Quantifying Abrasive and Adhesive Wear of Coatings with a Ball on Three Disk Configuration

J.M. Fildes, Ph.D., S.J. Meyers
Institute of Tribology and Coatings, 1020 Air Park Drive, Sugar Grove, Illinois 60554. USA.

R. Kilaparti, Ph.D.
College of Engineering and Engineering Technology
Northern Illinois University, 590 Garden Road, DeKalb, Illinois 60115. USA.

E. Schlepp
The Falex Corporation, 1020 Air Park Drive, Sugar Grove, Illinois 60554. USA.

1. Introduction

Measuring the wear rate of coatings is more challenging than measuring the wear rate of monolithic materials because coatings and substrates can have very different wear rates and the ideal test methodology would be to measure wear of the coating without causing breakthrough and comparing this to wear of the substrate for a similar period of time. In reality, wear tests of coatings are almost never done this way because it requires much trial and error to determine how long the test can run without causing breakthrough of the coating, and many coatings, especially very hard ones, are very thin, which makes it difficult to stop the test before the coating breaks through. In actual practice, the Archard equation has been adapted to address situations where the wear rate is a composite of that of the coating and of the substrate [1].

Studies of the tribology of coatings are typically done with either a metal pin on disk or a metal ball on disk configuration that utilizes an abrasive slurry or paste, and less frequently with a Taber abrader, which utilizes two body abrasion of an abrasive wheels on a rotating disk [2]. None of these test configurations realistically simulates sliding abrasive wear where loose abrasive particles become trapped between two sliding members, one member of which is often softer than the other and is cut as the particles are dragged in the sliding interface. Two body abrasion, such as with the Taber abrader, does not allow the particles to tumble as happened in three body abrasion, and as a result, two body abrasion usually produces wear rates that are substantially higher than are produced by three body abrasion. Three body abrasion with a slurry, such as in the conventional ball crater micro-abrasion test, does not simulate dry sliding abrasion because of the impact of the fluid component and relatively low concentration of particulate content.

A rubber surface sliding against a hard disk is ideal to simulate abrasive particles caught between two sliding surfaces since the abrasive becomes embedded in the rubber surface, which protects the rubber surface from experiencing abrasive wear and which also drags the abrasive over the specimen in a way that provides effective cutting action [3]. This is why the ASTM G65 test is so widely used, but it is a very aggressive test for thin coatings even when lower loads are used and it produces large scars with ragged edges that are difficult to profile.

We have previously reported the development of an improved ball crater micro-abrasion test that uses a ball-on-three-disk (BOTD) configuration with the ball being made from rubber to gain the advantages of both the ASTM G65 abrasion test and the ball crater micro-abrasion test [4]. The inclined BOTD geometry allows the specimens to be totally immersed in dry abrasive. Use of a rubber ball gives effective three-body abrasion and provides results that are highly correlated with the ASTM G65 method, and which provides cutting action that is closer to actual field conditions. The BOTD also provides three replicate measurements from a single trial.

The BOTD test produces scars that violate assumptions that were made to apply the Archard equation to the conventional ball crater micro-abrasion test, and this raises an issue as to how to compute the wear rate for the BOTD test data. Conventional ball crater micro-abrasion test scars have radii that are within a few percent of the radius of the ball. In contrast, the BOTD scars have radii that are substantially larger than the radius of the ball and the radii of the BOTD scars are extremely variable in that more wear resistant materials produce larger radii scars than less wear resistant materials (see reference 4).

The BOTD test also produces a range of scar depths, when measuring a series of materials that span relatively soft to very hard coatings, that is much broader than is encountered in the conventional ball crater micro-abrasion tests. The work reported herein examines the implication of these differences for computing the wear rate with data from the conventional micro-abrasion test and the BOTD test. An alternative development of a wear index for abrasive wear and adhesive wear testing with the BOTD is also described, and this provides significant insight into how the Archard equation functions as a wear index for systems in which there is breakthrough of the coating.

