil) on the phenolic composites suggested for automotive brakes [9]. Eriksson et al. carried out a research work on the nature of tribological contact in automotive breaks in disk pads. In this study, the term contact plateaus constantly was indicated as the higher asperities firstly making contact with the high irregularities of the disk (counter- body), in a brake system. It also presented an analysis on the wear mechanisms in automotive brakes produced by the contact surface variations causing rapid deterioration processes, affected by braking force changes, vibrations and wave motions in the brake pad and cast iron disk, and slow degradation processes where the thermally induced deformation, shape adaptation and contamination and cleaning played an important role [10-12]. Menapace et al. presented an approach related to reduction of copper in friction materials of brake and developed a new material by changing the microstructure of some of the ingredients by using ball milling. The testing and validation for wear behavior of this material has been done on pin-on-disc by doing different wear tests [13]. Peng et al. studied the behaviors of cu-based high speed train brake pads for different real braking conditions. The surface beahaviour and phase mainly depends on the state of friction film and it changes the nature of coefficient of friction and wear [14]. Petre et al. proposed a system for doing the study of the effect of thermal stresses on disc brake material of Dacia Logan car. It also proposed a mathematical model for calculating the influence of temperature during braking and experimental analysis for temperature effect on brake disc material [15]. Verma et al. studied the surface beahaviour of commercial brake pad against cast iron disc on pin on disc test rig. The tests were done under mild wear for different load and speed, due to copper the formation of tribological layer and wear debris takes place [16]. It also carried wear test for different temperatures and studied the formation of wear from mild to severe stage [19]. Xiao et al. studied the friction and wear behavior of different brake materials. The classification of friction materials and advantages and disadvantages of each friction materials were summarized [17]. Wahlstrom et al. investigated the effect of friction and disc materials on particle emission from disc brakes. The different novel material formulations were done with different methods and coatings and test ere carried on pin on disc for ranking the novel materials in terms of wear, particle number and mass rate [18]. Fan et al. proposed an attenuation function for prediction of quantity of removal of wear debris and mapped these wear debris concentration based on wear rate [20]. Yin et al. studied the extraction of new temperature set for characterizing the dynamic characteristics of disc brake's frictional temperature rise variations more objectively and comprehensively [21]. A very small cutout of the above mentioned basic parts of a brake system is shown in Fig. 1. A brake pad consists of a rather soft polymer matrix which covers numerous rather hard in homogeneities, such as quartz particles and metallic or organic fibers for instance. The brake disc and the polymer matrix produce wear particles that flow through the contact zone. Their size can vary between some nanometers and some micrometers. The contact zone between the brake disc and the hard particle is the area where nearly all the friction power is done [22-24].

