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# Laboratory study of the tribological properties of friction modifier thin films for friction control at the wheel/rail interface

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## Abstract

Friction plays a key role in wheel/rail wear, rolling contact fatigue, and other related railway maintenance and operational problems. The wheel/rail interfacial coefficient of friction is strongly dependent on the composition and rheological properties of the interfacial layer, commonly known as the “third body”. Typically, this interfacial layer comprises of various iron oxides as well as possibly oil or grease, sand, and water. Recently introduced railway practices have shown that the coefficient of friction of this interfacial layer can be *controlled* through the introduction of a (dry) engineered friction modifier composite (FM) at the wheel/rail interface. Subsequent field work has demonstrated a significant reduction in rail wear by the adoption of this technology. This work focuses on studying the interactions between FM and iron oxide/grease by using a specially designed pin-on-disk rheometer as well as a disk-on-disk Amsler tester. It was found that the shear strength of the FM-$Fe_2O_3$ composite films is controlled by the relative concentrations of FM and $Fe_2O_3$. The relationship of friction coefficient–concentration can be described by the equal wear model, according to which the FM component with a higher wear-resistance contributes significantly to the friction coefficient of the composite. In addition, grease shows two major impacts on FM films: disturbing film adhesion on steel surface, and reducing film shear strength. However, the friction coefficient of FM films, even under light grease contamination, increases with the sliding velocity over a velocity range of 1.38–63.4 μm/s.

*Keywords:* Friction modifier; Wear; Wheel/rail interfacial layer; Friction control

## 1. Introduction

During the past 50 years, heavier axle loads and increased train traffic and speeds have caused the wheel/rail contact environment to become more severe. As a consequence, the design limits of the steel have been exceeded leading to increased wear and fatigue, decreased rail life, and higher maintenance costs. Each year, wheel and rail wear costs the railroad industry millions of dollars. In the early 1980’s it was estimated that the North American railroad industry was spending $600 million annually for the replacement of deteriorated rail. A large portion of these expenditures was a direct result of severe wear [1–3]. The interaction between the wheel surface and rail surface produces two main damage mechanisms: wear and fatigue. The former creates debris and change in rail/wheel profile, the latter produces cracks that may develop into catastrophic failure.

The wear mode and friction condition at wheel/rail contact is location dependent. Kalousek [4] considered that the wheel tread/rail top is subject to a mixture of “fretting” and “oxidative” wear due to a combination of rolling and sliding motions. The fretting wear debris generated from this small relative motion consists of very fine (0.001–2 μm) plate-like particles. Most of the particles are oxidized to hematite ($Fe_2O_3$) and magnetite ($Fe_3O_4$). With moisture, the iron oxide can form a slurry with a low friction coefficient. In the absence of moisture, these oxides can build up into high shear strength layers with a thickness of several microns and yield high friction (>0.6). In contrast, the wheel flange/rail gauge face is subject to sliding with slip between the surfaces ranging from 0.5 to 10 mm. As a consequence, large metallic plate-

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like particles up to 2 mm in size are generated when there is no lubrication. The resulting coefficient of friction is high (0.4–0.6), and the gauge face wear rate is significant.

The solid debris, as well as the residual lubricants (oil or grease) [5], and environmental contaminants (sand, leaves, moisture) [6], form a composite layer at the wheel/rail interface which has been defined by tribologists as the "third body". This "third body" interfacial layer has three functions: it (i) transmits the load; (ii) separates the first bodies (wheel surface and rail surface); as well as (iii) accommodates their speed difference [7]. The friction coefficient at the wheel/rail interface is strongly related to the rheological properties of the third-body constituents [8]. Beagley [9] studied the wear debris from the top of a rail head and found the friction coefficient depends on (i) the degree of contamination of iron oxides; (ii) the shear strength of the oxide-contaminant mixture; (iii) the size and shape of the contact area; as well as (iv) the train speed. Grease and oil are also very common contaminants on top of rail. This is usually attributed to a migration of excess grease used for flange lubrication, or occasionally, oil or fuel leaked from a locomotive. When liquid (oil or water) is present on top of the rail, the friction coefficient of the wheel/rail interface is controlled by the rheological properties of the debris/fluid mixture, which is dependent on slip speed, load or contact duration. This is more complicated than pure oil lubrication under low rolling speed and high load, in which the friction is suggested to be determined solely by boundary lubrication, and is thus independent of slip speed, load or contact duration [10,11].

