JTTEE5 2:363-368

Characterization of Wear Damage in Coatings by Optical Profilometry

S. Dallaire, M. Dufour, and B. Gauthier

The accurate determination of the volume loss of plasma-sprayed coatings submitted to abrasive and erosive wear and the visualization of wear track or crater profiles are of major concern when ranking coatings, developing wear-resistant coatings, or identifying the mechanism responsible for failure. The determination of the volume loss by liquid displacement measurements is impractical when the size of coated pieces is large and the volume loss is small. For evaluating coating damage and directly measuring the volume loss, a three-dimensional surface mapping method is proposed. The three-dimensional image of the worn surface is obtained by a laser triangulation method. The experimental setup is basically composed of an illuminating source and a detecting device. The light source is focused on the sample surface, and the reflected light is then collected on a network of charge couple detectors linked to a computer. Because the spot location on the network is a direct function of the measured height, a three-dimensional image can be obtained after scanning the entire damaged surface so that the volume loss can be calculated easily. Intensity-coded depth images of the worn surface and computerized cross sections of the damaged area can also be obtained. Inspection of coatings damaged by abrasion wear or slurry erosion by optical profilometry reveals that the volume loss measurements by this technique are very accurate as opposed to the volume measured by liquid displacement methods or calculated from weight loss measurements. Moreover, intensity-coded depth images of worn surfaces and computerized cross sections of damaged areas provide relevant information about the coating performance or defects resulting from the deposition process.

1. Introduction

WEAR damage in coatings can be inspected by means of reflected light or scanning electron microscopy (SEM) and electron microprobe analysis. These techniques provide useful information on the formation of scars (abrasive wear) or craters (erosive wear) and the chemical composition of materials found on worn surfaces. Microscopy is an observation technique that is difficult to adapt to obtain quantitative results even when using advanced image analysis software.

Standardized wear test methods such as those described by ASTM[1-3] recommend reporting wear loss as a volume loss. This requires accurate measurements of the dimensions of scars, volume determination by liquid displacement methods, or knowledge of the density of the coatings. However, dimensions of wear scars are not easy to measure accurately, and the volume determination by liquid displacement measurements is inaccurate when the required volume is small and the specimen is large. Porous coatings also need to be sealed before measurement, making the interpretation of results troublesome. Moreover, the density of a coating usually is determined using published experimental data for dense materials. Corrections for coating porosity are thought not to improve the accuracy of density measurements.

Key Words: abrasive wear, contour mapping, erosive wear (slurry), optical profilometry, three-dimensional surface mapping, volume loss, wear damage

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Many spray powders are composite, contain different crystallographic phases, and undergo phase transformations and oxidation upon spraying. Co-sprayed powders could result in nonhomogeneous coatings, the actual composition of which is different from that of the starting material. This complicates determination of the density of coatings, which is required for converting a weight loss into a volume loss.

For evaluating coating damage and directly measuring the volume loss according to a particular wear test, a three-dimensional surface mapping technique is proposed. In addition to contour mapping damage within coatings, this technique allows determination of volume loss and provides relevant information for developing wear-resistant coatings.

2. Experimental Procedure

2.1 *Optical Three-Dimensional Mapping Profilometer*

Three-dimensional surface mapping has been used previously for coating failure analysis of hard coatings submitted to scratch and wear tests.[4] Mapping was performed by means of a stylus profilometer in conjunction with an X-Y displacement stage controlled by a computer. This setup is appropriate for measuring damage with depths of less than 10 μm and therefore is convenient for slightly damaged thin coatings. However, larger scale damage usually is found within thick thermal spray coatings during wear testing, and thus another measurement method is required.

Basically, the optical three-dimensional mapping profilometer is composed of three components: a laser range sensor, a servo-controlled X-Y displacement system, and a computer for data acquisition and analysis of results. The laser range sensor was designed for measuring the heights on a sample surface in

