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Abrasion Wear Resistance of Arc-Sprayed Stainless Steel and Composite Stainless Steel Coatings

S. Dallaire, J.-G. Legoux, and H. Levert

The abrasion wear resistance of stainless steel and composite stainless steel/titanium boride coatings arc sprayed with air and argon was evaluated. Stainless steel coatings arc sprayed with air were found to be slightly more resistant than bulk stainless steel, whereas those sprayed with argon were slightly less resistant. The wear resistance of composite stainless steel/titanium diboride coatings was from two to four times greater than that of bulk stainless steel, depending on the cored wire constitution and the type of gas used for spraying. Microstructural analysis, microhardness measurements, and optical profilometry were used to characterize the coatings and wear damage. By considering both the wire constitution and the spraying conditions, it was possible to fabricate composite stainless steel coatings that showed a 400% increase in wear resistance over bulk stainless steel.

1. Introduction

WEAR is an important production factor, leading to downtime, repair, and replacement in the mining, metallurgical, wood, paper, power generation, and other industries. In some circumstances, resistance to corrosion is also vitally important. Indeed, corrosion in combination with wear may seriously shorten component life.

Nonmetallic materials such as ceramics, plastics, and elastomers have been considered for applications such as transfer chutes, bunkers and coal conveyors, hydraulic transport pipelines, coal washing plant, and hydroelectric equipment, but have failed to fulfill performance expectations. Ceramics have low fracture toughness and poor fabricability, while organic materials have only moderate wear resistance over a narrow range of operating conditions and insufficient structural strength. Stainless steels offer a potential solution to these problems. Although they are not generally considered to be wear resistant, they have been used to a limited extent in applications involving both corrosive and abrasive/erosive environments (Ref 1). Different approaches have been taken to improve the wear resistance of stainless steels, including use of metastable steels to favor transformation to martensite during the wearing process, transformation-induced plasticity, and the dispersion of hard particles in a soft, corrosion-resistant matrix. The last approach was found to offer the best potential for wear improvement (Ref 1). Arc-sprayed stainless steel coatings have been considered because of their cost effectiveness and ease of fabrication. Originally manufactured components can be coated easily and worn components can be rejuvenated economically in shops or directly on site.

This study evaluated the wear resistance of arc-sprayed stainless steel and stainless steel/titanium boride coatings. Solid stainless steel wires and two different types of stainless steel cored wires containing different proportions of hard titanium boride particles were arc sprayed with air or argon to determine the influence of spray gases and the constitution of cored wires on abrasion wear resistance.

Keywords: cored wires, spray processing, stainless steel, titanium diboride, wear

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2. Experimental Procedure

2.1 *Materials and Arc Spraying*

Solid stainless steel (AISI 304) wires were arc sprayed using a Miller BP 400 (Miller Thermal, Inc., Appleton, WI, USA) arc spray system with argon or air as the atomizing gas. Stainless steel coatings containing titanium diboride particles were also produced by arc spraying cored wires with the same gases. The main characteristics of the cored wires are summarized in Table 1. Type 1 cored wire has a thicker sheath and a core richer in TiB_2 than type 2 cored wire. Details concerning the chemical compo-

Table 1 Constitution and characteristics of solid and cored stainless steel wires

Type of wire	Stainless steel sheath, content, wt%	TiB_2 within the core, vol%	Remaining metal within the core, vol%	TiB_2 within the entire wire, vol%	Sheath thickness, mm	Wire diameter, mm
Solid	100	...	...	...	...	1.60
Cored wire 1	80	82	18	24	0.30	1.75
Cored wire 2	56	55	45	30	0.16	1.60

sition of precursor powders and metal strips, the fabrication of cored wires, and their spraying have been published (Ref 2, 3). All the wires were sprayed under the same parameters (Ref 2, 3): arc voltage, 27 V; arc amperage, 100 A; gas pressure, 600 kPa; spray distance, 15 cm. Cooling was not provided on the back face of steel substrates, nor was any gas used to cool coatings or to sweep away the overspray. Arc-sprayed coatings were diamond ground to obtain flat surfaces and uniform roughness (R_a = 0.5 μm) prior to wear testing.