Previous work has focused on the study of the "natural" third body between the wheel and rail to explain the interfacial friction and adhesion behavior based on the composition of the third body layer [12]. However, more recently, researchers have begun to investigate the creation of an "engineered" third body layer as a means of controlling friction at the wheel/rail interface, especially between the wheel tread and rail head [13].

A novel technology, developed by Kelsan Technologies Corp., is based on creating an engineered composite to achieve the goal of friction control on the top of the rail. This waterborne product (KELTRACK®) can be brushed or sprayed on the top of the rail head to form a thin film after drying. The special rheological properties of this thin film enable the wheel/rail interfacial friction to be controlled in a range of 0.30–0.35, which will not impact on adhesion or braking requirements. The final film contains inorganic solids, film-forming polymers as well as existing railhead contaminants (oxides, etc.). In addition to controlled friction, this technology also provides "positive friction" at the wheel/rail interface. This refers to the characteristic of increasing friction with sliding velocity rather than the usual case of decreasing friction that can cause unfavorable stick-slip, squeal noise, and rail corrugation [14]. The performance of this novel technology has been tested widely in the field. These field tests confirmed that friction modifier (FM) technology can effectively reduce rolling resistance [15,16], rail wear [17], lateral (curving) forces [17,18], and noise level (wheel squeal) [19,20].

Although a large amount of field testing data involving friction modifier technology exist, no quantitative study on the tribology performance of FM films and its interactions with "natural" third body constituents has been reported. Here we will focus our work on two areas: (i) interaction of friction modifier technology with iron oxides; (ii) interaction of friction modifier technology with grease. A pin-on-disk rheometer is employed to investigate the shear stress versus displacement (shear strain) relationship of friction modifier-iron oxide composites as well as friction modifier-grease composites. The impact of grease on the friction and film-formation properties of friction modifier composites will be also examined on a disk-on-disk Amsler tester.

## 2. Experimental

### 2.1. Materials

The friction modifier (FM) films tested in this study were created using Kelsan's commercial friction modifier technology, KELTRACK®. This material is a water-based liquid, which can be applied directly to the top of the rail, forming a micron-scale FM film after drying. The calcium-based grease (Shell Cardura® WS) was obtained from Shell Co. and is generally used for rail gauge face lubrication. Its main composition includes proprietary mineral oil, graphite and molybdenum disulfide ($MoS_2$). Hematite ($Fe_2O_3$) was purchased from Aldrich with an average particle size of 5 μm.

### 2.2. Pin-on-disk rheometer

A pin-on-disk rheometer, specially designed by the Centre for Surface Transportation Technology of Canadian National Research Council (NRC-CSTT) was employed to examine film shear strength. A detailed description of the machine layout is available in Ref. [21]. For each test, a prepared sample is placed on top of an anvil and compressed by two profiled pins. The pins are stationary and loaded by dead weight to simulate the high contact pressure (∼900 MPa) at the wheel/rail interface. Rotation of the anvil at a controlled speed produces a torque moment, which is formed by equal and opposite frictional forces developing at each pin. A load cell located between the anvil and turntable measures load and torque, from which contact pressure, shear stress, and friction coefficient of the tested film can be calculated.

### 2.3. Disk-on-disk Amsler

The Amsler machine, located at NRC-CSTT, is a test device that runs two cylindrical disks against each other with a fixed percent slip [21]. Both disks are made from rail material. During testing the ratio of angular velocity of the faster lower disk to the slower upper disk is about 1.1. The creepage, the ratio of surface or slip velocities of the two disks, is adjusted to be 3% by modifying the diameters of the two disks (48 mm for the upper disk and 45 mm for the lower disk) [21].

## 3. Results

### 3.1. Shear strength of FM-iron oxide composites

In order to examine the friction-control ability of a FM film on the iron oxide-coated steel surface, a series of FM-$Fe_2O_3$ composites were tested on the rheometer. The shear strength versus sliding distance (displacement) relationship of the FM-$Fe_2O_3$ films was measured at a constant sliding speed of 1 °/min (2.67 μm/s). The shear stress-displacement curves are plotted in Fig. 1. Iron oxide is observed to generate a high value of shear strength, close to 500 MPa. With the addition of the FM component, the composite films exhibit a marked decrease in shear stress. For the compositions with a high percentage of $Fe_2O_3$ (75–90%), a distinct peak in the low displacement region is observed. The magnitude of this initial stress peak increases with the $Fe_2O_3$ content. In experiments where the maximum sliding distance was increased to 10,000 μm, one observed that the slope of the stress–strain curve becomes positive after 1200 μm. Fig. 2 highlights the relationship between the measured coefficient of friction ($\mu$) and $Fe_2O_3$ concentration in the composite layer. One should note that the effect of $Fe_2O_3$ concentration on $\mu$ is more significant at higher concentrations. For concentration ranges from 0 to 80%, the change of $\mu$ is relatively small.