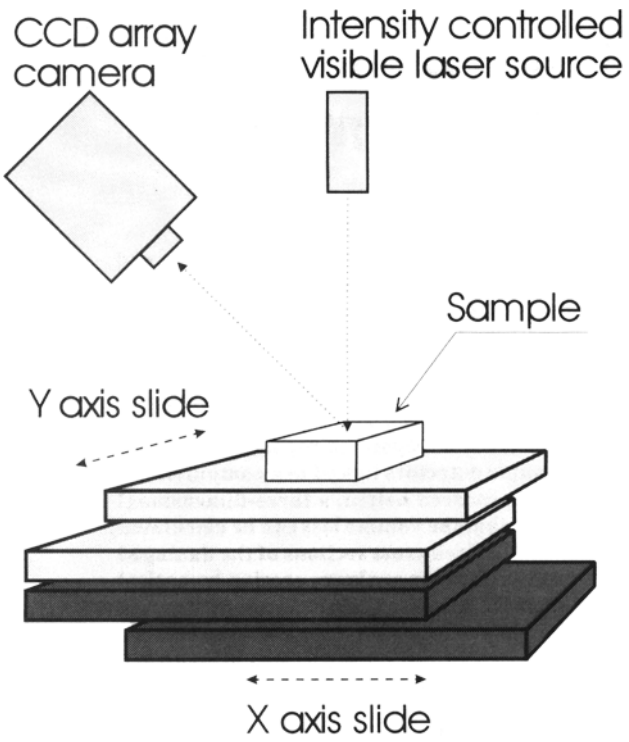

Fig. 1 Optical-mechanical arrangement of the inspection system for measuring three-dimensional surface geometry.

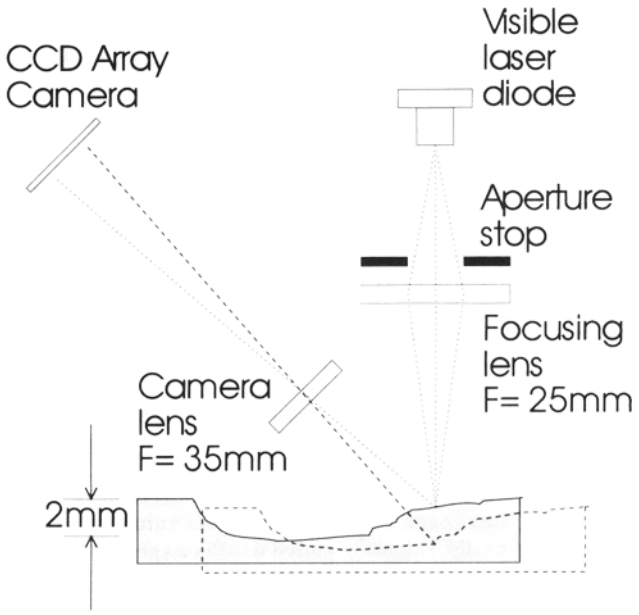

Fig. 2 Optical arrangement of the laser range sensor.

one single location of that surface for a defined period of time. As shown in Fig. 1, a laser diode source projects visible light at one point of the surface along a direction perpendicular to the surface. A charge-coupled device (CCD) camera collects the light scattered by the surface along a direction 45° away from the lighting direction. The complete surface of the sample is scanned using an *X-Y* displacement system composed of two motor-driven linear displacement slides. For the type of surfaces considered, the scanning displacement step and speed were adjusted to perform and store one measurement per 100 × 100 μm area of surface cells. An improved accuracy would require 25 × 25 μm surface cells at the expense of a 16-fold increase in scanning time.

Height measurements are calculated with the triangulation method (Fig. 2). The laser source projects a 50-μm diameter light spot normally to the examined surface. The light scattered 45° away from the laser light direction is collected by a camera lens that produces an image of the laser spot on the surface of the camera imaging plane. The location of the laser spot image on the detector plane changes along the path of a straight line proportionally with the surface height. After measuring the laser spot image location on the detector surface, the surface height can be calculated using simple trigonometric equations. For an irregularly worn surface, height resolution greater than 5 μm, within a 2-mm range, is achieved by assuming that the laser focuses on a flat surface.

In the present work, a two-dimensional camera and a frame digitizing board were used instead of a CCD array. Only a small portion of the grabbed images where the laser spot is expected to be found is analyzed. The camera was oriented in such a way that the laser spot image moves up and down the screen. The line index of the spot position within the grabbed image is digitally stored. Note that the line index is not affected by the video synchronization jitter.

The laser light intensity is controlled electronically during the measurement process to compensate for the large reflectivity variations due to rough metallic surfaces. The aperture stop size is fixed and used to correct the laser beam astigmatism and to adjust the projected laser spot diameter. Volumes of defects on a coating can be easily computed and three-dimensional pictures of the scanned surface can be produced with imaging software.

