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Simulation and Characterization of Used Brake Friction Materials and Rotors

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FRICTION MATERIALS FOR automotive brakes are complex composites containing three general classes of materials: chrysotile asbestos fiber, the foundation and reinforcing agent; modifiers that adjust or maintain the friction level and wear rate or control the noise properties; and an organic resin binder. Drums or discs (which are almost universally made of cast pearlitic gray iron) and the friction material form the rotor-stator friction pair which is the heart of the automotive brake. The brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and eventually dissipates it to the atmosphere. As a result of the energy conversion at the stator-rotor interface, the compositions and microstructures of the brake lining and rotor surfaces are altered.

At low service temperatures, the phenolic resin and organic friction modifiers in the friction material undergo ploughing and mechanical damage before they convert on the surface to compositions with slightly higher carbon/oxygen ratios. At somewhat higher use temperatures, the resin and organic friction modifiers convert to carbon more readily, and this in turn oxidizes to carbon dioxide. At the same time, the asbestos wears away more rapidly because of the reduced binder strength and volume at the surface. At still higher temperatures, the asbestos converts from its fibrous form to an olivine powder with little or no reinforcing value. When heat is generated at the sliding interface between stator and rotor much faster than it can be dissipated, the temperature rises and may reach a point where the lining or pad components decompose, oxidize, or melt. The sliding surface of the lining containing these reacted components is called the frictional heat affected layer (FHAL).

At low service temperatures, the surface asperities of the rotor are mechanically worked and the surface becomes essentially free of graphite. Also, the cementite plates in the surface layer are broken up and distributed as fine particles in a

ABSTRACT

A method has been developed to simulate worn-in-service brake friction materials and rotors. The simulated thin linings and worn rotors were prepared by grinding the materials to a predetermined level and then subjecting the prethinned friction couple to a moderate inertial-dynamometer conditioning sequence. The friction materials were characterized by optical microscopy and thermogravimetric analysis. The rotors were characterized by surface roughness measurements and scanning electron microscopy.

The simulated components were shown to have the same microstructure and chemical compositions as worn-in-service components. The extent of thermal and mechanical damage was found to be proportional to the duty cycles experienced. By the method described, the friction-affected layers of the simulated friction couple were found to be intermediate between those of a similar couple with 40,000 miles of light use and those of a couple with 3,100 miles of medium-duty durability use. These simulated components were then used in a study of the effects of worn brake components on braking system performance.

ferrite matrix. When the surface is subjected to very high temperatures, martensite forms at the rubbing surface with an accompanying increase in surface hardness (1, 2).*

Consequently, the thermal and mechanical forces which act at the friction couple interface produce a complex chemically and physically altered microstructure which cannot be accurately described for an average worn-in-service friction couple. For the brake degradation program described in Ref. 3, it was necessary to simulate thin worn linings. The objective of this paper is to describe a study where the objectives were to:

1. Develop a method to simulate worn-in-service linings and rotors.

2. Select suitable methods to characterize the thermally and mechanically damaged rubbing surfaces of used and simulated worn-in-service linings.

3. Demonstrate that the level of braking duty can be correlated with the extent of thermal and mechanical damage at the rubbing surfaces.

In the brake degradation program, the brake systems of two vehicles were studied—a custom-size vehicle equipped with disc fronts/drum rears and an intermediate-size vehicle with drum fronts/drum rears. Simulated used linings and rotors were prepared to match all the wheel combinations used in the program. The data reported here were for the front drum brakes of the intermediate-size vehicle and the corresponding simulated worn-in-service linings and drums.

EXPERIMENTAL PROCEDURES

FRICTION MATERIALS - Fig. 1 is a block diagram which shows the interrelationships of the experimental sequences performed for the friction materials.

Three combinations of used linings were used in this program. They are described as follows.

Combination A 40,000 Miles Light Use - A set of rear drum linings from a 10 X 2 in drum brake was obtained from an employee driving a 1969 intermediate-size vehicle on flat terrain in the Detroit area.

