

A Comparative Study of Tribological Behavior of Plasma and D-Gun Sprayed Coatings under Different Wear Modes

G. Sundararajan, K.U.M. Prasad, D.S. Rao, and S.V. Joshi

(Submitted 6 November 1997; in revised form 17 February 1998)

In recent years, thermal sprayed protective coatings have gained widespread acceptance for a variety of industrial applications. A vast majority of these applications involve the use of thermal sprayed coatings to combat wear. While plasma spraying is the most versatile variant of all the thermal spray processes, the detonation gun (D-gun) coatings have been a novelty until recently because of their proprietary nature. The present study is aimed at comparing the tribological behavior of coatings deposited using the two above techniques by focusing on some popular coating materials that are widely adopted for wear resistant applications, namely, WC-12%Co, Al_2O_3, and Cr_3C_2-NiCr.

To enable a comprehensive comparison of the above indicated thermal spray techniques as well as coating materials, the deposited coatings were extensively characterized employing microstructural evaluation, microhardness measurements, and XRD analysis for phase constitution. The behavior of these coatings under different wear modes was also evaluated by determining their tribological performance when subjected to solid particle erosion tests, rubber wheel sand abrasion tests, and pin-on-disk sliding wear tests. The results from the above tests are discussed here. It is evident that the D-gun sprayed coatings consistently exhibit denser microstructures and higher hardness values than their plasma sprayed counterparts. The D-gun coatings are also found to unfailingly exhibit superior tribological performance superior to the corresponding plasma sprayed coatings in all wear tests. Among all the coating materials studied, D-gun sprayed WC-12%Co, in general, yields the best performance under different modes of wear, whereas plasma sprayed Al_2O_3 shows least wear resistance to every wear mode.

Keywords abrasion, alumina coating, chromium carbide-nickel chromium coating, coatings, d-gun coatings, erosion, plasma spray coatings, sliding wear, tribology, tungsten carbide-cobalt coating

1. Introduction

Surface treatment technologies have been attracting a great deal of attention because they offer cost-effective ways to combat degradation resulting from mechanisms such as wear, oxidation, corrosion, or failure under an excessive heat load without sacrificing the bulk properties of the component material. Various surface modification techniques are available (Ref 1) offering a wide range of quality and cost. Since a vast majority of industrial components deteriorate and eventually fail due to one of several wear modes that may be encountered during normal operation (Ref 2) considerable attention has been devoted to the development of coating materials and processes specifically to combat the routine wear modes, namely, erosion, abrasion, and sliding wear.

Among the currently available coating processes, the thermal spray technique has gradually emerged as the most useful method of developing a wide variety of coatings to enhance the performance and durability of engineering components exposed to the above forms of wear (Ref 3, 4). Of all the thermal spray variants, the plasma spray process is the most versatile, while the D-gun technique was first developed exclusively to deposit WC-Co types of coatings to combat wear-related component degradation problems. However, the literature reveals that there have been very few studies (Ref 5) ascertaining the relative performance of plasma and D-gun sprayed coatings. This study presents a thorough comparison of the tribological behavior of some popular wear-resistant coatings, for example WC-12%Co, Al_2O_3, and Cr_3C_2-NiCr, deposited by the two above-mentioned techniques. To enable a comprehensive comparison of the above indicated thermal spray techniques as well as coating materials, the deposited coatings have been extensively characterized, and their tribological performance has been determined when subjected to solid particle erosion tests, rubber wheel sand abrasion tests, and pin-on-disk sliding wear.

G. Sundararajan and **D.S. Rao,** International Advanced Research Centre for Powder Metallurgy & New Materials, Opp. Balapur Village, RCI Road, R.R. District, Hyderabad 500 005, India; and **K.U.M. Prasad** and **S.V. Joshi,** Defence Metallurgical Research Laboratory, P.O. Kanchanbagh, Hyderabad 500 058, India.

2. Experimental Details

2.1 Substrate and Coating Materials

Mild steel (0.25%C, 0.7%Mn, 0.25%Si, 0.05%S) substrates were employed throughout for coating deposition. Samples with the following dimensions were used to prepare coated specimens for different wear tests:

- Erosion wear: 30 mm × 30 mm × 5.5 mm
- Abrasion wear: 75 mm × 25 mm × 15 mm
- Sliding wear: Disk—40 mm diam., 5 mm thick, pin—6 mm diam., 16 mm length

Table 1 Size analysis of spray-grade powders used

Powder	Manufacturer	Particle size, µm: Diam at 10%	Diam at 90%	Mean value	Particle shape
WC-12%Co	M/s. Sulzer-Metco	18.56	34.60	29.28	Dendrites and irregular
Al_2O_3	M/s. IPMS,Ukraine	17.26	49.17	39.37	Spherical
Cr_3C_2-25NiCr	M/s. Sulzer-Metco	17.96	39.37	27.26	Angular and irregular

Table 2 Plasma spray parameters employed for coating deposition

Parameter	WC-12%Co	Al_2O_3	Cr_3C_2-NiCr
Primary gas (Ar)			
Pressure, MPa	0.69	0.69	0.69
Flow, L/min	47.20	70.80	47.20
Secondary gas (H_2)			
Pressure, MPa	0.35	0.35	0.35
Flow, L/min	4.70	4.70	7.10
Carrier gas flow, L/min	17.50	28.30	17.50
Powder feed rate, g/min	60.50	22.70	41.50
Wheel, rev/min	13	10	15
Type of wheel	S	H	S
Plasma arc curent, A	400	500	500
Spray distance, mm	89.0	64.0	64.0

Table 3 D-gun parameters employed for coating deposition

Parameters	Powders: WC-12%Co	Al_2O_3	Cr_3C_2-NiCr
Gas flow ratio of O_2/LPG	4	…	…
Gas flow ratio of O_2/C_2H_2	1.12	2.44	1.142
Nitrogen, L/s	…	1.5	2.5
Air, L/s	4.0	…	…
Spray distance, mm	170	210	170