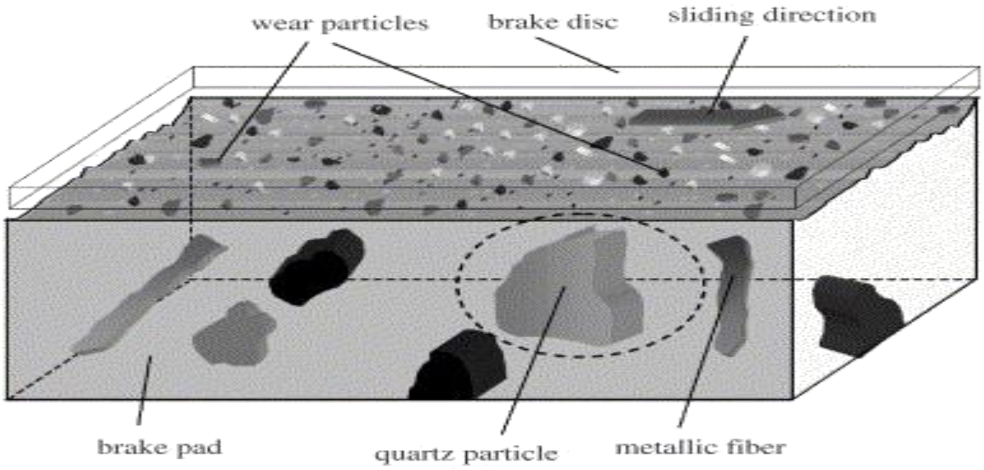


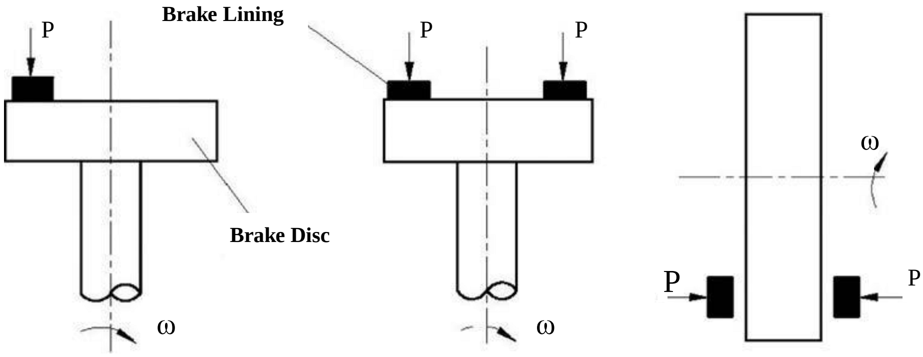
Fig.1 Cutout of a Brake System [13]

So the temperature will rise there rapidly. It can probably reach local values of up to 1500^{0}C. This leads to alloying or even melting processes and the inhomogeneity will rise contrariwise and perpendicular to the flowing direction. So the contact area increases, more heat will be generated. This accelerates its further growth. The worn disk and shoe pads as shown in Fig. 2 (b) & 2 (d) roughly used for 8 months, similarly unworn disk and shoe pads shown in Fig. 2 (a) & 2 (c). The high contact stresses presented at one side of the disk pad undergoes higher wear at one side of pad in contact with disk. In another case of drum brake wear mechanism caused by fatigue due to repeated impacts of drum during braking operation [25].

(a) **(b)** **(c)** **(d)**

Fig. 2 Worn & Unworn Brake Pads (a) unworn disc pad (b) worn disc pad (c) unworn shoe pad (d) worn shoe pad [25]

The influence of velocity on the wear of aluminum MMC sliding against phenolic brake pad were discussed and considered that some added special fibres are helpful for improving the wear performance of brake lining for automobiles [26, 27]. It is found that the present tribological experiments on brake materials of automobiles were mostly based on the small sample testing method. And the standard pin-on-disc friction tester was generally taken as experimental device. It simulates the disc braking by one or two brake lining samples contacting onto a round disc, shown in Fig. 3 (a).However, the actual disc brake brakes by two pieces of brake linings loading onto the disc at the same time, shown in Fig. 3(b). Therefore, the paring modality of the standard pin-on-disc friction tester is obviously different with the disc brake, which as a result causes easily some testing differences. What is more, the wear is generally expressed as volume or weight wear rate, which can be calculated by the thickness or weight variations of brake samples in braking. Each method cannot test the wear rate online. So the wear of disc brakes cannot be evaluated real timely [3].



(a) Pin-on-Disc Friction Tester **(b) Disc Brake**

Fig. 3 Schematic Diagram of Friction Pairing [3]

Wear Modelling for the Influence of Different Braking Parameters

Wear modelling is vital and resolute area in a brake system to analyze the performance relationship between all the variables and parameters. Modelling involves the proposing of theories, ideally ending with mathematical expressions by which a wear model may be formed. Wear models are generally imparted into two types one which having mathematical expressions are constructed from empirical data only, not derived from wear theories and another model contain theoretical explanations without mathematical expressions. Ordinary wear models incorporate some significant information, but not all, either because the information is not known or it is simply not incorporated into the model. Many authors discussed about formulation of wear model based on their interest and trying to interpret all known and well-expressed information about the brake wearing mechanism. Also, the investigation accomplished by researchers due to influence of different braking conditions like applied pressure, temperature and velocity on performance and life of brake was summarized in this section.