Combination B 18,700 Miles Plus Durability - A set of rear drum linings from an 11 X 2.5 in drum brake was obtained from a 1971 custom-size test vehicle at the Bendix Automotive Development Center. The total mileage was 18,700 miles. The final 3300 miles were durability-test miles. In this durability test, the duty of the stops varied 30.0 mph at 7 ft/s^2 deceleration rate to as high as 70.0 mph at 15 ft/s^2 deceleration rate. Several snubs such as 50-30 mph at moderate deceleration rates were also included. The average lining temperatures were 300 F on the fronts and 250 F on the rears. This duty would be typical of a Los Angeles suburbanite commuting to his downtown employment.

Combination C Simulated Worn-in-Service Thin Linings - A set of drum linings from a 10 X 2.5 in drum brake was simulated as thin linings and then dynamometer tested. The lining had a thickness of 0.035 in at the middle of the shoe before the dynamometer test sequence.

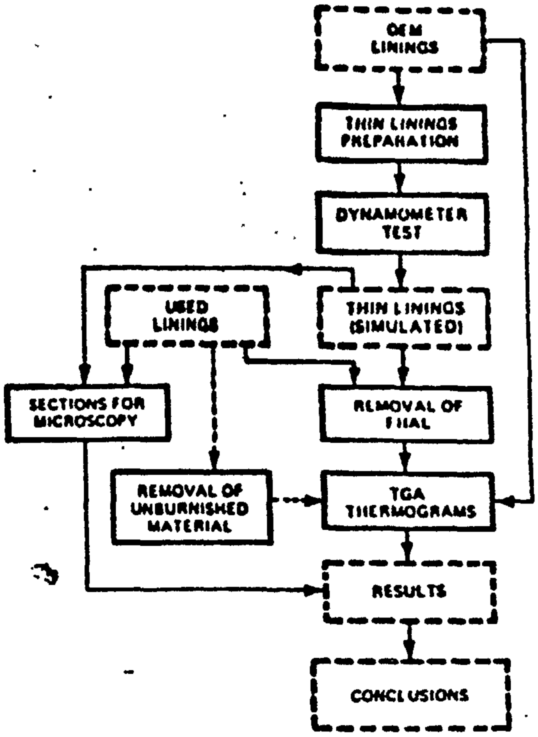

Fig. 1 - Experimental procedure for comparison of burnished linings

Proposed Simulation Method - The initial consideration for the simulation of a thin lining combination was the definition of the final thickness desired in the burnished condition. The minimum thickness recommended by the vehicle manufacturer is 0.030 in. Consequently, the following procedure was proposed to simulate thin worn linings.

A set of OEM (original equipment manufacturer) primary and secondary linings was obtained from the manufacturer. After bonding to the shoes, the linings were ground to a predetermined thickness of 0.035 in and a radius 0.015 in less than that of the simulated worn drum to be used with the linings.

The linings were then installed on a full-wheel inertial dynamometer at Bendix Automotive Control Systems Group, South Bend, Ind. The brake was run through the following conditioning sequence:

1. 200 Stop Burnish: 40.0 mph at 10 ft/s^2 deceleration operating at 250 F.

2. 10 Stop Fade: 60.0 mph at 15 ft/s^2 deceleration with 35 s intervals.

3. 12 Stop Recovery: 30.0 mph at 10 ft/s^2 deceleration

*Numbers in parentheses designate References at end of paper.

starting 2 min after the last fade stop and at 2 min intervals thereafter.

Characterization Methods - Laboratory procedures for characterizing friction materials were optical microscopy and thermogravimetric analysis. Details of these techniques are given below.

Optical Microscopy - Sections of material for optical microscopy consisted of at least a 1.0 X 0.5 in area of lining friction surface removed from the center of each lining. The material was mounted in bakelite or plexiglas such that the lining friction surface layer was perpendicular to the surface to be polished and such that the surface to be polished would show microstructure beneath the lining friction surface. The sample was then rough ground and polished. Examination with oblique reflected light at 50X using a Reichert Zetopan Microscope took place prior to photographing representative sections.

Thermogravimetric Analysis (TGA) - After the removal of the sections for microscopy, samples were removed for chemical analysis by thermogravimetry. The layers were removed by surface scraping with a sharp scalpel onto a lint-free paper. The correct amount was removed for layer 1 by adding the scrapings to a weighed vial until 12 ± 1 mg was obtained. (A sample of 10 mg was used in the subsequent analysis.) In most cases, four layers were removed; in some cases, only three were removed. The characteristics of these layers were then determined and a chemical composition estimated. Fig. 2 is a schematic diagram showing the thicknesses and depths of material analyzed.

