Kirk-Othmer Encyclopedia of Chemical Technology.

BRAKE LININGS AND CLUTCH FACINGS

Brake linings and clutch facings consist of friction materials. Friction materials technology encompasses friction material types, their applications, friction and wear characteristics, raw materials, manufacturing methods, and evaluation and test methods.

Brakes. During a stop, a brake converts the kinetic energy of the moving vehicle or machine part into heat, absorbs the heat, and gradually dissipates it into the atmosphere. A brake is a sliding friction couple consisting of a rotor (disk or drum) connected to the wheel or machine and a stator on which is mounted the friction material. The friction material is considered to be the expendable portion of the brake couple which, over a long period of use, is converted to wear debris and gases (1).

Clutches. During engagement a clutch transfers the kinetic energy of a rotating crankshaft (coupled to a power source) to the transmission and wheels. Any slippage results in the generation of heat, which is absorbed and eventually dissipated to the atmosphere by the clutch. Thus the clutch is basically a static friction couple that momentarily slides during gear shifts or other engagements. The clutch friction material facing is considered to be expendable.

Brakes and clutches operate both dry and wet. In dry friction couples, the heat is removed by conduction to the surrounding air and structural members. Wet friction couples operate within a fluid, usually an oil, which absorbs the heat and maintains the couple at relatively low (below 200°C) temperatures. The fluid also traps the wear debris.

Requirements Automotive brakes must satisfy a certain set of consumer expectations, which includes safety, comfort, durability, and reasonable cost. In technical terms, these expectations are translated into a set of specific requirements such as high and stable friction, no or minimal vibration and noise, and low wear rates for the friction material and rotor mating surfaces, all of which have to be achieved simultaneously at a reasonable cost. Particularly, the performance has to be stable under varying application conditions over extremes in temperature, humidity, speed, and deceleration rate for occasional or many consecutive stops. The requirements for use in machines are less stringent.

The preferred descriptive terms for brake or clutch friction materials according to usage are brake pads, used in disk brakes; brake linings, used in drum brakes; brake segments, used in medium truck drum brakes; brake blocks, used in large truck drum brakes; and brake disks, used in large aircraft brakes. Friction materials for clutches are called facings.

*Usage*Friction materials serve in a variety of ways to control the acceleration and deceleration of vehicles and machines. Materials may be as small as a clutch in a business machine or a brake on a bicycle to as large as jumbo aircraft brakes. The brakes on bicycles may have friction couples of iron sliding against iron in the coaster brake, or rubber-bound composite pads sliding against a steel or aluminum wheel rim in hand-activated brakes. Passenger cars may have disk brakes or drum brakes exclusively, or a combination of disk fronts and drum rears (2). The friction materials may be resin- or rubber-bound composites based on asbestos, metallic fibers, or a combination of other fibers. Trucks and off-highway vehicles usually have very large drum brakes; only a few have front disk brakes. These friction couples usually operate at higher friction levels and temperatures than those of passenger cars. Large aircraft are equipped exclusively with disk brakes that contain multiple rotor and stator arrangements having the most popular friction couple consisting of a sintered friction material sliding against a high temperature resistant steel. The newer aircraft brakes consist of carbon composites serving as both the rotor and the stator.

1. Types of Friction Materials

Prior to the mid-1970s, the most common type of friction materials in use in brakes and clutches for normal duty for original equipment installations and for the aftermarket were termed organics. These materials usually contained about 30–40 wt % of organic components and were asbestos-based (3).

After the mid-1970s, the downsizing of North American vehicles and the introduction of front wheel drive vehicles brought about the widespread usage of a new class of friction materials (4) called semimetallics, also called semimets and carbon–metallics. Because of the allegedly adverse health effects associated with asbestos [1332-21-4](qv) fibers, a second new class of friction materials called nonasbestos organics (NAOs) came about (5). Such materials are called either asbestos-free or nonasbestos friction materials (2).