The correlation between specific wear mechanism in brakes and the engineering models has an additional benefit obtained from including an experimental element in a design approach. In 1950s Archard presents a model to express the severity of sliding wear. The model was based on the contacting asperities formed at plastic junction during sliding. The area was expressed based on assumption unit volume material removed from unit contact region in different manners [28-30].

$$A_r = \frac{P}{H} = \frac{F_N}{H_v} \tag{1}$$

Where, P & F_N be normal load and H/ H_v is the hardness value of material. The volume of wear debris formed due to the asperities present at the interface between the sliding surfaces. The researcher's gives different idea about wear volume of particles removed based on different condition at the asperity [31],

$$V = \omega_s WL = K\frac{WL}{H_v} \tag{2}$$

Also, it assumes asperity is hemispherical over a distance d and total wear volume be [32-35],

$$V_d = \frac{1}{3}\frac{Wd}{H} \tag{3}$$

Hutchings defines wear volume with respect to shearing at the surface interface [36],

$$V = h.A_n \tag{4}$$

Where, ω_s is the specific wear rate, K is the wear coefficient, d & L be the sliding distance, h is the depth of wear, A_n is the normal area and V/V_d are the total volume produced due to wear debris. Archard, Rabinowicz and Holm was experimentally shows that wear volume linearly increases with load and sliding distance. The value of K varied based on physical models and experiments, it was nothing but the probability encountered results in the wear particle. The value of K taken in the wide range of 10^{-2} to 10^{-6}. Haichuan Ren et al. defines four equations of wear model for wear of brake pads based on sliding wear, relation between hardness and yield pressure, equation based on adhesion theory of friction [37-42],

$$W_H = a.\frac{NS}{H} \tag{5}$$

$$H = b.\gamma \tag{6}$$

$$\mu = \frac{\tau}{\gamma} \tag{7}$$

$$W_H = a.\frac{W_f}{\tau} \tag{8}$$

Where, W_H is the wear of brake pads, N is the normal load, S is the distance, H is hardness, γ is yield pressure, μ is coefficient of friction, W_f is friction work, τ is shear strength, a, b and α are constants. Yan Yin et al. was estimated wear rate for variable thickness of different samples by an empirical relation [3],

$$V = \frac{A_f(d_1 - d_2)}{2\pi R_f N F_m} \tag{9}$$

Where, A_f is the area of brake lining sample, R_f is the friction radius, N is revolutions of disc in a braking test, d_1 & d_2 are the mean thickness of the brake lining before and after a test, F_m is mean friction force in braking. The wear model of Laird Towel and Robert Riecker was further extend by T. Liu and S. K. Rhee with considering the influence of high temperature on wear of semi-metallic disc brake pads. The relation becomes [43, 44],

$$W_H = \begin{cases} x.W_f.e^{\phi T} & N \le N_0 \\ x.W_f.e^{\phi T}.\dfrac{N}{A} & N > N_0 \end{cases} \tag{10}$$

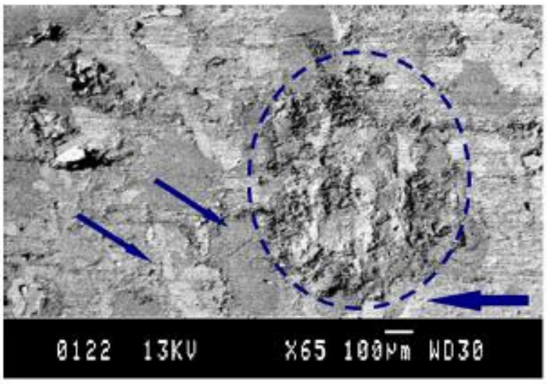
Here, T is the temperature of brake pad, A is the apparent area, N_o is the critical normal load and ϕ & x are constants.

According to these models the wear of brake pads wear of brake pads is not only dependent of friction force, relative velocity, duration of friction and shear strength, but also depends on temperature, material type, geometry, load history and resulting topography. So far, the wear of brake pads was investigated under a low level of normal load without the influence of temperature.