Because each major component or group of components has its own characteristic TGA thermogram, this analytical technique was selected to give a compositional analysis of the various components on the frictional heat-affected layer and the underlying layers. In the TGA technique, a small sample (usually 10.0 mg) was placed on a microbalance in a controlled atmosphere (usually flowing air at 40 cm^3/min). The sample was then heated at 20 C/min from 20-1000 C (Fig. 3). In some instances, the sample was heated to 1200 C if no stable residue value was obtained at 1000 C. The weight, recorded as a function of temperature, gives the TGA thermogram. The TGA instrument used in this work was a DuPont Model 950 thermogravimetric analyzer.

ROTORS - Fig. 4 is a block diagram which shows the interrelationships of the experimental sequences performed for the rotor materials.

Used Rotors - Two drums which had been used for 40,000 miles with combination A used linings (previously described) were obtained from an employee vehicle driven on flat terrain in the Detroit area.

Simulated Used Rotors - The simulated used drums were produced with the simulated thin used linings described in the previous section. They were produced from standard OEM drums.

Proposed Simulation Method - Two OEM drums were ground to a surface roughness of 20-30 μin (AA) which was chosen to simulate the roughness of the used drums. The drums were so prepared since work (1) at Bendix Research Laboratories has shown a correlation of both wear and coefficient of friction with surface roughness. This work has also shown that a particular lining combination tends to produce a certain surface roughness on the drum when steady-state con-

