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Tribological Properties of TiC-Fe Coatings Obtained by Plasma Spraying Reactive Powders

S. Dallaire and G. Cliche

Titanium carbide-based coatings have been considered for use in sliding wear resistance applications. Carbides embedded in a metal matrix would improve wear properties, providing a noncontinuous ceramic surface. TiC-Fe coatings obtained by plasma spraying of spray-dried TiC-Fe composite powders containing large and angular TiC particles are not expected to be as resistant as those containing TiC particles formed upon spraying. Coatings containing 60 vol% TiC dispersed in a steel matrix deposited by plasma spraying reactive micropellets, sintered reactive micropellets, and spray-dried TiC-Fe composite powders are compared. The sliding wear resistance of these coatings against steel was measured following the test procedure recommended by the Versailles Advanced Materials and Standards (VAMAS) program, and the inherent surface porosity was evaluated by image analysis. Results show that, after a 1-km sliding distance, TiC-Fe coatings obtained after spraying sintered reactive powders exhibit scar ring three times less deep than sprayed coatings using spray-dried TiC-Fe composite powders. For all coatings considered, porosity is detrimental to wear performance, because it generally lowers the coating strength and provides cavities that favor the adhesion of metal. However, porosity can have a beneficial effect by entrapping debris, thus reducing friction. The good wear behavior of TiC-Fe coatings manufactured by plasma spraying of sintered reactive powders is related to their low coefficient of friction against steel. This is due to the microstructure of these coatings, which consists of 0.3 to 1 μm TiC rounded particles embedded in a steel matrix.

1. Introduction

THERMAL sprayed cermet coatings, specifically those based on carbides, have been considered for use in sliding wear resistance applications.[1,2] Because of their brittleness, ceramics are susceptible to high localized stresses and cannot yield locally like metallic components. Embedding carbides in a tough metallic matrix, thus forming a noncontinuous ceramic sliding surface, can improve sliding wear resistance.

Coatings containing titanium carbide have been deposited by plasma spraying.[2] These coatings were obtained by spraying composite powders formed by blending and agglomerating titanium carbide and metallic powders. Even though these coatings exhibited good wear properties, improvement could be obtained by reducing the size and spacing of carbide particles and by changing their shape from angular to spherical. Angular particles act as stress concentrating sites and promote coating failure.

Recently, multiphase multilayer coatings containing round TiC particles less than 1 μm in size dispersed in iron have been obtained by plasma spraying of reactive micropellets.[3,4] This article discusses assessment of the wear properties of these coatings using the ball-on-disc sliding wear test procedure recommended by the Versailles Advanced Materials and Standards (VAMAS) program.[5] The wear properties of plasma spray synthesized coatings also are compared to those obtained by spraying composite powders containing agglomerated TiC and iron powders. The performance of TiC-Fe coatings is related to their porosity and microstructure.

Keywords: ball-on-disc test, plasma spray, reactive spraying, TiC-Fe coatings, sliding wear resistance

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2. Materials and Experimental Procedure

Multiphase multilayer TiC-based coatings were obtained by plasma sprayed micropellets consisting of ferrotitanium and graphite. Details concerning the synthesis of TiC-Fe materials and the fabrication of micropellets have been described earlier.[3,4]

The specific microstructure of these TiC-Fe coatings, consisting of a stack of TiC-rich and TiC-poor lamellae, depends on the composition of micropellets and the spraying parameters. In addition to carbide content, the hardness of TiC-rich lamellae is sensitive to spraying parameters related to the solidification and cooling of droplets. Use of a higher solidification rate of droplets results in harder TiC-rich lamellae.

In this study, the TiC volume content was fixed at 60%, and three types of coatings were deposited on mild steel discs for sliding wear tests. The first coating was obtained by plasma spraying of as-fabricated reactive micropellets consisting of ferrotitanium, iron, and graphite. The second type of coating consisted of depositing reactive micropellets sintered in a neutral atmosphere at 875 °C. The third type of coating was produced by plasma spraying of spray-dried particles consisting of titanium carbide and iron powders mixed together.