2. Experimental

BOTD abrasion tests were conducted with a 1.27 cm diameter neoprene ball (70 Shore A) and AFS50/70 sand. Tests were conducted on fresh samples for each of 60 RPM and 120 RPM for durations of 180 minutes. The track of the ball in contact with the three pads has a diameter of about 0.74 cm, so the sliding speeds were 0.023 m/sec were 0.046 m/sec, respectively. The sliding distance, S, is given by π * (ball-pad contact diameter) * revolutions per minute * test duration in minutes, and equals 8337 meters for 60 RPM and 16674 meters for 120 RPM. BOTD adhesive wear test were conducted with a 1.27 cm diameter 52100 steel ball, which is a commonly used ball bearing steel with a hardness of 62 to 64 R_c. The rotational speed was 60 RPM (0.023 m/sec) and the test duration was 30 minutes. The sliding distance was 1389.5 meters. The disk was 4140 steel, 34 R_c (335 HV), in all cases. The normal load of the ball on each of the three specimen disks was 0.34Kgf (3.34 N). All tests were conducted at ambient temperature. Two thicknesses of titanium aluminum nitride (TiAlN), which were fabricated by the same process, were examined along with uncoated 4140. The properties are shown in Table 1.

Composition	Thickness, um	Application Method	Process Temperature, C	Service Temperature, C	Hardness, HV	Coefficient of Friction	Thickness, um	Density, gms/cc
4140					335			7.8
TiAlN	2.49	PVD	250	900	3300	0.35	2.49	4
TiAlN	5.07	PVD	250	900	3400	0.35	5.07	4

Table 1 - Test Specimens

3. Theory

The typical way to measure the abrasion resistance of coatings and to compute a wear index with a ball on disk test is described by Rutherford and Hutchings [5]. The test involves using a ball on disk configuration with abrasive slurry and measuring the diameter of the wear crater, as a function of the sliding distance. The wear rate for a monolithic material is given by:

$$S * N = \frac{V}{k}$$

Equation 1

where S is the sliding distance, N is the applied load, V is the volume of material removed, and k is the wear rate. A plot of V against $S*N$ should be linear and have a slope of k. The wear rate will have units of volume / (sliding distance * load), which will typically be $mm^3/(mm\ N)$.

Measuring the wear rate of coatings is more challenging because coatings and substrates can have very different wear rates and wear test often cause breakthrough of the coating, which provides a wear rate that is a composite of that of the coating and of the substrate. In this case:

$$S * N = \frac{V_c}{k_c} + \frac{V_s}{k_s}$$

Equation 2

where the subscripts c and s denote the coating and substrate. When the scars are spherical, approximations of the volume of the coating and the volume of the scar can be substituted into equation 2 to obtain equation 3 from which the wear rates of the coating and the substrate are computed.

$$\frac{S * N}{b^4} = \left(\frac{k_s - k_c}{k_s * k_c}\right) * \left(\frac{\pi * t}{4b^2} - \frac{\pi * R * t^2}{b^4}\right) + \left(\frac{1}{k_s}\right) * \left(\frac{\pi}{64 * R}\right)$$

Equation 3

For equation 3, b is the scar diameter, t is the coating thickness, and R is the ball's radius. A plot of (SN/b^4) against $(\pi t/4b^2 - Rt^2/b^4)$ should provide a straight line. The value of k_s can be extracted from the intercept, and k_c can be extracted from the slope and the value of k_s.

Measuring the wear scar for several sliding distances for each material and using this data to compute the wear rate parameter for the coating, k_c, as described by equation 3, is not only time consuming, but is impractical for the BOTD abrasion test since the specimens are contained in a holder that is flooded with dry abrasive and removing the specimens and placing them back in the holder causes a substantially different amount of wear than running the test without interpretation. The BOTD test therefore requires a wear rate computation methodology that uses the wear only at a single point at the end of the test.

An equivalent procedure to that stated above for using a single point in time to measure the wear is to use Equation 1 to compute the wear rate of the steel substrate, k_s, from the scar volume of the uncoated 4140 trials. Equation 1 is also used to compute the wear rate of the coatings, k_c, where breakthrough did not occur in the test. When breakthrough did occur, the wear rate of the coatings is computed from a rearrangement of equation 2:

$$k_c = \frac{V_c}{S * N - \frac{V_{obs} - V_c}{k_s}}$$

Equation 4

where V_{obs} is the observed volume of the scar for the coating test and $V_{obs} - V_c$ provides an estimate of the volume contributed by the substrate to the observed scar. V_c is given by Equation 5:

$$V_c = \pi * t * \left(\frac{b^2}{4} - R * t\right)$$

Equation 5

where t is the thickness of the coating, b is the width of the wear scar, and R is the radius of the ball. For equations 1 and 5, the sliding distance S is given by the diameter of the wear scar on the ball times the revolutions per minute time the test duration, and N is the load on each disk.