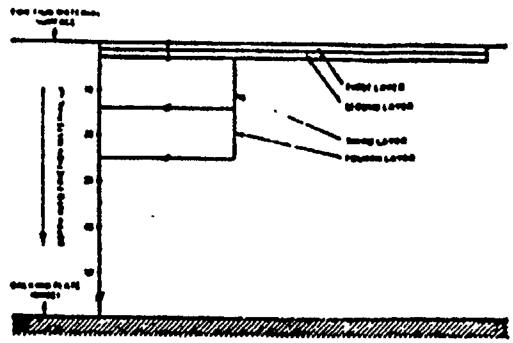

Fig. 2 - Schematic showing friction material layers analyzed

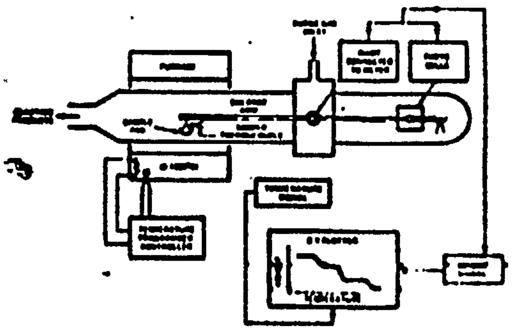

Fig. 3 - Schematic of thermogravimetric analyzer

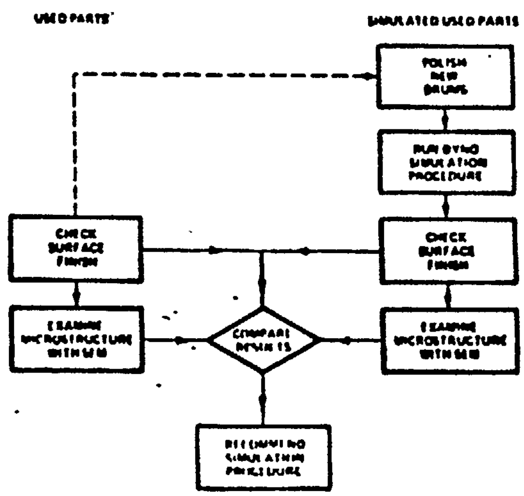

Fig. 4 - Used disc and drum simulation procedure

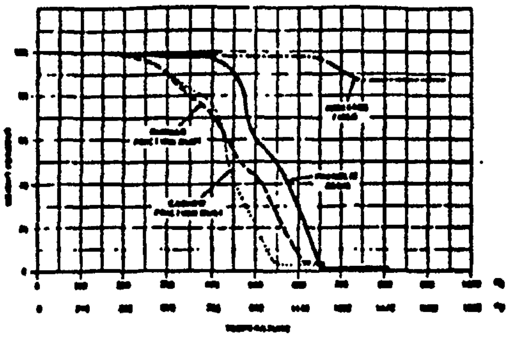

Fig. 5 - Typical TGA thermograms for common friction material components

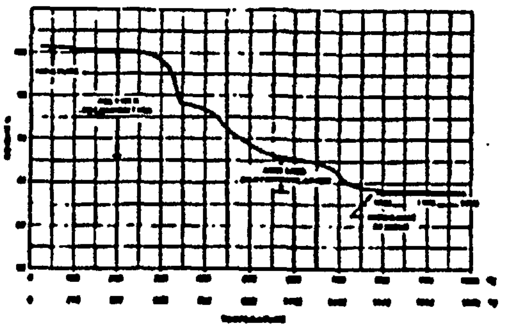

Fig. 6 - Typical TGA thermogram for unused friction material

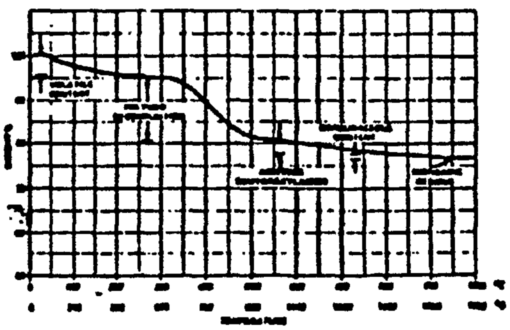

Fig. 7 - Typical TGA thermogram for frictional heat-affected layer of used friction material

ditions are reached. Thus the drums were finished as close to this steady-state point as found for used drums.

These polished drums were then run through the simulation method previously described.

Characterization Method - Each of the used drums was checked for surface finish at four locations. One sample was then cut out of the wear track of each used drum. These samples were then polished and etched for cross-sectional examination by scanning electron microscopy to determine the surface structure.

EXPERIMENTAL RESULTS

FRICTION MATERIALS - The following paragraphs describe the experimental results of this study as they pertain to the friction materials used.

Interpretation of TGA Thermograms - Fig. 5 shows TGA thermograms for typical brake lining components. Fig. 6 shows a typical thermogram for a friction material that has not been used; Fig. 7 shows a typical thermogram for a frictional heat-affected portion or layer of a friction material after use.

In almost all cases, 10.0 ± 0.1 mg of the friction material layer was analyzed. The thermogram weight changes were then normalized to 100%. Table 1 shows the TGA temperature ranges that could be related to known mechanisms of friction materials.

In several cases, especially for the top layer, the asbestos dehydroxylation weight loss did not have good definition. This was due in part to thermal reaction of the polymers to carbonaceous-type materials which lose weight in the TGA over the range 500-900 C. However, this was not a serious problem as the method of data presentation to show chemical-composition trends enabled a good comparison of lining degradation among the three sets of linings.

For each lining the following curves are plotted for the various lining layers: volatile content, polymer content, inorganic content (includes final TGA residue plus carbonaceous content), asbestos dehydroxylation, and asbestos estimate (plotted as 10X asbestos dehydroxylation weight loss as 100% asbestos loses approximately 10% (weight) in the same temperature range).

Table 1 - TGA Temperature Ranges and Known Friction Material Mechanisms

TGA Temperature Range C	TGA Temperature Range F	Mechanism
25-250	75-480	Loss of moisture plus low molecular weight pyrolysis products (called volatiles)
250-575	480-1170	Loss due to degradation of cashew, rubber, and resin polymers
575-800	1170-1475	Asbestos dehydroxylation
800-1000	1475-1832	Carbon oxidation
1000+	1832+	Inorganic residue - no further weight change

Thin Linings (Simulated) - The TGA thermograms of four sample layers taken from the primary lining have been plotted in Fig. 8 to show the progressive changes in the curve with changes in duty occurring at the different layer depths or locations. The OEM material thermogram shows the best definition, while the layer 1 shows a "washed-out" curve. Table 2 summarizes the TGA thermogram data for the primary lining of combination C. Fig. 9 is a plot of the estimated composition as a function of location for the primary lining of the