Coatings with thickness up to 500 μm were deposited onto grit-blasted mild steel substrates. Vickers microhardness measurements were performed with a diamond indenter under a 50-g

Table 1 Hardness and microstructural features observed within TiC-Fe coatings and the reference/substrate material

Material	Microstructural feature	Microhardness, kg/mm^2
1020 Steel	Ferrite and pearlite	175
	Mean grain size, 30 μm	
TiC-Fe coatings with blended and spray-dried TiC and Fe powders	Angular carbides	>2000
	Lamallae-containing dissolved TiC	800-1000
	Fe-rich lamellae	300-500
Plasma spray synthesized TiC-Fe coatings	TiC-rich lamellae	1400-1480
	Fe-rich lamellae	300-500
Plasma spray synthesized TiC-Fe coatings (sintered micropellets)	TiC-rich lamellae	1500-1560
	Fe-rich lamellae	300-600

Table 2 Sliding ball-on-disc wear test parameters

Ball material	AISI 52100 steel
Ball diameter	10 mm
Normal load	10 N
Sliding speed	10 cm/s
Sliding distance	1 km
Specimen temperature	23 °C
Coating surface roughness	$R_a = 0.5$ μm
Lubricant	None used

load. The microstructural features of these coatings are given in Table 1. Plasma-sprayed TiC-Fe coatings were diamond ground and polished to obtain flat surfaces and uniform roughness (R_a = 0.5 μm) prior to testing.

Sliding wear tests were carried out in air with a ball-on-disc device following procedures recommended by the VAMAS Program,[5] except that the rotating AISI 52100 steel ball mated against the stationary coated disc, to which the load is applied, as shown in Fig. 1. The friction torque was recorded during the test, and data were converted to obtain the frictional force. The primary test parameters used in this study are listed in Table 2.

The disc wear track depth and width were measured with a Surtronic 3 Taylor-Hobson profilometer. The surfaces were examined by scanning electron microscopy before the test and after wear was apparent. The porosity of the coating surface was evaluated by image analysis. Porosity is reported as the mean of ten measurements performed on high-contrast optical micrographs.

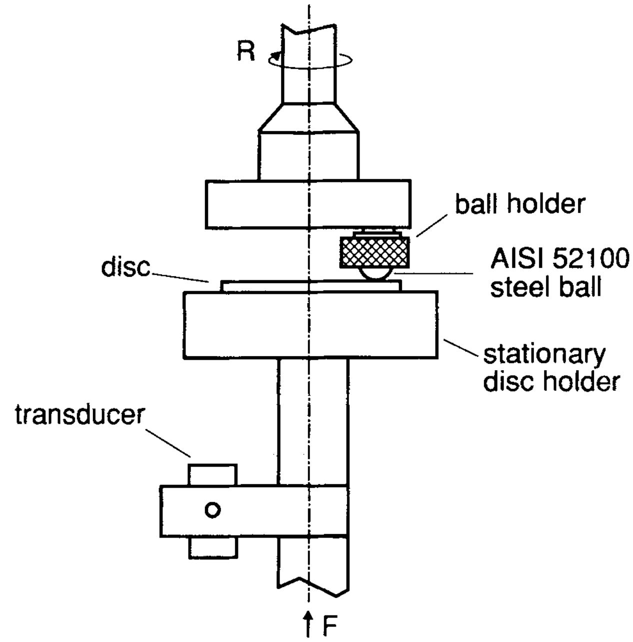

Fig. 1 Schematic of the ball-on-disc wear test apparatus.

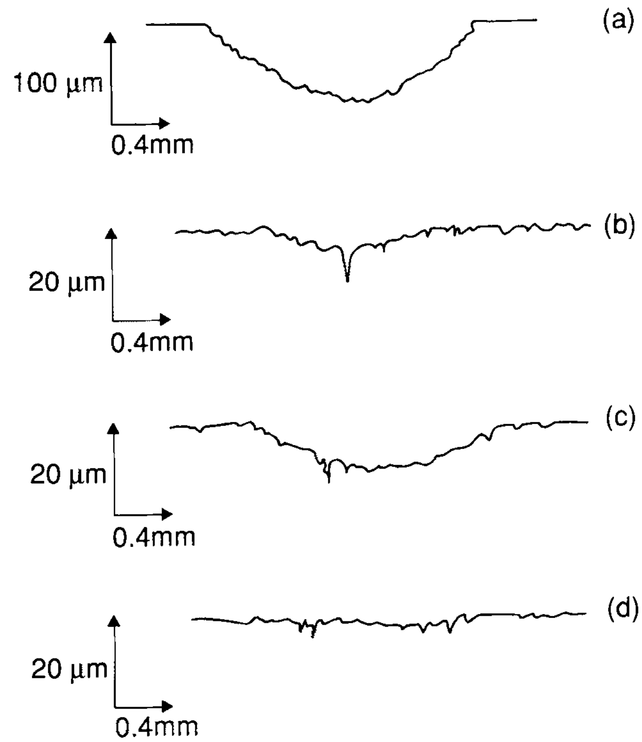

Fig. 2 Wear scar depth profiles for (**a**) steel and TiC-Fe coatings obtained from (**b**) blended and spray-dried TiC and iron powders, (**c**) reactive powders, and (**d**) sintered reactive powders.

