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# Synthesis and Performance of Plasma-Sprayed Polymer/Steel Coating System

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**Low friction thermally sprayed polymer-steel coatings for high contact pressure rolling/sliding systems were developed using high-energy plasma spraying. Polymers were applied as a thermally sprayed thin film (75-100 μm) over a thicker (250-750 μm) thermally sprayed steel coating. Twin roller rolling/sliding tests were performed at 5 and 35% creep and contact loads of 1700 N on a 5 mm contact face. A lower coefficient of friction (0.10-0.15) with increased durability, compared with that of an AISI 1080 steel thermally sprayed coating (coefficient of friction of 0.46), was observed under these rolling-sliding contact conditions. The polymer's ability to control friction and wear stems from the mechanical anchoring of the polymer film to the rough surface of the steel coating. The polymer film was characterized by scanning electron microscopy and Fourier transform infrared analysis.**

**Keywords** composite materials, friction and wear, novel materials, wear mechanisms

## 1. Introduction

Rolling/sliding systems include bearings, gears, and wheel/rail contact. In such rolling/sliding systems under conditions of high slide-to-roll ratios (or creep), unlubricated metal-to-metal contacts can approach friction coefficients of 0.7 (Ref 1). High levels of friction accelerate wear and deterioration in the contact zone as well as increasing the energy cost to run the system. For a rail car on railroad rails, the wheel/rail friction greatly affects the dynamics of the railcar axle sets and hence the stability of the railcar. High coefficients of friction lead to high lateral forces between the railcar wheel and the rail as the vehicle moves around a curve. These forces can be sufficiently significant as to widen the gage (the distance between rails) and even overturn the rail (Ref 2).

Lubricants are used to reduce and control friction between two moving parts and to reduce the wear between contacting surfaces. The majority of rolling/sliding contacts are currently lubricated using a number of liquid and semiliquid hydrocarbon lubricants. In fully fluid lubrication, a thick fluid film separates the contacting surfaces and the properties of the fluid determine the lubrication process. In boundary lubrication, a thin film separates the two surfaces, and both the lubricant and the surface material affect the lubrication process (Ref 3). Thin film lubricants, typically greases and oil films, need only be a few molecules thick, but they must be continuous between the moving parts to be effective.

It is not always possible or cost effective to have a continuous reservoir of lubricant. Rails, for example, are lubricated with grease periodically, but much of the grease is lost from the system shortly after application. Solid lubrication can mitigate these problems to a certain extent. Solid lubricants are often used where boundary lubrication is required and a migratory fluid lubrication system cannot be applied because of extreme operating environment constraints, such as extreme pressures or temperatures or is impractical (Ref 4, 5). However, the lubrication is generally only as good as the application system, and railroad applications present a unique set of challenges, foremost of which is the ability to reduce friction and mitigate wear processes on railroad rail without affecting the integrity of the railroad rail running surfaces. Thermally sprayed coatings fit the latter constraint ideally, initiating little or no change to rail surface metallurgy during and after application. To further examine the feasibility of a thermally sprayed coating system to provide lubrication in railroad rail applications, a plasma-sprayed AISI 1080 steel coating was used as the base coating layer for polymeric films, and the resulting system examined for utility in friction and wear reduction.

Polymers have been used in a wide variety of applications where low friction and wear are required (Ref 6-8). Common polymers used in tribological applications include polytetrafluoroethylene (PTFE), polyamides, and ultrahigh molecular weight polyethylene (UHMWPE). PTFE is a crystalline polymer and has seen numerous applications as a low-friction material. The low friction of PTFE under sliding conditions results from its ability to form oriented films on its own surface (Ref 9). A block of PTFE in contact with a harder counterface loses material as a series of laminae resulting in low friction ($\mu < 0.05$) but a high wear rate. This film transfer is unique to PTFE and has not been observed in other polymer systems. Polyamides (Nylons) have moderate friction coefficients, as low as 0.05, but the coefficient of friction is strongly influenced by the counterface roughness. Nylon is a crystalline polymer, but its crystallinity is considerably lower than that of PTFE (Ref 10). UHMWPE has very high wear resistance even in the presence of water. UHMWPE is a crystalline polymer similar to PTFE, where both polymers have a characteristic smooth molecular profile with the absence of side groups or kinks in the polymer chain (Ref 11).

Wear of polymers is complex and system specific. There have been many studies attempting to quantify and characterize

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polymer wear, especially in the biomedical field (Ref 12, 13). The current study is unique in that the contact conditions were severe (contact pressure = 1220 N/mm$^2$) and focused on the friction and wear behavior produced by rolling/sliding contact against rail steel. With the exception of PTFE and UHMWPE, polymer systems wear by a transfer of material from the bulk polymer surface to the counter-surface in a series of "lumps" (Ref 14). In the wear process, these lumps are flattened into a thin film that may or may not remain in the contact zone. A number of factors affect polymer wear including counterface roughness, hardness, and surface energy. Surface roughness determines the degree (amount) of polymer transfer and wear rate. Adherence to the counterface, once transferred, is controlled by both hardness and surface energy of the counterface. Temperature is critical as most polymers have low melting temperatures and low thermal conductivities. Additionally, a polymer's ability to heal itself will also influence the sliding behavior. These factors were recognized in the development of the thermally sprayed polymer/steel coating systems.