Table 2 - TGA Thermogram Data for Primary Lining Combination C

TGA Temperature Range, C	Proposed Mechanism	TGA Weight Loss, % First Scrape	Second Scrape	Third Scrape	Fourth Scrape	OEM Material
25-250	Low molecular weight pyrolysis products plus moisture	4.0	2.7	2.0	1.0	0.5
250-575	Polymer degradation	15.0	15.0	18.2	17.5	24.0
575-800	Asbestos dehydroxylation	3.0	7.0	7.8	8.0	8.0
800-1000	Carbonaceous content	1.5	–	–	–	–
1000+	Residue	76.0	76.0	72.0	73.0	68.0

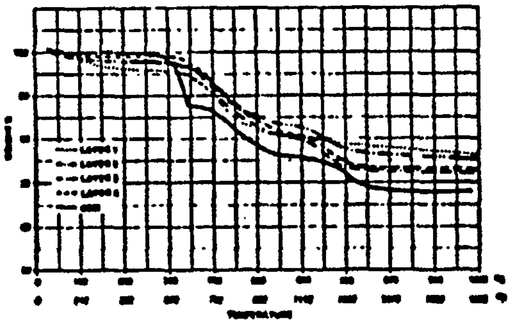

Fig. 8 - Progressive change in TGA thermograms for different samples from simulated worn-in service friction material

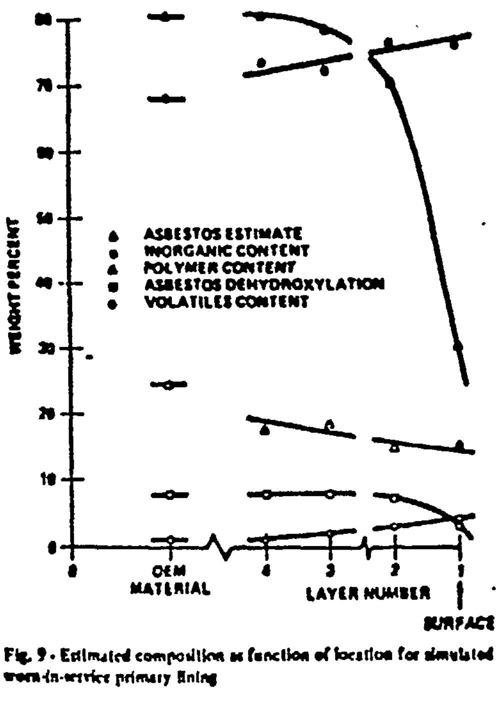

Fig. 9 - Estimated composition as function of location for simulated worn-in-service primary lining

simulated worn-in-service thin linings. These data were taken from Table 2.

Table 3 summarizes the TGA thermogram data for the secondary lining of the simulated worn-in-service thin linings combination. Fig. 10 is a plot of the estimated composition as a function of location.

Figs. 11 and 12 are 50X photomicrographs for the primary and secondary linings showing the cross section of the frictional heat-affected layer and its underlying structure.

Used Linings - For both sets of used linings, tables were prepared for each lining summarizing the TGA weight losses. Corresponding curves were obtained for the estimated composition as a function of location for each lining (Figs. 9 and 10). These curves are presented in the following section.

Comparison of Data for Used and Simulated Worn-In-Service Thin Friction Materials - A comparison of Fig. 11 and the other photomicrographs for the cross sections of the primary linings gave no concrete indication of the changes in lining chemistry which had taken place. Fig. 11 did show a darkened region below the rubbing surface while the other photomicrographs did not. A similar comparison of Fig. 12 and the other photomicrographs for the secondary linings was less revealing. No real conclusions could be drawn from comparisons based on color differences.

A better comparison could be obtained from the physical size and structure of the organic friction modifiers at the surface. In severe thermal damage, these materials shrink in size and become nonexistent at the rubbing surface, when compared to the same materials in the deep underlying regions. The linings of combination A (40,000 miles light use) showed no such change. The organic friction modifiers for the linings of combinations B and C did show similar, slight size reductions which indicated a slightly heavier duty than that undergone by combination A.