4. Results

Figure 1 provides the scar volumes for the BOTD abrasion and adhesion tests for the two different thicknesses of TiAlN. Only the scar volumes are shown because the BOTD scar volumes and mass losses are highly correlated. For example, the R2 values are 0.99 for the abrasion tests at 60 RPM and 120 RPM.

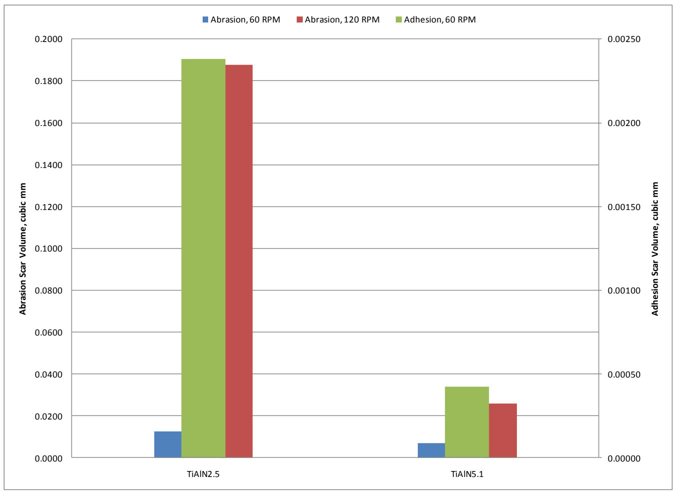

Figure 1 - BOTD Abrasion and Adhesion Test Results

The data in this figure demonstrate the inadequacy of mass loss or scar volume to be used as a metric of relative wear rates for a test scenario where all coatings are subjected to the same sliding distance. The inability of mass loss or scar volume to account for the different sliding distances of the 60 RPM and 120 RPM abrasion test is clearly shown as is the inability of mass loss and scar volume to accommodate thicknesses differences. This inadequacy occurs because the coating thickness varies for the various specimens of the same material and the test causes breakthrough of the coating in some case, but not in others as can be seen by comparing the scar depths to the coating thickness in Table 2.

Name	Composition	Coating Thickness, um	60 RPM Abrasion			120 RPM Abrasion			Adhesion		
			Scar Depth, um	Scar Width, mm	Scar Volume, mm^3	Scar Depth, um	Scar Width, mm	Scar Volume, mm^3	Scar Depth, um	Scar Width, mm	Scar Volume, mm^3
4140	4140		101.4236	4.087	0.6658	151.36372	4.240	1.07380	17.508	0.957	0.00631
Futura	TiAlN	2.49	10.4246	2.289	0.0123	81.35938	2.411	0.18768	10.139	0.772	0.00238
Lumena	TiAlN	5.07	2.5135	2.635	0.0069	6.74688	3.116	0.02573	5.435	0.437	0.00042

Table 2 - Wear Scar Dimensions

To overcome the problem with mass loss and scar volume as metrics of wear, we computed the wear rate from each test result using the approach described above for equation 4. The results are shown in Figure 2, from which it is seen that the volume-based wear rates do not provide equivalent wear rates as would be expected for: (a) the 60 and 120 RPM abrasion test results; (b) the two TiAlN thicknesses in the 60 RPM abrasion test and in the 120 RPM abrasion test; and (c) the two thicknesses of TiAlN in the adhesion test. The wear rates for all four abrasion test should have been equal, and the wear rate for the two adhesion tests should have been equal. In other words, the wear rate computation approach that is usually used in conventional ball on disk micro-abrasion test studies does not work for the BOTD results reported herein.