1.1. Asbestos-Based Organic Materials

The primary applications of asbestos-based organic frictional materials and their requirements are (*1*) primary drum brake linings providing high and stable friction at all temperatures and pressures; (*2*) secondary and nonservo drum brake linings providing stable friction and wear resistance; (*3*) Class A disk pads providing friction levels of 0.35–0.45, nonabrasive wear properties, quiet operation, and rotor compatibility; (*4*) Class B disk pads providing higher (0.45–0.60) friction and high temperature wear resistance at the expense of some low temperature wear resistance, noise properties, and rotor compatibility; (*5*) Class C friction materials consisting of both disk pads and block-type friction materials for extremely heavy-duty operations providing high (>0.50) friction and minimal fade at the expense of other brake characteristics such as wear resistance, rotor compatibility, and noise properties; and (*6*) clutch friction materials providing stable friction, good wear properties, quiet operation, and rotor compatibility combined with high strength properties. Class A friction materials were more common on vehicles built in North America; Class Bs were common in Europe and Asia.

The primary constituent of practically all asbestos–organic friction materials was asbestos fiber, with small quantities of other fibrous reinforcement material. Asbestos was chosen because of its thermal stability, its relatively high friction, and its reinforcing properties. Because asbestos alone did not offer all of the desired properties, other materials called property modifiers were added to provide desired levels of friction, wear, fade, recovery, noise, and rotor compatibility. A resin binder held the other materials together. This binder is not completely neutral and makes contributions to the friction and wear characteristics of the composite. The more commonly used ingredients can be found in various patents (6–9).

1.2. Nonasbestos Organics

NAOs came about because the replacement of asbestos became desirable and necessary. The 30–70 wt % asbestos in different formulations is replaced by other reinforcements, usually other fibers or other reinforcing materials plus property modifying ingredients. In all cases, the large amount of asbestos was replaced with smaller amounts of nonasbestos fibers, not only because of the processing differences, but because no single alternative fiber can replace asbestos for performance (5). Fiber combinations may be glassy: E-glass or synthetic mineral fiber (SMF) blown from slag; ceramic; metallic: steel, copper, or brass; wollastonite [14567-51-2]; or organic: cotton (qv), acrylic, polyaromatics, or cellulose-based (10). The nonfibrous reinforcers include various platy minerals such as mica [12001-26-2] and metallics such as porous metallic powders.

The NAOs found their niche slowly in the 1980s gradually replacing asbestos-based materials and some of the semimetallic front disk pads on U.S. vehicles.

1.3. Semimetallic Materials

Semimetallics, also called carbon-metallics, were introduced in the late 1960s but gained widespread usage in the mid-1970s, eventually taking more than 90% of the U.S. passenger car and light truck front axle business in the 1980s. These materials usually contain more than 50 wt % iron and/or steel components. They are primarily used as disk pads and blocks for heavy-duty operation.

Initially, the primary constituent of practically all semimetallics was iron powder in conjunction with a small amount of steel fiber (type I) (11). Later, large amounts of steel fiber were used along with small amounts of iron powder (type II). Various property modifiers, eg, ceramic powders, organic or rubber particles, and graphite powders, are added to enhance performance to desired levels, and a resin binder, which is necessary to hold the materials together in a mass, is also added (11). Compared to asbestos-based Class B organics that semimetallics originally replaced, semimetallics offered stable friction, improved fade resistance and durability, rotor compatibility, and quiet operation.

1.4. Sintered Materials or Cermets

Heavy weights and high landing speeds of modern aircraft or high speed trains require friction materials that are extremely stable thermally. Organic or semimetallic friction materials are frequently unsatisfactory for these applications. Cermet friction materials are metal-bonded ceramic compositions (see Composite materials) (12–14). The metal matrix may be copper or iron (15).

1.5. Carbon Composites

Cermet friction materials tend to be heavy, thus making the brake system less energy-efficient. Compared with cermets, carbon (or graphite) is a thermally stable material of low density and reasonably high specific heat. A combination of these properties makes carbon attractive as a brake material and several companies are manufacturing carbon fiber–reinforced carbon-matrix composites, which are used primarily for aircraft brakes and race cars (16). Carbon composites usually consist of three types of carbon: carbon in the fibrous form (see Carbon fibers), carbon resulting from the controlled pyrolysis of the resin (usually phenolic-based), and carbon from chemical vapor deposition (CVD) filling the pores (16).

1.6. Disk and Drum Materials

Gray cast iron is of reasonably low cost, provides good wear resistance and damping characteristics, and has long been in use as a brake drum or disk material for passenger cars and trucks. Copper or aluminum rotors have been evaluated experimentally (17–19) and alloy steel rotors are being used for certain nonautomotive brakes, including aircraft and trains. Dual structure composite rotors made with gray iron rubbing surfaces cast with steel hubs as stronger, lighter-weight rotors experienced noise and corrosion difficulties.