For the primary linings of combinations A, B, and C, Figs. 13 and 14 are plots of the data in Table 2 plus the data for the other two primaries. This is the most convenient method of comparing the state of the FHALs of combinations A, B, and C. Fig. 13 shows the variations of polymer content and volatiles content while Fig. 14 shows the inorganic content and asbestos dehydroxylation content as a function of thermal history (location in material). In all cases, the polymer content decreases at the rubbing surface while the low molecular

Table 3 - TGA Thermogram Data for Secondary Lining Combination C

TGA Temperature Range, C	Proposed Mechanism	TGA Weight Loss, % First Scrape	Second Scrape	Third Scrape	Fourth Scrape	OEM Material
25-250	Low molecular weight pyrolysis products plus moisture	8.0	4.5	2.5	1.0	1.0
250-575	Polymer degradation	16.5	19.5	27.0	26.5	32.0
575-800	Asbestos dehydroxylation	2.5	6.5	7.0	7.0	7.0
800-1000	Carbonaceous content	3.0	0.5	–	–	–
1000+	Residue	70.0	69.0	64.0	66.5	60.0

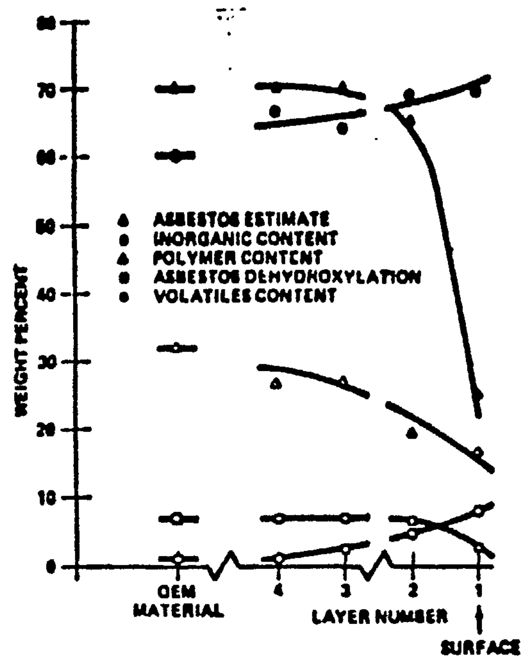

Fig. 10 - Estimated composition as function of location for simulated worn-in service secondary lining

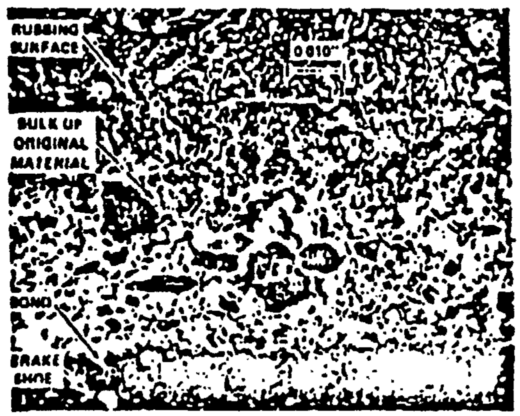

Fig. 11 - Cross section of simulated worn in service thin primary lining

Fig. 12 - Cross section of simulated worn in service thin secondary lining

weight volatiles content increases. In all cases, the inorganic content of the rubbing surface is higher while the asbestos content is lower. The extent of indicated reaction for all of these trends is gradual from the surface (layer 1) into the depth of the FIIAL (layer 4). In all cases, except for the asbestos dehydroxylation, the combination C lining is bracketed by the A and B materials.

For the secondary linings, the data from Table 3 and that for the other two materials were plotted on Figs. 15 and 16. These figures show the variation of volatiles content, polymer

Fig. 13 - Comparison of FHAL characteristics (polymer content and volatiles content) for primary linings

Fig. 14 - Comparison of FHAL characteristics (inorganic content and asbestos dehydroxylation content) for primary linings

Fig. 15 - Comparison of FHAL characteristics (polymer content and volatiles content) for secondary linings

