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Improved Wear Performance by the Incorporation of Solid Lubricants during Thermal Spraying

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For components that are required to function in sliding or rubbing contact with other parts, degradation often occurs through wear due to friction between the two contacting surfaces. Depending on the nature of the materials being used, the addition of water as a lubricant may introduce corrosion and accelerate the degradation process. To improve the performance and increase the life of these components, coatings may be applied to the regions subject to the greatest wear. These coatings may be engineered to provide internal pockets of solid lubricant in order to improve the tribological performance. In the present study, coatings containing a solid lubricant were produced by thermal spraying feedstock powders consisting of a blend of tungsten carbide-metal and a fluorinated ethylene-propylene (FEP) copolymer-based material. The volume content of this teflon-based material in the feedstock ranged from 3.5 to 36%. These feedstocks were deposited using a high velocity oxy-fuel (HVOF) system to produce coatings having a level of porosity below 2%. Sliding wear tests in which coated rotors were tested in contact with stationary carbon-graphite disks identified an optimum level of teflon-based material in the feedstock formulation required to produce coatings exhibiting minimum wear. This optimum level was in the range of 7 to 17% by volume and depended on the composition of the cermet constituent. Reductions in mass loss for the couples on the order of 50% (an improvement in performance by a factor of approximately 2) were obtained for the best performing compositions, as compared to couples in which the coating contained no solid lubricant.

Keywords coefficient of friction, high velocity oxy-fuel, sliding wear, solid lubricant, teflon, tungsten carbide-based cermet

1. Introduction

The incorporation of solid lubricants into coatings during the thermal spraying step can be used to produce self-lubricating surfaces having improved characteristics for applications involving sliding wear. Solid lubricants can be useful for conditions in which lubrication in the form of liquid or grease is either impractical or impossible,[1] *e.g.*, at temperatures either below the freezing point or above the boiling point of these lubricants and in situations where a vacuum or very low pressures are used. While many of the traditional approaches to lubrication rely on either a continuous or periodic addition of lubricant between the contacting surfaces, solid lubricants that are an integral part of the component can serve as internal pockets of lubrication, which are constantly being exposed as the part wears.

Examples of studies are available in the literature in which bulk components and coatings containing solid lubricants were produced by powder metallurgy[2] and thermal spraying.[1,3] Because both production methods involve high temperatures, the possibility of degrading the solid lubricant during processing is a concern for some materials. One major difference between these two processes is the exposure time at high temperature. Powder metallurgy often involves a heat treatment step lasting from minutes to hours; on the other hand, thermal spraying may expose the materials to higher temperatures but for periods of only milliseconds to seconds.

For some solid lubricants that would not normally survive prolonged exposure to temperatures over 1000 °C, it is possible to produce coatings containing these materials by thermal spraying.[4,5] This structure can be accomplished due to the relatively short residence time of the powders in the high-temperature environment of the thermal spray jet. Other factors, such as the particle size of the solid lubricant feedstock powders, will also play a role. While some of the solid lubricant initially present in the starting feedstock might be degraded or lost through particle surface evaporation or decomposition, under certain conditions, it appears that a portion of the solid lubricant is deposited and becomes part of the coating.

The present work, which has previously been summarized elsewhere,[6] was focused on producing thermally sprayed cermet coatings containing solid lubricants for improved sliding wear performance. The coatings were produced by spraying blends of the cermet and a teflon-based powder.

2. Procedure

2.1 Materials

Details on the composition of the primary powders used in this study are given in Table 1. The calculations to determine the overall composition (in terms of volume) of the various primary powders were performed by using the following values for the

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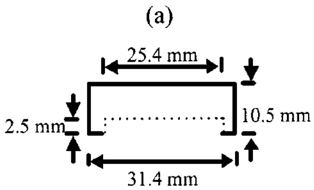


Fig. 1 Side view showing the geometry and size of (**a**) the stainless steel substrate and (**b**) the carbon-graphite disk

Table 1 Composition of the primary powders used to prepare powder blends

Powder	Weight content(a)	Volume content (calculated)
Nickel matrix cermet	90% WC	83.7% WC
	10% Ni	16.3% Ni
Cobalt-chromium matrix cermet	86% WC	76.6% WC
	10% Co	15.6% Co
	4% Cr	7.8% Cr
Teflon-based material	32.8% FEP(b)	66.5% FEP
	59.0% Mo	24.6% Mo
	4.1% Al_2O_3	4.4% Al_2O_3
	4.1% TiO_2	4.5% TiO_2

(a) From manufacturer
(b) Fluorinated ethylene-propylene copolymer

density (in g/cm^3) of the different constituents: 15.63 for WC,[7] 8.90 for Co,[7] 8.90 for Ni,[7] 7.19 for Cr,[7] 10.20 for Mo,[7] 3.97 for Al_2O_3,[8] 3.84 for TiO_2[8] (anatase), and 2.1 for fluorinated ethylene-propylene (FEP).[9] In the case of the WC-10Ni composition, two powders produced using different processes were used. One powder was produced by fusing and crushing (FC) and is designated as WC-10Ni (FC). The second material was manufactured using spray drying and sintering (SDS) and is identified as WC-10Ni (SDS). All four powders were commercially available. The three cermet powders had a particle size distribution reported by the manufacturer to be in the range of 15 to 45 μm and had been produced for high velocity oxy-fuel (HVOF) spraying.

The solid lubricant material was specifically engineered to produce a polymer-containing powder having characteristics suitable for use in thermal spray feedstocks.[10] The polymeric constituent was an FEP copolymer known by the trade name Teflon FEP. Throughout this text, this constituent will be referred to as teflon. Because teflon has a relatively low density and can be degraded at temperatures of a few hundred degrees, the manufacturer of this powder (Spray-Tech, Inc., Newtown, CT) used a process to tailor the material for use in thermal spraying. To protect the teflon particles from the high temperatures experienced during thermal spraying, a ceramic cladding of alumina-titania was applied to serve as a thermal barrier and help to limit degradation of the polymer particles. In addition, molybdenum particles were added to increase the mass and improve the flow characteristics of the material in the particle jet during the thermal spraying step. The particle size of the final product was reported as -53 μm.

In this study, feedstock materials for thermal spraying were prepared by mixing the cermet and polymer-based powders to produce various blends containing levels of the teflon-based material ranging from 3.5 to 36% in terms of volume. The mixing process consisted of a 1 h blending step in a V-blender, followed by an additional 1 h mixing in a shaker-mixer (Turbula Model T2C, Glen Mills Inc., Clifton, NJ). The computations to determine the level of teflon-based material in the various feedstocks were performed using a calculated density of 4.25 g/cm^3 for the teflon-based powder. Subsequent density measurements using a helium pycnometer found the density to be 4.04 ± 0.05 g/cm^3. This may indicate that there is closed porosity in the powder particles or that a slightly higher percentage of the lower-density constituents, teflon and/or ceramic, are present than reported by the manufacturer. If only the teflon portion of the teflon-based material is considered, the volume of solid lubricant calculated to be in the blends ranged from just over 2% to 24%.