2.2 *Abrasion Wear Test*

The abrasion wear resistance of arc-sprayed stainless steel and stainless steel/titanium diboride coatings was measured in accordance with the dry sand/rubber wheel abrasion test (ASTM G 65) (Ref 4). The testing method involves abrading a specimen with a grit of controlled size and composition. A force of 130 N maintained the specimen against the rubber-coated wheel. Quartz sand (50/70 mesh) (300 μm/212 μm) was introduced between the specimen and the wheel at a flow ranging between 4 and 6 g/s. The wheel rotates in the same direction as the flowing sand; the test ended after 2000 revolutions (Procedure B).

2.3 *Volume Loss Measurement and Wear Damage Evaluation*

An optical profilometer (Ref 5) was used to measure volume loss and to evaluate wear damage. This apparatus, composed primarily of a laser range sensor, allows the three-dimensional mapping of worn areas and can evaluate the volume loss on worn coatings with an accuracy greater than 1%, the accuracy between the wear volume losses performed on different composite coating samples being better than 10%. The optical profilometer also produces three-dimensional images of the worn surface and provides relevant information regarding the wear behavior of coatings.

2.4 *Microstructural Analysis*

Metallographic cross sections of sprayed coatings were examined using optical and scanning electron microscopy. The chemical composition of materials in specific areas was determined by x-ray dispersive energy spectroscopy. Scanning electron microscopy was also used to examine worn surfaces for scratches and for soft and hard features. The sizes (length and thickness) of lamellae were determined by image analysis of metallographic cross sections of coatings at a magnification of 400×; some 70 to 210 lamellae were observed depending on the coating being examined. This magnification enables the observation of lamellae up to 200 μm long. The mean length of lamellae was between 20 and 48 μm; their mean thickness was between 8.5 and 14 μm, depending on the type of coating. Spraying of wires generally produces larger droplets than spraying of powder, and the volumes of arc-sprayed lamellae are also greater than those of thermal spray processes that use powders (Ref 6). Therefore, arc-sprayed lamellae are thicker than those obtained from spraying powders. Diamond pyramid hardness measurements on coating cross-section features were performed using a Knoop indentor with a load of either 10 g (for cored wire 1) or 50 g (for cored wire 2, which contains large features). Results are reported as a mean of 30 measurements taken from random sample positions.

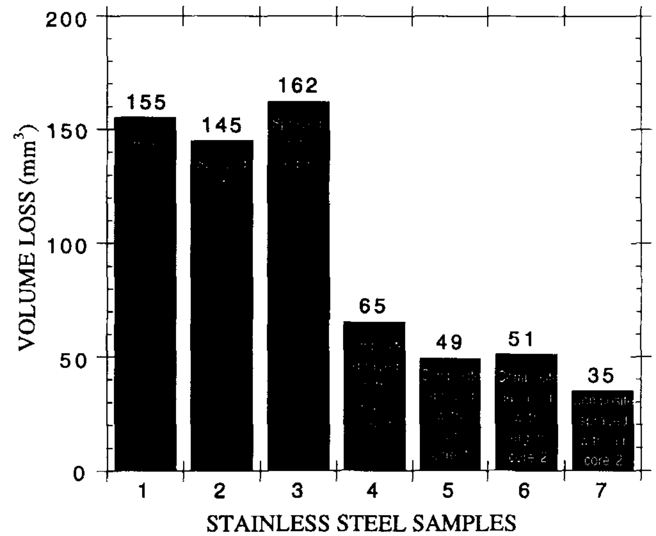

Fig. 1 Volume loss of bulk stainless steel and coatings

3. Results and Discussion

3.1 *Wear Resistance of Arc-Sprayed Stainless Steel Coatings*

The abrasion wear resistance of arc-sprayed stainless steel coatings is equivalent to that of bulk stainless steel. Coatings obtained by spraying with air, however, are better than those obtained by spraying with argon (Fig. 1). The volume loss of coatings sprayed with air (145 mm^3) is slightly lower than that of bulk stainless steel (155 mm^3), indicating that some wear improvement could be realized by spraying stainless steel with air.

3.2 *Wear Resistance of Arc-Sprayed Stainless Steel Coatings Containing Titanium Diboride Particles*

Wear resistance is considerably improved by spraying cored wires (Fig. 1). Depending on the type of cored wire, the TiB_2 content (24 or 30 vol%), and the spraying gas, stainless steel coatings containing TiB_2 particles (samples 4 to 7) showed a wear volume loss ranging from 2.3 to 4.6 times less than arc-sprayed stainless steel coatings (samples 2 and 3).