3. Results and Discussion

3.1 *Weight Loss of the Ball and Coatings*

Wear data obtained after a 1000-m (1-km) sliding distance are summarized in Table 3 for steel and TiC-Fe coatings. The weight loss due to wear includes both weight loss from the TiC-Fe coating and the steel ball. In a sliding wear test, material is transferred from the ball to the disc, particularly when the hardness differential is large.[6] Thus, it is impossible to evaluate

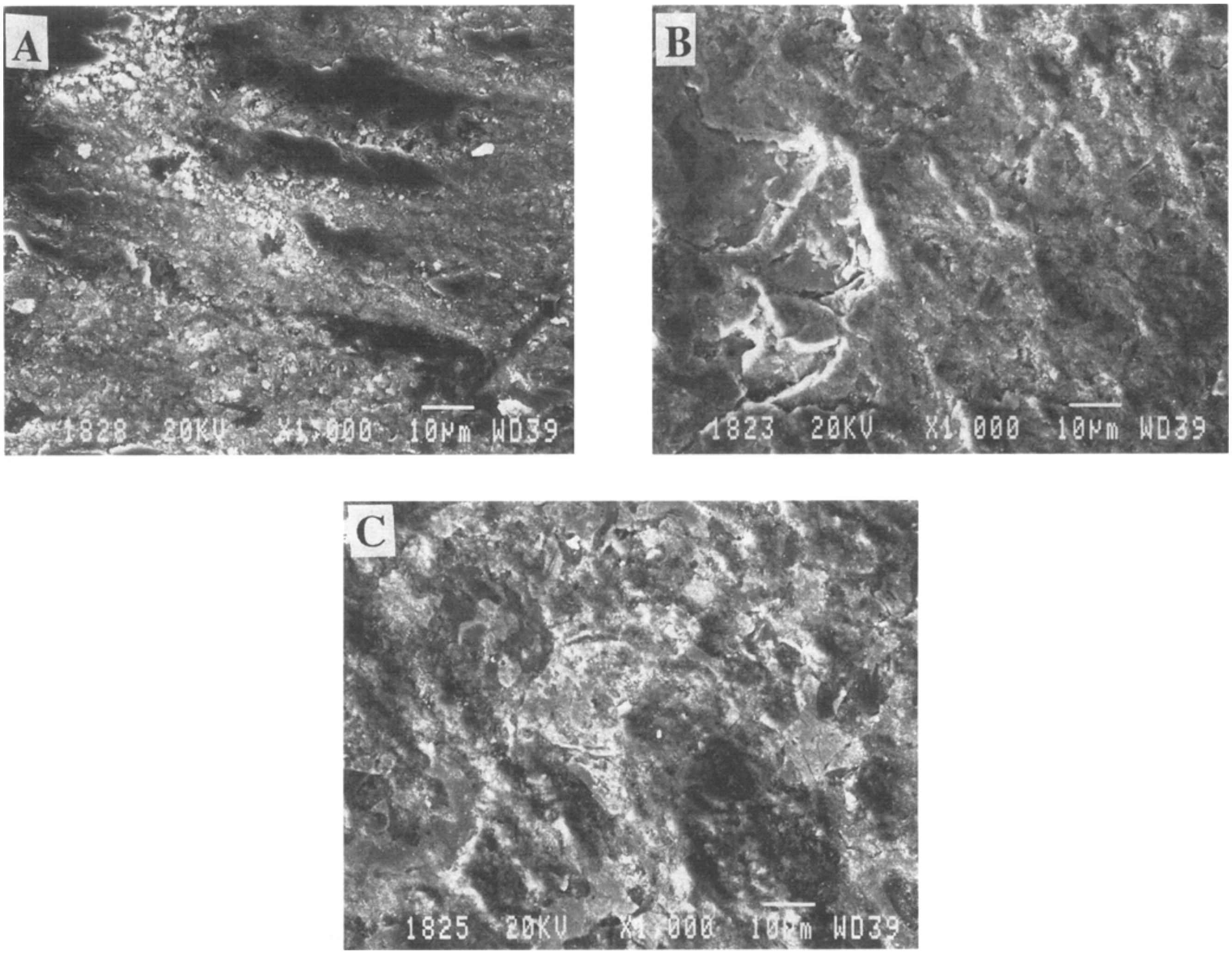

Fig. 3 Scanning electron micrographs of scars produced on TiC-Fe coatings obtained from **(a)** reactive powders, **(b)** sintered reactive powders, and **(c)** spray-dried TiC-Fe composite powders. Note in the left corner of (b) the surface fracture.

Table 3 Sliding wear data for TiC-Fe coatings

		Spray powder coatings, TiC-Fe			
Ball/disc	**Steel(a)**	**Spray-dried TiC + Fe**	**Spray-dried reactive**	**Spray-dried reactive and sintered**	**Accuracy(a)**
Total wear rate (ball and disc), mg/km..	53.4	5.7	4.9	3.9	0.2mg
Disc wear rate, µm/km	94	6	11	2	3%
Disc wear track width, mm	2.1	1.4	1.8	1.4	4%
Mean porosity, %	NA	21	32	27	NA
Standard deviation on porosity, %........	NA	2	3	5	NA

(a) NA, not applicable.

only the net disc wear loss. It is also worth mentioning that wear resistance is a system-dependent property.

Table 3 shows that TiC-Fe coatings obtained by plasma spraying of sintered reactive micropellets exhibit better wear behavior than steel and other types of TiC-Fe coatings. The wear rate of these coatings is low (3.9 mg/km).

3.2 *Surface Wear*

More information concerning the behavior of materials is obtained from the wear scar depth profile. The profiles for steel and all types of TiC-Fe coatings, as shown in Fig. 2, are similar even though the scar depths are different. The ripple features of the