Table 2 Conditions used for thermal spraying

Parameter	Value
Oxygen flow rate, m^3/h	58.6
Kerosene flow rate, L/h	23.5
Stoichiometry, O_2/Kerosene	1.21
Carrier gas flow rate (Ar), m^3/h	0.7
Powder feed rate, g/min	75
Barrel length, cm	10.2
Stand-off distance, cm	38
Traverse speed, cm/s	61
Step size, cm	0.5

The substrates on which the various feedstocks were to be deposited were machined from 312 stainless steel stock to produce a geometry of the thrust washer type shown in Fig. 1(a). The surface to be coated was roughened by grit blasting with an alumina grit prior to thermal spraying in order to improve the mechanical bonding between the substrate and the coating.

The carbon-graphite used for wear testing was a commercially available resin- infiltrated product (Grade CNFJ, National Electrical Carbon Canada, Mississauga, ON, Canada) consisting of a mixture of amphorous carbon and graphite. Although x-ray diffraction spectra were obtained and indicated the presence of graphite, no further effort was made to determine the ratio of the two carbon phases present in the product. The infiltration with resin resulted in a material having an apparent residual porosity of 1%. The typical value for the Shore hardness reported for the product was 84. Parts were machined from this material to produce disks having the size and geometry shown in Fig. 1(b). A hole (not shown) having a diameter of 0.5 mm was drilled in the side of each disk to a depth of approximately 5 mm to serve as a thermocouple well.

2.2 Coating Deposition

The various feedstocks were employed to produce coatings on stainless steel substrates using an HVOF torch (Model JP-5000, TAFA Technologies, Concord, NH). The parameter values used during spraying are shown in Table 2. The coatings were deposited on only the 3 mm wide raised portion of the substrate; the remaining surface was masked to protect it from the particle jet. Thirteen sets of coated samples, a set for each cermet powder containing no solid lubricant and ten compositions containing various amounts of the teflon-based material, were prepared. Several samples of each coating composition were

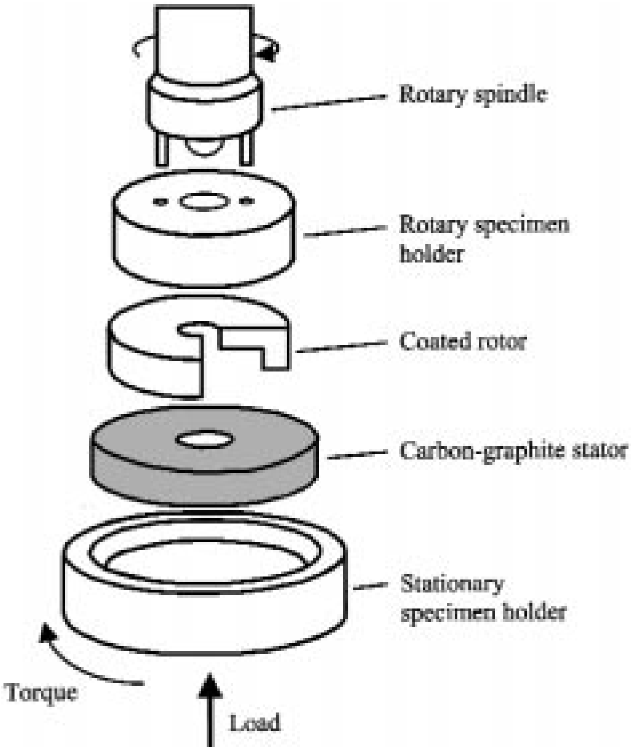


Fig. 2 Schematic of the setup used for sliding wear tests

produced simultaneously. The thickness of the coating deposited on the substrate varied among the compositions, ranging from 370 μm for the coating produced from the feedstock containing WC-10Co-4Cr to 600 μm for the one sprayed using the WC-10Co-4Cr + 3.5 vol.% teflon-based material.

2.3 Sliding Wear Tests

Tests were performed in order to determine the effect of the solid lubricant on the tribological performance of couples, which consisted of a coated substrate (rotor) and a carbon-graphite disk (stator). Prior to performing these tests, the surface of each coating was milled using a diamond wheel to produce a smooth, flat face. The surface was then subjected to several polishing steps, concluding with a final polishing using a 3 μm diamond paste to produce a mirror finish. The mating surface of each carbon-graphite stator was also lapped and polished to produce a high quality finish.

In preparation for the sliding wear tests, both the rotors and stators were cleaned, dried, and weighed. This included an ultrasonic cleaning step and, in the case of the stators, a 2 h heat treatment at 150 °C to eliminate entrapped moisture.

Wear testing was performed using a friction and wear test machine (Falex Multispecimen, Falex Corp., Aurora, IL) and a thrust washer configuration[11] under the conditions shown in Table 3. A schematic showing the wear test setup is presented in Fig. 2. The test couples consisted of a carbon-graphite stator, instrumented with a type K thermocouple to monitor temperature changes, and a coated rotor mounted to a rotating shaft. During a test, the temperature of the stator and the torque were logged at 10 s intervals and stored on a computer for later retrieval. Two couples were tested for each coating composition. Values for the coefficient of friction for the couples for each of the coating compositions were calculated using the values for the torque, the mean radius of the contact surface, and the applied load.[11] An average value of the coefficient of friction for a given coating composition was determined using the results from the two tests. This was accomplished by first eliminating the initial few minutes (break-in period) of data for each test. When a quasi steady state was attained, the average value was calculated by using the remaining data points from both sliding wear trials.

Table 3 Conditions used for evaluating tribological behavior

Parameter	Condition/Value
Environment	Air, no liquid lubricant
Rotational speed, rpm	1500
Tangential speed, m/h	8030
Load, N (lb)	66.7 (15)
Pressure, kPa (psi)	250 (36.4)
Duration, h	24

A sample of the wear debris was collected for analysis at the completion of each test. The rotor and stator were cleaned and dried, using the same procedure as used before the test, and then weighed to determine the mass change that had occurred. The results for each component of the couples for a given coating composition were combined and reported as an average value.