3.3 *Influence of Gas on Wear Performance of Arc-Sprayed Stainless Steel Coatings*

Solid stainless steel wires sprayed with air produce coatings that withstand wear slightly better than those arc sprayed with argon; that is, sample 2 is better than sample 3. The slight increase in hardness (Fig. 2) of these coatings compared to those sprayed with argon is probably responsible for their better wear performance. This higher hardness can be attributed to dissolved oxygen or nitrogen and the precipitation of Cr_2O_3 and CrN within stainless steel. Solid-solution and precipitation

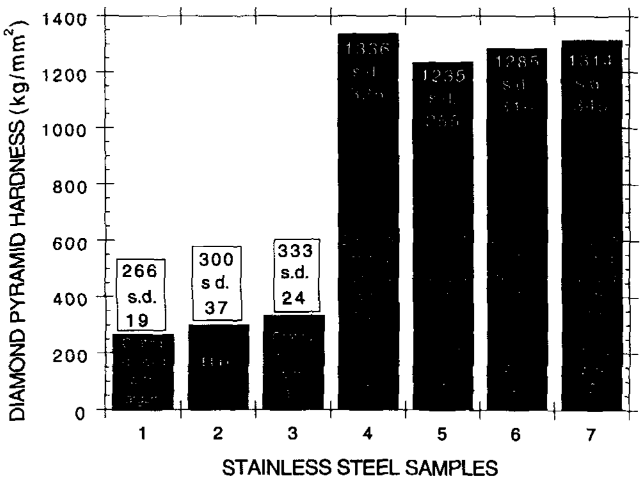

Fig. 2 Diamond pyramid hardness of bulk stainless steel and coatings

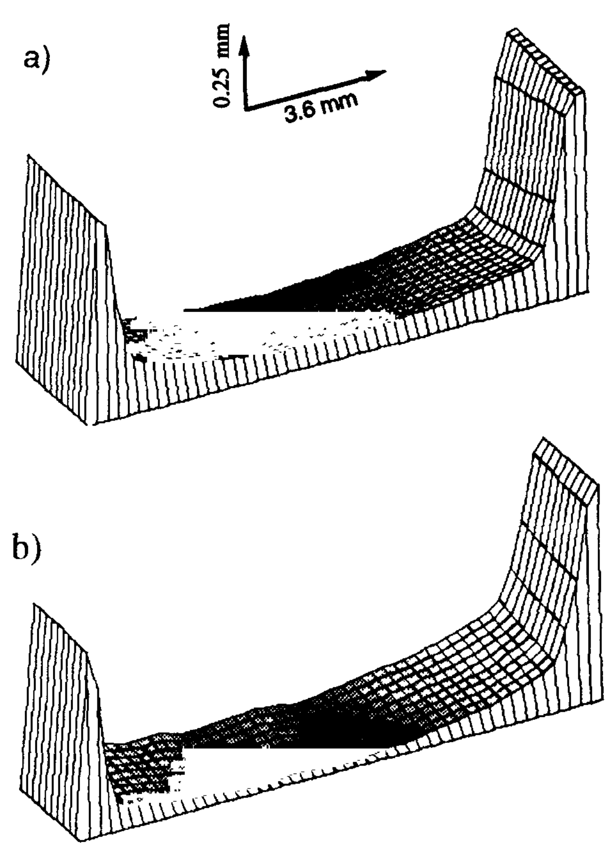

Fig. 3 Middle portion of the wear track profile for stainless steel coatings arc sprayed with (a) argon and (b) air

hardening are well-known strengthening mechanisms (Ref 7) that can contribute to improved wear resistance. However, the middle portion of the wear track profile in Fig. 3 shows that air-sprayed coatings (Fig. 3b) wear less evenly than coatings sprayed with argon (Fig. 3a), indicating that oxide stringers can adversely affect wear resistance. Indeed, because of their brittleness, oxide stringers promote lamellae pullout, which results in the large grooves visible in the wear track profile (Fig. 3b).