The load-dependence of the friction coefficient for the FM-$Fe_2O_3$ composite is also influenced by the weight ratio of FM and iron oxide (Fig. 3). In general, the $\mu$ values of all composite samples decrease with increasing contact pressure, especially in the range of 50–400 MPa. Above 400 MPa, the coefficient of friction stabilizes becoming independent of contact pressure. This indicates that the deformation mechanism at higher contact pressure differs from that at lower pressures. One can also observe, in the lower range of contact pressures, the increase of the concentration of the FM component in the composite layer reduces the dependency of the measured friction coefficient on contact pressure.

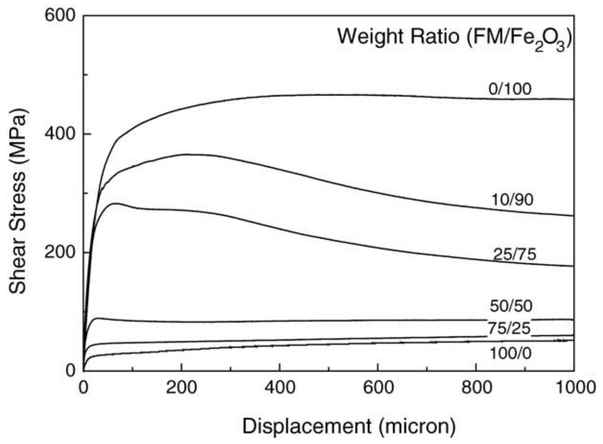

Fig. 1. Shear strength vs. Displacement showing data for a FM-$Fe_2O_3$ composites ranging from 0 to 100% $Fe_2O_3$ at a contact pressure of 880 MPa.

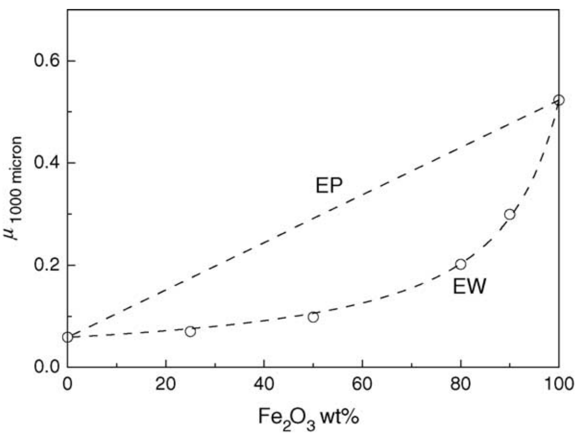

Fig. 2. $Fe_2O_3$ concentration dependence of the friction coefficient for the FM-$Fe_2O_3$ composite films. Two dashed lines were obtained from two simulation models: equal wear (EW) model and equal pressure (EP) model, about which a detailed discussion will be presented in the discussion section.

### 3.2. Shear strength of FM-grease

In order to better understand the impact of grease on FM films, we simplified the system and focused our first phase study on the FM-grease films in the absence of iron oxide. Two cases of grease-contaminated FM films were tested. The first sample, "Steel-Grease-FM (SGF)", involved coating the anvil surface with a thin layer of grease, on top of which the FM dispersion was applied and allowed to dry. This sample simulated when a layer of FM was applied on a grease-contaminated rail surface. In comparison, the "Steel-FM-Grease (SFG)" sample simulated when grease has been

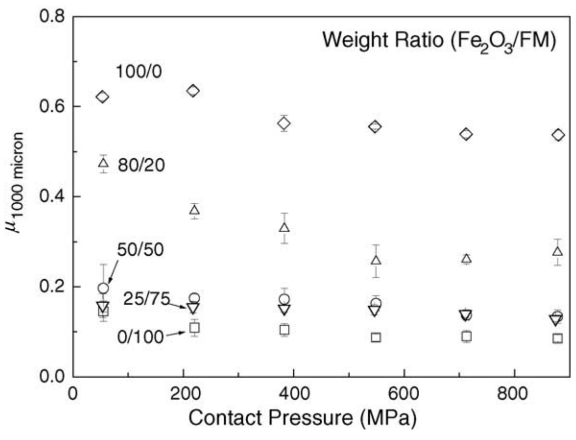

Fig. 3. Coefficient of friction for FM-$Fe_2O_3$ composites as a function of contact pressure. Note the decrease in friction coefficient with increased stress.