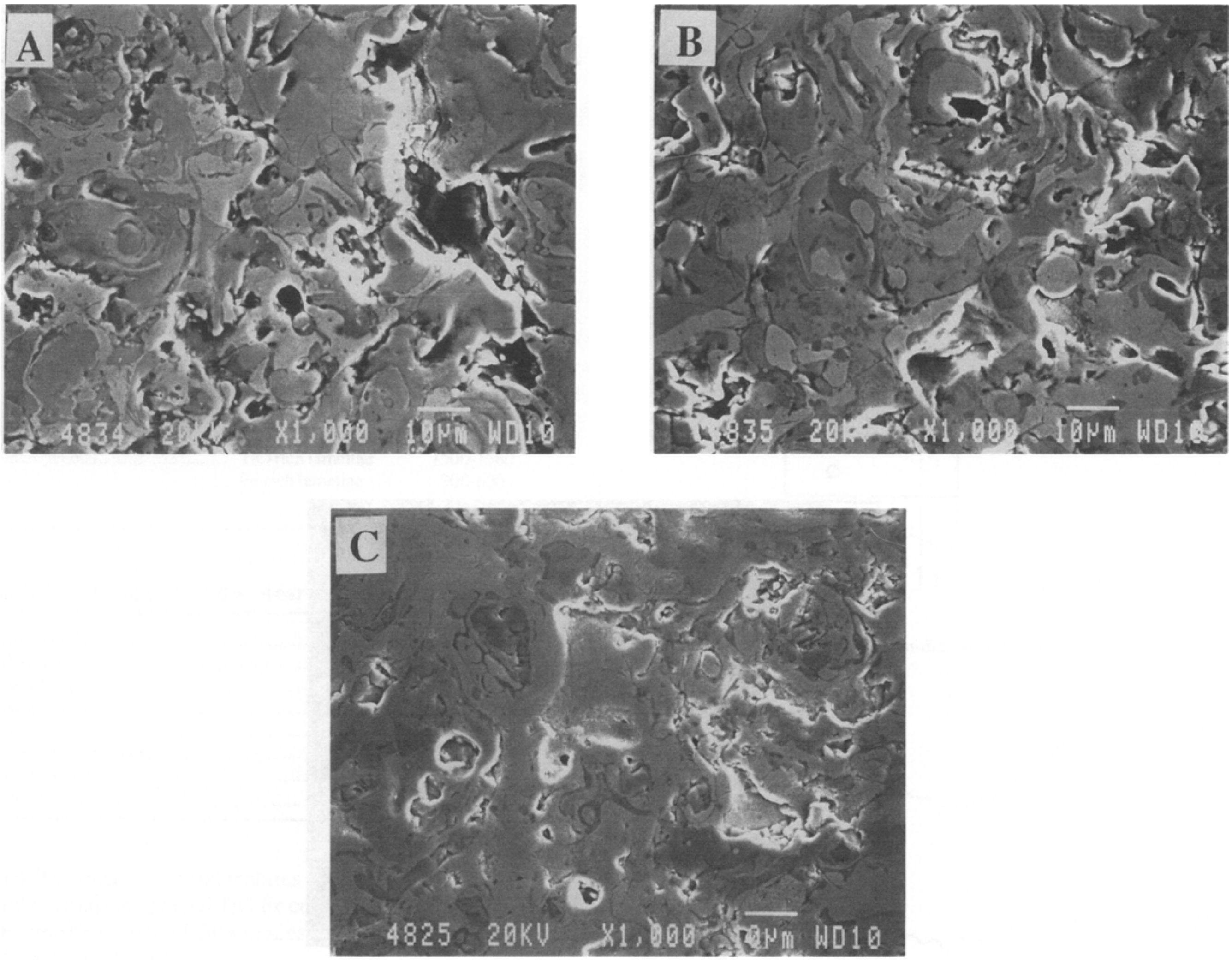

Fig. 4 Scanning electron micrographs of ground surfaces of TiC-Fe coatings obtained from **(a)** reactive powders, **(b)** sintered reactive powders, and **(c)** spray-dried TiC-Fe composite powders.

wear track (scar) indicate that steel coming from the ball is transferred onto the disc. Beyond these similarities, the different types of TiC-Fe coatings do not exhibit the same behavior in sliding wear applications. Indeed, a deep crevice can be seen at the bottom of the wear scar of the TiC-Fe coating obtained by spraying agglomerated TiC and iron powders. This crevice could result from a large and angular TiC particle acting as a single-point machining or plowing element. TiC-Fe coatings obtained by spraying of sintered reactive micropellets behave differently from other TiC-Fe coatings. Metal is transferred to the entire contact area, with little material removed from the coating.

Surface observation of scars (Fig. 3) confirms that material is transferred in the form of either thick tongues on coatings obtained by nonsintered reactive powders (Fig. 3a) or small islands on coatings obtained from sintered reactive powders (Fig. 3b) and also from