Thermal Interaction between Polymer-Based Composite Friction Materials and Counterfaces

F. ABBASI,[1] A. SHOJAEI,[1] A. A. KATBAB[2]

[1] Research Center of Iranian Railways, Italia Crossing, Vessal St., P. O. Box: 14155-6394, Tehran, Iran

[2] Polymer Engineering Department, Amirkabir University of Technology, Hafez Ave., P. O. Box: 15875-4413, Tehran, Iran

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ABSTRACT: Attempts have been made to improve the performance of polymeric composite friction materials for eliminating undesirable mechanical and thermal effects on the opposing surfaces. Elastic compression modulus and thermal conductivity of the moulded friction materials were found to be the most effective parameters upon the thermal interaction between the disc and brake pad. Effects of elastic modulus on temperature accumulation of the interface have also been studied. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 81: 364–369, 2001

Key words: polymer composite; friction material; thermal interaction; elastic modulus; thermal conductivity

INTRODUCTION

When a vehicle is stopped, the kinetic energy of the moving vehicle is converted into heat by the brake, which is gradually dissipated into atmosphere.[1] The last section of a brake system is a sliding friction couple consisting of a rotor connected to the wheel and a stator on which the friction material (pad, lining, or block) is mounted.

Polymeric composite friction materials are widely used as stator components of sliding friction couple of the brake systems for rail vehicles. For axle-mounted discs, these materials are called "brake pads," and for braking via contact with the wheel thread, they are called "brake shoes."

The main components of a friction material are the polymer matrix, fibrous filler, particulate fillers of metal or mineral, and solid lubricants.[2] Fillers are used in the friction compounds as an auxiliary material to achieve the predetermined friction coefficient (μ), wear, and thermal properties. The various components of the material have to be added into the friction material in the optimum proportion. For instance, low concentration of the resin leads to the weak physical properties of the cured material and high concentration leads to fall the friction coefficient at increased temperatures.[2] Depending upon the interactions between the filler particles and hard abrasive asperities, different wear features have been reported for different particle sizes.[3] With the particle size smaller than the asperity spacing, no load-supporting action is provided, and effects of cavitation debonding at the filler matrix interfaces (damage zone model) become important. Increasing the adhesion at the filler–matrix interfaces significantly improves the wear resistance of elastomers owing to the suppression of filler pullout (medium particles) and debonding cavitation at the interface (small particles).[4] The com-

Correspondence to: F. Abbasi.

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pound used as friction materials for brake pads not only must have the specified friction coefficient (μ) and wear properties for the particular application, but also have to meet a number of other requirements such as resistance towards thermal cracking, which is the result of thermal accumulation and low wearing effects upon the opposing surface.[2,5]

The object of the present work is to determine the most important characteristics of the brake pad that control the thermal interaction between the disc and pad, and found that elastic compression modulus and thermal conductivity of the molded friction material play important roles in the thermophysical properties and therefore performance of the pad.

EXPERIMENTAL

Sample Preparation

To prepare the required test samples, the designed formulation based on SBR, fillers, resin, etc., was compounded in a banbury mixer. The prepared compound was compression molded at 145°C and pressure of 6000 psi. The molded sample was postcured at 180°C for 12 h.

Compression Modulus Measurement

The compression modulus of the test specimens was measured using a Rockwell hardness machine[6] on which the ball was replaced by a cylindrical mandrel 13.3 mm in diameter. The minimum (preliminary) load was 10 kgf, and the maximum (total) load of 35 kgf. Before applying the load, the deflection of the test machine between minimum and maximum loads is first recorded and then the test piece is loaded sequentially. The minimum load is applied, and the dial is reset to zero (black graduated scale), with the test specimen placed in a central piston under the mandrel. The maximum load is then applied for 45 s, followed by a 10-s application of the minimum load. The dial is reset to zero, then the maximum load is applied again. The reading is then taken at the point when, after about 10 s, the needle shows a sudden deceleration. The deflection of the machine is then subtracted from this reading, and the net deflection expressed in graduations on the scale is multiplied by 2 to obtain the deflection Δh of the test specimen in μm. The modulus E is then