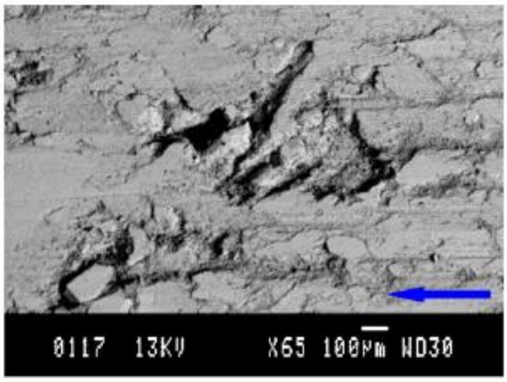
INFLUENCE OF CONTACT PRESSURE, TEMPERATURE AND SPEED ON WEAR BEHAVIOUR OF BRAKE MATERIAL SURFACES

Influence of Contact Pressure on Wear of Brake surfaces

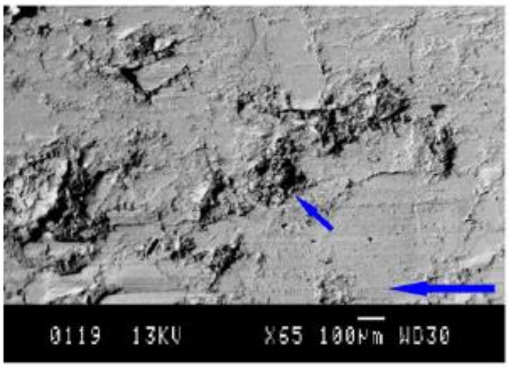
The main requirement of a brake pad is to slow down the car speed by transforming the kinetic energy into heat through friction work at the interface between brake pad and rotor disc. Blames always go to brake pads when a brake-related problem arises. This is because brake pads appear more vulnerable to various braking parameters such as pedal pressure, vehicle speed, disc temperature, and environmental conditions, dry or wet. Commonly, the influence approach of braking pressure to the friction and wear behaviors of friction materials can be concluded as four types: changing the actual contact area of friction pair, affecting the generation of friction films, influencing the component and organization of friction material, and changing the wear type [45]. The four different non-commercial frictional brake pad materials (NF1, NF2, NF4 and NF5) were evaluated and compared with other two chosen commercial brake pad materials (CMA and CMB). Fig. 5 shows samples of the SEM images of the NF1, NF2, and NF5 brake pad surface subjected to dry braking under nominal pressure1.33MPa in which one can see that the size and distribution of real contact area (patches or plateaus) are far from constant [4]. Fig. 5 (a) depicts patches "plateaus" of different sizes in the rubbing surface at nominal pressure of 1.11MPa. When pressure increased to 1.33MPa, steel fibres were brought up to the rubbing surface to resist the motion. Under a low braking pressure, the friction films are hard to be formed on the interface. With the increasing braking pressure, the asperities distributed on the contact interface are deformed and broken to form some debris. The debris is easily staved to form some loose granular films to increase the actual contact area [46]. Fig. 6 shows the wear rates obtained for all six friction couples under dry continuous braking against gray cast iron disc as a function of nominal contact pressure for two speeds, 1.3 and 2.1m/s. The general trend of these results is that wear rate decreases when pressure increased at both sliding speeds. The results also suggest that the wear rate is highly determined by the type or ingredients of the brake pad material. On macro and micro scale, the wear characteristics of brake pad/disc depend on the formation, growth and disintegration of contact plateaus, shape adaptation, and thermal-induced deformation [4].



