

Microstructure and Detachment Mechanism of Friction Layers on the Surface of Brake Shoes

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Automotive and truck brake shoe materials are complex composites of metals, ceramics, and polymers. These are designed to provide stable, reliable frictional performance over a range of vehicle operating conditions, exhibit acceptable wear life, and offer freedom from noise and sensible vibrations. During their use, friction brakes tend to form thin, third-body layers on their contact surfaces. Such tribo-layers play a part in frictional characteristics, and therefore it is of interest to study their structure and properties. This article describes the structure of the friction-induced layers that formed on commercially manufactured brake shoes on a trailer that was subjected to 4 years of highway driving. The layers consist of a thin, brittle crust of nanoscale particulate material that easily delaminates from the substrate. Polished cross sections were studied with both optical and scanning electron microscopy (SEM). Transmission electron microscopy (TEM) of extracted flakes revealed the complex, fine structure of the friction-induced layer. Realistic brake friction models should not use bulk properties of the starting materials, but rather should incorporate the properties of the fine-grained friction layers.

Keywords brake, drum brake, friction, transfer film

1. Introduction

Most heavy, long-haul trucks operating on U.S. highways use drum-type brakes on both the tractor vehicle and the trailer. This brake design uses a pair of curved, conformal shoes that press against the inside, rotating surfaces of the brake drum. Drums are usually fabricated from gray cast iron, typically containing about 3.5% carbon, and various additives for strength and toughness. Shoes, on the other hand, are much more complex materials. They typically contain a resin binder with additions of mineral fibers, fillers, friction-modifying compounds, abrasives, and metallic particles to modify heat flow characteristics. It is difficult to generalize about the composition and structure of friction films on brakes because both the compositions of the starting materials and the conditions that generate them vary greatly.^[1] However, these layers influence the performance of friction brakes, and characterizing them becomes a matter of both engineering and scientific interest.

During use, the contact surfaces of friction brakes acquire third body deposits. These layers vary in thickness from less than 1 μm to more than 5 μm , and are not uniformly distributed across the swept surfaces. It was previously shown, in wet and dry sliding experiments using cast iron pins sliding on flat discs of commercial automotive brake pad materials, that the tendency of friction-induced films to form depends at least in part on the moisture level in the sliding environment.^[2] Sliding experiments conducted in water tended to suppress the formation of these films and led to a friction spike just before the

system came to a stop. More recent work has addressed the structure and composition of third bodies on the surfaces of rotors of disc-type brakes.^[3,4]

Historically, friction materials were developed largely by empirical, or trial-and-error methods, although recent work was attempted to systematize the process using the mathematical principles of experimental design.^[5,6] Variants of brake materials are tested on vehicles, inertial dynamometers, or subscale laboratory tests, such as the Chase test and the friction assessment and screening test (FAST).^[7] Over the years, it became known that certain additives altered the thermal conductivity, reduced brake noise, or improved the wear, but the fundamental bases for the effects of additives were largely a case of speculation. Only a few detailed studies of friction-induced films on brakes have appeared in the materials literature (e.g., Ref. 3, 8, and 9), and except for the recent work of Eriksson,^[8] these seem to be primarily focused on friction films covering the surfaces of disc rotors or drums, rather than on the opposing surfaces of the shoes and pads. Surprisingly little information has been published on the internal fine structure of friction-induced films on heavily-used brake shoe surfaces, and it was therefore of interest to investigate the fine structure of friction layers on brake shoe materials.

2. Specimen Material Description

A worn brake shoe from a commercial long-haul trailer was used for this investigation. The shoe was one of a pair removed from the rear right of the trailer during routine maintenance. The brake shoes had been in service for four years. Specimens were removed from the surface of the brake shoe, near the center of the arc of contact. Each shoe in the pair was approximately 0.175 m wide and 0.410 m long, subtending an arc of approximately 118° of the swept internal surface of the drum. The composition of the proprietary shoe material was not known; however, it was a typical, resin-bonded commercial product, part number 13-0068 (Armada Inc., Nashville, TN).

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As discussed previously,^[1] the composition of friction materials typically contain 10-45 vol.% phenolic resin, 0-40 vol.% barium sulfate, 5-30 vol.% mineral or glass fibers, 3-30 vol.% cashew particles, 0-15 vol.% graphite, 0-8 vol.% metal sulfides, 0-10 vol.% abrasives, and 0-20 vol.% friction dust (a proprietary mixture of friction-modifying additives and fillers). Heavier-duty friction materials, like those for truck and trailer brakes, tend to contain a higher metallic fraction owing to the need to dissipate heat away from the frictional interface.