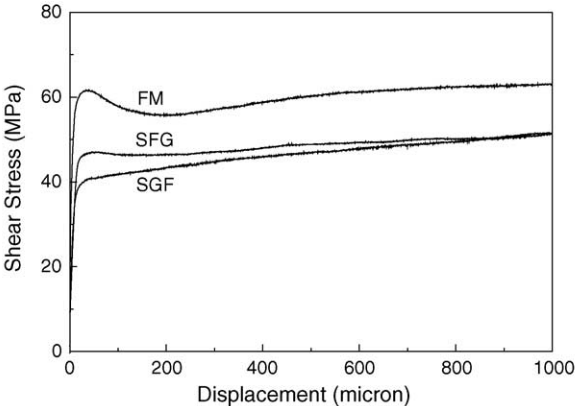

Fig. 4. Pin-on-disc rheometer test of grease effect on the FM films. The shear stress was measured at a sliding speed of 2.67 μm/s with a total displacement of 1000 μm. For the SFG sample, grease is brushed on the top of FM film. SGF is a FM film on grease-contaminated anvil surface.

applied onto a FM-conditioned rail surface. In both cases, the weight ratio of FM/grease was controlled around 4:1.

The shear strength curves of the two grease-contaminated FM films are compared with that of an uncontaminated FM film in Fig. 4. In general, the grease-contaminated FM films have lower shear strength values in comparison with the uncontaminated FM film. The critical shear strength for the baseline film is also higher than that SGF and SFG samples: 40 MPa for the SGF film and 47 MPa for the SFG film. After reaching the critical shear strength, the values of shear stress for both SFG and SGF films increases slightly with the displacement, and reaches almost identical values of 51 MPa at the displacement of 1000 μm.

### 3.3. Shear strength of FM-grease at varied sliding speeds

Two rheometer experiments were designed to monitor the friction level at varied sliding speeds. In the first experiment, the steady-state friction of the FM, SGF, and SFG films were measured at different sliding speeds ranging from 0.5 to 20 °/min (Fig. 5). All composites exhibited a positive $\mu$–velocity relationship.

The *dynamic* coefficient of friction of the FM, SGF, and SFG films under a step change of sliding speed was monitored in the second experiment (Fig. 6). The sliding speed was changed abruptly from one level to another level every 180 s. The velocity was initially maintained at 10% of the full speed (150 °/min), and then immediately changed to 100% of the full speed after 180 s. The cycle was then repeated for the duration of the test. One can observe that the measured $\mu$ value for all three types of FM films is dependant on velocity. More specifically, the $\mu$ value increases when the sliding speed is raised from 10 to 100%; conversely, the $\mu$ decreases when the velocity is reduced to 15 °/min. In the first 500 s of testing, the magnitude of the $\mu$ changes for the three films is similar. When the $\mu$ values of these films become comparatively steady (>500 s), the dependence of $\mu$ upon velocity change follows the order: SGF < SFG ≈ FM.

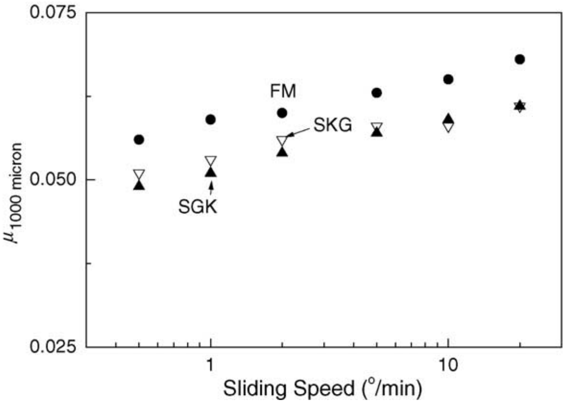

Fig. 5. Velocity dependence of $\mu$ at a displacement of 1000 μm for FM, SGK, and SKG films measured on the pin-on-disk rheometer.