3.4 *Influence of Cored Wire Constitution and Spraying Gas on Wear Performance of Stainless Steel Composite Coatings*

The influence of wire constitution and spraying conditions on the wear performance of composite coatings was not assessed. Neither the titanium diboride content of these wires (from 24 to 30 vol%) nor the mean hardness of coatings sprayed with air or argon (between 1235 and 1336 kg/mm^2) could explain a volume loss of between 35 and 65 mm^3. An abrading medium can scratch a material if its hardness is 20% higher than that of the material (Ref 8). Volume losses due to abrasion are considered low when the ratio between the hardnesses of the test material and the abrading medium is higher than 1.2 (Ref 9, 10). Considering that quartz sand has a hardness of 1100 kg/mm^2, a composite coating with a hardness of 1300 kg/mm^2 should withstand abrasion well. The relative wear resistance of coatings considered here could not be related to their relative hardnesses, contrary to general opinion (Ref 11). Indeed, although all the composite coatings (samples 4 to 7 in Fig. 2) have roughly the same hardness (taking into account data scattering), they exhibit different wear behavior (samples 4 to 7 in Fig. 1).

3.5 *Influence of Microstructure on Wear Resistance of Composite Stainless Steel/Titanium Diboride Coatings*

The stainless steel/titanium diboride coatings are composed of lamellae whose hardness depends on the TiB_2 content. Therefore, it may be more appropriate to relate their wear resistance to microstructure rather than to mean hardness.

The three-dimensional wear track profiles of worn arc-sprayed composite coatings (Fig. 4), illustrate the main differences in abrasion wear behavior. Coatings arc sprayed with wires having a thick metal sheath and a core richer in ceramic present a wear track with a relatively smooth surface (Fig. 4a). Composite coatings arc sprayed with air have deeper crevices than those sprayed with argon. The mean dimension of worn surface irregularities (10 to 15 μm) of coatings sprayed with argon corresponds to the mean thickness of sprayed lamellae (8.5 to 14 μm). The same small irregularities are also present on the worn surfaces of air-sprayed coatings. However, these wear profiles show crevices 100 μm deep. Wear seems to be related to the local fracture and pulling out of hard lamellae or to the cutting of soft lamellae. A material with a hardness higher than 1880 kg/mm^2 cannot be abraded by silica (Ref 12). Therefore, the proportion of coating lamellae having a hardness higher than 1800 kg/mm^2 could be a suitable parameter to consider. Indeed, Fig. 5 shows that coatings containing a higher proportion of high-hardness lamellae are more abrasion resistant. The hardness of 1800 kg/mm^2 corresponds to the number 9 in the mineralogical Mohs scale, whereas silica has the number 7. Coatings containing a higher proportion of these hard lamellae would therefore be more resistant to abrasion wear.

3.6 *Effect of Hard Lamellae Size on Wear Behavior*

The amount of very hard phases present cannot account for the differences in wear behavior observed. The wear track profiles of abraded coatings (Fig. 4) indicate that surfaces are not