In this investigation, a plasma-sprayed metallic coating using an AISI 1080 steel wire feedstock was deposited, followed by a thin (25-75 μm) plasma sprayed polymer layer. The development of the 1080 steel coating and its performance is detailed elsewhere (Ref 15). In rolling/sliding tests, the metallic coating alone demonstrated some reduction in the coefficient of friction from 0.7 (unlubricated railroad wheel steel on rail steel) to 0.46 (steel coating on rail steel). This reduction was attributed to the coating's resistance to severe abrasive wear. A yet lower coefficient of friction between the steel coating and the rail steel was desired. The steel coating was then used as the support layer for a thin polymer film applied specifically for lubricity. This paper will discuss the polymer/steel coating system development, its performance, and the subsequent analysis of the polymer film.

## 2. Experimental

Thermally sprayed coatings were deposited using a high-energy plasma spraying system with a 200 kW gun adapted to feed both wire and powder. The high energy system allows for the deposition of multiple wires and/or powder stock simultaneously. A lower energy system may be used to duplicate the coatings developed in this study but will yield a lower deposition rate. A Miller Thermal Rotohopper powder feeder and a modified Linde MIG wire feeder were used for feedstock delivery. The plasma-spraying parameters were set to produce high-quality coatings from wire feedstock and remained constant during the application of the steel coating. Plasma gas flow rates for steel coatings were 230 standard liters per minute (slpm) nitrogen and 30 slpm hydrogen and controlled using a mass flow controller with feed gas pressures of 1.4 MPa. The Plazjet gun was operated at a constant current of 400 A, with voltage varying with gas flow rate. The working distance from gun to target was 235 mm. For the polymer powder application the gas flow rates were adjusted to 200 slpm nitrogen, 50 slpm hydrogen with a working distance of 255 mm. The wire injection and powder injection points were fixed at 10 and 25 mm, respectively. Powder feeder gas flow rate varied between 23 and 30 slpm. The powder feed rate was maximized to ensure adequate polymer powder was injected into the plume, with the polymer powder being injected downstream to minimize degradation. The roller test samples were sprayed on their periphery while being rotated at 200 rpm and cooled with $CO_2$ gas to avoid overheating.

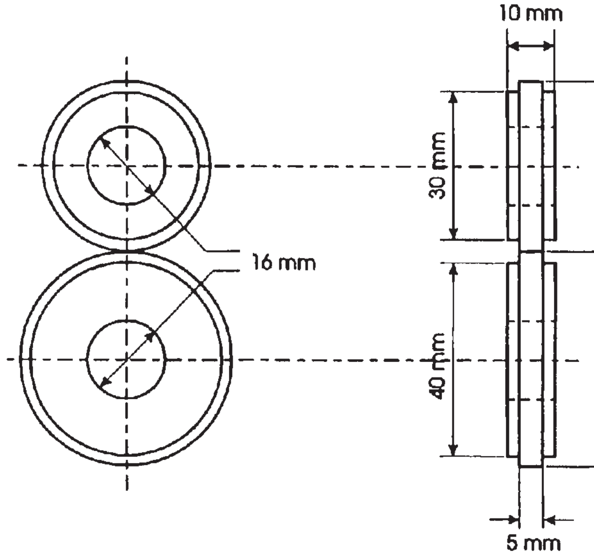


**Fig. 1** Schematic drawing of mated Amsler rollers. Shown dimensions yield a creep value of 35%.

The steel coating was deposited using 1080 steel wire feedstock. Several polymer powders were evaluated: Nylon 11, Nylon 11 blended with a solid lubricant, UHMWPE, UHMWPE blended with a solid lubricant, PTFE (Teflon), and PTFE blended with Nylon 11. The solid lubricant consisted of 25 μm $MoS_2$ powder. The ratio of the polymer to $MoS_2$ varied between 2.5:1 and 4:1 by weight.

Coating system performance was tested under dry and water lubricated rolling/sliding conditions on an Amsler twin roller test machine and measuring the coefficient of friction and the wear behavior of the coating. The Amsler machine is a twin roller dynamometer capable of mechanically measuring friction coefficients over a range of creepage. The test geometry consists of two rollers mated against one another (Fig. 1), each driven by a separate shaft, geared such that one shaft rotates 1.104 times more than the other. By varying roller diameter the creepage can be varied from 0 to 100% under loads up to 2500 N. The creep was calculated using Eq 1 while contact pressure was determined using Eq 2:

$$\text{Creep} = 2\,(1.104D_2 - D_1)/1.104\,(D_2 + D_1) \qquad \text{(Eq 1)}$$

where $D_2$ is the diameter of bottom roller, and $D_1$ is the diameter of top roller;

$$P_o = 0.418\,(LE/R)^{0.5} \qquad \text{(Eq 2)}$$

where $P_o$ = contact pressure in N/mm$^2$, $L$ = load in N, $E$ = elastic modulus of steel ($2.1 \times 10^5$ MPa), and $R = [1/R_1 + 1/R_2]^{-1}$ where $R_1 = D_1/2$ and $R_2 = D_2/2$.

It is noted that the exact modulus for the coatings is unknown as the coatings are composite in nature. The modulus for steel was subsequently used as an estimate. All of the coatings were tested at 35% creep and with a contact pressure of 1200 MPa.