### 3.4. Microscopic observation of FM-grease

The contact patches of the FM films after rheometer tests were examined under an optical microscope. The most severe damage was observed on the SGF composite. Poor film adhesion on the contaminated anvil surface caused the film to peel off when the pin was raised. Additional investigation showed cracks in non-contact areas. Through these cracks, grease could be observed under the film. This indicates that the oil from the grease was not absorbed by the film. This is also supported by the wet film surface observed on the SFG sample.

### 3.5. Friction coefficient of FM-grease from Amsler

Fig. 7 shows the relationship between the measured coefficient of friction and time at a specific creep (3%) for the FM-grease samples as tested on the Amsler apparatus. The contact surface of the upper disk was coated by a thin FM film

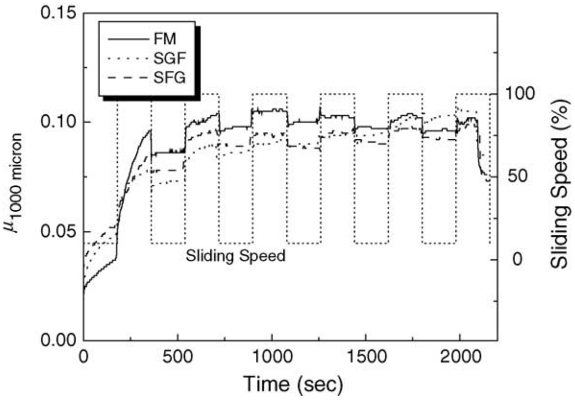

Fig. 6. Comparison of $\mu$ values of grease-contaminated FM films in response to a step change of sliding speed: 10% ↔ 100%. The full-scale speed is set as 400 μm/s (150 °/min).

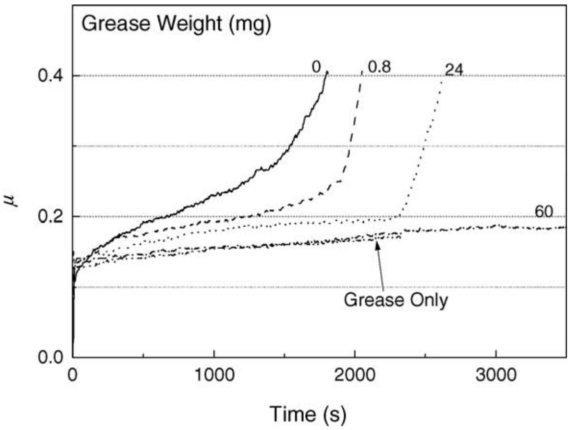

Fig. 7. Amsler test results of FM films interacting with grease. The shown values are the weight of grease coated on the surface of lower disk. The weight of the FM film coated on the upper disk is controlled around 2–3 mg.

with a weight of 2–3 mg. Grease was brushed onto the contact surface of the lower disk and its' weight was controlled from 0 to 60 mg. After rolling of the two disks, grease would be transferred to the surface of the upper disk and interact with the FM film. For tests with grease only, a flat $\mu$ curve (~0.17) was observed which only slightly increased with rolling time (or cycles). This contrasts significantly with test data when only the FM sample is tested on the Amsler. In this case, the $\mu$ curve can be divided into three distinct phases: (i) a run-in part with a fast increase of $\mu$; (ii) a relative stable part (film-contact); and (iii) a second fast $\mu$-increase part (steel-contact). Typically, we see a smooth transition between the latter two phases. In general, all testing which included the FM film exhibited an "N"-shape behaviour when describing the $\mu$–time relationship. Addition of grease to the FM film was also observed to cause an abrupt transition between the aforementioned latter two phases.

Fig. 7 also demonstrates that grease does proportionally impact on the $\mu$ value during that the period of relative stability. In the extreme case when too much grease is applied (i.e., 60 mg grease against 2 mg FM), the FM-grease samples exhibits a similar $\mu$ level to that of grease.