(a)



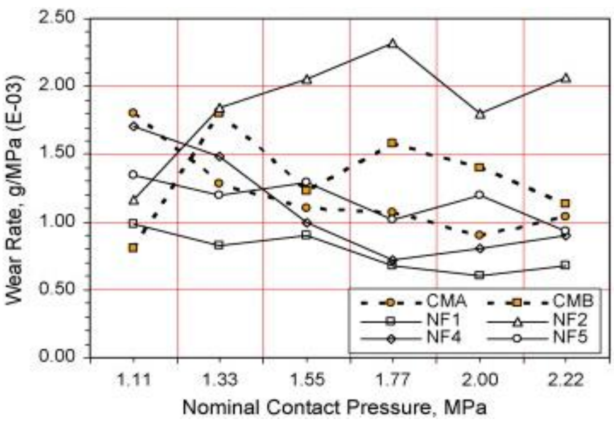
(b)



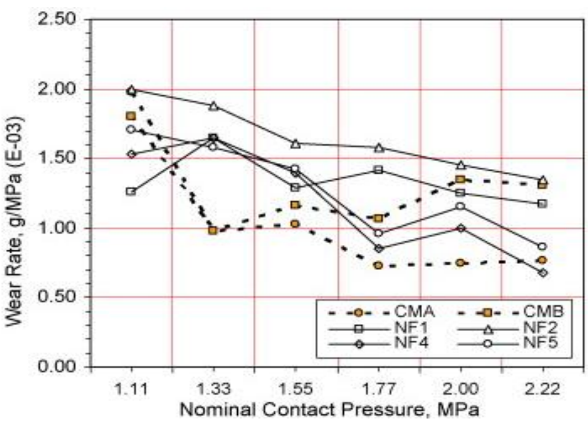
(c)

Fig. 5 SEM Images of Non-Commercial Brake Pad Materials Subjected to Dry Braking Under Different Nominal Contact Pressure:(a) 1.11MPa, 2.1m/s, NF1/GCI-DRY;(b) 1.11MPa, 2.1m/s, NF2/GCI-DRY; (c) 1.11MPa, 2.1m/s, NF4/GCI-DRY. [4]

The mechanism of the friction film formation in multiphase materials is very complicated and strongly depends on the thermal history of sliding interface. In the case of normal braking applications, it is known that the organic constituents, fibrous materials, and solid lubricants play important roles in establishing the transfer layer at the friction interface and this transfer layer become significant and more effective at higher pressure [47].



(a) Dry Sliding, velocity 1.3 m/s and Test Time 300sec



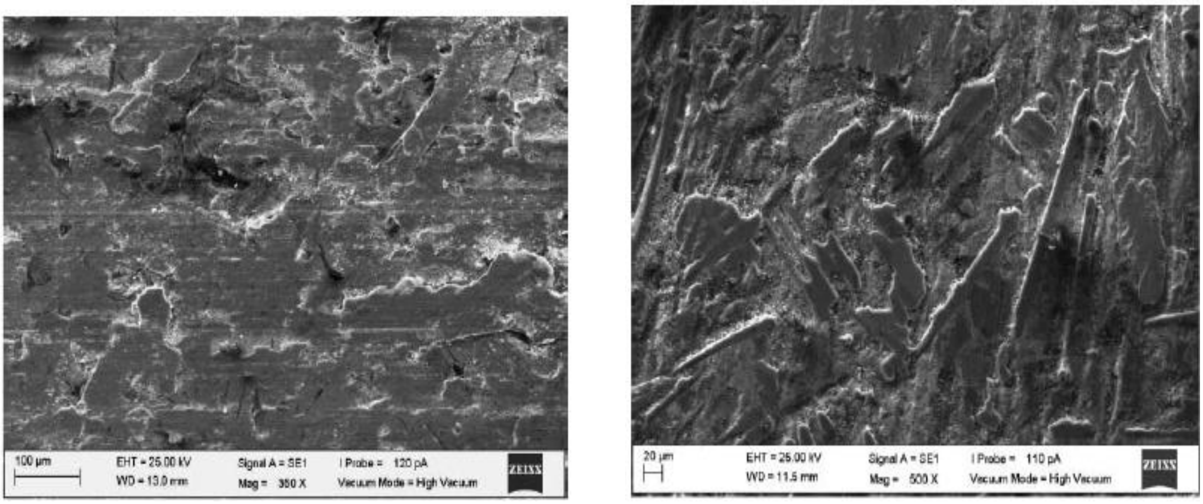
(b) Dry Sliding, velocity 2.1 m/s and Test Time 300sec