Table 4 Erosive wear test conditions

Erodent	silica
Erodent particle size, µm	150-250
Nozzle to sample distance, µm	10
Impact angle, degree	30
Impact velocity, m/s	140 ± 5
Test temperature, °C	25

Table 5 Abrasive wear test conditions

Abrasive material	silica
Rotation speed of the wheel, rev/min	200
Load used, N	50.0
Duration of each test, s	60
Sand feed rate, g/min	200

Table 6 Sliding wear test conditions

Disk speed, rev/min	490
Sliding velocity, m/s	0.821
Track radius, mm	16
Test temperature, °C	25
Sliding distance, km	4.68
Load applied, N	5
Pin size	6 mm diam, 16 mm length
Disk size	40 mm diam, 5 mm thickness
Disk material	Mild steel (0.25%C) with WC-12%Co or Al_2O_3 or Cr_3C_2-25NiCr coatings
Pin material	Mild steel (0.25%C) pin coated with the same material as disk

In the case of sliding wear tests, both the pin and the disk were coated with the same material.

The spray-grade powders of WC-12%Co and 75%Cr_3C_2-25%NiCr used for coating deposition on test specimens were procured from Sulzer-Metco, USA, while the Al_2O_3 powder was supplied by the Institute for Problems of Material Science, Kiev, Ukraine.

2.2 Precoating Substrate Preparation

Prior to coating by both plasma and D-gun coating processes, the substrates were always roughened by air blasting using an alumina grit of ~30 mesh. The blasting was performed at an air pressure of approximately 0.5 MPa. Subsequent to grit blasting, the samples were cleaned with acetone in an ultrasonic cleaner.

2.3 Powder Characterization

Particle size analysis of the three spray powders was performed using the laser particle size analyzer CILAS 920 (Cilas Le Sens de la Mesure, Marcoussis, France). This equipment is designed to measure particle sizes in a continuous range from 0.7 to 400 µm. Particle size ranges exhibited by each of the powders used are given in Table 1. The powder particle size determined from the analysis generally conforms to the particle size range given by the respective manufacturers. A scanning electron microscope (JEOL) was used to observe the morophology of the powders. The shapes of the powder particles assessed are also indicated in Table 1.

2.4 Deposition of Coatings

Plasma spray deposition of all three coatings was performed using a METCO 7MB atmospheric plasma spray unit. The spray parameters employed for depositing the three coatings under investigation are listed in Table 2. The D-gun unit used was of Ukrainian origin. A combustible gas mixture, consisting of oxygen and either acetylene or liquefied petroleum gas (LPG), was periodically detonated using a spark plug, and the D-gun parameters employed for coating deposition are listed in Table 3. Care was taken to ensure that the coating thickness on test specimens identified for any specific wear test was approximately

Table 7 Coating thickness, porosity, and surface roughness of D-gun and plasma coatings

Coating	D-gun coatings (average values)			Plasma coatings (average values)		
	Surface roughness R_a, µm	Porosity, %	Thickness, µm	R_a, µm	Porosity, %	Thickness, µm
WC-12%Co	3.8	1.19	180	6.0	5.50	180
Al_2O_3	3.5	1.18	240	9.6	4.55	270
Cr_3C_2-25NiCr	4.0	1.22	210	8.8	3.10	220

the same for both plasma spraying and D-gun coating to facilitate comparison.

2.5 Characterization of Coatings

The microstructural features of the coated specimens were studied using standard metallographic techniques. From each of the three coatings deposited by both plasma and D-gun spraying, a small piece was cut, and its cross section was mounted, polished, and observed under an optical microscope. The porosity of the coatings was measured using a metallurgical microscope fitted with a Q-520 Image analyzer (Leica, Cambridge, England). Scanning electron microscopy (SEM) analysis of the as-coated specimens was performed to study the surface morphology of as-sprayed coatings. Vickers hardness values were obtained on the cross-sectioned surface of each plasma and D-gun sprayed coating using a Leitz microhardness tester (E. Leitz, Inc., Rockleisp, NJ) under 200 g load. The coatings thicknesses were measured by an eddy current coating thickness gage and by using an optical microscope. A Philips x-ray diffractometer (Philips Electronics, Manwah, NJ) was used to identify the various phases present in the D-gun and plasma sprayed coatings as well as in the corresponding powder to ascertain the changes in phase constitution taking place during spray deposition. Surface roughness of D-gun and plasma coatings was measured using a SURTRONIC-3 PLUS surface roughness tester (Rank Taylor Hobson Limited; Leicester, England). In this text the parameter R_a was measured and used to quantify the coating surface roughness with being defined as the arithmetic mean of the departures of the profile from the mean line.

2.6 Wear Tests

Erosion Tests. To evaluate the erosive wear resistance property of the plasma sprayed and D-gun coated samples, solid particle erosion tests were conducted using a room temperature erosion rig (Ref 6). The test conditions employed for erosion testing of the coated samples are given in Table 4. Each coated specimen was subjected to erosion by particulate impact for a fixed period of time (4 min), ultrasonically cleaned with acetone, dried, and weighed in an electronic balance. The weight loss by the test specimen during each exposure was thus determined. The dimensionless erosion rate was then calculated as the ratio of the weight loss of the test specimen to the weight of the erodent particles causing the loss. The above procedure was repeated until the dimensionless erosion rate attained a constant steady state value. From this steady state erosion rate, the volume-based erosion rate (expressed in cubic centimeters per gram) was also calculated, because various coatings have different densities and their volume-based erosion rates are possibly better indicators of the erosion behavior of these coatings. Although the erosion tests on all the coatings were performed at two different erodent velocities of 75 m/s and 140 m/s (Ref 6), the results from low velocity erosion tests are excluded for conciseness.