## 4. Discussion

### 4.1. Comparison of friction results from different experiments

Both the rheometer and Amsler can measure the friction coefficient values of FM composite films. However, readers should be careful in comparing this data since they are measured differently (motion mode, pressure distribution, surface roughness, etc). The friction coefficient obtained on the rheometer is due to a pure sliding friction. The friction coefficient obtained from the Amsler test is caused by a hybrid of rolling and sliding conditions. Another noted difference is the surface roughness of the steel surfaces between which the FM film is sheared. The roughness of the anvil and pin (Ra = 0.17 μm) used for the rheometer is lower than that of the contact surfaces (Ra = 2.3 μm) of the Amsler disks.

An analytical comparison of the friction results from these two types of measurements has been presented in Ref. [21].

### 4.2. Deformation mechanism of FM Films

All FM films, even in the presence of $Fe_2O_3$/grease contamination, show both elastic and plastic deformations under shear (see Figs. 1 and 4). According to the theory proposed by Hou et al. [8], the FM film between the pin and anvil deforms elastically at low shear stress, but begins to deform plastically when the stress exceeds a critical level. In the elastic range, shear stress increases linearly with displacement with a slope characterized as elastic shear modulus. Above its elastic limit, the deformation of the layer with increased shear stress can be accommodated in a number of ways: (i) rolling of solid particles within the layer; (ii) cutting of surface asperities to form wear particles and create new surface; and (iii) plastic deformation of the layer.

In an engineered third-body layer, the friction modifier particles, as well as other solid contaminants, are encapsulated in a polymeric matrix. Considering the addition of polymer–particle interaction, the contribution of rolling of hard particles within the film is limited. However, at a very high concentration, those solid particles can pack together to form agglomerates inside the polymeric matrix. Under this scenario, rolling or shifting of particles becomes possible. This could possibly explain the different shear stress behavior of FM-$Fe_2O_3$ composites at high $Fe_2O_3$ concentration. In addition, the second factor (cutting of asperities) should dominate only when the FM film is worn out causing direct contact of metal asperities. Plastic deformation is the most important mechanism that controls the rheological behavior of FM films.

Theoretically, the plastic deformation of a solid film can be characterized by the plastic shear modulus, which is calculated from the slope of shear stress versus displacement curve after the critical limit. However, our tested samples did not exhibit such a simple tendency in the slope of their friction curves (Fig. 1). After reaching a maximum value, the shear stress decreased slightly but then increased again with displacement. It appeared that the sheared film reached a quasi-steady state at the critical displacement. In 1966, Brown and Richards [22] studied the shear strength of powder samples and found that the density of powder assemblages strongly affects their shear strength. The tightly packed powders exhibited a distinct initial shear stress peak at a lower strain; such an observation was not evident when testing loosely packed powders. Saffer and Marone [23] observed similar phenomenon with silicate powder mixtures (smectite + quartz). The magnitude of the peak stress decreased with the increased quartz content. They suggested that the observed peak and subsequent decreases in frictional strength, with respect to strain, reflect shear-enhanced compaction and alignment of platy clay minerals during early stages of shearing. Saffer and Marone also mentioned that this shear strain response is commonly observed in clays and clay-rich soils, and is generally due to the alignment of clay particles.

However, the FM composites is a more complicated matrix, as compared to a simple powder aggregate, due to number of constituents including various solids, polymers and other compounds. When two shearing surfaces are separated by a continuous granular layer, this layer can support the bearing pressure and provide a weak path within which shear can occur. Shear can occur in the solids, in the bulk of the compacted layer, or at the upper or lower interface with the solid bodies. Behavior can involve elasticity rolling, shear, or fracture. In some cases, a powder layer might be viewed as a continuous, viscous fluid, but in other cases one might need to consider the rule of periodic discontinuities that occur if the semi-continuous layer fractures in tension [24]. For polymer composite materials, not only the shear properties of each component should be considered but also their mutual interactions. Overall, the following factors should be considered during discussion of shear strength behavior of FM composites: (i) the elastic and plastic deformation of polymer materials; (ii) the deformation mechanism of particle aggregates inside the polymeric matrix; (iii) the interaction between the filler particles and the matrix; and (iv) the interaction between film surface and substrate surface.

The first factor is closely related to the yielding behaviour of the polymer. Usually shear yielding and crazing contribute together to the polymer yielding. The second and third factors depend on the concentration of solid particles and their surface property. For example, Fig. 1 indicates that the shear strength of FM-$Fe_2O_3$ mixture is influenced by the presence of $Fe_2O_3$ particles, especially at high $Fe_2O_3$ concentration. At the low concentrations of iron oxide, the shear stress curves of FM-$Fe_2O_3$ films are similar to that of the pure FM film without the initial shear stress peak. However, at high concentrations (>75%), many particle aggregates can exist inside the polymer matrix. For the particles inside the aggregates, the relative motion between the particles becomes more important and influential to the shear behavior of FM-$Fe_2O_3$ composites.