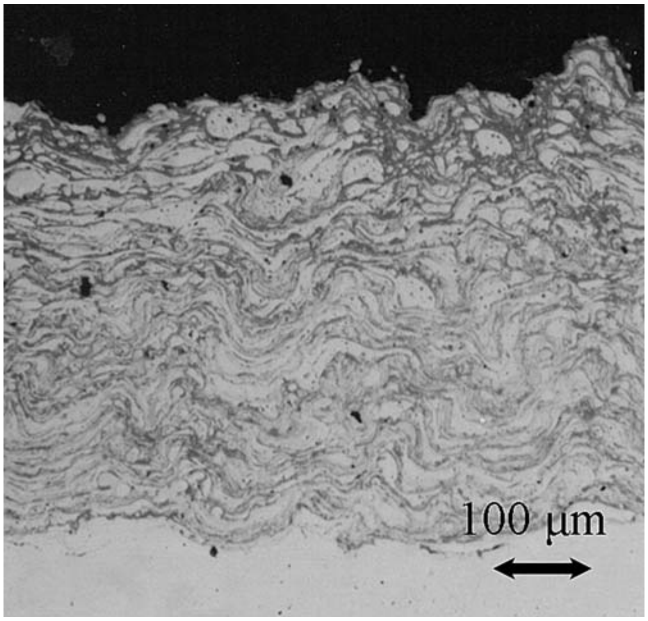


**Fig. 2** Photomicrograph of 500 μm thick 1080 steel plasma sprayed coating without polymer overlay, (as-polished)

Durability was determined by counting the number of revolutions until coating failure or a coefficient of friction increase to 0.30. All of the coatings were observed optically at 50× and 200× and also examined in the scanning electron microscope (SEM) using secondary electron imaging to magnifications up to 5000×.

Fourier transform IR spectroscopy (FTIR) was performed on Nylon 11 samples in the form of as-melted neat powder, as-sprayed coating, and of the remaining film following wear testing to evaluate changes in the polymer due to the thermal spray process and/or due to rolling/sliding contact.

## 3. Results

### 3.1 Structure

The microstructure of the 1080 steel coating is shown in Fig. 2, which consists of steel splats interspersed with oxide films. The thickness of the steel coating varied from 250 to 750 μm. It was found that the 250 μm coating had the best resistance to catastrophic debonding (the sudden separation of the coating from the substrate). The thickness of the polymer coating was greater than 100 μm at the beginning of the wear test but was quickly reduced to less than 10 μm within 100 revolutions. This reduction in thickness in the early stage of wear testing was universal to all polymers tested. Both the Nylon 11 and UHMW were fully melted, adherent films, but the PTFE film consisted of partially melted particles that did not wet the surface. Attempts to melt the PTFE with longer dwell times resulted in rapid degradation (burning).

Besides optical microscopy and scanning electron microscopy (SEM), the Nylon film was analyzed using FTIR using the attenuated total reflectance (ATR) mode. ATR detects surface region characteristics (1-5 μm) relative to the bulk and was used because the film was applied to a flat aluminum coupon. Nylon 11 was the only polymer analyzed as it had the best performance. Nylon is the trade name for a class of polymers known as the polyamides.

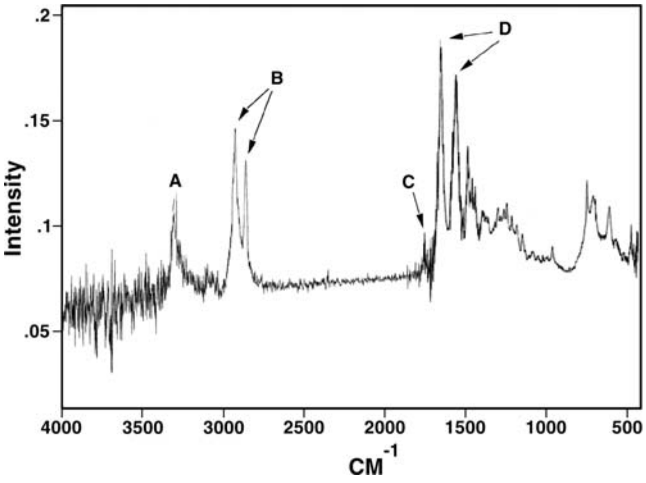


**Fig. 3** FTIR spectrum of as-sprayed nylon 11 film, using ATR. The letters represent the following: (A) Amide I stretch (3309 cm); (B) C-H stretch of methylene groups (2925 cm and 2856 cm); (C) carbonyl (C-O) stretch (1734 cm); (D) Amide II stretch (1639 cm and 1643 cm)

The spectra yielded specific information about the various bonding linkages of the nylon structure. Figure 3 is a characteristic FTIR spectrum of an as-sprayed nylon sample. The wave number (cm$^{-1}$) defines the important peaks and yields definitive structural information, whereas the relative intensity (*y* axis) is dependent on sample thickness and other external factors, and can vary between like-samples. The behavior of the amide linkage was examined in particular. The peak at 3309 cm$^{-1}$ (labeled A), is the amide 1 peak, which represents the stretching between nitrogen and hydrogen. Stretching between carbon and hydrogen in the methylene groups is illustrated by peaks at 2925 and 2856 cm$^{-1}$ (labeled B). The carbonyl peak, which represents stretching between the oxygen and carbon in the amide linkage, is located at 1734 cm$^{-1}$ (labeled C). Finally, the amide 2 peak, at 1569 cm$^{-1}$ (labeled D), represents vibration within the entire amide linkage. Any shift in these peaks, within identical samples, represents structural changes.

All of the nylon spectra: melted, as-sprayed, and worn, were similar with no gross differences. Five samples at each condition were tested with the results being repeatable and consistent. Only when the nylon was pyrolized by intense heating did the spectrum become unrecognizable. Subtle differences did indicate that some changes had taken place. Figure 4 is the result when the as-melted FTIR spectrum was subtracted from the as-sprayed spectrum. A negative peak around 1660 cm$^{-1}$ indicates an increased intensity in the carbonyl peak (number of C-O bonds) of the as-sprayed nylon. The negative peak results when the as-sprayed peak is subtracted from zero, as no peak exists in the as-melted sample at the shifted location. The nylon was melted in air in a low-temperature oven. The spectrum of a worn nylon film had a shift in the Amide II peak (Fig. 5), indicating a slight change of molecular structure. The worn Nylon film was the material transferred to the lower roller during the wear performance test.