Figure 1(a) is a scanning electron micrograph (SEM) of a polished cross section of the pad material showing a range of constituents. The upper left center of the image shows a bundle of fibers; each fiber is approximately 20 μm in diameter. In fractured pieces of shoe material, such fiber bundles were seen extending from the fracture surfaces like translucent, golden brushes. Electron microprobe analysis revealed these fibers to be calcium aluminosilicate. The blocky, medium-gray particle near the center of the figure is typical of the size and morphology of the calcium silicate additives. The whitest-appearing particles are typically barium sulfate. There is a wide range of

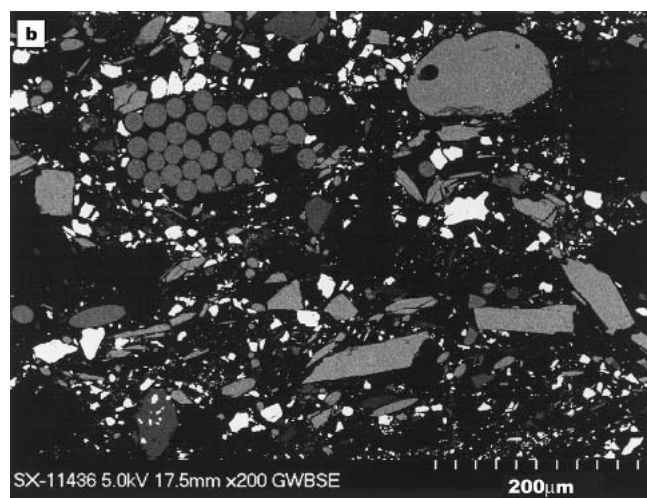
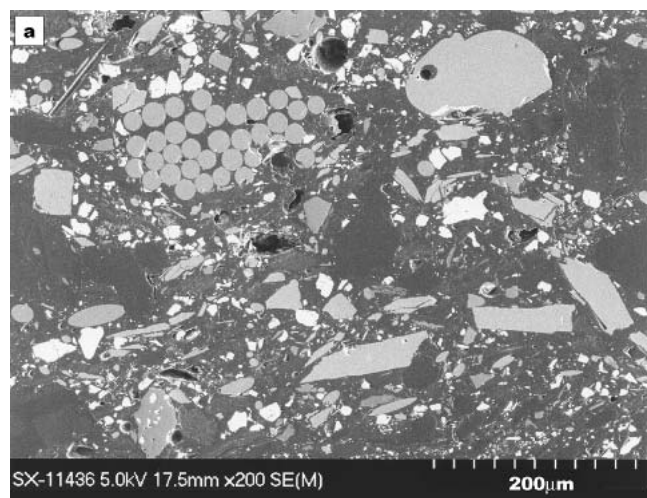


Fig. 1 (a) Polished cross section of the pad material showing a range of constituents (SEM); (b) BSE image of the shoe material's structure showing atomic number contrast between phases

particle sizes in the material. Metallic cutting-chip-like particles, observed in other views, were likely to be metals added to enhance heat transfer. Backscattered electron (BSE) images of the shoe material's structure indicated a mixture of low and high atomic number species (Fig. 1b). Higher atomic number species tend to backscatter more electrons and thus appear brighter in the image. The matrix material was shown to contain amorphous carbon and thus was largely polymeric and noncrystalline.

3. Wear Surface Features

Some areas of the worn shoe were shiny to the naked eye, suggesting extensive plastic deformation and smearing of the surface layers. Other areas were rougher in appearance, suggesting the pullout or delamination of surface material. Figure 2 is a photograph of the contact surface. A combination of normal incidence illumination and oblique lighting was used to reveal the topography. Some areas retain shiny friction films and others reveal grooved material below areas of delaminated film. Blisters were common on the layer-covered areas of the surface. Probing the surface with a hand-held stylus demonstrated that the friction-induced layers are only loosely bound, contain subsurface fissures that enable buckling, and are mainly held on by the contact pressure between the shoe and the drum. Networks of fine microcracks were evident.