### 4.3. Friction control by FM on $Fe_2O_3$-covered surface

The friction coefficient of FM-$Fe_2O_3$ composites (after a displacement of 1000 μm) is plotted in Fig. 2 as a function of $Fe_2O_3$ concentration. Fig. 2 indicates that the friction of the FM-$Fe_2O_3$ composite is not simply dependent on the relative concentrations of the constituents, nor their respective coefficients of friction. It has been suggested that when a composite sample is sheared under sliding motion, the load carried by each phase depends on the wear resistance and volume fractions of the phase. There are three different models to predict the friction of multiphase composite samples: equal pressure (EP), equal wear (EW), and intermediate (I) pressure [25]. The definition of these three models relies on how the total applied load is carried by each component in a composite. In the EP mode each component carries load in proportion to their volume fraction and independent of their wear-resistance. The friction coefficient should therefore vary linearly from the $\mu$ of the matrix to the $\mu$ of the filler. In contrast, the loads in the EW mode depend on the volume fraction of each component and its wear-resistance. The component with a higher wear-resistance dominates the friction coefficient of the composite. The intermediate pressure model combines aspects of the above two models. The friction data for the FM-$Fe_2O_3$ composites perfectly follows the EW model, which means the FM part has higher wear-resistance and thus contributes more to the overall friction coefficient of the composite layer. Therefore, even in a wide degree of iron oxide contamination (0–80%), the friction coefficient between two steel surfaces can still be controlled by using friction modifier technology. For example, the reported coverage of iron oxide debris on the top of rail varies widely, i.e., from 0.02 $mg/cm^2$ to about 0.4 $mg/cm^2$ [26], depending on the rail locations. In general, if the application rate for the friction modifier technology is about 100–500 ml/mile [17], the weight ratio between FM and oxide debris would range from 0.3 to 2.0. But various field test results show that the friction modifier technology still can effectively control the rail top friction even in this wide range.

### 4.4. Grease effect on FM films

The experimental results indicate that grease affects FM films in two areas: the film formation and the measured coefficient friction. The engineered polymeric FM film cannot absorb the mineral oil from the grease; the "wet" surface is easily identified in both SFG and SGF films. In addition, the SFG film shows no penetration of oil from the grease side to the steel substrate. In other words, when grease is present on a FM-conditioned railhead, the adhesion between the film and the steel surface is not affected. In contrast, the FM film shows rather poor surface wettability on a grease-contaminated metal substrate. This phenomenon is due to the oil having a rather lower surface tension than either water or steel. The reported critical surface tension (20 °C) values for these three compounds are: 28.9 (oil), 72.5 (water), and 55.0 (steel) mm/m, respectively [27]. The oil/grease-contaminated steel surface has a surface tension much lower than that of waterborne FM dispersion. This low surface tension of substrate leads to the inadequate wetting, unsatisfactory edge covering, and crater formation of the FM film.

The grease effect on the friction performance of FM films was proven in the rheometer tests (Fig. 4) and Amsler tests (Fig. 7). This influence of grease on the tribological performance of FM films can be related to the lubrication characteristics of grease and its' damage to the adhesion bonding of the FM film to the steel surface. When grease interacts with a FM film, the oil compound of the grease can either form a thin layer between the film and disk surface, or coat the surface of worn film particles. Thus the friction level of the film is reduced and the FM film adhesion to the steel surface is weakened. As a result, the film becomes easier to abrade and remove from the disk surface. During the Amsler test of a clean FM film, the smooth transition between the film-contact phase and the disk-contact phase is hypothetically attributed to the chemical modification of the disk surface by the FM film. When the disk surfaces are contaminated by grease, this surface modification can be effected or even arrested. Characterizing the chemical composition of the disk surface at different periods would help us to assess this theory. An extreme example is the sample with 60 mg grease (Fig. 7). After the complete destruction of the FM film, grease spread to the entire contact area between two disks. This causes its $\mu$ values to be similar to the grease sample.