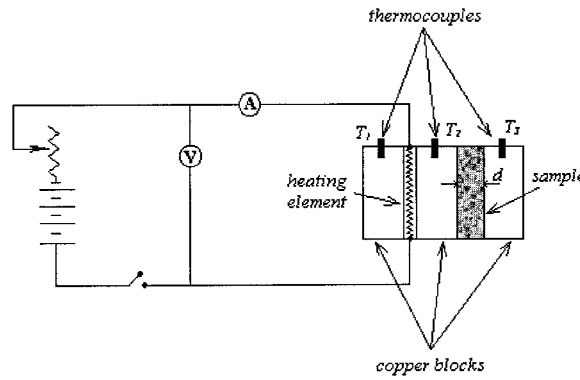


Figure 1 Schematic of the apparatus used for thermal conductivity measurement.

calculated as the average of six measurements according to the following equation:

$$E = \frac{(35-10)\times 9.8066}{\pi \times \frac{d^2}{4}} \times \frac{h}{\frac{\Delta h}{1000}} \frac{N}{\text{mm}^2}$$

$$E = \frac{3.122 \times 10^5 \times h}{d^2 \times \Delta h} \frac{N}{\text{mm}^2} \tag{1}$$

where h is the height in mm, d is the diameter in mm, and Δh is the deflection of test specimen in μm.

Thermal Conductivity Measurement

The schematic of the apparatus used for thermal conductivity (λ) measurement is shown in Figure 1. The temperature reading was taken in the steady state, when the temperature variation in each of copper blocks was not more than 0.1°C over a period of 10 min. The test samples were blocks ($50 \times 50 \times 10$ mm^3) that were prepared from composite brake pads. During testing, ambient and sample temperatures were kept about 20 and 100°C, respectively. Thermal conductivity λ is then calculated from the equation:

$$W = \frac{Q}{t}$$

$$J = \frac{W}{A}$$

$$\lambda = \frac{J}{\frac{\Delta T}{d}} \tag{2}$$

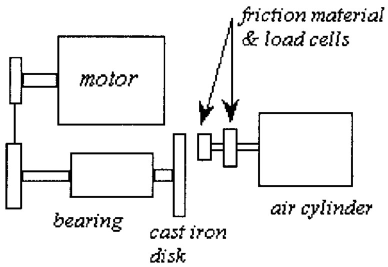


Figure 2 Schematic of the apparatus used for small specimen testing.

where Q is the heat in Ws or J, t is the time in s, W is the heat per time unit in W or J/s, A is the surface area in m^2, J is the heat flux in W/m^2, ΔT is the difference of temperature between the two sides of sample in °C, d is the thickness of the sample in m, and λ is the thermal conductivity in W/m°C or J/ms°C.

Evaluation of Disk–Pad Interaction

A dynamometer test offers a rapid method to determine the performance of a pad. The schematic of the used dynamometer is given in Figure 2.[7] This apparatus has been developed such that a small specimen of friction material could be brought in contact with a rotating cast iron disk, the speed of which is controlled by a motor.

A small friction specimen is pushed to the face of the rotating disk by a pneumatic cylinder. The normal force is measured with a load cell and the friction force is evaluated via a calibrated strain gage bridge mounted on the load arm. The temperature of the friction specimen was measured with a thermocouple embedded into the back of the specimen (included back plate). Two different cured pads, having a compression modulus of 1300 N/mm^2 and 270 N/mm^2, respectively, were selected.

In addition to dynamometric tests, such as temperature measurement between the friction materials and discs, the ideal means to test thermal damaging is to assemble different types of composite brake pads on the axle-mounted discs with complete vehicle, then investigation the performance of discs during the specified periods of time. All friction materials were subjected to evaluation in vehicle tests in actual braking conditions. The vehicles used had the weight of 53,000–60,000 kg and braking pressure of 5 atm.

RESULTS AND DISCUSSION

It has now become obvious, that the mechanical and tribological properties of polymer-based composite friction materials are related to the properties of their components,[8] and the way they interact. The size and distribution and, particularly the kind of metallic particles, determine the thermal conductivity of the composites, which plays an important role in the characteristics of the friction materials.