Abrasion Tests. To evaluate the abrasive wear resistance property of the plasma sprayed and D-gun coated samples, a dry sand-rubber wheel abrasion test rig was used. The conditions used for abrasion testing are given in Table 5. Abrasion test samples were pressed against the chlorobutyle rubber wheel rotating at fixed revolutions per minute at a specified force by means of a lever arm, and abrasive silica particles were introduced between the test specimen and the rotating wheel. The rotation of the wheel was such that its contact force moved in a direction opposite to sand flow. The lever arm axis was placed such that it was approximately tangential to the rubber wheel surface and normal to the direction in which load was applied. The specimens were cleaned ultrasonically with acetone and weighed before and after the tests. The loss in weight was calculated. As before, the volume loss of each of the coatings was also determined. As in the case of erosion testing, the abrasive wear behavior was evaluated at three different loads of 0.5 kg, 5 kg, and 13 kg (Ref 6). However, results from tests with the 5 kg load alone are discussed.

Sliding Wear Test. The sliding wear tests were performed using a pin-on-disk tribometer employing the conditions listed in Table 6. After the initial calibration of the tribometer, the coated disk was fixed in the disk holder while the coated pin was inserted in the pin holder and allowed to be in contact with the disk. The number of rotations of the disk was preset to correspond to a predetermined sliding distance, and the machine was then allowed to run continuously without interruption. Both the coated pin and coated disk samples were ultrasonically cleaned in acetone separately and weighed before and after the test. From these weight measurements, the weight loss due to sliding wear (and the volume loss) was calculated separately for both pin and disk.

3. Results and Discussion

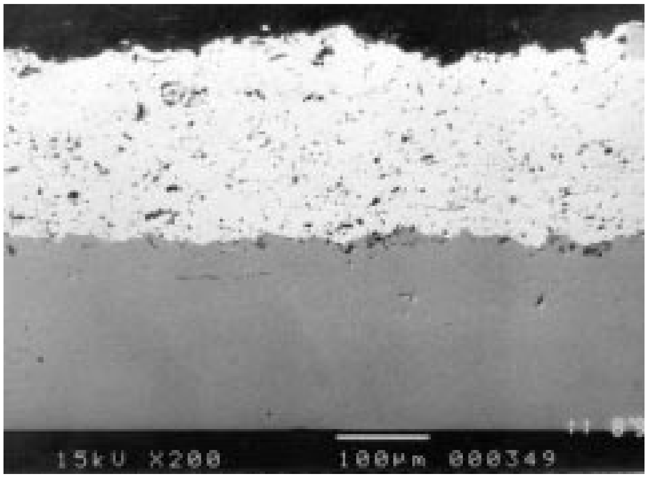
3.1 Coating Thickness and Roughness

Table 7 presents the thickness and roughness of all the coatings. The surface roughness value of all three atmospheric plasma spraying (APS) coatings are substantially higher than the corresponding roughness exhibited by D-gun coatings. The D-gun deposited coatings, therefore, can be used without the postcoating surface finish operation in some applications. Table 7 also provides the thickness values of the various coatings. The coating thickness lies in the range from 180 to 270 µm.

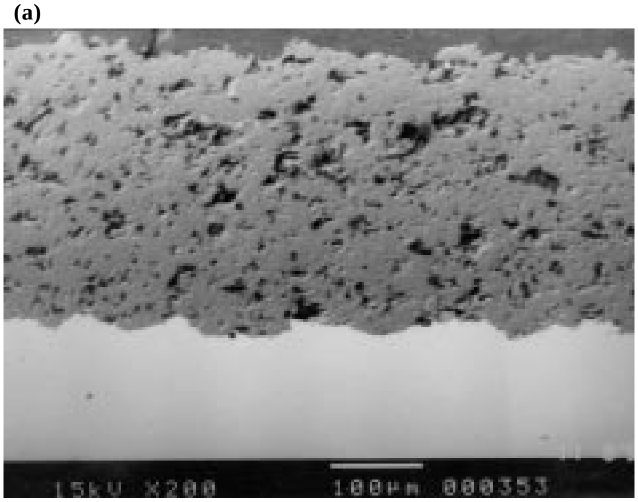
3.2 *Microstructures and Porosity of As-Deposited Coatings*

Figure 1 depicts the microstructures of all three as-deposited APS coatings while as-deposited microstructures of all the D-gun coatings are shown in Fig. 2. A comparison of the as-sprayed microstructures of the APS and D-gun coated WC-12%Co reveals that the APS coated layer is relatively less dense than the corresponding D-gun coatings. The D-gun coating also has a finer carbide distribution than the plasma sprayed coating. As in the case of the WC-12%Co coatings, it is also evident from the micrographs of the Cr_3C_2-NiCr and Al_2O_3 coatings that the D-gun deposited layers are generally more dense than the corresponding plasma sprayed layers. These findings can be attributed to the significantly higher particle velocities that are obtained in D-gun spraying (Ref 7-9). Similar findings have also been reported in the literature (Ref 10).

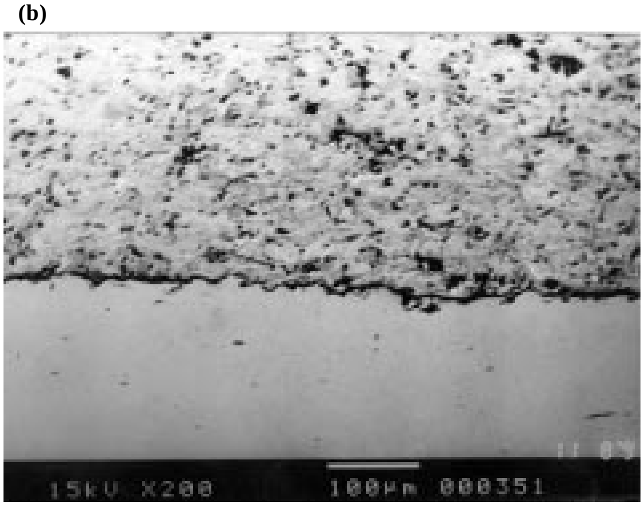
The lower porosity exhibited by D-gun coatings, as evident from Fig. 1 and 2, was further quantified using the digital image analyzer. The results from such an exercise, reported in Table 7, clearly indicate that the porosity values of all three D-gun deposited coatings are lower than those exhibited by the APS coatings by a factor in the range from 3 to 5.