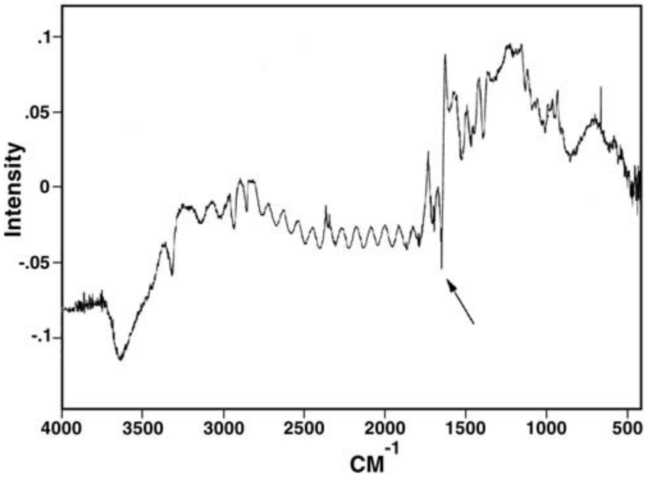


**Fig. 4** FTIR resultant subtractive (as-sprayed-as melted) of two nylon 11 films. The arrow represents the shift in the carbonyl (C-O) peak when the nylon is plasma sprayed vs. simply melting in an oven.

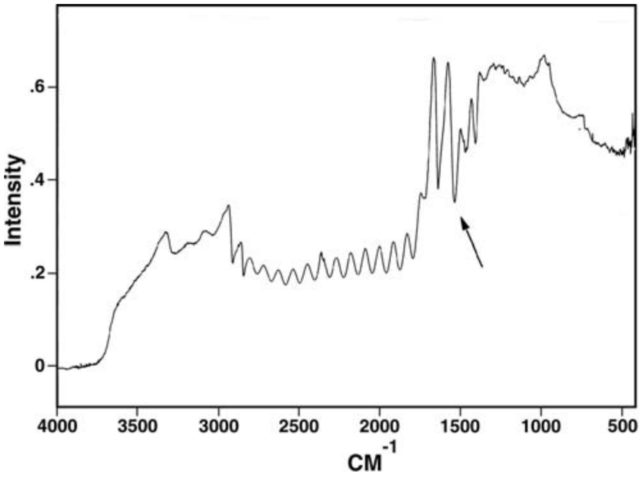


**Fig. 5** FTIR resultant subtractive (as-sprayed—as worn) of two nylon 11 films. The arrow represents the shift in the Amide II peak when nylon is transferred to the bottom roller during wear testing.

### 3.2 Performance

Table 1 summarizes the durability and friction behavior of the different polymer coatings tested. The durability average and range are given. Note only samples with steel coatings with a nominal thickness of 250 μm are presented. Thicker steel coatings had a higher probability of debonding prematurely during testing, thereby masking the lubricating behavior of the polymers. The durability in revolutions was the primary metric by which the coatings were compared. The friction coefficient was also important, and its reduction formed the basis of this study. The polymers behaved in a very similar manner in that the coefficient of friction (μ) would start at 0.05-0.08 and gradually increase until the polymer film was nearly depleted. Once the friction coefficient exceeded 0.3, the degradation increased rapidly, and the polymer film wore off completely within 2000 revolutions.

**Table 1 Wear test results showing average durability of 1080 steel coatings with various polymer overlays (coatings)**

| | Average durability(a) | | | |
|---|---|---|---|---|
| Coating system | Revolutions | Distance, m | Std. dev.(b) | Range(b) |
| UHMWPE + Graphite | 9,024 | 992.2 | 494.6 | 1020 |
| UHMWPE + $MoS_2$ | 9,524 | 1047.2 | 601.1 | 1540 |
| UHMWPE | 9,318 | 1024.6 | 578.0 | 1260 |
| Nylon 11 + Graphite | 8,384 | 921.9 | 437.9 | 1000 |
| Nylon 11 + $MoS_2$ | 10,548 | 1159.8 | 770.6 | 1790 |
| Nylon 11 | 12,732 | 1399.9 | 600.9 | 1560 |
| 50 PTFE-50 Nylon 11 | 5,504 | 605.2 | 404.3 | 890 |
| 75 PTFE-25 Nylon 11 | 5,156 | 566.9 | 431.2 | 1130 |
| PTFE | 3,968 | 436.3 | 435.3 | 870 |

(a) Wear performance testing parameters: 35% creep, $P_o$ = 1220 N/mm$^2$ (MPa), 200 rpm. (b) Calculated using revolutions. All coatings applied over a 250 (±30) μm 1080 steel coating

Nylon 11 had the best performance and was chosen to undergo large field scale testing, reported elsewhere (Ref 16). The performance of Nylon 11 did not improve with the addition of solid lubricants. Statistically, the performance can be considered equivalent to neat Nylon 11 given the large scatter in the Nylon 11 data. The solid lubricant's added benefit may have been negated by the lack of bonding between the $MoS_2$ powder and the parent nylon. The UHMWPE had very good performance, approaching that of nylon in terms of durability. The initial friction was the same for both nylon 11 and UHMWPE with μ = 0.05 to 0.08. The addition of solid lubricants to the UHMWPE powder had no measurable effect in reducing friction and increasing durability.