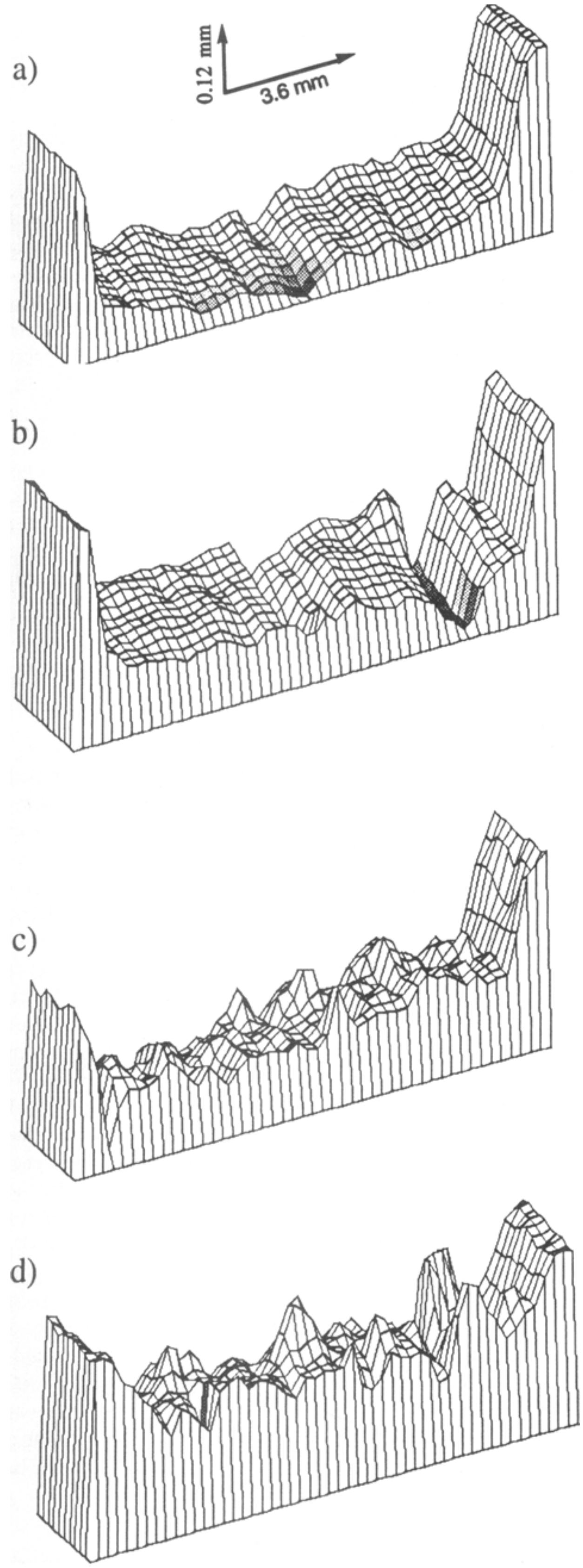

Fig. 4 Middle portion of the wear track profile for composite stainless steel coatings obtained by arc spraying. (a) Cored wire 1 with argon. (b) Cored wire 1 with air. (c) Cored wire 2 with argon. (d) Cored wire 2 with air

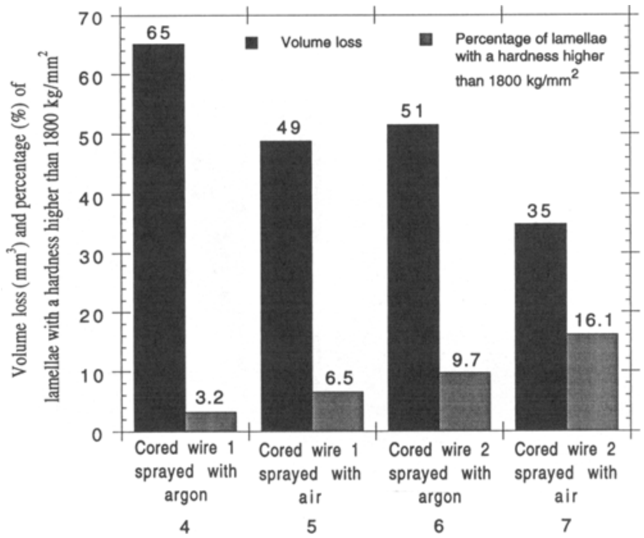

Fig. 5 Volume loss of arc-sprayed composite stainless steel coatings in terms of content of phases harder than 1800 kg/mm^2

evenly worn. Since these sprayed lamellae are composed of the same microconstituents (stainless steel and TiB_2), perhaps their size is a factor. Indeed, examination of the worn surfaces at a magnification higher than that allowed by the optical profilometer revealed interesting microstructural features influenced both by the constitution of the cored wires and by the spraying gases. Arc spraying of cored wire 1 (containing 82 vol% TiB_2) and argon produced coatings with smaller hard lamellae than those obtained by spraying the cored wire 2 (55 vol% TiB_2 content) and air, as shown by backscattered electron images of worn surfaces (Fig. 6a and c; dark areas indicate the location of hard phases).

Topographic images of these same analyzed regions (Fig. 6b and d) support previous observations. The abraded surface of the coating obtained by spraying cored wire 1 (rich in ceramic) and argon is almost uniformly scratched. Small pits corresponding to particle pullout or porosity are visible. In contrast, the worn surface of the most abrasion-resistant coating contains large bumps and cavities (Fig. 6d), as indicated previously by the wear track profile (Fig. 4d). Obviously, comparisons between Fig. 6(c) and (d) show that large lamellae rich in ceramic resulted in large bumps not attacked by the abrading medium and that the large cavity visible in Fig. 6(d) is due to the pullout of a large lamella. The runoff-like pattern on the border of the cavity, being the signature of a fragile rupture, indicates that a large lamella surrounded by an oxide layer was pulled out. Note that the size of some large hard lamellae was close to that of the abrading medium.