2.2 *Abrasion Wear Testing*

The abrasion wear resistance of sprayed coatings was measured in accordance with the "Dry Sand/Rubber Wheel Abrasion Test," (ASTM G65).[2] This testing method has four recommended procedures that can be used depending on the specific wear resistance of coatings and their thicknesses. Procedures A and B (as described below) were used to evaluate the wear resistance of plasma-sprayed coatings and arc-sprayed coatings, respectively. The measurement method consists of abrading a specimen with a grit of controlled size and composition. A force of 130 N maintained the specimen against the rubber-coated rotating wheel. Quartz sand (50/70 mesh) (300 μm/212 μm) was introduced between the specimen and the wheel at a flow rate of 4 to 6 g/s. The wheel rotates in the same direction as the flow of sand. In Procedure A, the test ended after 6000 revolutions, whereas in Procedure B it ended after 2000 revolutions. Wear is usually reported as a volume loss.

2.3 *Slurry Erosion Testing*

Slurry erosion tests were also carried out on sprayed coatings to evaluate the capability of the optical profilometer. These tests were performed using an in-house apparatus consisting of an air-powered double-diaphragm slurry pump. The recirculating slurry, consisting of filtered tap water with grade 55 grit (270

Table 1 Volume Loss due to Abrasion Wear Measured by Water Displacement and Optical Profilometer Methods

Coating	Volume loss, mm^3 Water displacement	Optical profilometer	difference, mm^3
WC-Co.....	13.0 ± 5%	12.5 ± 1%	0.5
TiB_2-Ni-Fe...	13.5 ± 5%	11.5 ± 1%	2.0
Fe-TiB_2.....	23.5 ± 5%	25.1 ± 1%	1.6

μm) silica particles, was pumped from a tank and forced to impinge on the test surface. The velocity of the slurry was measured to be 18 ms^{-1} with an electromagnetic flowmeter. Because the concentration of silica was high, it was assumed that the velocity of the eroding medium was equal to the velocity of the slurry jet. All samples were maintained at 90° and exposed for 300 and 900 s. The samples were weighed before and after the erosion test, and the volume loss was measured by optical profilometry.

2.4 *Tested Coatings*

The coatings that were submitted to the abrasion wear test were high-energy plasma-sprayed WC-Co coatings deposited following recommended spray parameters, plasma-sprayed TiB_2-Ni-Fe and Fe-TiB_2 coatings described earlier,[5-7] and arc-sprayed stainless steel/TiB_2 coatings currently under development.[8] The TiC-Fe coatings manufactured for sliding wear resistance applications[9-11] were slurry erosion tested.

3. Results and Discussion

3.1 *Accuracy of Measurement*

The optical profilometer was first calibrated to perform measurements in 3-mm deep cavities. The accuracy of the apparatus was determined after measuring the volume of a slot of known dimensions machined in a mandrel. The difference between these measured volumes was lower than 0.7%.

3.2 *Volume Loss Comparison: Liquid Displacement versus Optical Profilometer Methods*

The volume loss of WC-Co (82 vol% WC), TiB_2-Ni-Fe (60 vol% TiB_2), and Fe-TiB_2 (45 vol% TiB_2) plasma-sprayed coatings submitted to the abrasion wear test (ASTM G 65-91, procedure A) were measured by both the water displacement and optical profilometer methods (Table 1). Depending on the type of coating, the difference in volume loss can reach 15%. This difference probably arises from inaccuracies in measuring the difference in volume before and after the wear test by the water displacement technique. Indeed this technique is particularly sensitive to weighing measurements because it requires at least three measurements. Moreover, measurement errors can be introduced because of gas adsorption on worn coating surfaces and coating porosity. This could result in over- or underestimation of the volume wear loss.

3.3 *Contour Mapping of Abrasion Wear Damages*

Examination of wear damage in coatings can be performed with the help of intensity-coded depth images, the darkness being directly related to the defect depth. Figure 3(a) shows the representation in gray tones of the wear track formed on the surface of a TiB_2-Ni-Fe coating. The wear track is slightly darker than the surface coating, and a small black spot can be observed along line B. A computerized cross section along line A (Fig. 3b) reveals that the coating is evenly worn, whereas along line B (Fig. 3c) an abyss is observed. This defect most likely results from a large particle that was incorporated within the coating during the spraying process. This large particle was composed of many individual spray particles that agglomerated and stuck to the powder injection tube and thereafter was carried toward the substrate.