4. SEM and Back-Scatter Images of Polished Cross Sections

A polished cross section was prepared to reveal the structure of the friction-induced layers. Optical microscopy, SEM, and BSE imaging were used to examine it, but of these, the latter two techniques seemed most revealing and their results will be discussed here. Figure 3 shows an SEM image of a polished cross section obtained at a location near the center of the worn



Fig. 2 Features on the contact surface of the brake shoe. Shiny areas are retained patches of friction films. Some areas show blisters. The distance between the rivet holes is 57 mm (optical image).

brake shoe. The sliding direction was normal to the plane of the cross section. A thin layer of fine-grained material has become detached from the surface and is in the process of being removed. The friction-induced film thickness on this cross section ranged from about 1.4 μm for the curved end to about 15 μm for the deepest deposit. Its structure was extremely fine, and too small to be easily resolved by optical microscopy. The concave curvature of the uplifted flake suggests the presence of near-surface, compressive stress.

A higher-magnification BSE image of the same flake is shown in Fig. 4. The material comprising the surface layer and the flake forming from it has a much finer microstructure than the material below it. Microfractures followed a series of irregular and sometimes parallel paths, leading to variations in the thickness of loose flakes. Therefore, one cannot ascribe a precise thickness to friction-induced layers, nor to the particles that separate from them.

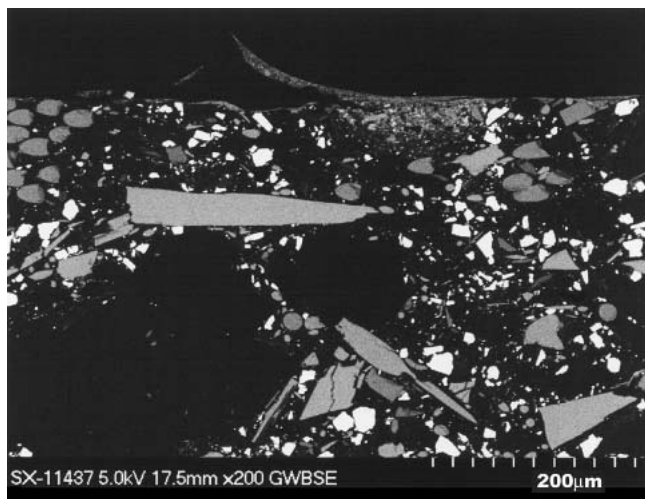


Fig. 3 Cross section of the sliding surface near the center of the worn brake shoe. The sliding direction was normal to the plane of the cross section (SEM).

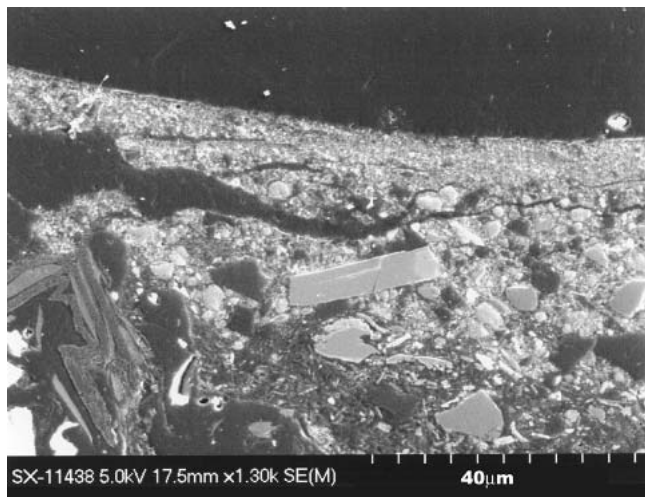


Fig. 4 The same flake shown in Fig. 3, but at higher magnification (BSE image)

Still higher magnifications of the cross section of a hinged, nearly detached flake reveals an intricate mixture of fine particles, many of them less than 100 nm in diameter (Fig. 5a). There was no apparent difference in particle size distribution through the thickness of the flake, as illustrated by Fig. 5(b), which shows the edge of the underside of the separating flake. Severe compression, shear, and fracturing of the brake shoe constituents during sliding contact is evident in this mechanically mixed friction layer.