3.7 *Effect of Wire Constitution and Spraying Gas on Wear Behavior*

As observed earlier, cored wire 1 (composed of a thick metal sheath and a core rich in ceramic) produces coatings that do not contain large hard lamellae that withstand abrasion well. However, these coatings are as hard as those produced using cored wire 2 (composed of a thin metal sheath and a diluted core). The difference of 6 vol% TiB_2 between these two types of coatings

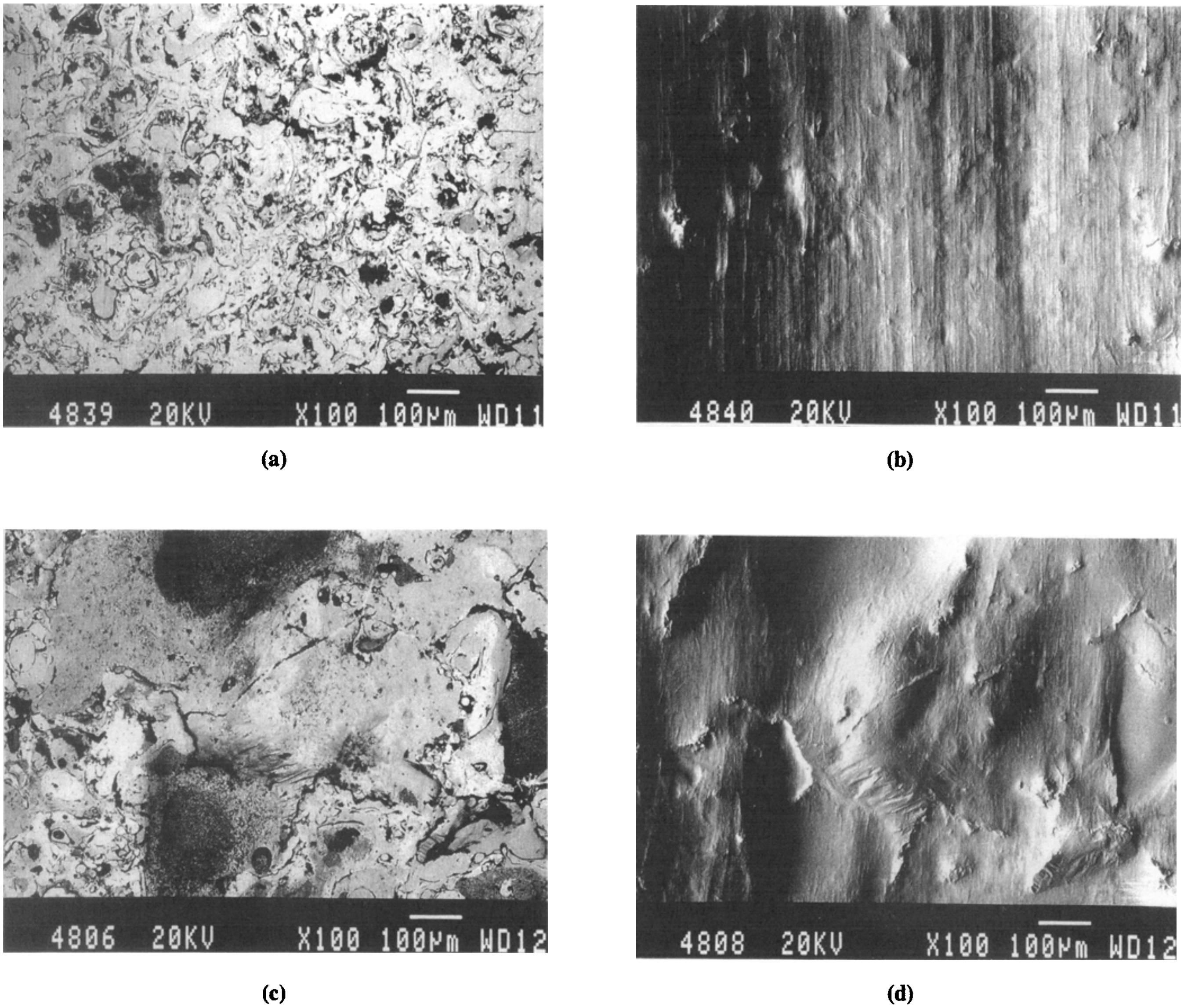

Fig. 6 Worn surfaces. (a) Backscattered electron image and (b) topographical image of a composite stainless steel coating obtained by arc spraying with cored wire 1 and argon. (c) Backscattered electron image and (d) topographical image of a composite stainless steel coating obtained by arc spraying with electron cored wire 2 and air