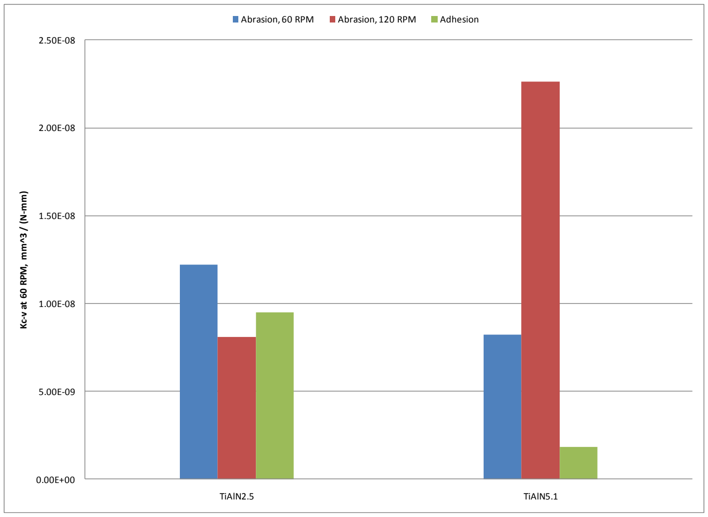

Figure 2 - Wear Rates Based on Scar Volumes

5. Discussion

The historical use of scar volume to compute a wear index is attractive because the scar volume can be obtained from easily made mass loss measurements. Nonetheless, scar volume is a linear function of wear in ball on disk tests only over modest amounts of wear. Common sense as well as a critical analysis of the literature indicates that it is the depth of wear of a coating that is linearly proportional to sliding distance regardless of the geometry of the scar as long as contact stress is not a factor [6]. Although the BOTD tests reported herein are not constant pressure tests, the abrasion test contact stress are very low and therefore are essentially constant, and the contact stresses for the adhesion test decline rapidly for the first few microns of wear and beyond this scar depth the contact stresses are less than is reported in the literature to make a difference in the wear rate [7].

The reason for the failure of the wear rate computation process described above for equation 4 is that the BOTD test specimens included relatively soft materials and very hard materials, so the observed wear scars cover a large range of volumes, and this violates an assumption that is implicit in using volume to compute the wear index as embodied in equations 1 and 2 in that the scar volume is assumed to be a linear function of the sliding distance (or extent of wear). In reality, the scar depth is a linear function of the sliding distance and, in the case of a spherical scar, the volume is a linear function of the sliding distance (or scar depth) only for modest amounts of wear (or a modest range of volumes).
This can be seen by examining the geometry of a sphere. A spherical wear scar defines a small circle of a sphere, for example the circle defined by the plane *K'C'A'* in Figure 3. For simplicity, only the circular cross section that occurs at the apex of the spherical scar needs to be considered, as is shown on the right in Figure 3. The width of the scar is w, the depth is *d*, and the radius is *r*.

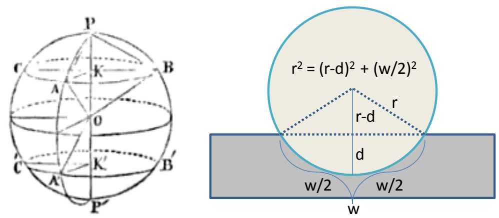

Figure 3 - Solid Geometry of a Spherical Scar

The relationship shown in Figure 3 can be used to establish that the scar volume for a spherical scar is related to the depth of the scar by:

$$V = \pi * d^2 * \left[r - \frac{d}{3}\right]$$

Equation 6

In other words, the scar volume varies as the square of the scar depth as is shown in Figure 4 for two different ball diameters. The range of scar depths in Figure 4 is what was observed in the BOTD tests reported herein. Although the scar volume or mass loss is a linear function of the extent of wear over a narrow range of scar volumes, which is why equation 3 works in studies reported in the literature, the scar depths in the BOTD studies reported herein (Table 2 above) cover too large of a range for this to be the case.

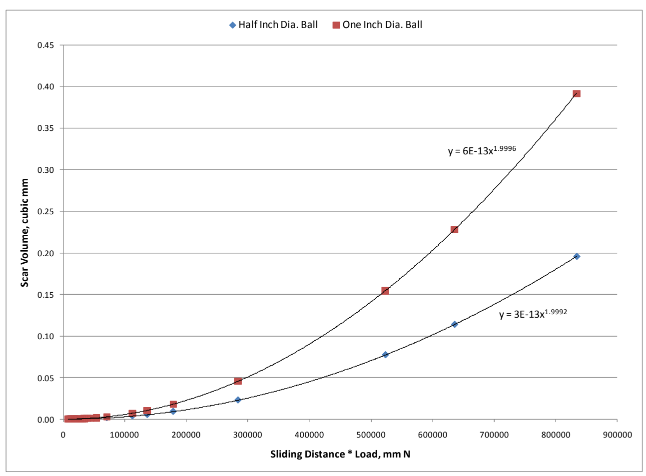

Figure 4 - Scar Volume vs. Sliding Distance * Load (3.336 N)