2.4 Characterization

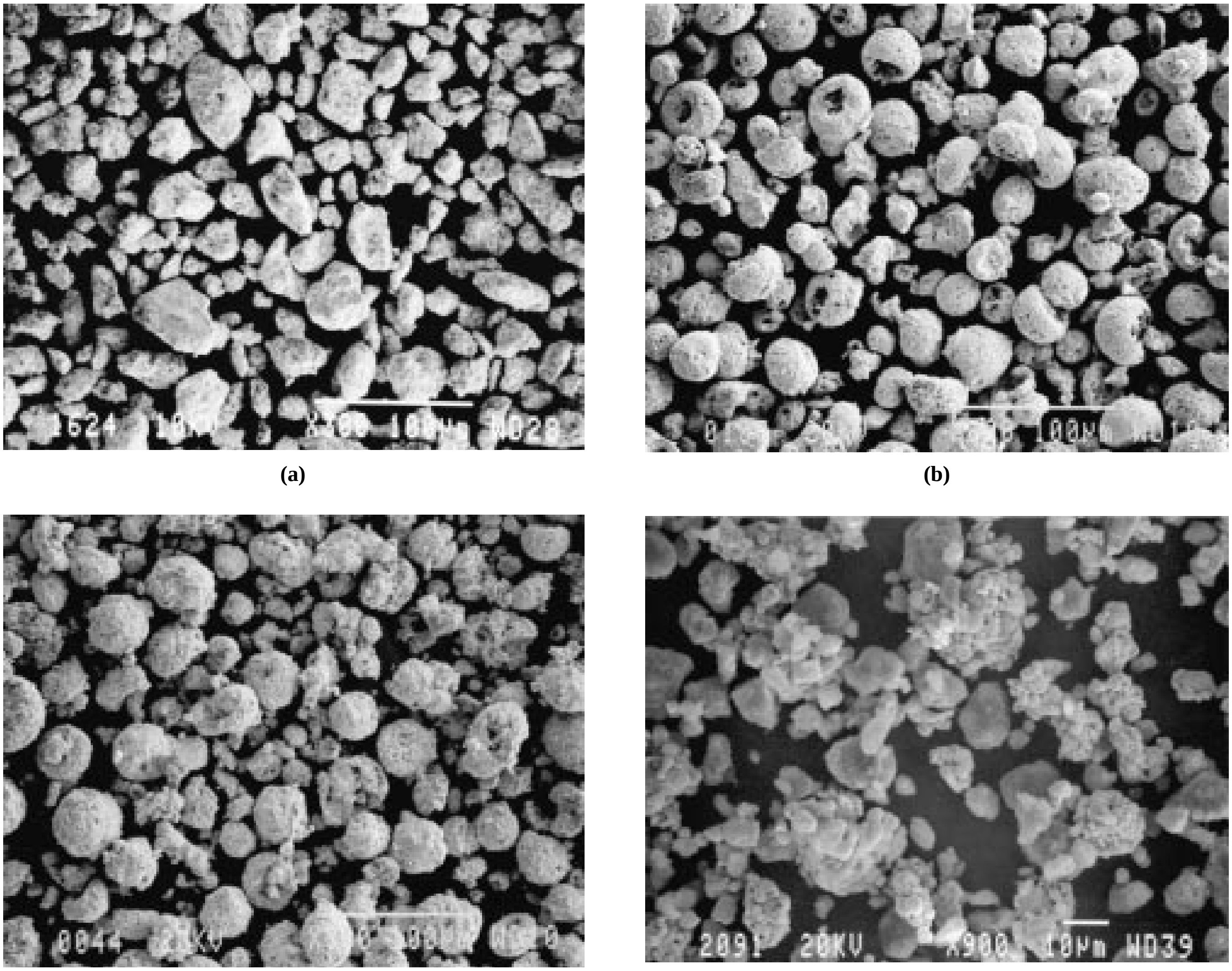
Various tests were performed to characterize the starting materials, coatings, and products of the wear tests. Characterization of the microstructure of the starting primary powders and coatings was performed using a scanning electron microscope (SEM) (JSM-6100, JEOL, Tokyo) equipped with an energy-dispersive x-ray spectrometer (EDS) (Analyzer eXL, Link Systems, High Wycombe, United Kingdom). This equipment could be used to obtain x-ray maps to determine the distribution of the various elements. Samples used for this characterization were vacuum impregnated with an epoxy resin and then polished to a mirror finish using a procedure described previously.[12] The porosity level of coatings was determined by image analysis using images obtained with the SEM.

The surface roughness of the various components was determined using a stylus profilometer. Measurements were made on the stators and rotors before the sliding wear tests and on the wear tracks following these tests. The microhardness of the coatings under a 100 g indentation load was measured on polished cross sections using a microhardness tester (Micromet II, Buehler, Lake Bluff, IL) equipped with a Vickers diamond pyramid indenter.

3. Results and Discussion

3.1 Powder Characteristics

Micrographs showing the morphology of the four primary powders used in this study are presented in Fig. 3. The morphological features of the two cermet powders containing nickel can be seen to be different. The powder produced by FC (Fig. 3a) is more angular than that produced by SDS (Fig.



(a)

(b)

(c)

(d)

Fig. 3 Micrographs of the four primary powders: (**a**) WC-10Ni (FC), (**b**) WC-10Ni (SDS), (**c**) WC-10Co-4Cr, and (**d**) the teflon-based material

3b), which tends to be somewhat spherical having a relatively smooth surface. The WC-10Co-4Cr powder (Fig. 3c) was also produced by SDS. The teflon-based material (Fig. 3d) has a different appearance and a particle size distribution that extends to smaller sizes than that of the cermets. The distribution of the various elements within this material can be observed in the EDS x-ray maps shown in Fig. 4. These maps were obtained from a region of the surface shown in Fig. 3(d). No map was obtained for the elements contained in the FEP copolymer (carbon and fluorine). The low atomic number of these elements prevented detailed mapping with the equipment being used. Inspection of the maps indicates that, although all three elements are often found together, the Ti (from TiO_2) and Al (from Al_2O_3) tend to be more closely associated. On occasion, these elements can be found in regions where there appears to be no Mo. It is assumed that the polymer phase is situated in close proximity to the ceramic phase within which it was encapsulated.

3.2 Characterization of Coatings

Typical microstructures at different magnifications for two cermet coatings and coatings produced from blends containing the teflon-based material are shown in Fig. 5. Image analysis indicated that for all compositions the level of porosity was less than 2%. The dark regions seen in Fig. 5(c) and (d) are predominantly zones in which teflon-based material is located. This was identified by comparing images from the SEM in the backscattered and secondary electron modes and through elemental mapping. Analysis is ongoing to determine to what extent the teflon fraction of the teflon-based material in the feedstock powder was retained in the deposited layer. Preliminary results using various analytical techniques have indicated that there may be substantial loss of the polymeric species during the spraying process. In Fig. 5, the teflon-based material, including Mo, is present in pockets that are often somewhat elongated in the direction parallel to the plane of the substrate, due to flattening of the parti-