(a)



(b)



(c)

Fig. 1 Typical cross-sectional microstructures of as-sprayed APS coatings (a) WC-12%Co, (b) Al_2O_3, and (c) Cr_3C_2-NiCr

3.3 *XRD Analysis*

The powders and coatings were also subjected to x-ray diffraction (XRD) analysis to identify the major phases present. Results are presented in Table 8. In the case of WC-Co coatings, while WC and Co were the major phases present in the D-gun coatings, the APS coatings predominantly contained W_2C and other complex phases indicating decarburization of the carbide. Similar to Cr_3C_2 coatings, APS coatings contained complex phases not found in either the D-gun coating or the original powder. Lastly, while the feedstock alumina powder was entirely α-alumina, it partly transformed to γ-alumina during D-gun coating, whereas the transformation to γ-alumina was virtually complete in the case of APS coating. Thus, XRD results show that the phase constitution of the feedstock powders is largely maintained during spraying of D-gun coatings, but this is generally not the case with APS coatings.

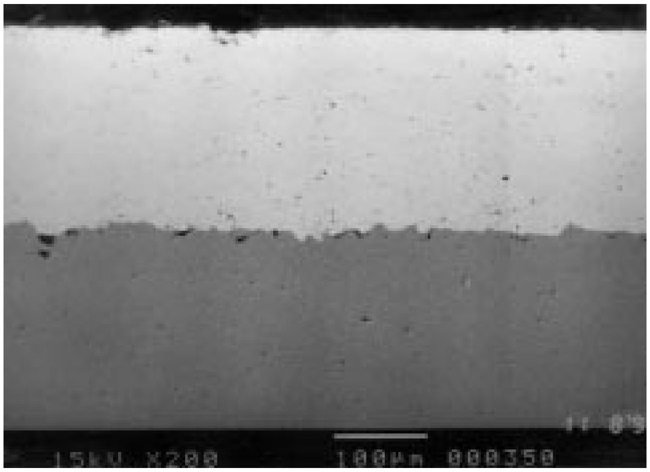
3.4 *Microhardness Measurements*

The average hardness values measured in all the coatings are given in Table 9. The hardness of D-gun coatings is consistently higher than that of its APS counterpart; this finding is consistent with the trends reported in other studies comparing plasma and D-gun sprayed coatings (Ref 11). This finding may be partly attributed to the previously noted superior microstructures resulting from the D-gun process. The hardness values obtained are similar to those reported in another recently reported study comparing the properties of APS and D-gun coatings (Ref 5).

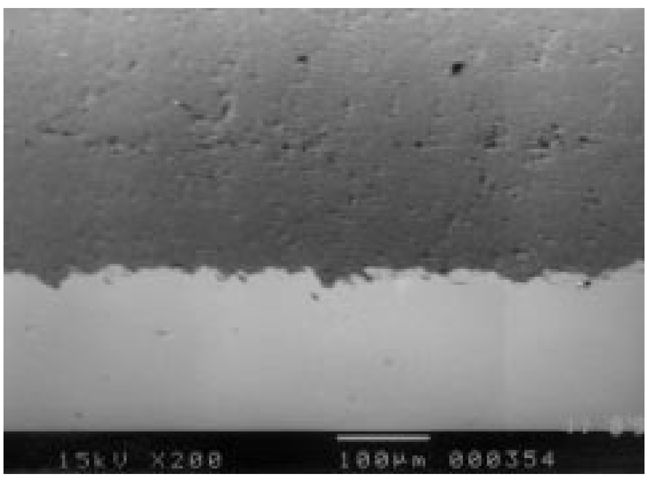
3.5 *Wear Test Results*

Erosion Test Results. The data ensuing from the erosion tests performed on the various coatings can be depicted in numerous ways. Often, it is considered informative to calculate the incremental erosion rate as a function of the cumulative weight of the erodent. Such data for erosion testing of APS WC-12%Co and APS Cr_3C_2-NiCr coatings is shown in Fig. 3 where the incremental erosion rate of the coatings, in milligrams of weight lost by the specimen per gram of the silica erodent impacting it, is plotted against the cumulative weight of erodent impacting the specimen. Figure 3 reveals that, in each case, the incremental erosion rates of the coatings decrease from an initial high value and reach a steady state value represented by the flat region of each dynamic erosion rate curve. A similar trend is also observed in high velocity erosion testing of both D-gun coated WC-12%Co and a bare mild steel substrate. These data are also superimposed on Fig. 3 to facilitate comparison. The evolution of the steady state erosion rate has also been determined to be similar in all other coatings, thereby suggesting that it is independent of the spray process as well as the coating material.