The relatively lower shear strength of the grease layer is one of challenges we faced when we tried to apply the "third body" rheological model [8] to the grease-contaminated FM films in order to explain its rheometer results. The present model assumes the "second body"—the interface between the wheel/rail and the "third body" layer is considerably thin enough that there is no slip at these interfaces. But this assumption becomes unreliable in our experiments in the presence of grease. Hence, a combination of a slip in the grease layer and an elastic or plastic deformation of the FM film might be occurring during the rheometer experiment. Further work is required to explain this process; a consideration of the grease factor should be incorporated into the future rheological mode.

### 4.5. *Velocity dependence of friction coefficient of FM films*

Many fundamental studies of sliding friction show that, for a wide range of materials, friction decreases as the sliding velocity increases. The reason for this was explained by Blau [28] as: (i) the elevated surface temperature causes formation of oxides that lubricate the surface; (ii) the shear strength of most materials decreases at high frictional temperatures; and (iii) when the surface melts due to frictional heat, the molten liquid can lubricate the asperity contacts. Blau believed that a different type of friction–velocity relationship can be obtained in a smaller velocity ranges and under certain conditions.

Figs. 5 and 6 indicate that the friction coefficient of FM films, even under light grease contamination, increases with the elevated sliding velocity over a velocity range of 0.5–20 °/min (1.38–63.4 μm/s). As a result, the "negative" friction characteristic of most metal surface can be modified to have "positive" behaviour to prevent many related problems, i.e., stick-slip. Further research is necessary to obtain a more detailed concept of the friction interface and tribology mechanism during the sliding of a FM film between two steel surfaces. However, it is worthwhile to look at some possible mechanisms that could introduce positive friction characteristic. The additional energy introduced during the sliding motion can cause an increase of temperature, a change of wear rate and surface roughness, or a change of surface microstructure. A positive friction–velocity relationship can be due to:

- (Increasing) velocity increases the wear rate, which in turn roughens the surface and intensifies the plowing and cutting contributions to friction [28].
- The increased frictional heat by an increased sliding velocity softens surface and increases asperity contact.
- Since polymers are viscoelastic materials, sliding speed has a significant effect on their friction behaviors. For viscoelastic materials, an increase of sliding velocity is equivalent to a drop of temperature (time–temperature superposition theory). For example, Eiss and McCann [29] found that, for smooth surface of acrylontrile butadiene styrene copolymer (ABS) sliding at high normal load in a pin-on-disk apparatus, the friction force–velocity curve had a negative slope at low velocities and a positive slope at high velocities.

## 5. Summary

(1) The shear stress and friction behavior of the FM-$Fe_2O_3$ composite films are controlled by the relative contents of FM and $Fe_2O_3$. When the $Fe_2O_3$ concentration is high (75–90%), the shear stress–displacement curves of the FM-$Fe_2O_3$ films show a distinct peak at the low displacement region. The magnitude of this stress peak increases with the $Fe_2O_3$ content. This phenomenon could be due to the aggregation of $Fe_2O_3$ particles inside the FM polymeric matrix.

(2) The shear stress–strain (displacement) relationship of the FM-$Fe_2O_3$ composites should be controlled by (i) the elastic and plastic deformation of polymer materials; (ii) the deformation mechanism of particle aggregates inside the polymeric matrix; (iii) the interaction between the filler particles and the matrix; and (iv) the interaction between film surface and substrate surface.

(3) The concentration-dependence of the friction values of FM-$Fe_2O_3$ composites obeys the equal wear model; specifically, the FM component has a higher wear-resistance and contributes significantly to the friction coefficient of the composite. In a wide range of iron oxide concentration (0–80%), the friction of two steel surface still can be controlled in a relatively small range of friction by using friction modifier technology. This indicates the friction-control ability of FM films is effective under a wide range of $Fe_2O_3$ contamination on the rail head.

(4) Grease affects FM films in two major ways: disturbing film adhesion on steel surface, and reducing friction level. The grease-contaminated steel surface has a lower surface tension than that of FM dispersion, causing inadequate wetting, unsatisfactory edge covering, and crater formation of FM film. The influence of grease on the tribological performance of FM films should be related to

the lubrication characteristic of grease and its' damage to the adhesion between the FM film and the steel substrate.

(5) The friction coefficient of FM films, even under light grease contamination, increases with the sliding velocity over a velocity range of 0.5–20 °/min (1.38–63.4 μm/s). This indicates that the positive friction characteristic can be kept under a light grease contamination.

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