Unlike Nylon 11 or UHMWPE, plasma-sprayed PTFE did not form a continuous coating, and as a result it degraded within 5000 revolutions. PTFE has a large melt viscosity index, meaning that even when molten the viscosity remains high and the PTFE's ability to wet a surface is limited. Increasing the plasma power level only degraded the PFTE powder and did little to increase adhesion. In an effort to increase adhesion, up to 50% Nylon 11 was blended with the PTFE. It was thought that a mixture might perform better than either neat powder, with the PTFE providing low friction and nylon providing adhesion and integrity. The result was better performance as a function of added Nylon. However, the performance was still far inferior to that of neat Nylon 11.

## 4. Discussion

After a large number of preliminary tests were run, it became apparent that the best coating/polymer combination was a 250 μm thick plasma sprayed steel coating topped with a 100 μm thick plasma-sprayed coating of Nylon 11. The performance of the Nylon 11 was superior to the other polymers tested, UHMWPE and PTFE. Overall, nylon maintained a lower friction coefficient for a greater number of cycles. This combination had the best friction control and longest life as defined by the number of cycles to failure. Because of the nylon's superior performance, the physical and mechanical degradation was studied in-depth.

### 4.1 Performance

All the polymer/steel coatings degraded in a similar manner, with only the number of revolutions (before the friction coefficient reached 0.3 and barring debonding of steel coating) varying. The degradation can be described in four stages. Initially (Stage I) excess polymer is "shed" and lost from the system, resulting in a thin polymer coating, less than 10 μm thick. At this point (Stage II) equilibrium is reached and may last 1000 to over 10,000 revolutions depending on the polymer. The coefficient of friction remains relatively constant, around 0.1-0.15. In Stage III, a polymer film on the order of 1 μm thick develops on the opposing uncoated roller. Stage IV commences as the polymer film begins to disintegrate exposing a narrow ring of polymer-free steel coating. This region expands until full metal-to-metal occurs across the full contact width of the rollers. At this point, the coefficient of friction increases to over 0.3, and the steel coating begins to wear. The friction coefficient quickly jumps to 0.46, the characteristic value for steel coating on wheel steel. Figures 6(a) and (b) illustrate the coating as observed visually in the wear performance test and in the SEM for Stage I. Figures 7-9 illustrate stages II through IV, respectively. A further explanation of the sequence follows.

In Stage I, the contact stresses squeezed out the excess polymer, which has low shear strength, from the contact region. The polymer is also pressed into the convolutions of the as-sprayed steel coating surface, acting as a mechanical anchor. This convolution was observed extensively and is detailed elsewhere (Ref 16). The thickness of the polymer coating after "shedding" was on the order of 10 μm, as measured in the SEM. This thickness was consistently obtained during run-in of the sample regardless of the initial as-sprayed polymer thickness. Figure 6(a) illustrates the surface texture of the polymer as it shears under the high contact pressure and is ripped from the surface and pushed to the edge of the test roller. This run-in and loss of the bulk of the polymer always occurred within 500 revolutions. Even with lower contact pressures (700-900 N/mm$^2$ versus 1220 N/mm$^2$) the excess polymer was lost from the system within 500 revolutions.

Stage II was an equilibrium phase that lasted in excess of 10 K revolutions for the Nylon 11. The integrity of the polymer coating was maintained by the anchoring of polymer material in the valleys of the steel coating. The unique convoluted surface morphology of the steel coating allowed the polymer to lubricate for long cycle times. This equilibrium stage was observed in all polymer/steel coating systems tested, with the major difference being duration of equilibrium behavior. The duration of this stage is critical as it defines useful life of the polymer/steel coating system. During Stage II, the friction coefficient varied between 0.1 and 0.15 for Nylon 11 and UHMWPE but was below 0.10 for PTFE. Stage II in some cases exceeded 10,000 revolutions for the Nylon 11, whereas UHMWPE lasted 6000 revolutions, and the PTFE less than 2000. It is believed that the Nylon 11 had the right combination of adhesion, cohesion, and shear strength to allow it to maintain a thin lubricating film longer than the other two polymers.