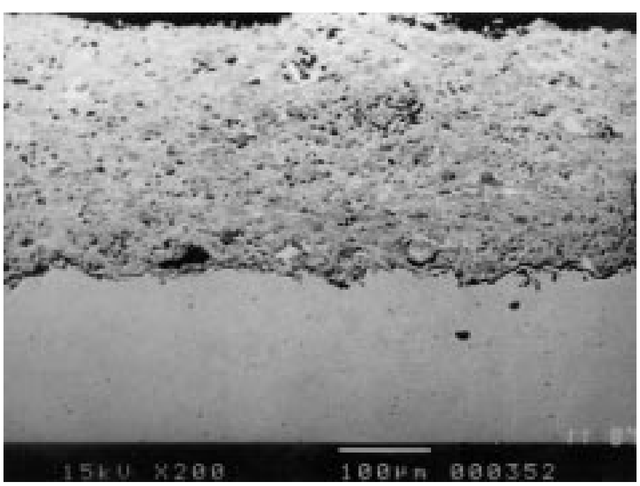
As expected, the steady state erosion rates under high velocity impact of erodent particles were consistently higher as compared to the values obtained from low velocity erosion testing (Ref 6). While the low velocity erosion results have been ex-



(a)



(b)



(c)

Fig. 2 Typical cross-sectional microstructures of as-sprayed D-gun coatings (a) WC-12%Co, (b) Al_2O_3, and (c) Cr_3C_2-NiCr

Table 8 Phase constitution of powders and coatings

	Identified major phases		
Coating	**Powders**	**D-gun coatings**	**Plasma coatings**
WC-12%Co	WC, Co	WC, Co, W_2C (minor)	W_2C, Co_3W_3C, Co_6W_6C, WC (minor)
Al_2O_3	αAl_2O_3	αAl_2O_3, γAl_2O_3	γAl_2O_3
Cr_3C_2-25NiCr	Cr_3C_2, NiCr	Cr_3C_2, NiCr	Cr_3C_7, Cr_3C_2, Ni

Table 9 Microhardness values of various coatings

	Microhardness (VHN) at 200 g load	
Coating	**Air plasma sprayed**	**Detonation gun**
WC-12%Co	1070	1199
Al_2O_3	693	1141
Cr_3C_2-NiCr	798	972

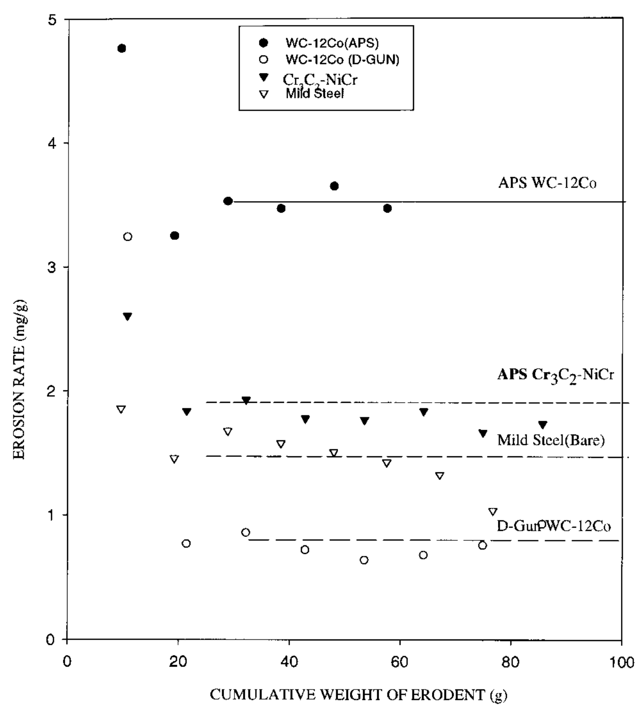


Fig. 3 Typical evolution of steady state erosion rate in APS and D-gun coatings. Incremental erosion rate versus cumulative weight of impinging particle for some select coatings as well as a bare mild steel substrate

cluded here for reasons of brevity, the steady state erosion rates (represented in milligrams of coating weight loss per gram of impacting erodent) obtained from high velocity erosion testing using the two thermal spray processes are shown in Fig. 4 to facilitate a comparison between the performance of APS and D-gun coatings. Figure 4 shows that the erosion rate of all APS coatings is much higher than those of the corresponding D-gun coatings. In both APS and D-gun coatings, alumina coatings were determined to have the lowest steady state erosion rate. The erosion rates of APS coatings are even higher than the erosion rate of mild steel.

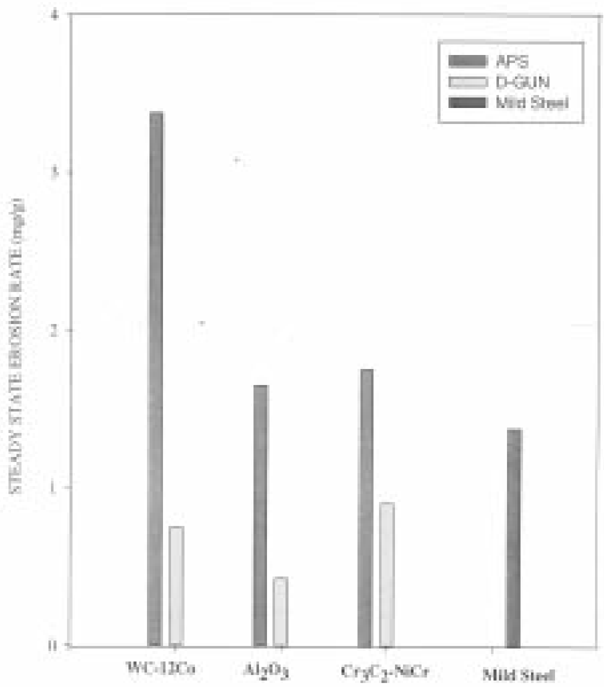


Fig. 4 Comparison of steady state erosion rate (weight basis) of APS and D-gun coatings