5. Fine Structure of Friction Layer Fragments

Specimens of loose fragments lifted from the surface of the brake shoe were prepared for transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM). High-magnification studies of thinned sections of these flakes revealed the submicrometer structure and composition of the materials. Figures 6 and 7 reveal a complex mixture of phases. Arrows in Fig. 6 indicate agglomerated regions of iron oxide

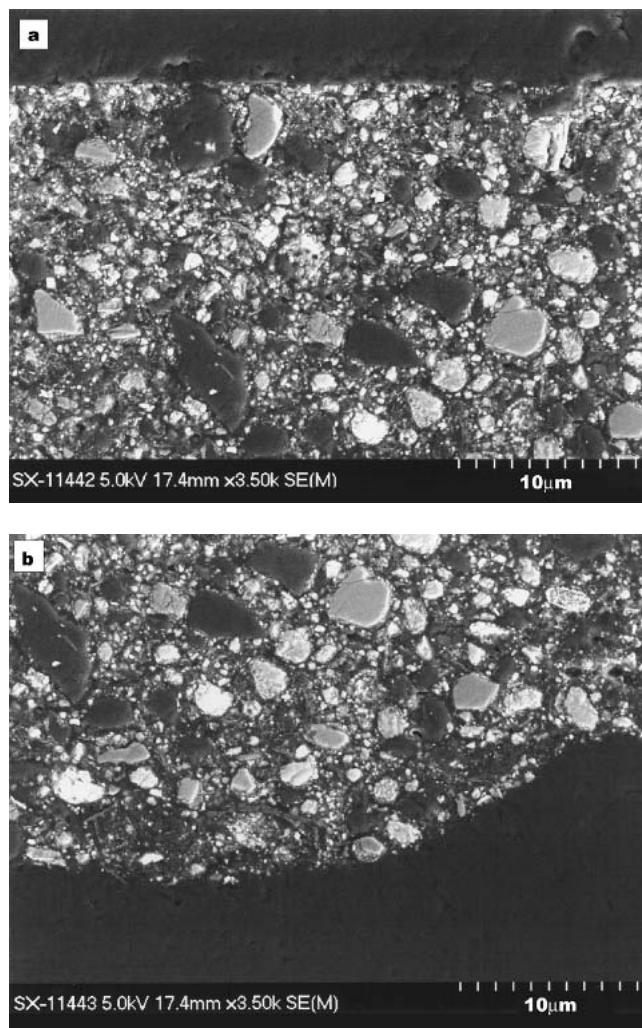


Fig. 5 (a) Fine structure adjacent to the top (contact) surface of the hinged, nearly detached flake shown in Fig. 4; (b) bottom surface of the flake adjacent to the intralayer fracture surface

particles. Iron oxide also surrounds other blocky/large phases in the surface layer (primarily barite [BaSO_4] and wollastonite [CaSiO_3]). There is a wide size range of particles in this layer, ranging from a few tens of nanometers to several micrometers in diameter. The major phase in the top layer (and loose flakes) is iron oxide, which is distributed between/around the two main

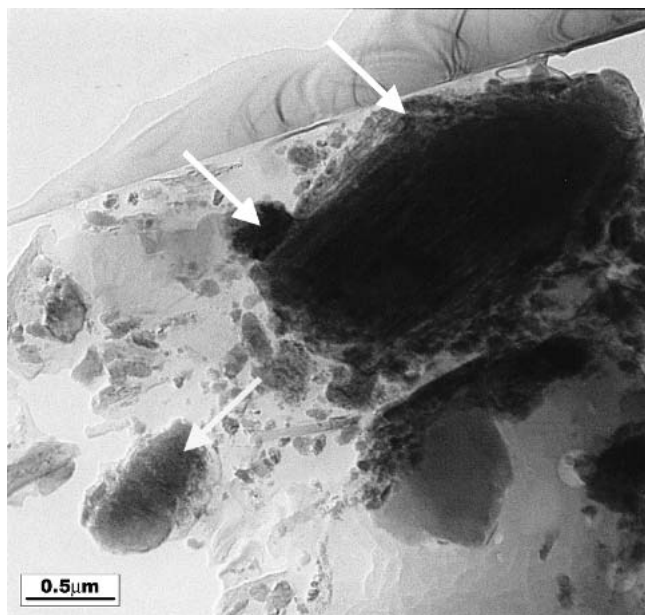


Fig. 6 TEM image of the fine-structure of a flake removed from the brake shoe surface. The large dark block is wollastonite. Arrows indicate agglomerated iron oxide particles.