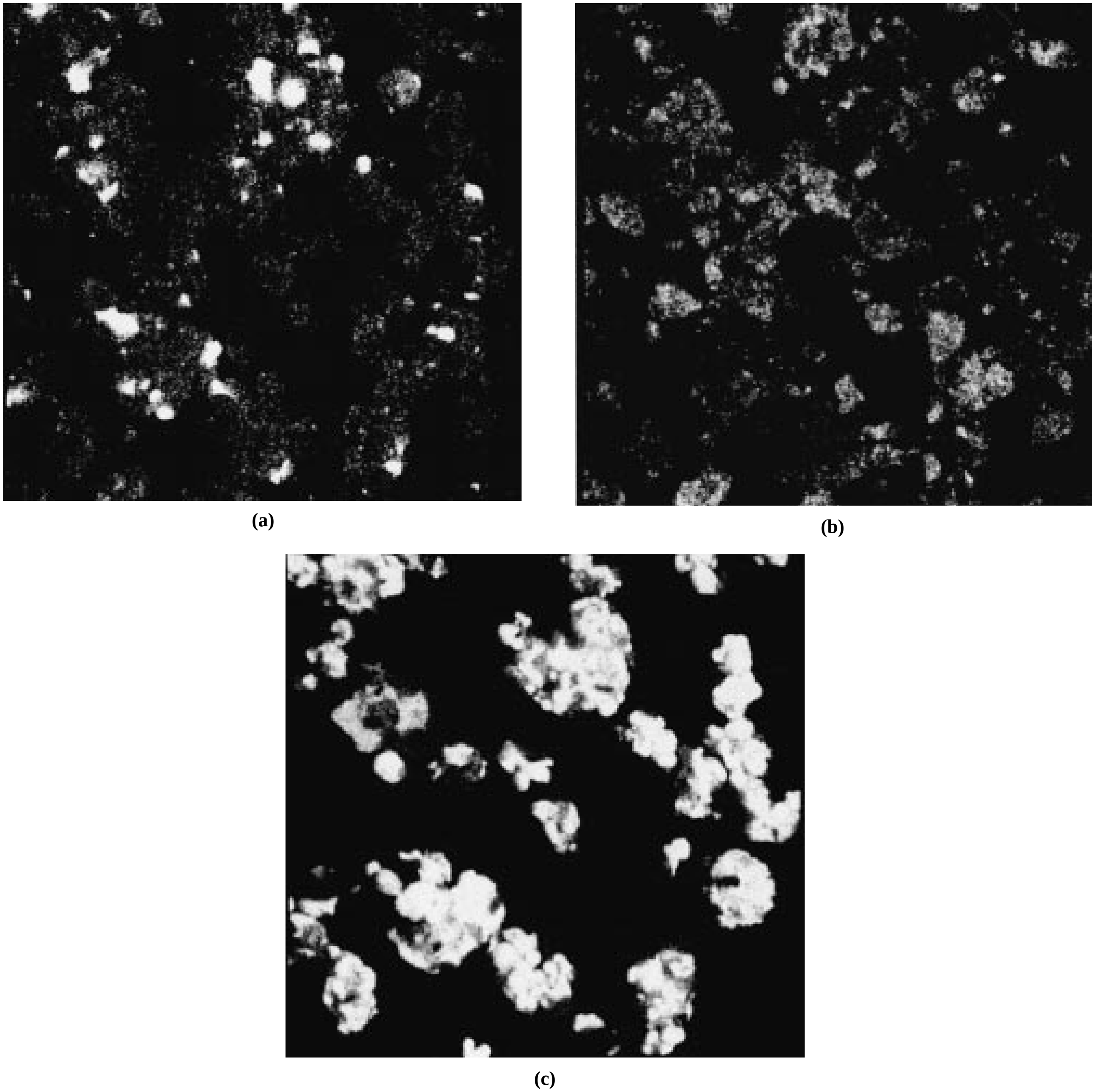


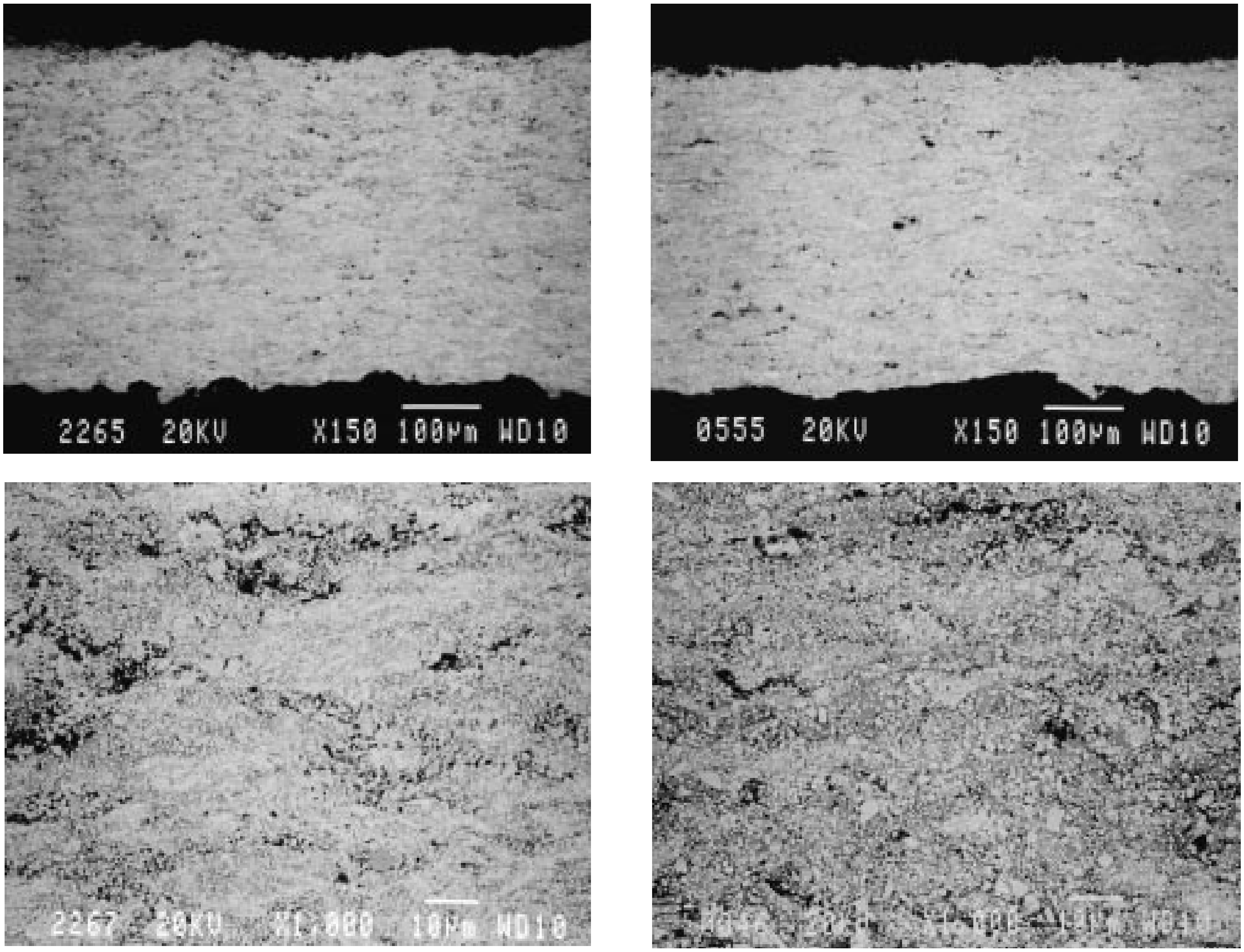
Fig. 4 X-ray maps showing elemental distribution of (**a**) Al, (**b**) Ti, and (**c**) Mo within the teflon-based powder for a region of the sample shown in Fig. 2(**d**) at the same magnification

cles upon impact. The diameter of these zones varies in the range of approximately 5 to 10 μm.