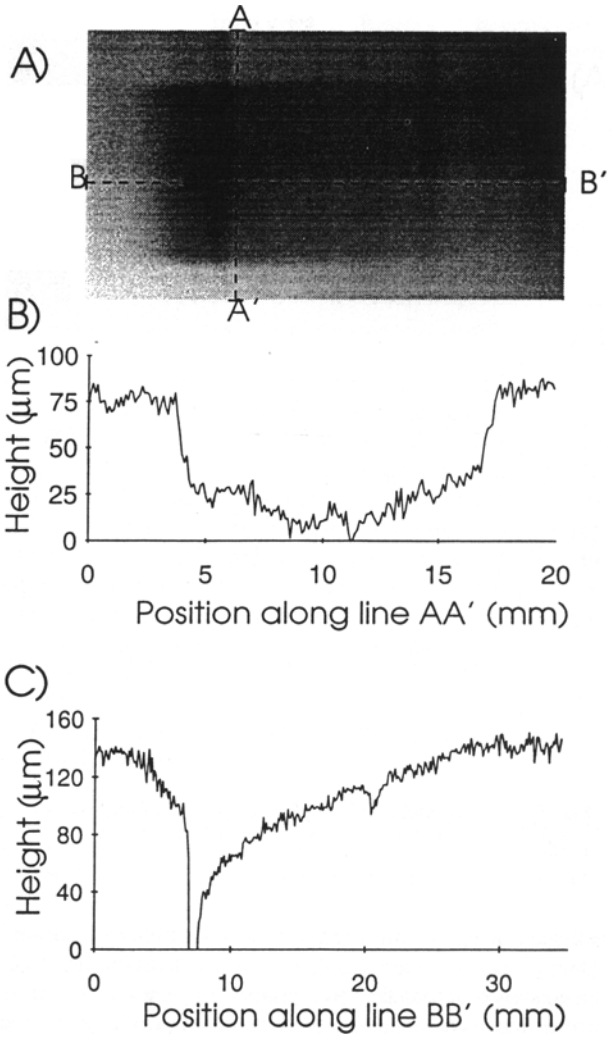

Fig. 3 Worn surface of a TiB2-Ni-Fe coating. (a) Intensity-coded depth image and computerized cross sections along lines A-A′ (b) and B-B′ (c).

Other defects can be observed on worn coating surfaces. Figure 4 shows the intensity-coded depth image and the computer-

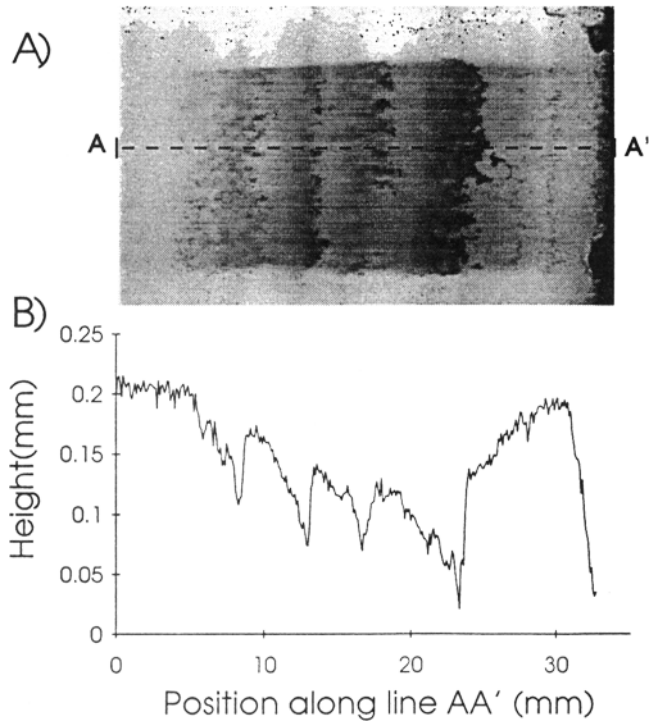

Fig. 4 Worn surface of a Fe-TiB_2 coating. (a) Intensity-coded depth image and (b) computerized cross section along line A-A′.

ized cross section along the wear track of a Fe-TiB_2 coating. The coating experienced more damage in some locations. Because the spacing between the more prominent wear damaged regions is even and corresponds to the step size between each spray pass, these defects resulted from divergent sprayed particles. The particles rebounded from the plasma stream because of their large size and light density. Such divergent particles, being incompletely melted and nonhomogeneous in composition, form weaker zones in sprayed coatings, as shown in Fig. 4. The optical profilometer measurements indicated that a 25% improvement in wear performance could be obtained after eliminating these large defects.