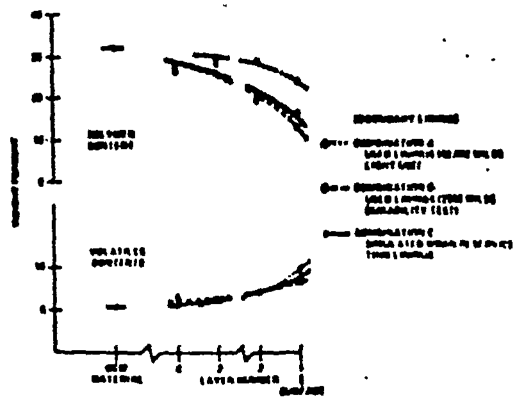

Fig. 16 - Comparison of FHAL characteristics (inorganic content and asbestos dehydroxylation content) for secondary linings

Table 4 - Surface Finish Data for Rotors

Roughness Sequence	Intermediate Vehicle Used Drums RR	Intermediate Vehicle Used Drums LR	Intermediate Vehicle Simulated Worn-in-Service Drums LF
Before Testing:	(OEM Specifications 60-120 µin)		20-30 µin (AA)
After Testing			
Part 1	11-72	18 72	12-17
Part 2	12-22	12-17	12-17
Part 3	20-28	14-17	14-20
Part 4	16-23	18-27	14-20
Average	15-24	15-23	12-19

content, inorganic content, and asbestos dehydroxylation content as a function of thermal history (location in material). In all cases, the polymer content decreases at the rubbing surface while the low molecular weight volatiles content increases. In all cases, the inorganic content of the rubbing surface increases while the asbestos content is lowered. The extent of the indicated reaction is more abrupt from the surface layer (layer 1) into the depth of the FHAL (layer 4) than for the corresponding primaries. In all cases, the combination C lining is bracketed by the A and B materials.

ROTORS - Table 4 shows the results of the surface finish readings for the used rotors and for the simulated worn-in-service intermediate vehicle drums along with the OEM specifications. Comparing the simulated drums with the worn-in-service drums, it can be seen that the simulation procedure used produced a surface roughness very close to that of drums used for 40,000 miles. This was to be expected if the drum starts at a surface roughness close to the steady-state point caused by the linings. The worn-in-service drums were run with the same linings as the intermediate vehicle, and thus the steady-state point was the same.

Fig. 17 - Typical gray cast-iron microstructure (1000X SEM reduced 75% for reproduction)

Fig. 18 - Cross-sectional microstructure of simulated worn-in-service intermediate vehicle drums (10,000X SEM reduced 63% for reproduction)

Thus, to simulate the worn drum surface finish, a roughness of 20-30 μin (AA) should be produced on the intermediate vehicle drums before the worn component simulation procedure (200 stop burnish + 10 stop fade + 12 stop recuvery) is run on the dynamometer in order to simulate used drum surface finish.

Recent work (2) at Bendix Research Laboratories has shown that the microstructure of the cast iron friction surface (drum or disc) varies with usage. Therefore, cross-sectional examinations were made on selected samples with the scanning electron microscope in order to compare simulated worn parts with parts worn in service.

Fig. 17 shows a typical gray cast iron microstructure. The microstructure consists of graphite and pearlite. The black flakes are graphite and the pearlite consists of alternate layers of ferrite (α iron the gray phase) and iron carbide (cementite, Fe_3C- the white phase).

Figs. 18 and 19 show two cross-sectional photomicrographs of the used intermediate vehicle drums. The rubbing surface of the drum was approximately in the middle of both pictures. Two phenomena can be observed in these pictures. First, the graphite flakes do not continue all the way to the surface of the drum. The graphite near the surface was removed and the void formed filled by pearlite. Second, the pearlitic structure was disturbed at the surface, the cementite platelets being broken up and dispersed in the ferrite matrix.