cannot explain the large difference in volume losses observed. The formation of molten droplets at the tips of the wires and their gas atomization and spraying to form wear-resistant coatings are important phenomena that should be considered.

3.8 *Effect of Atomizing Gas on Lamellae Size*

The spray gas is an important process parameter that controls microstructure and thus wear resistance, all other spraying parameters being maintained constant. Indeed, because each gas has its own transport properties (viscosity, density, mass flowmeter for a given pressure), it also produces different spray droplets. The lamellae length size distribution measured for the four arc-sprayed composite coatings (Fig. 7) indicates that air-sprayed coatings contain more small lamellae than those sprayed with argon. Cored wires with a thick sheath also produce coatings with a higher proportion of small lamellae. Thus, air removes small particles from metal sheaths more easily than argon. A larger amount of fine particles is also produced from thick-sheath cored wires. These small particles did not contain ceramic to a large extent, even though their hardness never fell below 700 kg/mm^2. Therefore, the lamellae coming from the molten core are expected to be larger and less diluted by the metal sheath when sprayed with air rather than argon or when a thick metal sheath is used. As mentioned earlier, large amounts of large lamellae with high hardness improve wear resistance. The large relief shown on wear track profiles (Fig. 4) is undoubtedly related to the presence of these large lamellae within coatings.

4. Conclusions

Stainless steel composite coatings that are four times more abrasion wear resistant than bulk stainless steel can be produced

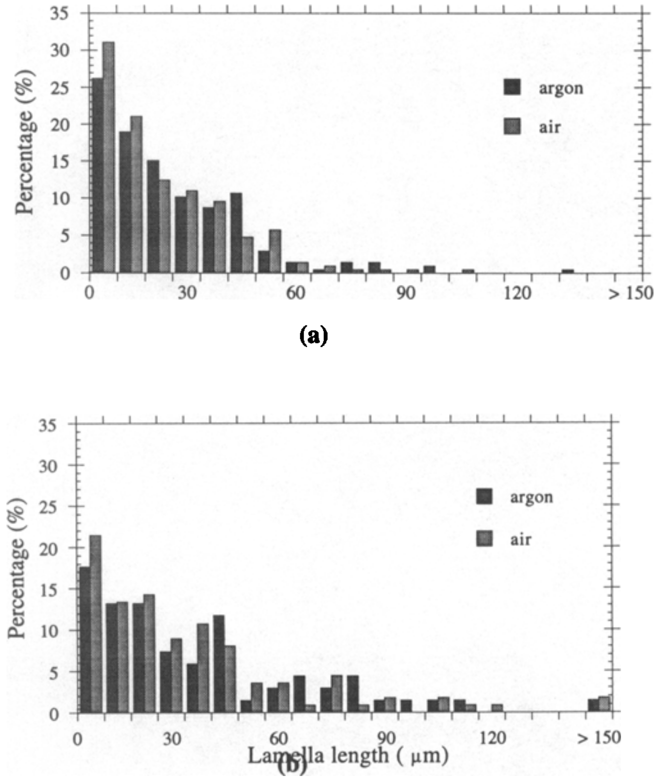

Fig. 7 Lamellae length size distribution within arc-sprayed composite stainless steel coatings obtained with (a) cored wire 1 and (b) cored wire 2

by arc spraying composite stainless steel cored wires. The wear resistance of these coatings depends on the amount, size, and hardness of sprayed particles. Air was more efficient than argon in producing wear-resistant coatings, but inert gas mixtures are preferable, because oxidation of chromium within coatings could alter corrosion properties. Wear resistance depends on the manner in which cored wires are sprayed. Better understanding of the dynamics of droplet formation and transport with various gases would contribute to the fabrication of arc-sprayed composite coatings with enhanced properties and to their industrial acceptance for demanding applications.

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