The optical profilometry studies of a stainless steel/TiB_2 coating obtained by arc spraying reactive core wires also provide useful information about the microstructure of these coatings and their degradation mechanism. Figure 5 shows the intensity-coded depth image and two computerized cross sections performed at 90° on the white spot that is shown in Fig. 5(a). This coating underwent ASTM G65-91 procedure B abrasion wear testing. The white spot corresponds to a coating zone that has been abraded to a lesser degree by the silica sand. The wear track exhibits the same feature in different measurement orientations. These wear-resistant areas are large droplets containing TiB_2 from the core of the wire, which were embedded in the less resistant stainless steel matrix. The silica sand preferentially erodes the matrix around such hard features, thus loosening them.

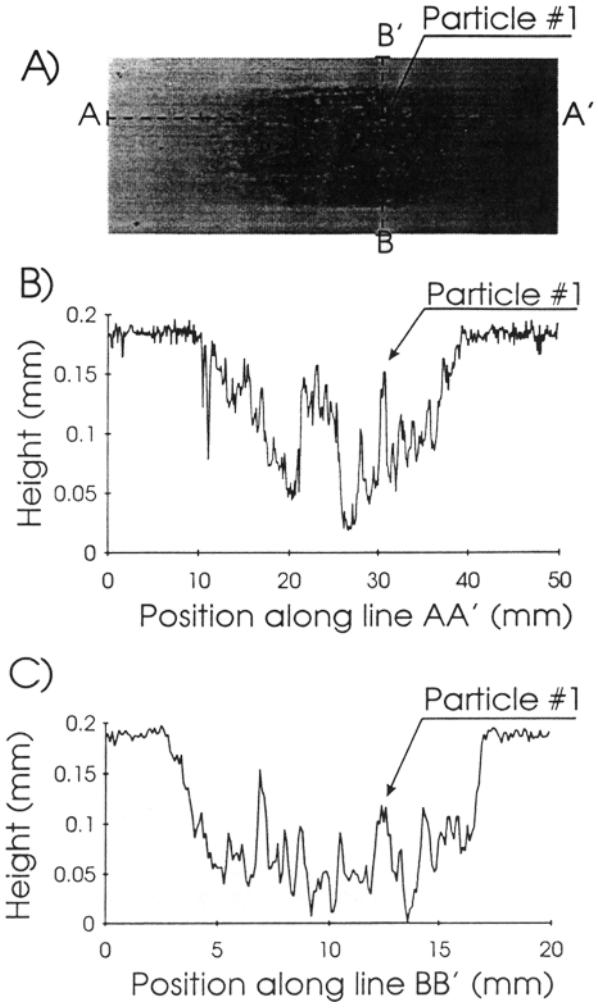

Fig. 5 Worn surface of an arc-sprayed stainless steel/TiB_2 coating. (a) Intensity-coded depth image and computerized cross sections along lines A-A′ (b) and B-B′ (c).

3.4 *Contour Mapping of Slurry Erosion Tested Coatings*

The volume loss of TiC/steel coatings eroded in the slurry erosion test described above were also evaluated with the optical profilometer. Figure 6 shows the intensity-coded depth image and the computerized cross section along the line A-A′ of the damaged surface of a TiC-Fe coating (60 vol% TiC). The crater formed within this coating is typical of materials undergoing this erosion test; for example, all of the TiC-Fe coatings tested exhibited the same feature.