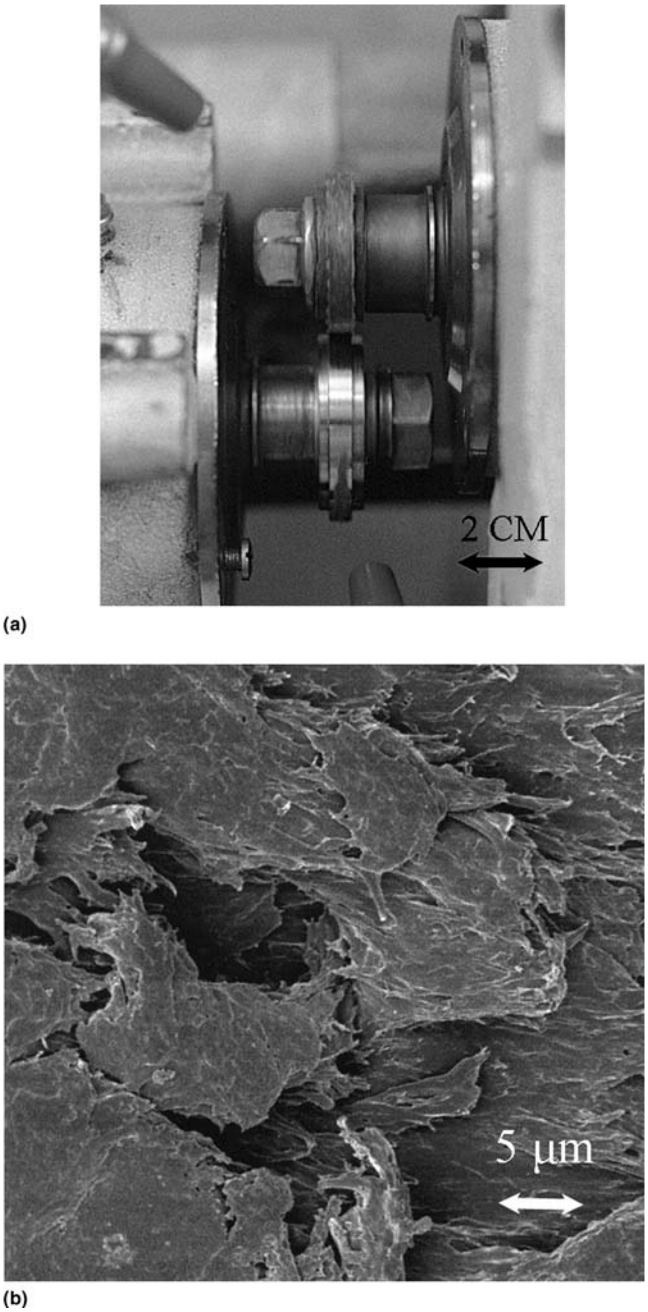
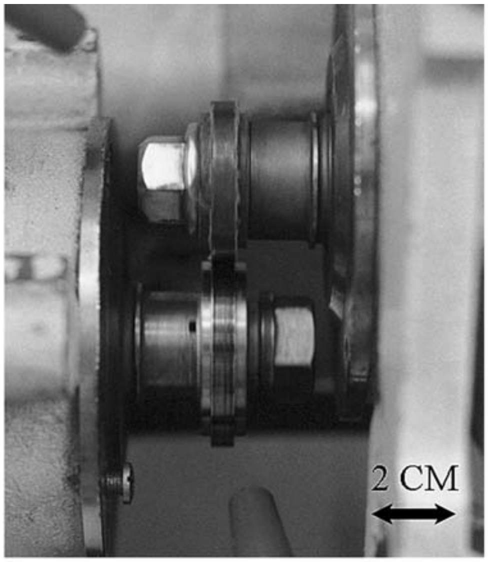
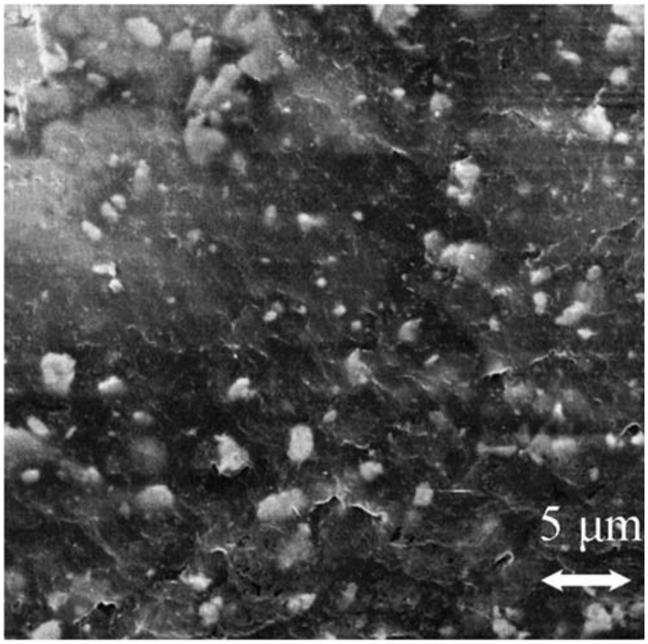


**Fig. 6** (a) Photograph of nylon 11/steel coating "shedding" excess polymer during Stage I. (b) SEM micrograph showing morphology of nylon coating during Stage I.

Stage III occurs when a measurable polymer film transfers to the opposing roller. The transferred film reaches an equilibrium thickness of 1 μm on the opposing roller, supplied by the polymer film of the sprayed roller. At the onset of this stage the coefficient of friction increased to roughly 0.25 within 2000-3000 revolutions. During Stage II the friction coefficient is continually creeping higher indicating that a true "equilibrium" is not present, rather the degradation of the polymer is relatively slow (compared with metal on metal) and the thin polymer film is wearing and changing structure. Once the layer formed on the bottom roller, the lubricating effect was greatly diminished. This could be caused by two things: a polymer-polymer contact interface is less lubricious than a polymer-steel contact interface or the Nylon 11 would adhere to itself causing the polymer coating



(a)

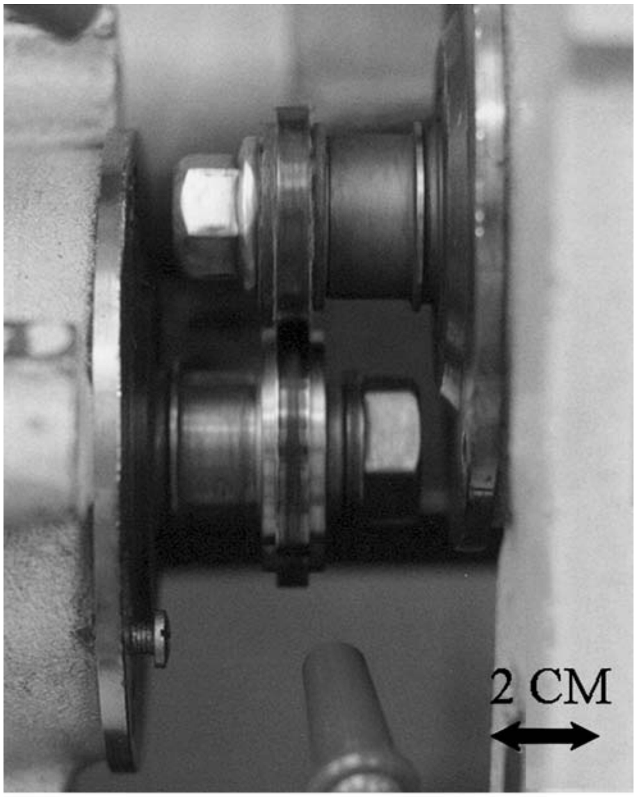


(b)