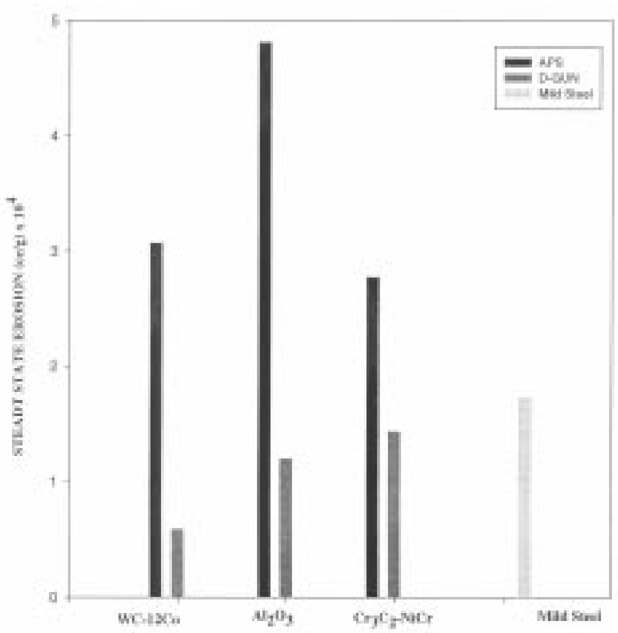


Fig. 5 Comparison of steady state erosion rate (volume basis) of APS and D-gun coatings

Though the erosion data of Fig. 4 indicate that D-gun alumina coating has the least erosion rate, a reevaluation of the data was warranted because a mere inspection of the eroded specimens was sufficient to indicate that the damage to the APS alumina coating specimen subsequent to high velocity erosion testing was clearly excessive as compared to other coatings. In an effort to explain this observation, the data in Fig. 4 were recalculated on a volume basis. The steady state erosion rate represented in terms of volume of the coating eroded in cubic centimeters per gram of erodent impacting the test specimen is depicted in Fig. 5. Presentation of erosion data in such a manner effectively normalizes the erosion rate determined from various coatings with the respective coating densities. The following plasma-sprayed coating densities reported elsewhere (Ref 12) were assumed for converting all the weight-based wear rates to volume-based wear rates: WC-12%Co, 14.5 g/cm^3; Al_2O_3, 3.4 g/cm^3; Cr_3C_2-NiCr, 6.2 g/cm^3. Because the D-gun coatings are expected to be denser than the plasma-sprayed coatings, and these findings are confirmed by the microstructures presented in Fig. 1 and 2 as well as by the image analysis results summarized in Table 7, the volume-based wear rates calculated for D-gun coatings using the above density values are, in fact, somewhat over predicted. Despite this, as evidenced by Fig. 5, a comparison of the volume-based erosion rates clearly shows that the APS alumina coatings suffer most significant erosive wear, while D-gun coated WC-12%Co performs the best. This finding is consistent with the visual observation made on tested specimens. Because the volume-based erosion rates relate directly to the thickness of the coating consumed due to resulting wear and, therefore, to any dimensional changes in the coated component, such volume-based calculations afford more realistic comparison of erosion behavior and have greater utility.

Abrasion Test Results. All the APS and D-gun coatings studied were also subjected to abrasion wear tests. From the weight loss measured on all the coated test specimens subjected to a rubber wheel abrasion test under a 5 kg load, it was noted that the total weight loss in all the APS coatings is much higher than that obtained with the corresponding D-gun coated specimens. Of all the above coatings, the APS WC-12%Co coating was found to exhibit the maximum weight loss, whereas the D-gun coated alumina specimen underwent minimum weight loss. However, for reasons discussed earlier, the abrasion test data were also calculated on a volume basis and are shown in Fig. 6. The D-gun coated WC-12%Co suffers minimum volume loss when compared to all other coatings. As in erosion, the APS alumina coatings appear to perform the worst among all the coatings that were studied. While D-gun coated WC-12%Co stands out as having the best performance under wear conditions, the other two D-gun coatings are found to exhibit largely similar performance. Similarly, in plasma spraying, alumina coating is by far the worst performer while the other two APS coatings exhibit nearly identical behavior. Viewed on a weight basis as well as on a volume basis, all the coatings studied were found to substantially suppress abrasive wear when compared to the bare mild steel substrate.

The weight loss of the coatings during abrasion tests conducted at a higher load of 13 kg was predictably higher than the corresponding weight loss at 5 kg load for all coatings due to the significantly higher load applied. The relative ranking of the various coatings was, however, found to be largely unchanged with the D-gun coated WC-12%Co outperforming all the other coatings.

Sliding Wear Test Results. The wear rates of all the coated pins, determined as the volume loss of the coated pin in cubic centimeters per kilometer of sliding distance, are presented in Fig. 7. All the APS coatings exhibit a consistently higher wear rate than the corresponding D-gun coatings, which show significantly lower wear. The APS alumina coating performs the worst under sliding wear conditions from a volume loss standpoint. From both weight as well as volume loss considerations, the superior performance of D-gun coated WC-Co was obvious. Furthermore, from both considerations, all the coated specimens yielded a significantly lower wear rate as compared to bare mild steel.

Although not discussed here, the wear rates of the coated disks were also determined by dividing the weight loss of the disk in milligrams by the corresponding sliding distance in kilometers. From such data, the wear rate of the coated disk virtually followed the wear of the coated pin in terms of ranking in both APS and D-gun coatings. This was also true when the volume-based wear rates of the disks and the pins were compared.