Fig. 6 The Variations of Wear Rate Against Nominal Contact Pressure for Non-commercial and Commercial Brake Pads Tested Under Dry Braking Condition. [4]

When the braking pressure increases to a higher value, more debris will be formed, embedded, stacked, and filled into the worn surface to generate more granular films. Gradually, these loose granular films may connect each other to form a dense sheet film with a larger area [48]. The variation in wear rate of a copper based powder metallurgy for train's brake when the braking pressure is increased from 0.49 to 0.98 MPa while the speed is maintained stationary. The braking pressure is within a low range, the increase in temperature will not be obvious, and the strength of matrix material decreases slightly [49]. With a further increase in braking pressure, the temperature will increase gradually, which decreases the strength of matrix materials due to the wear rate keeps increasing.

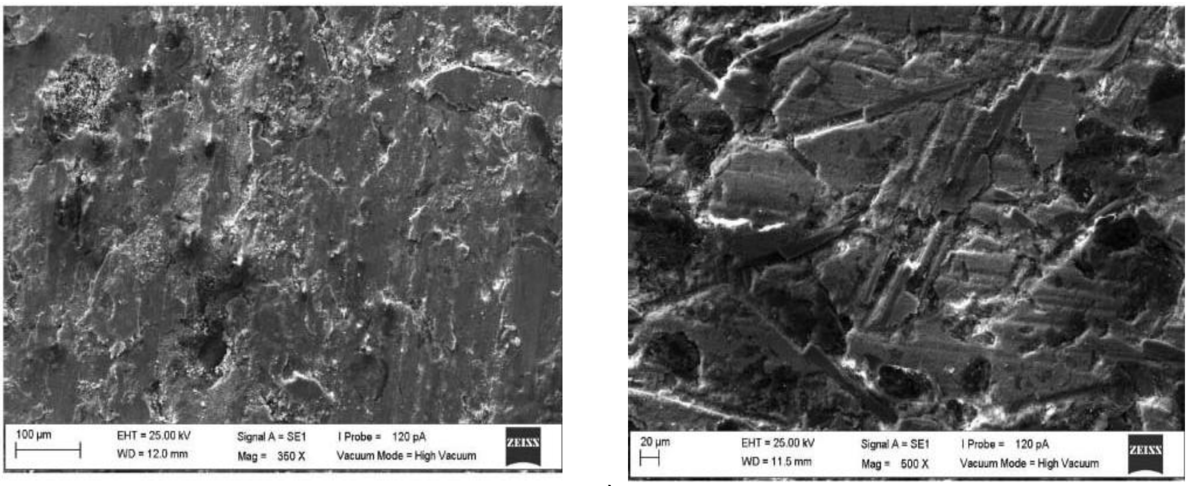
Influence of temperature on wear of Brake's Surfaces

The rise in temperature influences the wear of braking surface. The surface temperature is not uniformly distributed on the interface. The temperature of asperities may be much higher than that of surface, which then forms local high-temperature zones. The increase in friction with increasing time and temperature was primarily correlated to the formation of primary plateaus. Broken fibers and hard particles, which were embedded on the surface of the composites, represent the primary plateaus, and smooth protruding patches on the surface represent the secondary plateaus. In general, Novolac-type phenolic resins are widely used as a binder for friction materials and several modified phenolic resins have been developed for better friction properties [49]. A common problem with binder resins is that they are not heat proof, because the friction heat generated during the brake easily raises the temperature at the friction interface above the decomposition temperature of the binder resin, resulting in an abrupt change in friction force during braking [50].