Developments in metal-matrix composites technology has resulted in aluminum matrix materials filled with silicon carbide [409-21-2], SiC, (see Carbides, silicon carbide) particles (15 to 60 vol %) that provide the possibility of weight reduction for brakes (20). These composite materials are being tested and evaluated.

2. Friction and Wear

2.1. Friction

An analysis of friction mechanisms suggests that a frictional force is likely to consist of several components such as adhesion-tearing, ploughing (or abrasion), elastic and plastic deformation, fracture, shearing of a friction film (glaze) (21), and asperity interlocking, all occurring at the sliding surface. Relative contributions of these mechanisms presumably depend on the normal load and sliding speed as well as the temperature. (Material properties are known to depend on these variables). In the case of automotive friction materials, the coefficient of friction is usually found to decrease with increasing unit pressure and sliding speed at a given temperature, contrary to Amontons' law (22–24). This decrease in friction is controlled by the composition and microstructure of friction materials.

As the temperature of the sliding interface increases, the coefficient of friction varies. This variation is unpredictable, and there exists no general trend except that at extremely high temperatures the coefficient may become very low (<0.15). This temporary loss in friction is referred to as fade (25). Like automotive friction materials, aircraft cermet friction materials exhibit decreasing coefficient of friction with increasing unit pressure (12).

Effectiveness, essentially a measure of the stopping efficiency, can be expressed in a number of different ways: as the coefficient of friction, deceleration rate, hydraulic or air line pressure required, torque developed, or distance required to stop a vehicle. Effectiveness levels used by consumers are typically decelerations of 0.15 to 0.30 G achieved at line pressures of 1.2 to 2.5 MPa (12 to 25 bars) in normal braking, increasing up to 0.50 to 0.80 G in panic situations requiring 5.5 to 11.0 MPa (55 to 110 bars). The various temperatures are identified for passenger cars as cold (under 100°C), normal (150–250°C), or hot (above 300°C). Effectiveness can be measured new or off-rack (without any prior use), preburnished (after little prior use), burnished (after moderate use), and faded (after use at elevated temperatures). Although the same terms are used for all friction materials, for large aircraft materials the temperatures are cold, under 300°C; normal, 400–600°C; and hot, above 700°C. The normal fade-free maximum operating temperatures of various friction materials may be summarized as drum linings and clutch friction materials, 250°C; Class A organic disk pads, 300°C; Class B organic materials and blocks, 350°C; semimetallics, 400°C; and cermets and carbon composites, 700°C.

Friction peaking is an increase in friction known to occur during or after prior high temperature operation. Imbalance occurs when friction peaking or fade causes one wheel or axle to change in friction, yielding side-to-side or front-to-rear imbalance. Friction stability is the ability of the friction materials to produce similar friction or friction changes at all wheels through all duty cycles and especially during a return to normal operation after a temporary severe duty. Recovery from fade is the ability of the friction material to return to its prefade friction level. Speed sensitivity is the ability to maintain effectiveness at varying surface or rubbing speeds. Most materials show losses in effectiveness at higher speeds with semimetallics being the notable exception. Load insensitivity is the ability to maintain effectiveness at various weight loadings. The ability of a friction material to recover from loss in effectiveness as a result of exposure to water is called water recovery.

2.2. Wear

For a fixed amount of braking the amount of wear of automotive friction materials tends to remain fairly constant or increase slightly with respect to brake temperature, but once the brake rotor temperature reaches $>200^\circ\mathrm{C}$, the wear of resin-bonded materials increases exponentially with increasing temperature (26–29). This exponential wear is because of thermal degradation of organic components and other chemical changes. At low temperatures the practically constant wear rate is primarily controlled by abrasion, adhesion, and fatigue (30, 31).

When a friction material slides against a rotor, microstructural changes take place on the sliding surfaces of both the friction material and the rotor. The degree of these changes depends on the severity of the sliding conditions: the normal load, the sliding speed, the interface temperature, and the environment. The sliding action generates wear particles from the surfaces, compacts them into a layer, and shears the layer at the same time. This shear layer, either on the friction material or on the rotor, is called a friction film or glaze (or transfer film) (21). The mechanisms involved in wear particle generation are believed to be abrasion, fatigue, fracture, adhesion, and thermal degradation.