Influence of Wear Intensity. The wear intensity of a wear mode is directly related to the efficiency with which the material is removed as debris by that particular wear mechanism or mode. In the case of sliding wear, the wear constant K defines the efficiency of material removal. Because the value of K usually lies in the range of 1×10^{-06} to 1×10^{-03}, for many metallic materials undergoing dry sliding wear, the efficiency of material removal is extremely low. In abrasive wear, in contrast, the value of K lies in the range of 0.1 to 1%. Finally, under erosion conditions, the efficiency of material removal generally lies in the range of 1 to 10% for metallic materials and coatings (Ref 13). Therefore, the wear intensity is the least under sliding wear

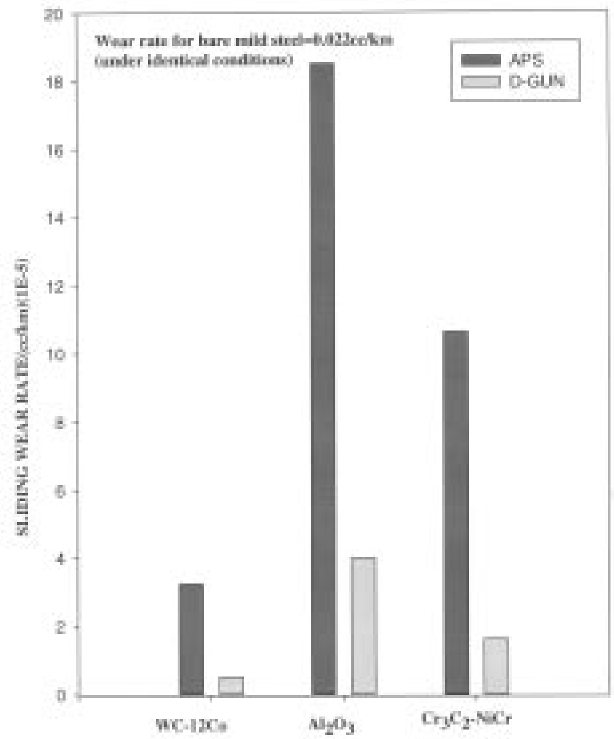


Fig. 7 Comparison of pin wear rate (volume basis) of APS and D-gun coatings determined from pin-on-disk sliding wear tests

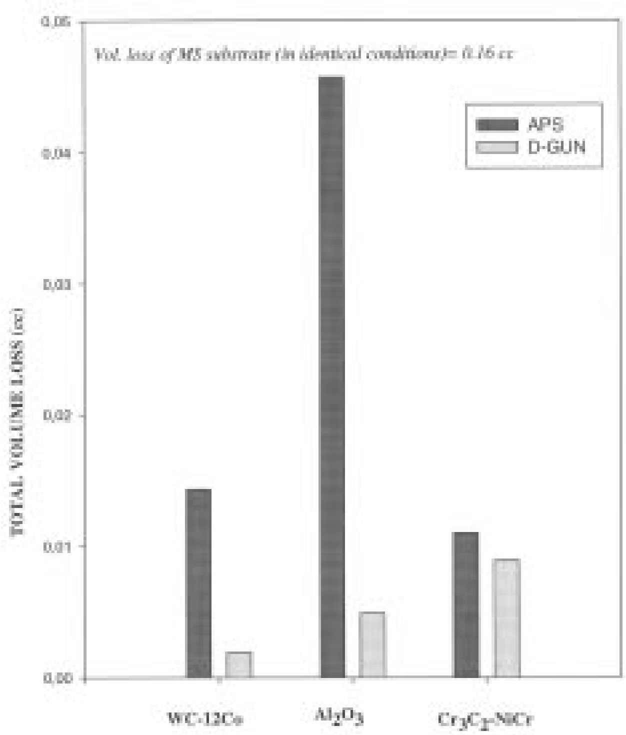


Fig. 6 Comparison of abrasive wear (volume basis) of APS and D-gun coatings at 5 kg load

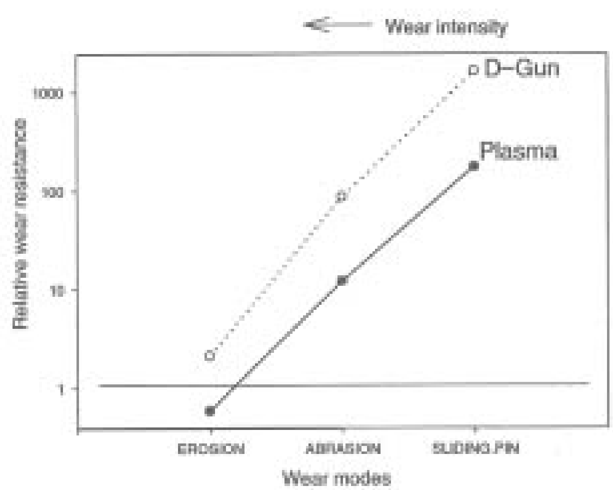


Fig. 8 Relative wear resistance (relative to mild steel) of APS and D-gun coated WC-12%Co under various wear modes

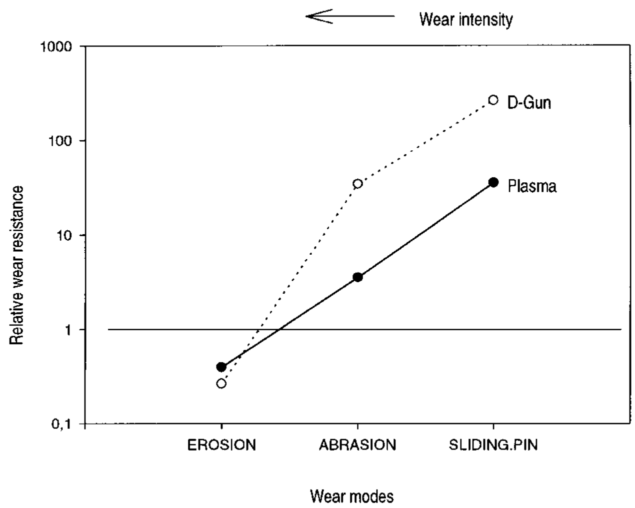


Fig. 9 Relative wear resistance (relative to mild steel) of APS and D-gun coated Al_2O_3 under various wear modes