The Vickers hardness numbers for the three cermet coatings containing no solid lubricant were 1323 ± 106, 1192 ± 95, and 1278 ± 47 for the WC-10Ni (FC), WC-10Ni (SDS), and WC-10Co-4Cr, respectively. The microhardness of the coatings containing the teflon-based material was not determined. It should be noted, however, that the hardness of the coating is expected to decrease as the volume fraction of the softer teflon-based material increases.

3.3 Tribological Performance

Wear Testing. Results from the sliding wear tests showing the mass loss for the rotors and stators for the various coatings being studied are presented in Fig. 6. These results indicate that the addition of the teflon-based material can have a positive effect on the performance of these couples with regard to the mass loss of the two components. There is, however, an optimum composition, which tends to produce a minimum in the mass loss of one or both components. For the WC-10Ni composition, the



(a) (b)

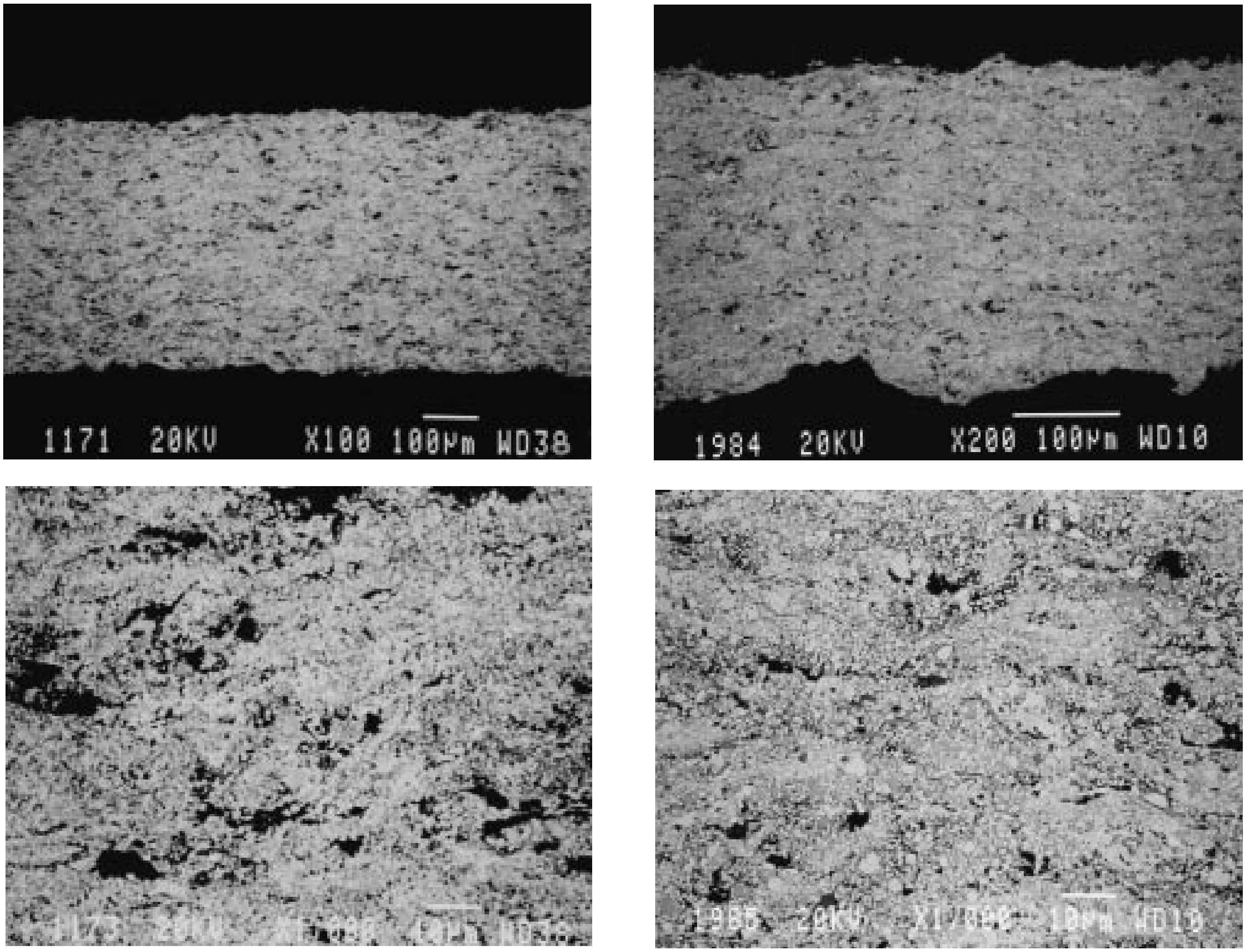
Fig. 5 Micrographs at two magnifications of the coatings produced from feedstocks of (**a**) WC-10Ni (SDS), (**b**) WC-10Co-4Cr,

feedstock containing approximately 17 vol.% of the teflon-based material yielded a coating that exhibited the lowest wear. The stators against which the WC-Ni surfaces were sliding experienced the lowest wear for coatings produced from feedstock compositions containing 10 to 17 vol.% of the teflon-based material. In the case of the WC-10Co-4Cr compositions, the wear for both the stator and rotor was lowest for the couples in which the coating on the rotor was produced using the feedstock containing 7 vol.% of the teflon-based material.

The results for the WC-10Ni compositions indicated that small additions (3.5 to 7 vol.%) of the teflon-based material led to increased wear of the coating. The nature of the change that gave rise to this initial increase is not yet fully understood. Further increases in the level of teflon-based material to the range of 10 to 26 vol.% resulted in a decrease of up to approximately 50% in the mass lost by the coating in the sliding wear test. Increasing the concentration of teflon-based material to 36 vol.% produced a large increase in the wear experienced by the coating. At this level, the mass loss was approximately 60 times greater than for the WC-10Ni coating containing no teflon-based material and more than 100 times higher than the best coating composition.