3.5 *Volume Loss and Weight Loss Comparison*

The weight and volume losses due to slurry erosion after 300 and 900 s for different TiC-Fe coatings are reported in Table 2. These coatings, which are resistant to sliding wear, are not much

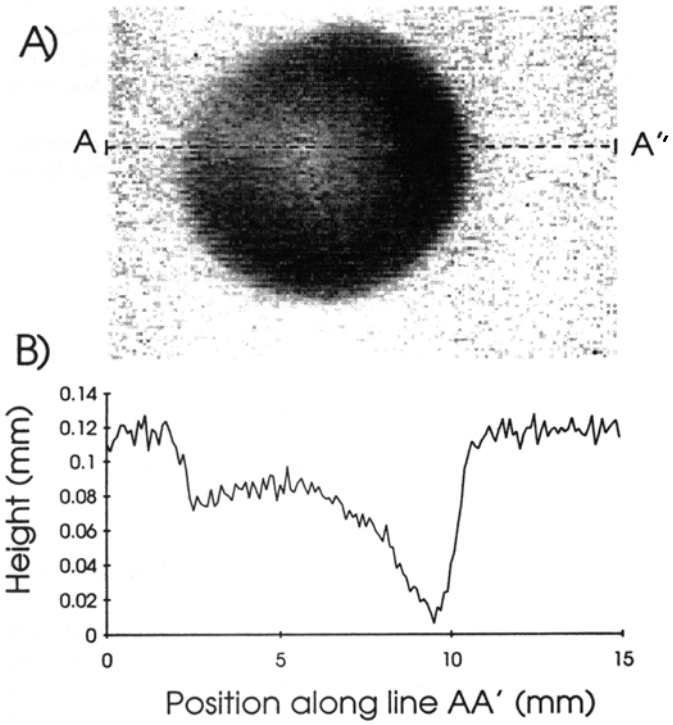

Fig. 6 TiC-Fe coating exposed to the slurry erosion test. (a) Intensity-coded depth image of the surface. (b) Computerized cross section along line A-A'.

more resistant than steel to hard particle erosion. However, they were selected in this study because they demonstrate the typical difficulty of converting weight loss into volume loss. Indeed, the density of these coatings cannot be determined accurately because the carbide stoichiometry present within them is unknown.

Erosion tests carried out for 300 s resulted in relatively small volume loss, as shown in Table 2. A cavity with a volume as small as 3 mm^3 was measured with the optical profilometer. Good reproducibility of measurements performed with this apparatus was verified by detecting a 1% difference in volume in duplicate tests. After 900 s, the volume loss from different coatings was approximately 3.3 times greater than after 300 s, thus confirming that the volume loss determined by the slurry erosion test can be proportional to exposure time.

Weight loss also increases with exposure time and can be used to rank coatings. However, a constant variation of weight loss with exposure time is less evident, and the relative wear loss of one type of coating in comparison with another is not maintained. Weight loss measurements therefore cannot be used to predict the life of coatings or to rank them with accuracy.

It can be argued that weight loss could be a valid evaluation of wear loss. Obviously, it is true if no errors in measurements exist. However, the slurry erosion test consists of damaging the surface of a coating by forming a crater in a defined location with a stream of hard particles impinging the surface at a given

Table 2 Slurry Erosion Wear Data for TiC-Fe Coatings

Spray powder	Spray dried TiC + Fe powders	Reactive powders	Reactive and sintered powders
Volume loss, mm^3			
After 300 s	3.30	3.97	4.48
After 900 s	10.94	12.90	14.82
Ratio of (900 s)/(300 s)	3.32	3.25	3.31
Weight loss, mg			
After 300 s	12.30	17.20	21.70
After 900 s	49.60	78.50	73.20
Ratio of (900 s)/(300 s)	4.03	4.56	3.37

angle. Admittedly, weight loss measurements include incidental material detachment from the entire specimen and most likely weight loss resulting from the impingement of divergent hard particles striking the surface in other locations. Therefore, the cavity left after the slurry erosion test does not have the volume of the weighed material. The conversion of weight loss in terms of volume loss is questionable even if the density of the eroded material was determined for the reasons mentioned above. Moreover, there is no correspondence between the weight and volume losses, and therefore, it is not possible to evaluate the density of coatings.

5. Conclusion

Standardized wear test methods require that wear loss should be reported as a volume loss, and evaluation of worn damage must be performed with a technique that is capable of accurately measuring this volume loss.

The optical profilometer is a suitable and accurate method for measuring the volume loss on worn coatings that are severely damaged. Moreover, this measurement technique can help in understanding the degradation mechanism of coatings, identifying defects that occur on spraying and providing useful information for the development of wear-resistant coatings. By using a similar principle, this technique can be adapted to measure either a smaller volume loss, as found with coatings submitted to sliding wear, or an increase in volume due to swelling of the coating or material transfer.

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