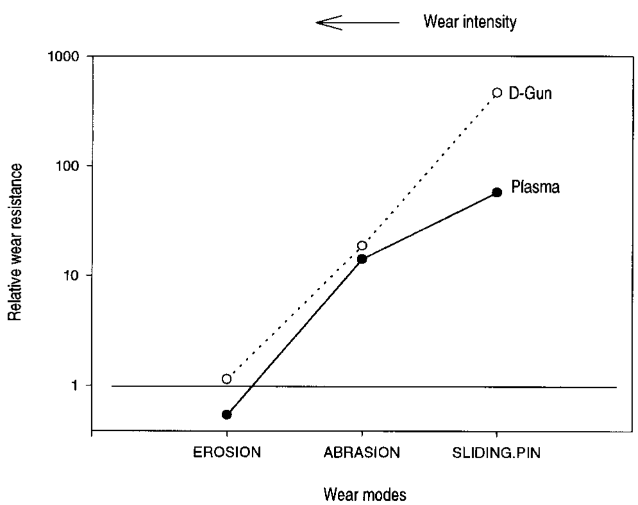


Fig. 10 Relative wear resistance (relative to mild steel) of APS and D-gun coated Cr_3C_2-NiCr under various wear modes

conditions and the most severe under erosion conditions. The wear intensity under abrasion is between that of sliding wear and erosion.

The wear resistance of the coating relative to the substrate (defined as the relative wear resistance) should depend on the wear mode and its intensity. To check whether such an expectation is justified, the influence of the wear intensity on the relative wear resistance for WC-Co, alumina, and chromium carbide coatings are illustrated in Fig. 8, 9, and 10, respectively. Despite the type of coating, the relative wear resistance decreases substantially as the wear intensity is increased. Thus, the same coatings that perform exceptionally well under sliding wear conditions do not perform well under erosion conditions. In fact, some of the coatings actually cause the wear rate of the substrate to increase when tested under erosion conditions (see Fig. 8 to 10). The methodology to be followed for design of coatings for wear resistance has to consider the operating wear mode as well as its intensity.

4. Conclusions

Based on the results, the following conclusions may be drawn:

- D-gun sprayed coatings consistently exhibit denser microstructure and higher hardness than the corresponding APS coatings.
- Presumably, as a consequence of the above, the D-gun sprayed coatings are also found to outperform the corresponding APS coatings under all the wear modes studied.
- The ranking of the coatings depends on whether the wear data are compared on a weight basis or a volume basis. The volume-based wear rates allow a more realistic comparison, as they relate directly to the thickness of coating consumed due to resulting wear and, therefore, to any dimensional changes in the coated component.
- The D-gun sprayed WC-12%Co possesses the highest erosion wear resistance, whereas APS alumina has the least erosion wear resistance among the coatings studied.
- Under abrasion test conditions as well as sliding wear conditions, the D-gun sprayed WC-12%Co coatings exhibit minimum volume loss, and APS alumina exhibits maximum volume loss.
- A summary of coating performance under different wear modes clearly reveals that D-gun coated WC-12%Co always outperforms all other coatings, while the APS alumina exhibits the poorest performance among the coatings studied.
- Wear intensity has a dramatic influence on the performance of the coatings relative to the bare mild steel substrate. The severity of wear experienced by the material undergoing wear increases with progression from sliding wear to abrasive wear and finally to erosive wear. The present study indicates that improvement in wear resistance afforded by the coating decreases sharply as the wear intensity increases, regardless of the nature of the coating or the coating technique employed.

Acknowledgements

The authors are grateful to Mr. D. Jayaram, Mr. V.S.R.A. Sarma, Mr. D. Sen, and Mr. K.R.C. Somaraju for their help in generating the coated specimens. The cooperation of Mr. Manish Roy, Mr. B. Venkataraman, and Mr. N. Ravi for the use of their tribological and characterization test facilities is also acknowledged. The authors also thank the director of DMRL for granting permission to publish this work.

References

1. R.F. Bunshah, *Deposition Technologies for Films and Coatings*, Noyes Publications, 1982
2. G. Sundararajan, Surface Engineering for Wear Resistance, *Met. Mater. Process.*, Vol 5, 1994, p 215
3. S.V. Joshi and R. Sivakumar, Protective Coatings by Plasma Spraying: A Review, *Trans. Indian Ceram. Soc.*, Vol 50, 1991, p 9
4. K.G. Budinski, *Surface Engineering for Wear Resistance,* Prentice Hall, 1988

5. Y. Wang, Friction and Wear Performance of Detonation Gun and Plasma-Sprayed Ceramic and Cermet Hard Coatings, *Wear,* Vol 161, 1993, p 69
6. K.U.M. Prasad, "Plasma and D-Gun Sprayed Wear Resistant Coatings: A Comparative Study under Different Wear Modes," M. Tech. Thesis, Regional Engineering College, 1997
7. R.G. Smith, The Principles of Detonation Coating, *Science and Technology of Surface Coatings,* B.N. Chapman, Ed., Academic Press, 1974, p 271
8. Y.A. Kharlamov, Detonation Spraying of Protective Coatings, *Mater. Sci. Eng.,* Vol 93, 1986, p 1
9. Y.A. Kharlamov, Bonding of Detonation Sprayed Coatings, *Thin Solid Films,* Vol 54, 1978, p 271
10. J.E. Nerz, B.A. Kushner Jr., and A.J. Rotolico, Microstructural Evaluation of Tungsten Carbide-Cobalt Coatings, *J. Therm. Spray Technol.,* Vol 1, 1992, p 147
11. G. Sundararajan, K.R.C. Somaraju, and D.S. Rao, The Prospects for the Development of High Performance Alumina Coatings Using Detonation Gun Technique, *Surface Modification Technologies X,* T.S. Sudharshan, K.A. Khor, and M. Jeandin, Ed., The Institute of Materials, 1997, p 369
12. METCO Technical Bulletins for WC-12%Co, Al_2O_3 and Cr_3C_2-NiCr Powders, July 1979, Sept. 1979 and Oct. 1973
13. G. Sundararajan, M. Roy, and B. Venkataraman, *Wear,* Vol 140, 1990, p 369