A somewhat similar trend was observed for the stators sliding in contact with the WC-10Ni coatings. There was an initial increase in mass loss with small additions of the teflon-based material, followed by a decrease in wear to a minimum as more teflon-based material was added. Beyond this point, the mass loss increased as the level of the teflon-based material increased. The stator that experienced the least wear had a mass loss 30% less than that measured for the stator sliding in contact with the WC-10Ni (SDS) coating containing no lubricant. At the highest concentration of the teflon-based material, the wear was quite severe, approximately 20 times greater than the base coating composition.

Because the results for the various coatings containing WC-10Ni indicated that high levels of the teflon-based material had a detrimental effect on the sliding wear performance, a narrower composition range was evaluated for the coatings containing WC-



(c)

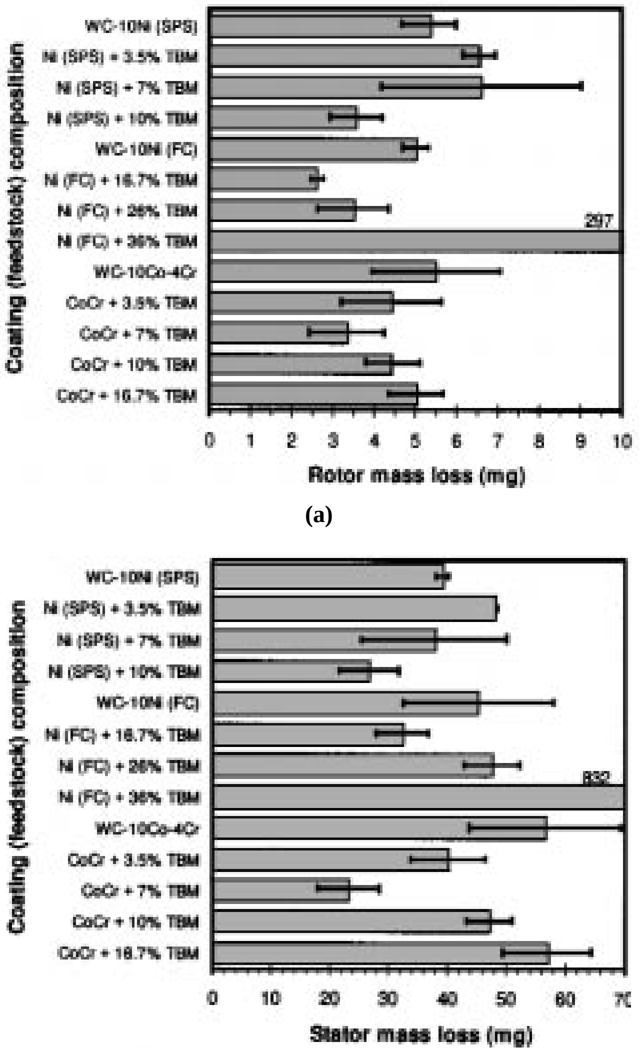
(d)

Fig. 5 (continued) Micrographs at two magnifications of the coatings produced from feedstocks of (**c**) WC-10Ni (SDS) + 10 vol.% teflon-based material, and (**d**) WC-10Co-4Cr + 7 vol.% teflon-based material

10Co-4Cr. The results, shown in Fig. 6, indicate that the addition of the teflon-based material, even at low levels, decreased the wear. For the best WC-10Co-4Cr coating composition, produced using the feedstock containing 7 vol.% of the teflon-based material, the mass loss was reduced by 40% for the rotors and 60% for the counterfacing stators. Beyond this minimum, the wear increased with increasing levels of the teflon- based material. At a level of teflon-based material of approximately 17 vol.%, the mass loss had reached a value similar to that measured for the couples involving the WC- 10Co-4Cr coating having no solid lubricant present.

The addition of the less dense teflon-based material results in lower density coatings. Therefore, due to the differences in specific volume, comparison of the mass loss data for the different coating compositions is not necessarily the best way to rank the performance. Comparison of the volume loss is a more direct approach. Results of the calculations to determine the volume loss of the various compositions are shown in Fig. 7. The calculations to convert the mass loss measurements to volume loss values were made using several assumptions. It was assumed that the coating composition was identical to that of the feedstock from which it was produced, *i.e.*, there was no degradation of the constituents during spraying, and the deposition efficiency was identical for all species in the feedstock. It was presumed that the coating was fully dense, *i.e.*, porosity was ignored. The value for the overall density of the material that was worn away was taken as that of the fully dense coating. Implicit in this last assumption is that there is no preferential removal of a particular species during the sliding wear tests.

The results, shown in Fig. 7, reveal that the relative change arising from the presence of the teflon-based material is slightly different when expressed in terms of the volume loss. The best performing WC-10Ni coating containing the teflon-based material had a volume loss approximately 40% lower than that of the base (FC) material. The worst performing coating from this group had a volume loss 80 times greater than the base material. Similar small changes in the relative performance of the series of coatings containing WC-10Co-4Cr as the base material can be observed when the wear is expressed in terms of a volume loss.



(a)

(b)

Fig. 6 Mass loss results for (**a**) the rotors and (**b**) counterfacing stators during 24 h sliding wear tests. The coating compositions are identified by the constituents in the metal matrix and, when present, the volume percent of teflon-based material (TBM). The endpoints of the (error) bars represent the two values from which the average mass loss was determined

Coefficient of Friction. The results of the measurement of torque (converted to coefficient of friction) and temperature for three compositions from the series of coatings involving WC-10Co-4Cr are presented in Fig. 8. These results show that for the WC-10Co-4Co + 7 vol.% teflon-based material composition, which was identified as being optimum for minimizing wear, there are fewer spikes present in the traces (Fig. 8b). It is believed that these spikes are produced due to the presence of debris between the sliding surfaces. For materials exhibiting higher rates of wear, more events occur in which there are momentary increases in torque as a particle of debris passes (and may be momentarily trapped) between the two contacting surfaces.

The results for the average value of the coefficient of friction for each of the coating- stator combinations are shown in Fig. 9. It should be noted that each value was determined by averaging the measurements made during the two runs for each combination. This represents a total of several thousand points for each case. By comparing these results with those presented in Fig. 6, it can be observed that there is no direct correlation between changes in the coefficient of friction and the wear performance. In fact, although the addition of the teflon-based material had a significant effect on the wear rate of both the coating and the counterfacing carbon-graphite material, the effect of this addition on the coefficient of friction for the couples was much less pronounced. As can be seen in Fig. 9 for the three series of coatings, the maximum reduction in the coefficient of friction achieved by adding teflon was in the range of 10 to 15%. This can be observed in the three series by comparing the base cermet coating (WC-10Ni (SPS), WC-10Ni (FC), or WC-10Co-4Cr) with the teflon-based-material-containing coatings in the same series. It is also apparent that the standard deviation associated with these measurements is relatively large. It also should be noted that the coating resulting in the lowest coefficient of friction for a given series of compositions was not necessarily the optimum one for minimizing the mass loss of the components in sliding wear.