The wear, W, of friction materials can best be described by the wear equation (32, 33): $W = KP^aV^bt^c$ where K is the wear coefficient, P the normal load, V the sliding speed, t the sliding time, and $a,b,$ and c are a set of parameters for a given friction material–rotor pair at a given temperature.

Wear is an economic consideration. Wear resistance generally, but not always, is inversely related to friction level and other desirable performance characteristics within any class of friction material. The objective is to provide the highest level of wear resistance in the normal use temperature range, a controlled moderate increase at elevated temperatures, and a return to the original lower wear rate when temperatures again return to normal. Contrary to common belief, maximum wear life does not require maximum physical and mechanical properties.

Asbestos-based and NAOs have wear parity within their classes. At low temperatures, Class A organic materials and semimetallic materials wear at a substantially lower rate than Class B organic materials. At extremely high temperatures, the wear rate of Class B organic materials is the best, that of semimetallics in next-best, and that of the Class A organics materials is worst. In the intermediate range, semimetallics are the best, followed by the Class B organic materials. Semimetallics tend to have a high initial or break-in wear rate, which usually becomes lower after conditioning at intermediate temperatures.

Cermet or carbon friction materials operate at substantially higher temperatures than the normal automotive or truck materials. Still the wear rates of these materials increase with the brake temperature. One unique feature of these materials is the formation of a glazed friction film at high temperatures that reduces the wear rate and stabilizes the friction level. Without this glazed layer the wear rate is usually very high.

3. Raw Materials

3.1. Binders

In selecting a resin binder system the processing characteristics must be considered along with the frictional and physical properties. Two types of systems are used. In wet processing, the binder is a viscous liquid, usually a resole or a solution, having characteristics suited to thermoplastic processing techniques. In dry processing, the binder is a powdered material, usually a novolak, that is mixed directly with the other materials; it does not cross-link until heat and pressure are applied. In carbon–carbon composites, resin solution is coated onto graphite fiber and dried before being preformed.

Synthetic resins, such as phenolic and cresylic resins (see Phenolic resins), are the most commonly used friction material binders, and are usually modified with drying oils, elastomer, cardanol [37330-39-5], an epoxy, phosphorus- or boron-based compounds, or even combinations of two. They are prepared by the addition of the appropriate phenol and formaldehyde [50-00-0] in the presence of an acidic or basic catalyst. Polymerization takes place at elevated temperatures. Other resin systems are based on elastomers (see Elastomers, synthetic), drying oils, or combinations of the above or other polymers.

Metals such as copper, iron, or a combination of the two, usually modified with tin, bismuth, and/or lead are used as binders of sintered friction materials where deformation under the high forming pressure is required to lock together the property modifiers within a matrix. Metals such as copper, iron, zinc, aluminum, and occasionally lead are also used as friction modifiers.

3.2. Fibrous Reinforcements

The asbestos usually used in friction materials is chrysotile [12001-29-5], $3MgO \cdot 2SiO_2 \cdot 2H_2O$, the principal mineral of the serpentine group (34). Long fiber asbestos, eg, Grade 5, is generally used when dry processing techniques are employed in manufacturing. Shorter fiber asbestos, eg, Grade 7, is used for wet processing techniques. The two grades differ considerably in length of fiber, bulk, absorptiveness, cost, and reinforcing value. Longer fibers permit the bending of secondary linings from flat blanks to curved segments.

Steel, copper, and brass fiber may have a variety of aspect ratios, shape, ie, straight versus curved fibers and cross-sectional geometry, surface roughness, and chemical compositions. Fibers having tight specifications in terms of cleanliness, chemical composition, and aspect ratio are necessary. The fibers are usually machined from larger metallic forms.

Glass fibers and glassy fibers such as SMF or ceramic fibers are generally more thermally resistant than asbestos. The primary criterion for asbestos substitutes is suitable performance and processing characteristics and that they do not become harmful. The E-glass fibers are made by drawing molten glass through noble metal mandrils. SMF is blown from molten slag. Wollastonite is mined and ground into usable forms.