agglomerated TiC and iron powders (Fig. 3c). Because a steel ball is used and all coatings contain steel, it was not possible to distinguish the ball material from the coating material by surface analysis.

3.3 *Role of Porosity*

Porosity is thought to play a role in explaining the behavior of TiC-Fe coatings. The bulk porosity lowers the tensile strength and leads to large particle removal. Surface porosity after grinding consists of cavities that form sites that are favorable to the adhesion of metal.[7]

As evaluated by image analysis, surface porosity of TiC-Fe coatings ranges from 21 to 32%. Less porous coatings are obtained by spraying agglomerated TiC and iron powders. Coatings obtained after spraying sintered reactive powders are less porous (27%) than those obtained from nonsintered reactive powders (32% porosity). Because the porosity reported here is the mean of ten measurements performed on each coating sample, the differences between each coating should be considered

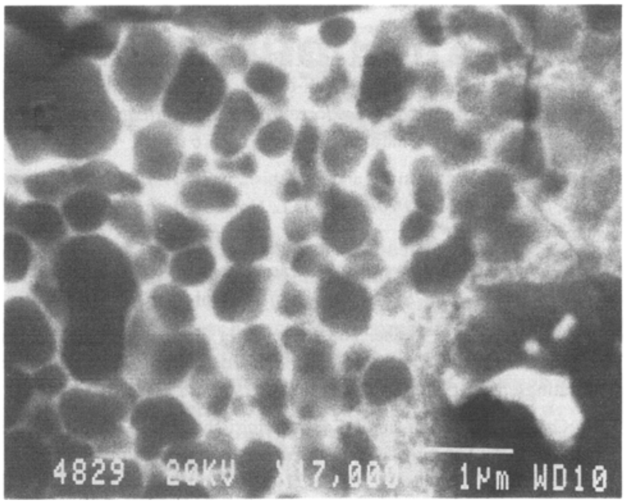

Fig. 5 Scanning electron micrograph of the surface of a TiC-Fe coating obtained from reactive powders, showing small and rounded TiC crystals next to one another.