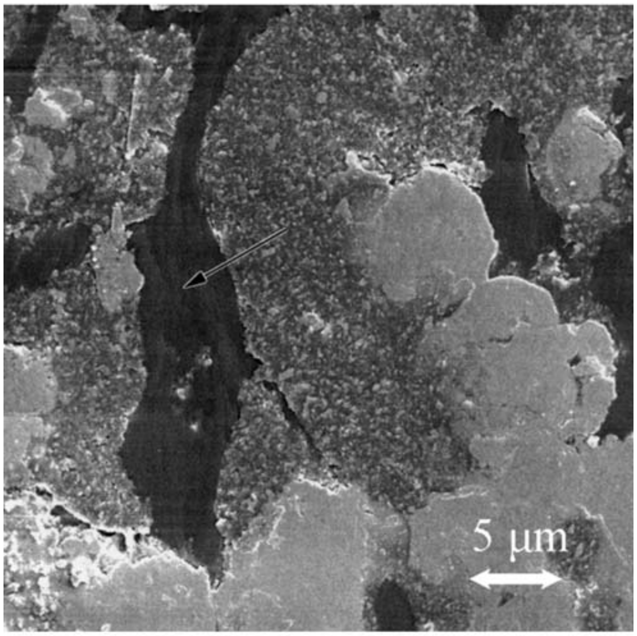
**Fig. 7** (a) Photograph of nylon 11/steel coating during the steady-state wear of Stage II, bottom roller is essentially clean of any transferred polymer. (b) SEM micrograph showing morphology of nylon coating during Stage II. Coating remains continuous throughout this stage.

to be removed and reapplied in the contact zone. This continuous "working" of the polymer would weaken its structure and allow for material to be lost from the system. Figure 8(a) illustrates the thin Nylon 11 coating covering the steel coating. Darker areas represented valleys where excess polymer was anchored. These valleys may have also provided a reservoir for the polymer coating to repair itself as the thinner layers wore away.

In Stage IV, metal-to-metal contact is initiated as the polymer film is removed, leaving a narrow ring of exposed steel coating. The ring's width expands until the polymer coating is completely removed at the surface, resulting in metal-to-metal contact across the full contact width of the rollers. At this point, the coefficient of friction rose to over 0.3, and the tests were termi-



(a)



(b)

**Fig. 8** (a) Photograph of nylon 11/steel coating during Stage III. Significant polymer transfers to lower roller causing friction to rise. (b) SEM micrograph showing morphology of nylon coating during Stage III. Arrow denotes reservoir of nylon 11 created by high-contact pressures.

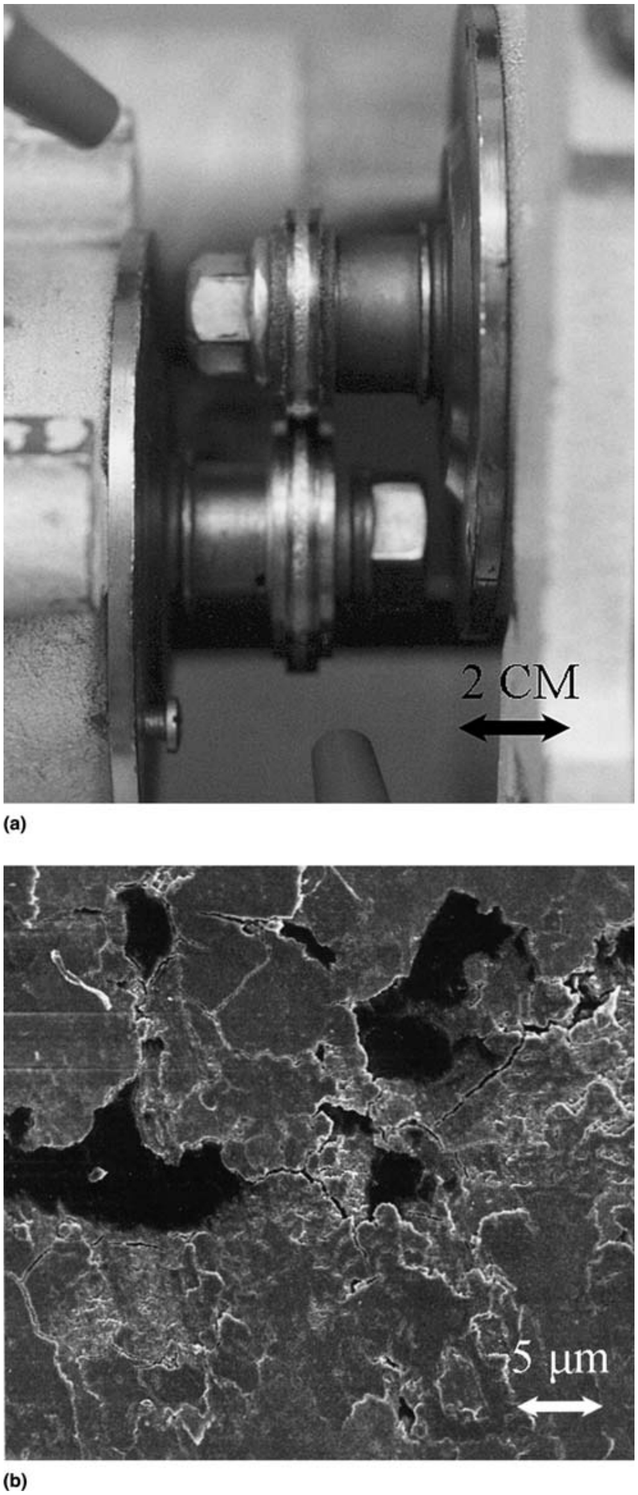


**Fig. 9** (a) Photograph of nylon 11/steel coating during Stage IV. Polymer begins to wear through yielding metal-metal contact and ever increasing friction. (b) SEM micrograph showing morphology of nylon coating during Stage IV. Measurable polymer only remains in valleys (dark areas).