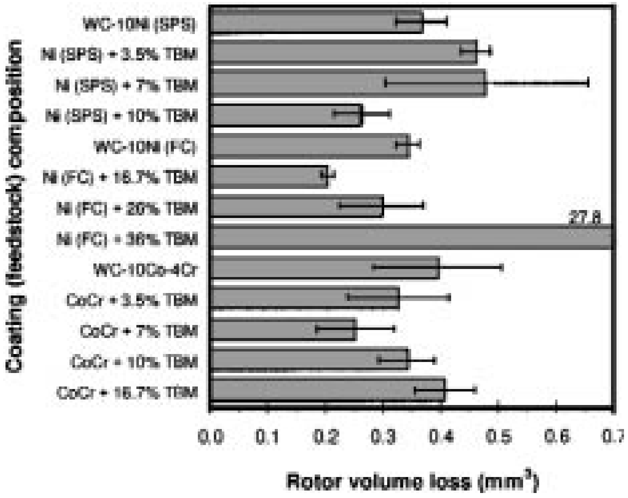
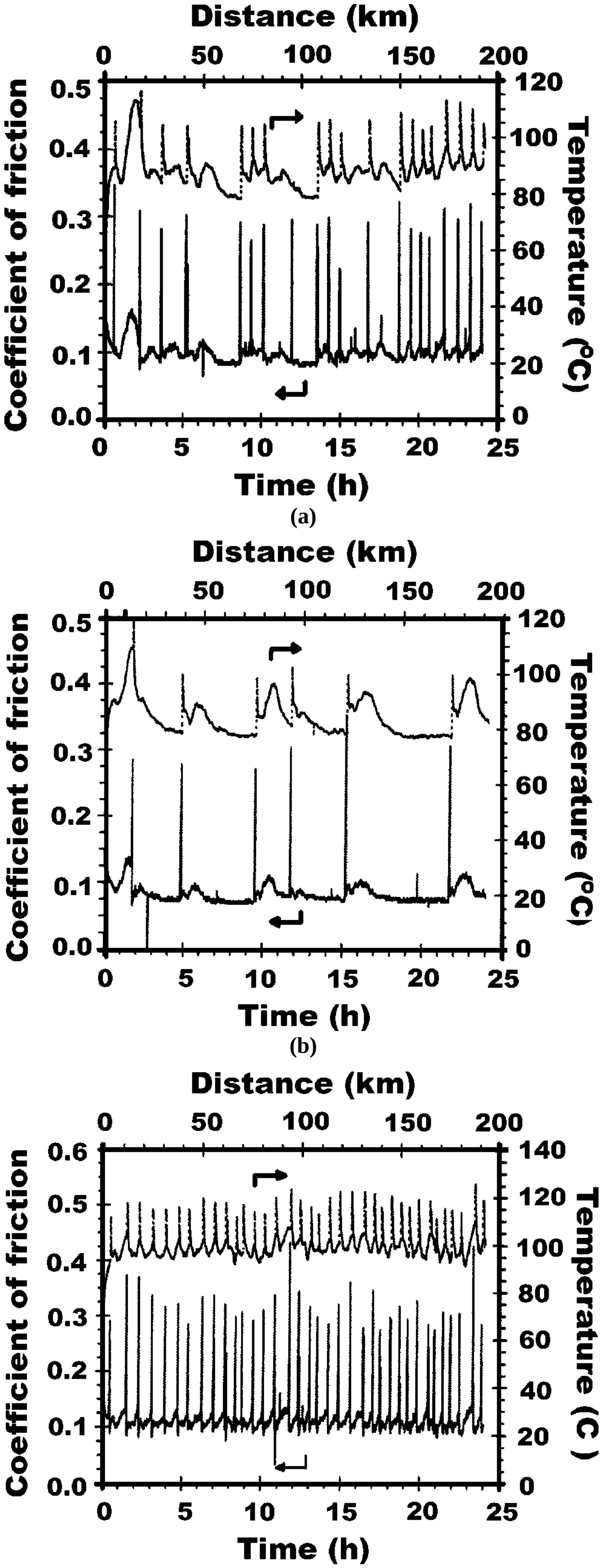


Fig. 7 Calculated volume loss experienced by the coated rotors during 24 h sliding wear tests

Based on these results, it is clear that the explanation for the change in wear resistance with the addition of teflon-based material is more complex than just an effect on the coefficient of friction. It is believed that a combination of several factors gave rise to the effects observed in this study. The addition of the teflon-based material affects the coefficient of friction and produces a composite coating having a lower hardness. It also can affect the bonding or cohesive properties of the coating. Therefore, it is expected when the amount of the teflon-based material in the coating is increased, a level will be reached where the positive effect of teflon as a lubricant will be offset by the negative effects of the reduction in hardness and cohesive strength of the coating. This latter change would result in a less wear-resistant coating from which particles could be more easily removed.

Analysis of Wear Surfaces and Debris. The EDS analysis following the wear tests indicated that the debris was comprised mainly of carbon-graphite in the form of flakes and of constituents found in the mating coating, including grains of WC. Some of the debris generated from the coating was found embedded in the surface of the stators. The presence of this debris would tend to destroy any lubricating layer that might normally form.



(a)

(b)

(c)

Fig. 8 Trace of the coefficient of friction and temperature for wear tests involving coatings produced using feedstocks of (**a**) WC-10Co-4Cr, (**b**) WC-10Co-4Cr + 7 vol.% teflon-based material, and (**c**) WC-10Co-4Cr + 16.7 vol.% teflon-based material