(a) SF30 **(b) GF30**

Fig. 7 SEM micrographs of the worn surfaces after testing at 200^{0}C (V = 3.2 m/s, P = 625 N) [52]



(c) SF30 **(d) GF30**

Fig. 7 SEM micrographs of the worn surfaces after testing at 350^{0}C (V = 6.7 m/s, P = 625 N) [52]

The surface temperature is not uniformly distributed on the interface [45, 46]. The temperature of asperities may be much higher than that of surface, which then forms local high-temperature zones. The temperature transfers inside through friction interface, and its distribution is associated with the thermo-physical properties of friction material [50-52].When the rough surface of the specimen was worn, the primary plateaus formed, thereby increasing the possible area of real contact between the specimen and the counterface. Further, as the possible area of real contact increased and the surfaces were worn smooth, the element of elastic contact increased and, accordingly, the area of real contact. However, with increasing temperature and speed, the worn surfaces of the composites were observed to generally have many broken and pulled-out fibers, fiber/matrix debonding, and limited secondary plateaus, as can be seen in Figs. c & d.

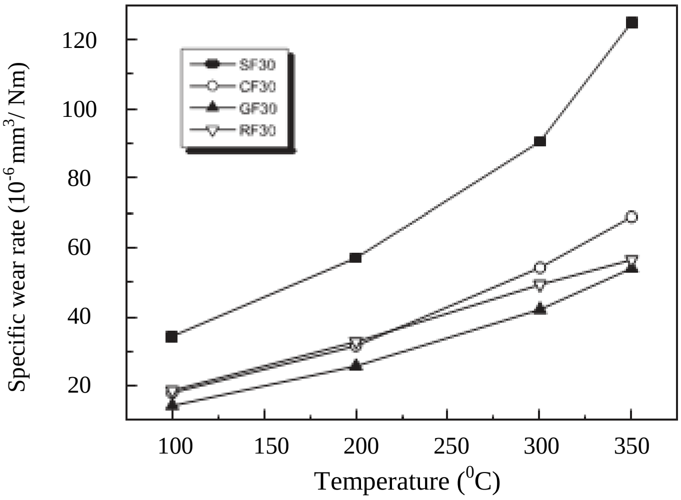


Fig. 8 Effect of Temperature on the Specific wear Rate of Different Materials (P = 625 N, V = 6.7 m/s). [52]

The increase in temperature caused thermal penetration, which resulted in softening of the matrix resin. This caused weakening of the bond strength of the fiber–matrix interface [53]. Both the thermal degradation and the pull-out of fibers contributed to the higher specific wear rate at high temperatures. For example, the variation of wear rate with temperature for the friction material filled with steel wool fiber and scanning electron microscopy (SEM) micrographs of the worn surface of the specimen with steel fibers after testing at 200^{0}C and 350^{0}C are shown in Fig. 7. It can be seen that the wear rate keeps climbing with the increasing temperature, which demonstrates that the wear of friction material is more serious at a higher temperature, as shown in Fig. 8. Overall, the wear rate decrease at the beginning period. However, after the temperature reaches a certain value, the wear rate begin to increase with the increase in temperature. In detail, it was pointed out that when the temperature is within a low range, bumps on the interface of friction pair begin to mesh mechanically [54].

Influence of Sliding Velocity on Wear of Brake's Surfaces

The wear rate of friction material often varies as the sliding velocity changes, and the amount of variation in the wear was highly dependent on the ingredients in the brake material. The effects of sliding velocity on the specific wear rate of the same and different brake friction material was studied by the past researchers. As the actual contact area between pair of brake friction material is much lower than its nominal contact area, the direct influence of initial sliding velocity on the wear behaviors can be ignored. The specific wear rate for the series of fibers like RF30, GF30, CF30 & SF30 in the brake friction material was found to increase with increasing sliding velocity and temperature [53]. The high asperities is present on the couterface of brake material causes increase in rate of repeated type of impact loading while increase in sliding velocity. This loading increases the frictional thrust, which causes the localized vibration and chattering at the sliding surface interface. Due to that increasing the debonding and fracture of the reinforcing fibers takes place [55]. The SF30 has highest specific wear rate and GF30 has lowest specific wear rates were observed and as indicated in fig. 9. The asbestos and non-asbestos brake pad (NABP) material compared with a commercial brake pad (CMBP) against gray cast iron disc under dry condition by using pin-on-disc test rig [56].The test were conducted at a sliding velocity of 2-20 m/s and sliding distance upto 42km. The running in region has high fluctuations in wear rate as compared to sliding velocity of 12 m/s. The thin layer formed due to the rapid transferring of film on the counterface, which prevents the increase in wear rate of brake pad material. NABP material have greater wear resistance as compared to ABP and NABP. The initial braking velocity has higher influence on wear rate compared with initial braking pressure. The hitting frequency and speed between asperities determined by braking velocity, which plays an important role in wear. The higher velocity and worse braking condition causes higher heat generation [3]. Under the braking with a low speed, the friction films have not yet been formed. The absorbed moisture and oxygen lubricate the contact interface to cause a low wear rate.