This analysis suggests that the wear rate index for the BOTD tests reported herein should be based on scar depth rather than on scar volume. Paralleling the development of equations 1 through 3, the wear rate of a monolithic material, be it the uncoated substrate or a coating for which breakthrough does not occur during the test, is given by:

$$S * N = \frac{d_{obs}}{k}$$

Equation 7

where d_{obs} is the scar depth. In this case, the units of the wear rate k are mm / N mm. For a coated substrate where breakthrough occurs in the test, the wear rates of the substrate and coating are related to the scar depth by:

$$S * N = \frac{t}{k_c} + \frac{d_s}{k_s}$$
Equation 8

where t is the thickness of the coating and d_s is the depth of the scar in only the substrate. Equation 8 can be rearranged and (d_{obs}-t) substituted for d_s to give the coating wear rate:

$$k_c = \frac{t}{S * N - \frac{d_{obs} - t}{k_s}}$$
Equation 9

The BOTD results were reanalyzed by using equation 7 for computing the wear rate for uncoated 4140 and for coated specimens where breakthrough did not occur and using equation 9 when breakthrough did occur. The results are shown in Figure 5. Comparing Figure 5, which is based on scar depth, to Figure 3, which is based on scar volume, shows that basing the wear rate on scar depth produces results that make more sense.

All four wear rates for TiAlN (for the abrasion test at 60 RPM and 120 RPM for the two thicknesses) are equivalent, and the two wear rates for the two thicknesses of TiAlN in the adhesion test are close in value with about a 15% difference. Of special significance is the fact that the TiAlN wear rate for the 60 RPM abrasion tests did not produce breakthrough, so this wear rate is a direct measure of the intrinsic wear rate for TiAlN, whereas the other three values come from tests where different amount of breakthrough (spanning a small amount to a significant amount) occurred (see Table 2) and for which the wear rate of the substrate has to be eliminated.

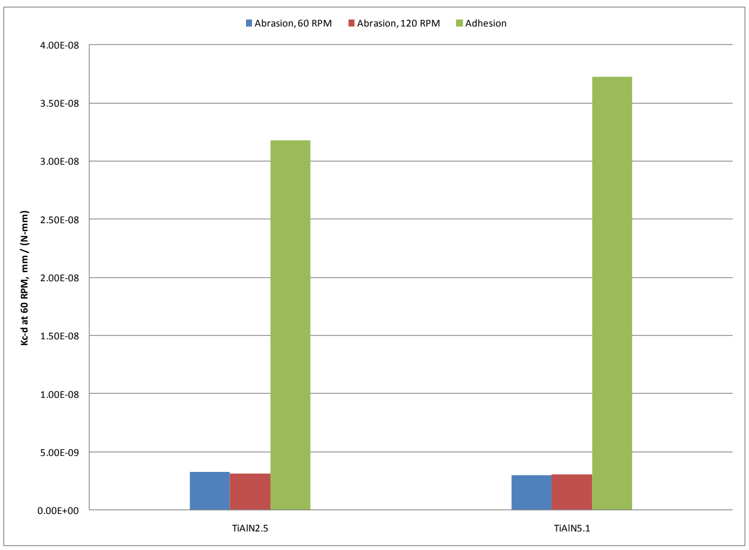

Figure 5 - Wear Index Based on Scar Depth

The coating wear rate as expressed by equation 9 can be derived in another manner that provides insight as to the nature of the wear rate and also allows the validity of the wear rate to be experimentally confirmed. When breakthrough occurs, the observed amount of wear in the test, W, is given by the following equation where f is the fraction of the test sliding distance, S, to breakthrough of the coating:

$$W = f * k_c + (1 - f) * k_s$$
Equation 10

It is well know that the wear rate of coated metal cutting tools remains low for some period after the coating is visibly worn through, so in actuality, this equation should probably contain a third term, which has been ignored here, for the wear rate that exists for some time after breakthrough occurs, which is a mix of the coating and substrate wear rates.

We can estimate the fraction, f, of the test duration to coating breakthrough in the BOTD abrasion test from the ratio of the coating thickness to the scar depth. The basis for this is Taylor's law, which is well established and which describes wear as a brief period of relatively high wear during break-in, followed by a long period of uniform wear at a low or modest rate, leading to a brief period during which the wear rate increases exponentially and rapidly leads to failure, Figure 6.