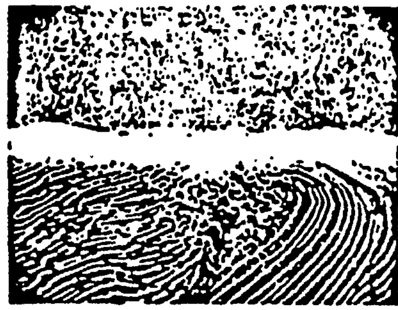

Fig. 19 - Cross-sectional microstructure of simulated worn-in-service intermediate vehicle drums (10,000X SEM reduced 63% for reproduction)

Fig. 20 - Cross-sectional microstructure of used drum from an intermediate vehicle after 40,000 miles (5000X SEM reduced 63% for reproduction)

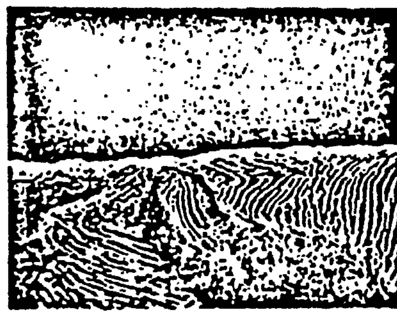

Fig. 21 - Cross sectional microstructure of used drums from intermediate vehicle after 40,000 miles (5000X SEM reduced 63% for reproduction)

Figs. 20 and 21 show two cross-sectional photomicrographs of simulated worn in-service intermediate vehicle drums. The lower photograph shows the pinch out of the graphite flake near the surface similar to the used intermediate vehicle drums. Both photographs show the disturbance of the pearl lite structure near the rubbing surface as exhibited by the used drums.

CONCLUSIONS

For the brake degradation program, it was necessary to simulate a set of thin used linings. A method was developed for producing and characterizing simulated thin linings and their compositions at their frictional heat-affected layers to those of linings from customer usage. The combination C linings were compared to two other sets of linings: combination A linings, which had undergone 40,000 miles of light duty (representative of flat terrain driving in northern climates); and combination B linings, which had undergone 3300 miles of durability testing (representative of hilly terrians or southern, warmer climates with much city freeway driving). By the TGA method, the surfaces of combination C linings were found to be intermediate in composition to those of the other two combinations and the method of conditioning them did indeed produce linings similar to those of normal consumer-type driving.

The recommended procedure for simulating worn friction material was as follows:

1. Grind the linings or pads to nominal dimension required for thin friction material testing.
2. Run 200 stop burnish, 10 stop fade, and 12 stop recovery with drums and/or discs that are to be used in the test sequence.

The comparisons of rotor surface finish and the cross-sectional microstructure of parts used in service with simulated worn parts indicated that a valid simulation procedure has been also derived for drums and rotors.

The recommended procedure for simulating worn drums and discs is as follows:

1. Machine drum or disc to nominal dimension required if drum is to be oversized or the disc is to be thin.
2. Polish the drum surface to 20-30 μin surface finish and the disc surface to 10-20 μin surface finish.
3. Run 200 stop burnish, 10 stop fade, and 12 stop recovery with linings that are to be used with the drums or discs in further testing.

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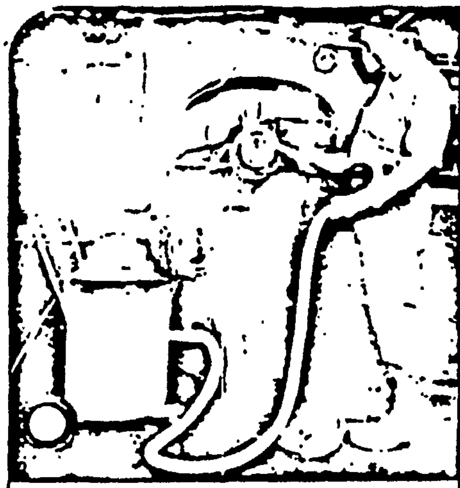

AB-7515 PRODUCT SPECIFICATIONS

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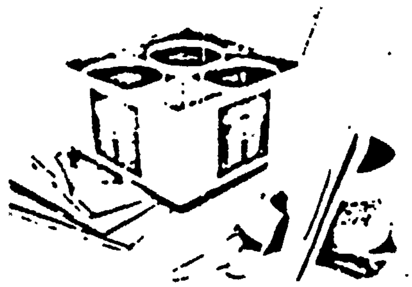
- *10' x 1½" I.D. flexible plastic hose, with connector, crevice tool and duster brush accessories.
- *Steel platform chassis with two 8" rubber wheels and front caster for mobility in service areas.
- *Durable chrome and epoxy finish.
- *Dimensions 35" h x 20" w x 24" deep.
- *Shipping Weight — 56 lbs. F.O.B. Cleveland, Ohio



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