Several types of organic fibers are used: the cellulose-based include cotton (linters), solkafloc, paper (qv), sisal, and other natural fibers; synthetics include acrylics and polyaromatics. Unique are the acrylic and polyaromatic pulps made by microcutting the surfaces of softened fibers. The high surface and charge effects impart processability as well as low temperature reinforcement properties at the expense of higher costs. Carbon–graphite fibers are produced by carbonization–graphitization of organic or pitch fibers by techniques that provide parallel alignment of the carbon chain to the fiber length for maximum tensile strength.

Organic clutch materials contain continuous-strand reinforcements in addition to fibrous reinforcements. These include cotton (primarily for processing), other organic yarns, carbon–graphite yarn, and asbestos yarn, and brass wire or copper wire for high burst strength.

3.3. Nonfibrous Reinforcements

Because of the higher costs associated with nonasbestos fibers and the performance requirements needed in replacing asbestos, platy minerals such as mica and talc, and metal powders such as iron and copper, are being used as a portion of the total reinforcement package in NAOs.

3.4. Property Modifiers

Property modifiers can, in general, be divided into two classes: nonabrasive and abrasive, and the nonabrasive modifiers can be further classified as high friction or low friction. The most frequently used nonabrasive modifier is a cured resinous friction dust derived from cashew nutshell liquid (see Nuts). Ground rubber is used in particle sizes similar to or slightly coarser than those of the cashew friction dusts for noise, wear, and abrasion control. Carbon black (qv), petroleum coke flour, natural and synthetic graphite, or other carbonaceous materials (see Carbon) are used to control the friction and improve wear, when abrasives are used, or to reduce noise. The above mentioned modifiers are primarily used in organic and semimetallic materials, except for graphite which is used in all friction materials.

Abrasive modifiers are used in several types of friction materials. Very hard materials such as alumina, silicon carbide, and kyanite [1302-76-7] are used in fine particle sizes in organic, semimetallic, and cermet materials that are generally less than 74 μm (200 mesh). Particle size is limited by the fact that large particles of such hard materials would groove cast-iron mating surfaces. Larger particle sizes are possible for harder mating surfaces in the special steel rotors used with sintered materials.

Minerals are generally added to improve wear resistance at minimum cost. The most commonly used are ground limestone (whiting) and barytes, though various types of clay, finely divided silicas, and other inexpensive or abundant inorganic materials may also perform this function.

Metal or metal oxides may be added to perform specific functions. Brass chips and copper powder are frequently used in heavy-duty organics where these metallics act as scavengers to break up undesirable surface films. Zinc chips used in Class A organics contribute significantly to recovery of normal performance following fade. Aluminum is also used. Most of these inorganic materials tend to detract from antinoise properties and mating surface compatibility.

Solid lubricants are added to help control high friction characteristics in high speed or heavy-duty applications where high temperatures are generated. Molybdenum disulfide [1317-33-5], MoS_2, may be used alone or in a complex compound formed by grinding with fine natural graphite, and zinc sulfide [1314-98-3], ZnS. Other compounds include calcium fluoride, cryolite [15096-52-3], Na_3AlF_6, rare-earth oxides, and metal sulfides, eg, iron, antimony, or zinc (see Lubrication and lubricants).

4. Manufacturing

An important balance exists between composition that must satisfy performance requirements and ease of manufacture. Various processes employed in the plastics processing industry are used for manufacturing friction materials. Organic linings that must bend also require higher resin contents and longer fibers. Heavy-duty blocks using reduced resin loading for improved performance require molding-to-shape. Sintered and carbon friction materials require high pressure forming and high temperature treatment in inert atmospheres. Woven and some clutch materials require special fiber-forming methods.

The processing of asbestos-based materials has been developed around the unique properties of asbestos, where the fiber bundles open during mixing to entrap the friction modifiers and resin, giving a consistent mix that can easily be compacted. The introduction of NAOs produces a variety of processing problems as the generally stiffer glassy and metallic fibers do not mix or preform as do asbestos-based formulations. The addition of organic pulps, the use of solvent plus drying techniques, or other processing aids are needed for NAOs, especially to control the higher dustiness of basic asbestos-free formulations.