Table I The Values of Elastic Modulus (E) and Thermal Conductivity (λ) of Different Composite Materials

Material	I	II	III	IV
E (Average) (N/mm^2)	271.3	1286.0	1304.3	3335.7
Standard Deviation	13.3	16.9	14.9	31.9
λ (kJ/mh°C)	3.44	0.92	2.5	4.56

In the molded materials I to III, the rubber behaves as a continuous phase that results in lowering the modulus of the pad, but steel wool acts as a reinforcing agent. In material IV, asbestos fiber was used as a reinforcing agent instead of steel fibers, and resinous material together with rubber powder were employed as the continuous matrix.

The results of compression modulus [obtained from eq. (1)] and thermal conductivity [obtained from eq. (2)] measurements are presented in Table I. Also, a typical photograph of an intact disc surface, before being assembled on the axle is shown in Figure 3. It can be seen from Figure 4 that the pad based on compound I has not put adverse effects on the surface of the rotating disc until a 70,000-km period of working.

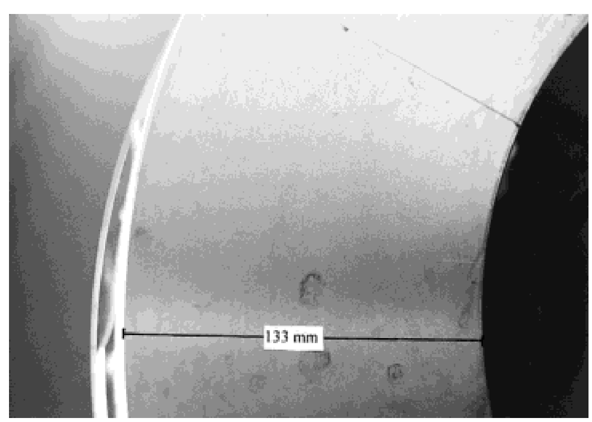


Figure 3 The surface of unworked discs before contact with brake pads.

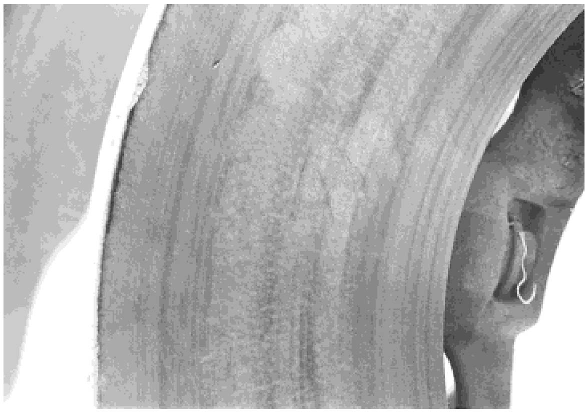
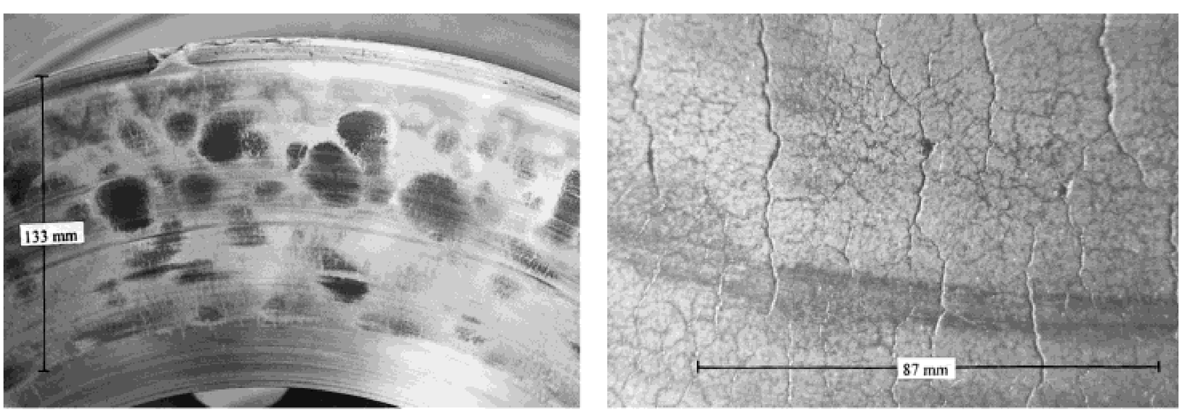


Figure 4 Photograph of disc after more than 70,000 km working with material I.