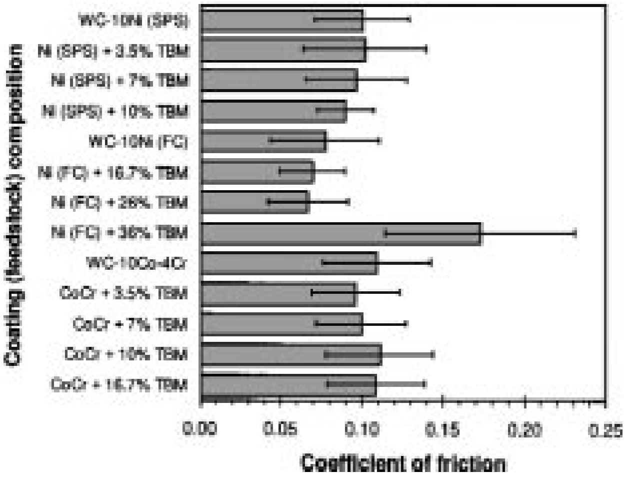
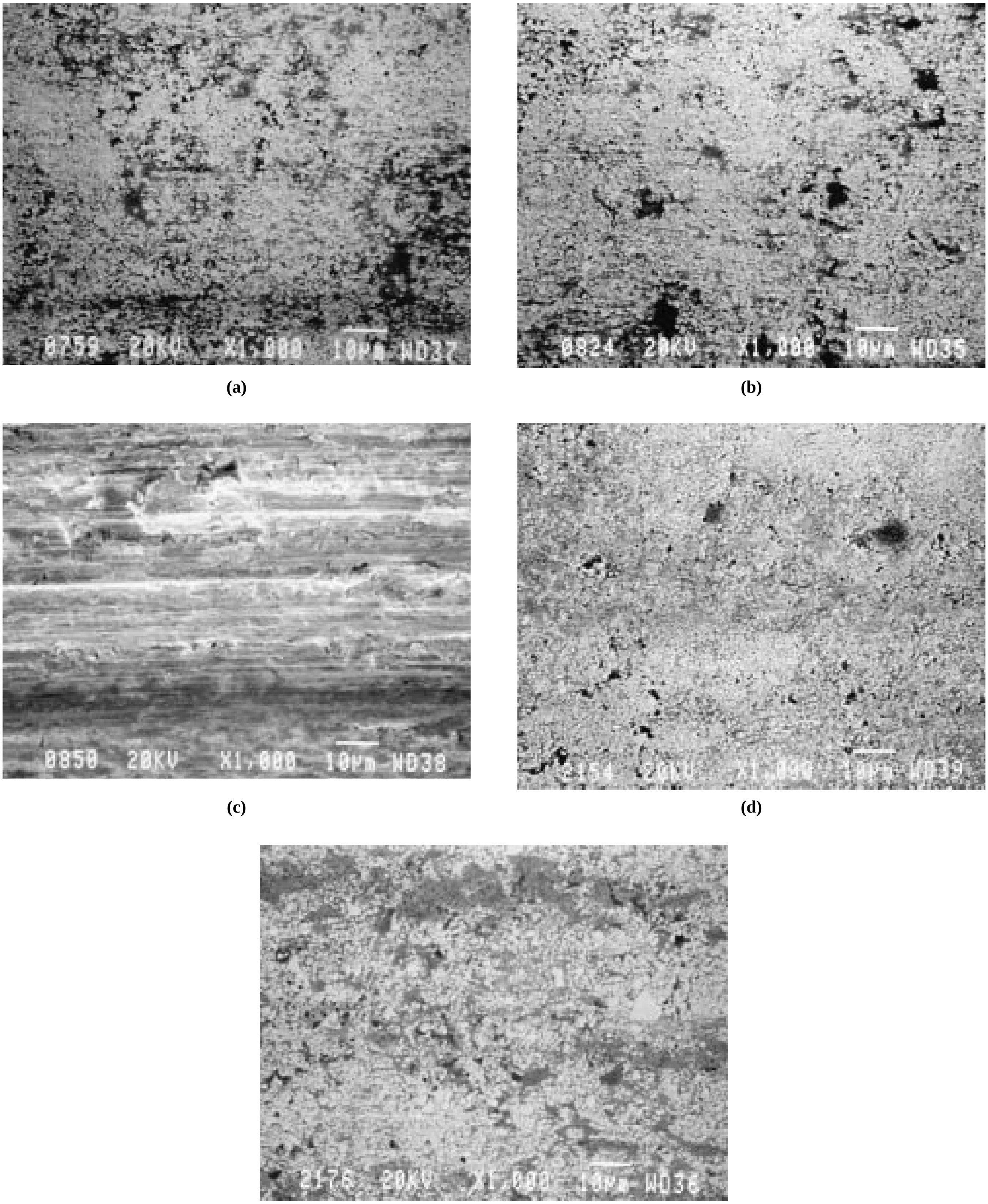


Fig. 9 Coefficient of friction for the various couples identified in Fig. 5

The worn surfaces of several of the rotors are shown in Fig. 10. No direct correlation was found between the surface roughness of the rotors and stators following the wear tests and their performance in sliding wear. For the best performing couples, it was found that the surface roughness of the components following the test was similar to, or less than, that measured prior to testing (less than 0.4 μm (Ra) for the coating and less than 0.7 μm (Ra) for the stator). Observation and analysis of these surfaces did not reveal pronounced differences between the base cermet and the best performing coatings. The results from EDS mapping revealed, as expected, the presence of Mo in the coatings containing the solid lubricant. The analysis to obtain direct evidence of the presence of the polymeric species in these coatings is ongoing. It should be noted that the coating with the highest solid-lubricant content (Fig. 10c) had a much different appearance than the other coatings following the sliding wear tests, exhibiting relatively deep scarring and evidence of a ploughing or gouging activity. This behavior is consistent with the effect of the teflon-based material on the hardness and cohesion of the coating. At high levels of solid lubricant, the constituents of the coating, including the WC grains, could be removed from the coating more easily. As part of the debris, these grains would scar the softer coating as they are dragged between the two sliding surfaces. The best performing coating compositions exhibited little scarring or evidence of grain pull out.

4. Conclusions

Feedstock powders for thermal spraying were produced by blending a solid lubricant material, containing an FEP copolymer, Mo, and thermally insulating oxide ceramics, with a tungsten carbide-based cermet. It was found that the addition of the solid lubricant could have a beneficial effect on the tribological performance of coatings produced by thermal spraying these powders. When tested in sliding contact with stationary carbon-graphite disks, the optimum concentration of teflon-based additive required to minimize wear depended, to some extent, on the nature and composition of the base cermet. Additional work is required to determine the amount of teflon-based material actually



(a) (b) (c) (d) (e)

Fig. 10 Worn surface of coated rotors following the sliding wear tests of couples involving (**a**) WC-10Ni (FC), (**b**) WC-10Ni (FC) + 17 vol.% teflon-based material, (**c**) WC-10Ni (FC) + 36 vol.% teflon-based material, (**d**) WC-10Co-4Cr, and (**e**) WC-10Co-4Cr + 7 vol.% teflon-based material incorporated into the deposited coating. However, in terms of the feedstock composition, it was found that, for WC-10Ni coatings, a concentration of the additive of 10 to 17% by volume in the powder blend used to produce the coating resulted in the lowest mass loss for the couple. For WC-10Co-4Cr, the best performance was obtained for coatings produced from a feedstock containing 7% by volume of the additive. For the best performing compositions, there was an improvement in performance by a factor of approximately 2, as compared to the mass loss experienced by couples involving the base cermet material. These results, showing a significant decrease in wear using engineered coatings produced from feedstocks containing teflon-based solid lubricants, have important implications for the design and lifetime prediction of components employed in applications involving sliding wear.

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