4.1. Linings

Most linings are produced from resin wet mix by either an extrusion or a rolling process. Initially, the fibrous reinforcement and the friction modifiers are mixed with a liquid resin at approximately 50°C. The binder solvent serves as a plasticizer to yield a dense puttylike mass having good wet strength. In the extrusion process, the mix is heated to approximately 90°C and extruded at 14–28 MPa (2–4 kpsi) as a flat, pliable tape that is dried for 2 h at 80°C. In the rolling process, the mix is partially dried, sized into particles, then fed between two rolls of slightly different speeds to align the fibers in the flat, pliable tape or green lining that is formed. The green lining is then cut to length, formed into an arcuate segment at 150°C, then placed in curved mold cavities and cured 4–8 h at 180–250°C. Final grinding produces the finished brake lining.

4.2. Segments

Segments for heavy-duty use such as for medium-sized trucks are produced by a dry-mix process. The fiber, modifiers, and a dry novolak resin are mixed in an appropriate mixer. The blend is then formed into about a 60 by 90 cm preform (or briquet) at 3–4 MPa (400–600 psi). The briquets are hot-pressed for 3–10 min at 140–160°C and then cooled. The resin is only partially cured at this point to be thermoplastic when subsequently reheated for bending. The hot-pressed preforms are then cut to desired size and bent at 170–190°C and cured in curved molds for 4–8 h at 220–280°C. Final grinding produces the finished segments.

4.3. Disk Pads

Organic and semimetallic disks are produced by somewhat similar processes after the mixes are formed. The mix for organics is prepared in an intensive mixer. The mix for semimetallics generally requires a less intensive blender. The mix is then pressed into preforms at room temperature and 28–42 MPa (4–6 kpsi) pressure. These preforms are then hot-pressed at 160–180°C for 5–15 min at 28–55 MPa (4–8 kpsi). Sometimes the preforms can be eliminated, thus going directly to hot-pressing. The pads are cured at 220–300°C for 4–8 h, and then surface ground to produce the finished disk pads.

In many instances the friction material mix is integrally molded into holes within the backing plate or shoe. Painting of the final assembly, less common in North America, is the rule in Europe and Asia. For controlling brake squeal, noise insulators are widely used. These noise insulating layers are bonded or mechanically attached to the back side of the friction material backing plate.

4.4. Blocks

The mix for organic blocks is prepared as for segments and the mix for semimetallic blocks is prepared as for semimetallic disk pads. Preforms are formed at 10–17 MPa (1.5–2.5 kpsi). To reduce blisters in hot-pressing, the preforms may be heated to 90°C for 15–30 min. The blocks are formed at 130–150°C at 14–21 MPa (2–3 kpsi) for periods of 10–30 min. After slitting to width, the blocks undergo grinding of internal and external radii. Final cure may be in an unconfined form at temperatures as low as 180°C for 15 h or in confined form at temperatures as high as 280°C for 6 h. Grinding, drilling, and chamfering produce the final block.

4.5. Clutch Materials

Methods for producing most manual clutch friction materials are concerned with the placement of the reinforcement strand or wire within the matrix using some sort of winding operation. Processing includes: molding of mix without strands or wire; molding of mix around strand or wire preforms; or weaving curable preforms. In the first two cases, a dry mix is used. In the latter case, a wet mix is prepared and a strand is run through the premix to pick up the viscous mass along the strand which can be woven after drying. After hot-pressing and curing, the surface is ground to final shape.

For automatic transmissions where the clutch is immersed in oil, paper-based clutch facings are employed. For trucks and heavy off-road equipment, cermet friction materials are also used. Sintered cermet segments are attached to a metal plate to form the clutch facing.

4.6. Woven Bands

Woven bands for heavy-duty operation are produced by an expensive process that begins with an asbestos or nonasbestos fiber cord, which may be reinforced with wire, being passed through a wet mix to pick up resin and modifiers. The saturated cord is then woven into tapes that pass through heated rolls to partially cure the resin. The material can be postcured at low temperatures (ca 160°C) to remain as a flexible roll lining or postcured at higher temperature (180–230°C) to form rigid segments. Such materials are used in large band brakes used to control large machinery.

4.7. Cermets

Cermet materials are manufactured using the powder metallurgy technique (see Metallurgy, powder). Desired amounts of individual ingredients are weighed, mixed, compacted, sintered, and coined or recompacted. The sintering is performed in a reducing or neutral atmosphere, and the sintering temperature has to be high enough so that the metallic ingredients adhere to each other.