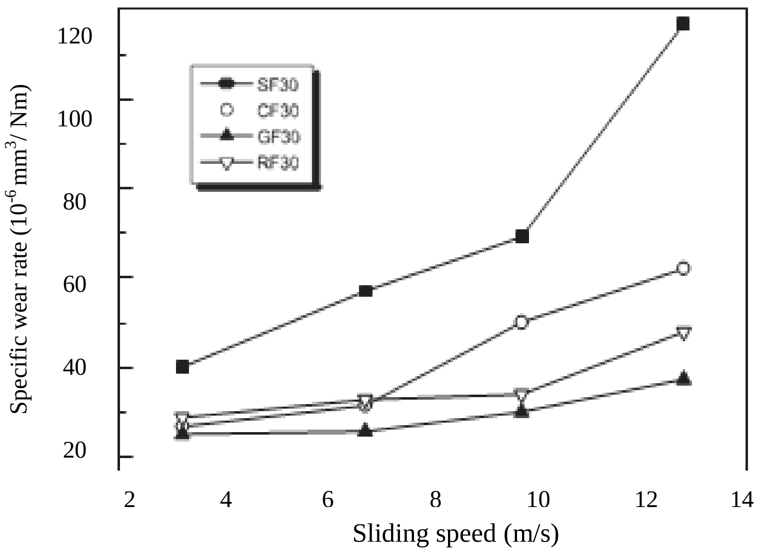


Fig. 9 Effect of sliding Speed on Specific Wear Rate on Different Brake Material [52]

The worn surfaces of some typical composites and corresponding wear debris were coated with a thin layer of gold for observation the morphology using a scanning electron microscope. The worn surfaces of specimens RF30, CF30, GF30, and SF30 tested at sliding speeds of 3.2 and 9.7 m/s.

CONCLUSION

Based on the nature of contact between brake surfaces should be intricate and diverse. Due to the dynamic nature many factors affect the performance of brake with time. Different wear models studied by past years and by referring these studies following conclusions are to be summarized:

1) The surface properties of brakes studied for various stages of operation at different conditions. Also doing the study of impact of environment with concern to the worn out phase of brake. This wear is causes generally due to the influence of sliding velocity, applied pressure and surface temperature.

2) The wear modelling of brakes related to two types of models one which give information about amount of energy required for certain level of brake wear at different operating parameters. This is provides the information only about life and operating parameters but did not provide information about wear rate of brake and operating parameters. Another model provides relation between operating parameters, wear rate and wear energy of brakes but did not gives relation between life and operating parameters of brake. These models offers information and possibilities for intelligent braking behavior during braking operation at different conditions and parameters.

3) The wear rate decreases with increase in contact pressure between the brake surfaces under dry condition while it increases with increase in contact pressure under wet condition. On the other hand, wear rate should be low at low temperature but with increase in temperature wear rate also increases because of asperity present in contacting surfaces gets distributed with influence of temperature and pressure. These deformed and broken asperity produce wear debris causes more heat generation on the surface. In the case of sliding velocity of brake surface interface, the wear rate increases continuously with increasing sliding velocity. The rate of wear is slow at the medium velocity of sliding of brakes surface.

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