Figure 5(a), shows the topograph of the disc surface after being in contact with the pad based on material IV. The formation of hot spot sites on the surface of the disc is clearly seen. The light elliptical spots are believed to be formed first, followed by the merged dark spots below it.[9] Figure 5(a) demonstrates the early stage of the martensite band formation on the disc followed by continued hot spotting. The original hot spot sites expand to become a region of tempered martensite, laced with predominantly radial cracks. Such a disc is needed to be replaced before being fractured, otherwise bending and hoop stresses from the high brake loading might cause the microcracks to grow into the structural cracks [Fig. 5(b)].

Figure 6 shows the surface topographs of the discs, which have been worked in contact with material II and III. It is obviously seen that the surface of the disc in contact with material III has been less thermally affected than material II. This could be explained to be due to the higher thermal conductivity of material III, which leads to lower heat accumulation in the interface with the disc. On the other hand, the composite material with high modulus but high thermal conductivity (III) can behave almost similar to the material with low compression modulus (material I) [Fig. 6(b)].

During the process of stopping the vehicle, kinetic energy is converted to heat at the sliding interface of the friction pairs. This is then dissipated primarily by conduction through the friction pairs and by convection and radiation to the atmosphere and adjacent components; secondly by absorption leading to the chemical, metallurgical, and wear processes at the interface.[10] The dissipated energy (frictional heat), which transfers into the disc, is because its temperature is raised. The temperature rise of the disc can be predicted by the model and technique suggested for the for the braking process.[11,12] However, in severe braking conditions, the increase in the temperature of the disk surface is unequal in its distribution, which is due to the formation of hot spots over the disc. Critical hot spots can lead to a cast iron fracture because of the associated high thermal stresses from phase transitions during heating and martensite formation upon subsequent cooling. When martensite forms at a hot spot, the site becomes elevated from the associated volume increase, relative to surrounding



(a) (b)

Figure 5 Photographs of the disc surface after being contacted with material IV: (a) early stage in the formation of martensite band on the disc, after nearly 3000 km; (b) conversion of microcracks to structural cracks, after nearly 15,000 km.

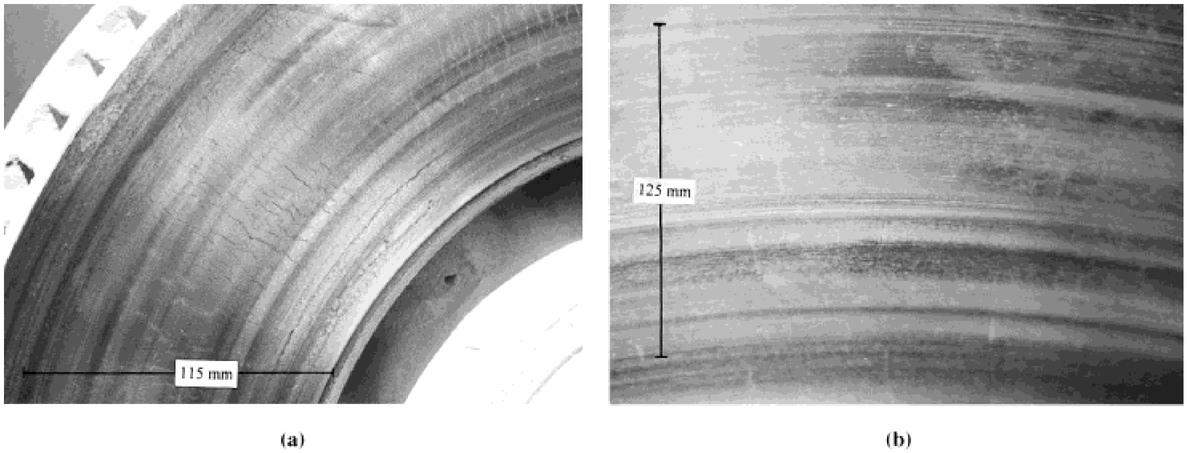


Figure 6 Photographs of discs after nearly 30,000 km contact with the brake pads made from: (a) material II; (b) material III.