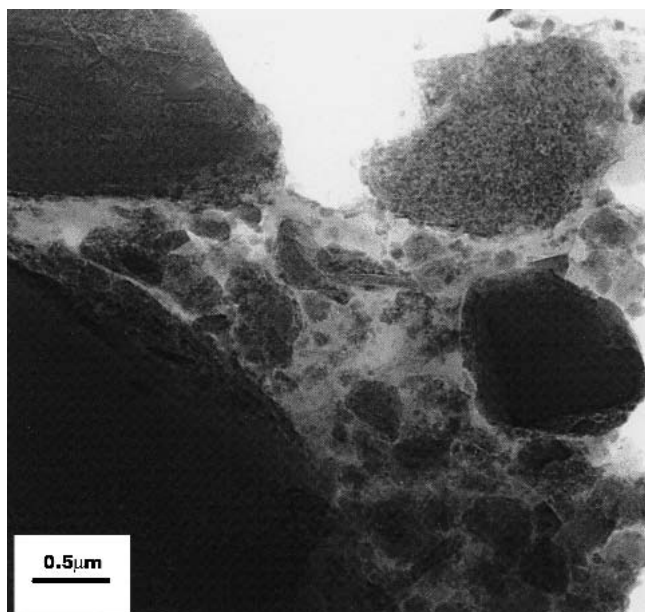


Fig. 7 The STEM enabled both imaging and chemical analysis of the constituent particles. The rounded particle to the right of center is BaSO_4 , the relatively large rounded particle at the lower left is CaSiO_3 , and most of the mid-sized particles between them are iron oxide.

constituents of the brake pad: wollastonite and barite. Electron microprobe studies of the cross sections of shoe material indicated an absence of iron or iron oxide; hence, the iron in these specimens probably originated from the surface of the cast iron counterface.

6. Discussion

Friction materials take a great deal of abuse in service, and yet they must provide controlled braking friction and acceptable wear resistance against the chosen counterface material (usually gray cast iron). When braking contact first occurs, changes occur in the microgeometric roughness and microstructures of the contact surfaces. These changes are mitigated by a combination of mechanical stresses (compression and shear) and friction-induced heating. The friction material starts out as a relatively coarse-grained composite containing hard particles (angular or rounded abrasives), soft particles (friction modifiers and fillers), and viscoelastic, polymeric binder material. Extensive shear occurs in the soft materials nearest the surface, where tractions are highest. The thickness of the layers varies, but at some locations was in excess of 25 μm. Friction layers on cast iron brake counterfaces tend to range from less than 1 μm to more than 5 μm. Thus, friction-induced layers on the shoe (or pad) side of the friction couple can be an order of magnitude or more thicker than those on the drum (or rotor) side. That result should be expected because friction materials are generally softer and lower in shear strength than their ferrous counterfaces.

The compressive contact stress, coupled with shear, causes fracture of the more brittle components in the near-surface zone and enables mechanical mixing of submicron particle fragments with more ductile species to form a microcomposite. This layer is distinct in microstructure and properties from the underlying friction material. The boundary between the friction-induced film (or layer) and the underlying bulk material is rather distinct in most cases, and separation of the film occurs both in the boundary and in branched fissures within the friction layer itself. Sanders et al.^[10] observed that wear particles from brakes tend to be in the size range of 1-3 μm. Such sizes are more typical of the thickness of the frictional transfer layer on the drum or rotor surface than on the friction material. However, optical microscopy and SEM of the microcomposite friction layers indicate their propensity for fine-scale crack propagation and delamination. Such branched cracking can create loose, irregular platelets that are a fraction of the full layer thickness. In addition, crushing of loose debris particles in the friction interface can further reduce their size.

7. Conclusions

With few exceptions, past studies of friction films on brakes have largely focused on deposits on the drum or rotor surfaces; the current work studied the films developed on the friction material. The structure of the friction-induced layers on the surfaces of used trailer brake shoes was fine-grained, and its constituent particles were several orders of magnitude finer than the structure of original material. Incorporation of cast

iron counter-body wear debris added iron oxide and graphite to its composition, as well. The brittle layers were easily detached from the brake shoe surface because of multiple, sometimes parallel fracture paths both within the layers and between the highly deformed layer and the underlying material. Major constituents of the layer were wollastonite, barium sulfate, iron oxide, and amorphous carbon. Particles less than 100 nm in diameter were common in the friction layer.

Modelers of brake material behavior should recognize that the structure and properties of in situ formed friction films are quite different from those of the bulk starting materials, and micromechanical and microthermophysical property measurements of the films will be required to enable realistic modeling of interfacial processes.

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