4.8. Carbon Composites

In this class of materials, carbon or graphite fibers are embedded in a carbon or graphite matrix. The matrix can be formed by two methods: chemical vapor deposition (CVD) and coking. In the case of chemical vapor deposition (see Film deposition techniques) a hydrocarbon gas is introduced into a reaction chamber in which carbon formed from the decomposition of the gas condenses on the surface of carbon fibers. An alternative method is to mold a carbon fiber–resin mixture into shape and coke the resin precursor at high temperatures and then follow with CVD. In both methods the process has to be repeated until a desired density is obtained.

5. Evaluation Methods

5.1. Chemical, Physical, and Mechanical Tests

Manufactured friction materials are characterized by various chemical, physical, and mechanical tests in addition to friction and wear testing. The chemical tests include thermogravimetric analysis (tga), differential thermal analysis (dta), pyrolysis gas chromatography (pgc), acetone extraction, liquid chromatography (lc), infrared analysis (ir), and x-ray or scanning electron microscope (sem) analysis. Physical and mechanical tests determine properties such as thermal conductivity, specific heat, tensile or flexural strength, and hardness. Much attention has been placed on noise/vibration characterization. The use of modal analysis and damping measurements has increased.

5.2. Dynamometer and Vehicle Testing

Friction materials are evaluated in the laboratory by a great variety of tests and equipment. Evaluations of friction and wear characteristics using sample dynamometers such as the Chase machine are on the decline. In the most reliable sample test machines the output torque is controlled so that different materials all do the same amount of work. One disadvantage of sample test machines is that the ratios of friction-material area to rotor area and friction-material mass to rotor mass are quite different from the ratios used on vehicles (35). The heat generation, storage, and rejection conditions are therefore quite different, resulting in unreliable data. A second disadvantage is that only one material is tested, whereas in vehicles having drum brakes two types of friction materials may be used together and there are interaction effects. The advantage is mainly one of economics: more tests at less cost.

The full brake dynamometer, when properly instrumented and controlled, reflects the actual brake performance in a vehicle with reasonable accuracy. High initial investment is recovered through operation independent of the climatic conditions and by a fully automatic operation for extended periods, minimizing personnel costs.

Numerous vehicle test procedures are used by different organizations. Performance tests are essentially designed to appraise initial effectiveness, burnish and normal effectiveness, fade and recovery, and final effectiveness. Side-to-side and front-to-rear balance can also be determined. Only vehicle tests can determine noise/vibration properties accurately. Wear measurements are generally made in accelerated performance tests, but the results are a reflection of high temperature wear properties and are usually not valid for predicting normal driving wear. More valid predictions of normal wear life result from specifically designed extended road traffic wear measurement tests involving a great number of stops with restricted maximum temperatures.

Vehicle tests are considered the ultimate in friction material evaluation, but to be accurate these tests must be carefully designed to eliminate variations caused by changing conditions. Controlled-temperature tests and parallel-test controlled vehicles normally perform the function satisfactorily but at increased cost.

6. Environmental and Health Considerations

6.1. Manufacturing

Asbestos-based friction materials have been virtually phased out for new vehicle installations because OSHA regulations have limited the exposure of workers to airborne asbestos fibers. High performance friction materials can only be produced by the dry-mix process and this tends to be dustier than other processes. In 1974 the time-weighted average was set by OSHA at 5 fibers/cm^3, and reduced in stages as follows: in 1976 reduced to 2.0, in 1986 to 0.2, and in 1990 to 0.1 fibers/cm^3. The cost of capital equipment to effect these improvements is extremely high. EPA has passed a ban on asbestos in commerce requiring the complete elimination of asbestos friction materials in phases beginning in 1994. However, the legality of this action has been challenged.

Asbestos and other fibers in a wide variety of bundle sizes or even individual fibrils are in commercial usage. The handling of asbestos and other fibers causes degradation of the larger fiber bundles to fibers having diameters less than two micrometers that remain airborne for extended periods of time. These airborne fibers are prone to inhalation and lung entrapment. The exact definition of harmful fibers and the mechanism by which they affect the body is not accurately known.

Some friction materials may contain other potentially harmful materials. Lead has been found in some secondary linings, Class B and C organic disk pads, and other friction materials as lead metallic particles, oxides, and sulfides. Several original equipment and aftermarket suppliers are known to have a policy against incorporation of lead or other potentially harmful materials in their products.