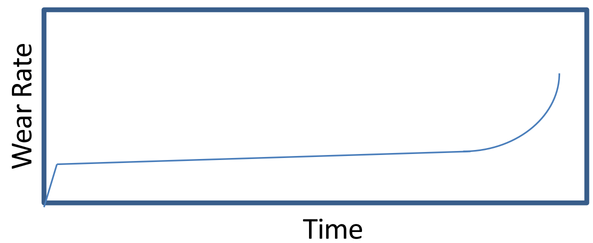

Figure 6: Taylor's Wear Law

The value of f in the BOTD abrasion test is computed in the cases where the coating did not breakthrough from the coating thickness t and the observed scar depth d_{obs} by:

$$f = \frac{t}{d_{obs}}$$
Equation 11

in which case the ratio will be greater than one, indicating that a longer test would have been required to reach breakthrough. In the case where coating breakthrough did occur, f is computed using:

$$f = 1 - \frac{d_{obs} - t}{d_{4140}}$$
Equation 12

where d_{4140} is the scar depth for the uncoated 4140 substrate for the same test conditions. The wear rate is obtained from:

$$k'_c = \frac{t}{f * S * N}$$
Equation 13

As expected, the values obtained for k_c' from equation 13 using the scar data in Table 2 are exactly the same as the values obtained for k_c from equation 9 and reported in Figure 5. This shows that the wear rate index, k, that is widely reported in the literature is the thickness of the coating divided by the fraction of the test sliding distance to breakthrough, which is not an obvious interpretation from equation 9.

A wear rate based on scar depth such as in Equations 7 and 8 rather than on volume has an additional advantage in that only the depth of the wear scar needs to be measured. More importantly, the approach embodied by Equation 10 provides a way to validate the wear rate index if the fraction of the test sliding distance to coating breakthrough can be detected by some means.

We have found that measuring friction during the adhesion test sometimes provides an indication of when breakthrough occurs. This appears to happen when breakthrough of the coating involves delamination, in which case the friction rises substantially during breakthrough and then returns to the lower value it had prior to breakthrough. The rise and fall of the friction occur over a fairly narrow time duration. We have found that the time at which the friction returns to the lower value that existed prior to breakthrough provides an estimate of the fraction of the sliding distance for coating breakthrough that corresponds well with the fraction computed from Equation 12. Table 3 provides the comparison for three different coatings that span a wide range of hardness, scar depths, wear rates, and fractions of the test sliding distance to breakthrough.

Coating	Thickness, um	Scar Depth, um	Eq. 12 Fraction of Test Sliding Distance to Coating Breakthrough	Friction-Based Fraction of Test Sliding Distance to Coating Breakthrough
DiaCr10	1	18.1	0.024	0.036
MnP	8.9	18.8	0.434	0.444
TiAlNLF	4.15	12.33	0.533	0.521

Table 3 - Fraction of Sliding Distance to Coating Breakthrough

The fact that wear rate of the coated test specimen returns to the wear rate of the steel substrate at the end of coating breakthrough rather than at the beginning is consistent with the well established observation that the wear rate of coated metal cutting tools remains low for some time after the coating is visibly worn through.

6. Conclusions

The scar volume (or mass loss) based wear rate index that is commonly described in the literature for the ball crater micro abrasion tests with abrasive slurry is appropriate only over a modest range of scar volumes where the volume is a linear function of the sliding distance. For larger ranges of scar volumes such as are encountered in testing relatively soft as well as very hard coatings, a volume-based wear index does not provide results that would be expected for different thicknesses of the same coating, or for changes in the sliding distance. In this case, the wear index needs to be based on the depth of the scar rather than the scar volume, which is also more consistent with the theory from which the wear index was developed. We have developed a depth-based wear index that is similar to the commonly used volume-based one, and we have shown that it provides results that would be expected for different thicknesses of the same coating, and for changes in the sliding distance.

We also used an alternate approach to derive this wear index that shows that the index is the thickness of the coating divided by the fraction of the test sliding distance to breakthrough. Since this approach explicitly provides the fraction of the test time to coating breakthrough, the predictions can be tested by detecting coating breakthrough by another means. We found that monitoring the friction during the adhesion test sometimes identified when coating breakthrough occurred, and in these cases, which covered breakthroughs early in the test through late in the test, excellent agreement was observed between the computed and friction-based times to breakthrough.

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