nated. Several samples were run to failure, resulting in a final coefficient of friction approaching 0.46, which is the equilibrium friction of plasma-sprayed 1080 steel coating without any subsequent polymer coating. Continued testing would either result in adhesive failure of the steel coating at the coating/substrate interface or continue in an equilibrium wear mode based on steel coating-to-steel contact.

The polymer/steel coating system's performance was found to be the best with plain Nylon 11. Perhaps other polyamides (such as Nylon 6,6) may have performed better and could be tested in future trials. Surprisingly, neither solid lubricant improved the performance of the Nylon or the UHMWPE. Visually, the addition of molybdenum disulfide ($MoS_2$) or graphite gave the polymer coating less of a continuous appearance. Any added benefit of the solid lubricant may have been negated by the lack of bonding between the $MoS_2$ or graphite powders and the bulk polymer coating. Further study utilizing varying sizes and different ratios (of $MoS_2$ especially) may be able to discern the effect, if any, of the solid lubricants.

The test parameters were chosen so the extreme contact conditions of wheel on rail could be simulated. When the Nylon 11 and UHMWPE were tested at 5% creep or when the contact pressure was reduced to 900 N/mm$^2$, the durability increased 400% to 40,000-50,000 revolutions before the coefficient of friction increased above 0.3. At these less extreme conditions, there was little difference between the UHMWPE and Nylon 11, although only 3 samples each were done at these conditions. This is promising as other less demanding applications may be able to benefit from these coatings.

### 4.2 Structure

FTIR results showed minimal changes to the Nylon molecular structure caused plasma spraying and during rolling/sliding contact. Nylon did not appreciably change its molecular structure as a result of thermal spraying or by passage through the contact zone. Nylon melted in a furnace had essentially the same structure as Nylon that was plasma sprayed. Only when the nylon was oxidized at high temperatures, turning dark brown to black in color, was the molecular structure significantly changed. The robust nature of the nylon was valuable in that deposition by plasma spraying could be monitored by simply observing the deposit color, and no special precautions were required, beyond cooling, during plasma spraying. The slight change in the carbonyl peak did indicate some oxidation of the nylon structure had occurred. The number of C-H bonds was reduced while the number of C-O bonds increased. Figure 5 illustrated this by the presence of the negative peak (arrow). This is to be expected given the exposure to high temperatures in an oxidizing atmosphere. Another slight change in structure is shown in Fig. 5, which is the spectrum from the transferred Nylon 11 film. The negative peak (also noted by an arrow) represented a slight shift in the Amide I and Amide II linkage intensities indicating the transferred film has a less ordered structure than the as-sprayed polymer. This is consistent with the observations and conclusions that polymer transfer causes significant mechanical deformation of the structure and thereby reduces any crystallinity present following plasma spraying.

### 4.3 Applications

This coating system was developed initially for use on railroad tracks, particularly on the gauge face of the high (outside) rail in curves. Subsequent large scale testing on real track indicated the durability of the polymer/steel coating system was not adequate to justify the capital costs of application in the field. The durability varied as did friction reduction, and because of the preliminary results, further testing was abandoned. Nonetheless, this type of coating system may find use in other areas with less hostile loading and sliding conditions. Limited testing indicated the polymers' ability to lubricate was more a function of the metal coating's topography than the actual metal coating material. Thus, more economical coating materials, i.e., powders and a lower power deposition system could be used to achieve a similar type of coating system. The polymer deposition efficiency was estimated at 20%. Further work in increasing this efficiency could be done, depending on the application and materials used.

## 5. Conclusions

The reduction of wear and friction was accomplished by establishing a thin polymer film mechanically anchored to a thermally sprayed steel coating. The coefficient of friction ranged from an initial coefficient of friction of 0.05 to a final value of 0.30 under rolling/sliding conditions at 35% creep and a 1220 MPa (N/mm$^2$) contact pressure.

FTIR data indicated the molecular structure of the Nylon 11 changed minimally during plasma spray deposition and wear testing, showing only evidence of some oxidation and loss in crystallinity. It is believed that these changes had little effect on overall coating performance.

Four degradation stages were identified. These stages were observed in every polymer coating system tested under rolling/sliding conditions. Development of mechanical interlocking between the polymer coating and the steel coating surface was identified during the initial stage of testing and considered a substantial factor in coating performance.

This study opened up many possible variations in both testing and coating development that could be implemented to improve understanding and increase performance of self-lubricating plasma-sprayed coatings. This study was part of a larger project looking at the feasibility of using coatings to reduce wheel/rail friction and wear. These results represent qualifying tests, and the authors recognize that larger quantities of tests (perhaps 10 or more) would be required to increase the confidence levels of the coating's performance. Other polymer systems could be explored with varying size and quantity of solid lubricants. Also, not discussed in this paper is the geometry effect of applying a coating rail profile as opposed to the small Amsler roller surface. Additionally, the coatings could be tested in other types of sliding wear fixtures.

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