6.2. Wear Products

Friction material and rotor emissions are generated by normal wear. Because of large-scale usage and the potential health hazard of asbestos, asbestos organic friction materials and wear debris have been extensively studied (1, 36–38). Below 250°C, abrasive, fatigue, and adhesive wear are considered to be the most important mechanisms and the wear rates are low. Above 250°C, organic friction materials begin to pyrolyze or oxidize such that both gases and particulates are released.

In order to define the extent of emissions from automotive brakes and clutches, a study was carried out in which specially designed wear debris collectors were built for the drum brake, the disk brake, and the clutch of a popular U.S. vehicle (1). The vehicle was driven through various test cycles to determine the extent and type of brake emissions generated under all driving conditions. Typical original equipment and aftermarket friction materials were evaluated. Brake relines were made to simulate consumer practices. The wear debris was analyzed by a combination of optical and electron microscopy to ascertain the asbestos content and its particle size distribution. It was found that more than 99.7% of the asbestos was converted to a nonfibrous form and that only 3.2% of the total asbestos was emitted to the atmosphere. A second study of brake emissions adjacent to a city freeway exit ramp on the downwind side indicated that the asbestos emissions were so low as not to be distinguished from the background on the upwind side (37).

7. Future Prospects

The trend began in the 1970s toward more energy-efficient passenger cars and trucks is putting an increased demand on friction materials performance, resulting from smaller and lighter brakes. More efficient vehicles have manual transmissions and smaller brakes. Organic friction materials continue to serve the drum brake industry, but are being replaced by a trend to 4-wheel disk brakes, which are also preferred for antiskid brake systems. As brakes become smaller, producing higher brake temperatures, the Class A NAOs are expected to become less suitable, requiring Class B NAOs. Most recently NAOs having reduced metal contents have started to replace some semimetallics, and “LoMets” and “NoMets” are being explored. Trucks and other heavy vehicles are also moving toward more efficient disk brakes. More sintered friction materials are expected to appear in the heavy-vehicle clutch market. At the same time, aircraft continue to move toward light carbon brakes.

Future brakes must satisfy health standards and most vehicle manufacturers have moved toward removing all asbestos from brakes. Lighter weight rotors and calipers based on aluminum-based metal-matrix materials are also on the horizon for lighter vehicles requiring a whole new family of compatible friction materials.

There is much interest and concern for noise/vibration-free brake systems and there is much activity toward friction couples having reduced noise/vibration properties. In addition to better noise insulators, brake modifications in the form of different materials, different designs, and improved friction materials formulations and/or processes are being developed and implemented.

8. Economic Aspects

The friction material industry consists of several large organizations having many divisions, as well as more than 60 smaller companies. The primary suppliers’ approximate worldwide market share, trade names, and joint ventures/licensees (jv/l) as of mid-1991 were: Allied-Signal (21%): Bendix, Certified, Jurid, Bendix Europe (Valeo), and Energit with jv/l: Bendix-Mintex, Induben, Incolbestos, Varteks, Mex-Para, Kayaba, Hankuk, others; British Belting and Asbestos (BBA) (17%): Mintex, Don, Textar, Fressek, Frenosa, AP, and SBF, with licensees: Bendix-Mintex, Plasbestos, Nisshinbo, others; Turner-Newell (13%): Ferodo, Beral, Nuturn, Belaco, and jv/l: JBI; ICI Industries (6%): Abex and jv/l: Canparts, Abex, Nisshinbo, and Frendo; General Motors (5%): Delco and Inland with jv/l: Ambrake (Akebono), Sumitomo; Echlin (4%): Echlin, Distex, R&D,and licensees: Itapsa, Friction Materials Inc; Japan (17%): Akebono, Nisshinbo, Asahi Asbestos, Hitachi, Japan Brake, others; and others (16%) that individually supply more than 0.4%: Raymark (Raybestos), Carlisle, Friction Products (Thiokol, Brassbestos), Rutgerswerke AG (Pagid, Cobreq, and Hipag), ITT (Galfer), A/S Roulands, Thermoid, Wellman, Krasne, Friction Tech, Wu-Tai, Hangzou, Sangshin, and others. Most of those in the United States are registered with the Friction Materials Standards Institute, Paramus, New Jersey.

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M. G. JACKO
S. K. RHEE
Allied-Signal Inc.

Related Articles

Composite materials; Metallurgy, powder