cast iron. The elevated spots continually wear down, and new ones appeared. The high temperature of these hot spots certainly influences the thermal fatigue. The mechanism of the formation of hot spots is as follows: during heating, the compressive stress under the brake pad rises by the restrained thermal expansion up to yielding (in a radial direction). This yielding starts at separate points, resulting in the formation of "hills." These hills are fed by thermal expansion of the local metal and by pushing in of metal yielding from the surrounding area, which is in compression. The cause of the local yielding could be an unequal temperature distribution, an existing unequal stress field, or another cause of instability.[13] Therefore, to avoid high local temperature one must attempt to design a friction material so that the generated frictional heat generated is uniformly distributed over its working area. The real contact area between the friction material and counterface is much less than the nominal area of contact. The surface of the disc, which is in contact with the pads, will become flattened due to the abrasion. The pads will deform elastically and conform to some degree with the contacting surface of the disc. The less rigid the material of the pad, the greater will be the degree of conformity, as illustrated in Figure 7.[14]

Consequently, to keep the temperature at a low level, the contact area should be relatively large (material needs to be soft), and the locus of the contact area has to traverse the whole area of the pad once per each revolution of the disc. This dictates a low modulus for the material and conformability to the opposing surface. This is because the frictional heat could be dissipated mechanically, and the temperature of the contact area cannot increase more than a definite level. In the case of the friction material with medium modulus, high thermal conductivity helps to conduct a major part of the generated heat through the pad and, therefore, preventing the increase in the contact temperature. Figure 8 shows the maximum temperatures obtained from a dynamometer for different friction materials.

CONCLUSION

The dissipation of the energy (frictional heat) put into the disc raises the disc temperature. The

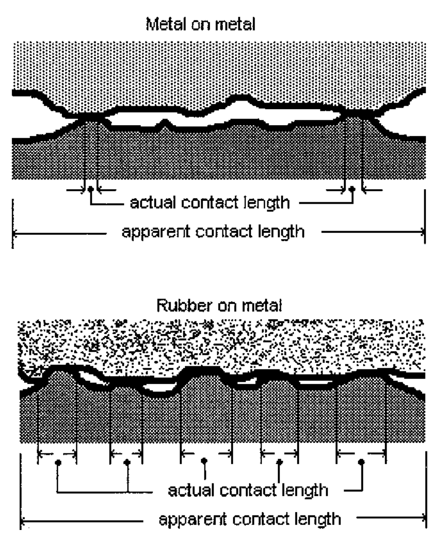


Figure 7 Contact between two surfaces.

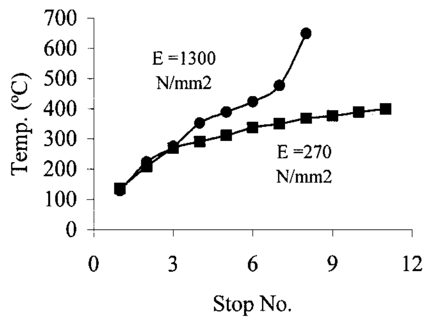


Figure 8 Maximum disc temperatures reached by high and low modulus during stopping on a dynamometer from 700 rpm. Brake pressure = 10 kg cm^{-2}, braking time = 10 s.

increase in temperature is not uniformly distributed over the disc surface. The input heat is accumulated on the disc, which results in high local temperature. One, therefore, has to design a friction material so that the generated frictional heat is uniformly distributed over the working area of the friction material, which prevents the high local temperatures. To minimize the increase in temperature, the contact area should be relatively large, and therefore, the material is needed to be soft enough. This means that the material should possess a low modulus and be conformable to the opposing surface. This enables the generated frictional heat to be dissipated mechanically, which prevents the increase of the temperature in the contact area. In the case of the friction material with high modulus, high thermal conductivity is needed to help the conduction of the heat through the pad.

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