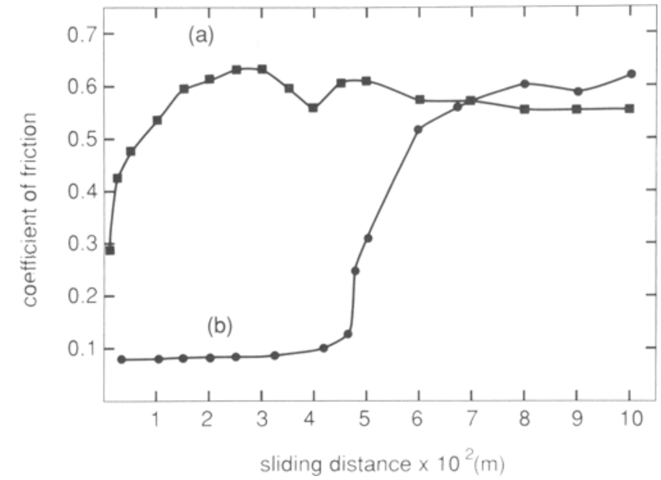

Fig. 6 Variation in the dynamic coefficient of friction as a function of the sliding distance for TiC-Fe coatings obtained from **(a)** spray-dried composite TiC-Fe powders and **(b)** sintered reactive powders.

rather than the absolute value of porosity. The standard deviation for such porosity measurements ranges from 2 to 5% of the mean value reported, as shown in Table 3. It is reasonable to assume that surface porosity corresponds to the bulk porosity of coatings and that the relative porosity values would be maintained even if there is measurement variability due to polishing procedure.

Sintering reactive powders makes them denser and improves their deposition efficiency.[4] The pore sizes of the TiC-Fe coatings are also different. Observation of ground surfaces, as shown in Fig. 4, reveals that the TiC-Fe coatings obtained from nonsintered reactive powders also have larger pores than other types of TiC-Fe coatings.

Therefore, it is thought that the large surface porosity and large pore size of TiC-Fe coatings obtained from nonsintered reactive powders contribute to the weakness of these coatings compared to other types of TiC-Fe coatings. Large cavities act as a cutting tool that removes material from the ball and thus promote the adhesion of more metal in subsequent cycles so that large tongues of material form. Because porosity decreases strength in an exponential manner,[8] more material is removed from the coating that is the most porous. The same behavior can be observed for other types of TiC-Fe coatings, but to a lesser extent.

Although more porous than TiC-Fe coatings obtained from agglomerated TiC and iron powders, TiC-Fe coatings obtained from sintered reactive powders are more wear resistant. Smaller islands of transferred and oxidized material are formed on the scar surface of these coatings, as shown in Fig. 3. Less material is transferred onto the surface, and there is very little removal of the coating material (see also Fig. 2). The microstructure of these plasma spray synthesized coatings is probably responsible for this behavior. They are composed of micron-sized TiC crystals dispersed in a ductile matrix with small spacings between the crystals (Fig. 5), which contributes to better yield strength than TiC-Fe coatings obtained from agglomerated TiC and iron powders.

3.4 *Frictional Behavior*

The frictional behavior of these two types of coatings is also different. As shown in Fig. 6, the coefficient of friction of steel sliding against TiC-Fe coatings obtained from agglomerated TiC and iron powders reaches 0.6 after a sliding distance of 200 m. This value corresponds to the coefficient of friction of steel. The frictional properties of these coatings are similar to those of the softer material of the couple as observed earlier.[6] Conversely, the friction behavior of TiC-Fe coatings obtained after spraying sintered reactive powders is vastly different. The coefficient of friction is as low as 0.1 up to approximately 500 m. Thereafter, it increases sharply to 0.6. This increase in the coefficient of friction is likely due to subsurface breakdown resulting from porosity. Such a surface collapse is shown in Fig. 3(b). Coefficients of friction lower than 0.1 have been reported recently for monolithic TiC-ferrous matrix composites containing between 72 and 42 vol% TiC with particle sizes between 0.31 and 0.62 μm.[9] The TiC-Fe coatings obtained after spraying sintered reactive micropellets contain 60 vol% TiC with particle sizes ranging from 0.3 to 1.1 μm (Fig. 5).

3.5 *Role of Debris*

The interfacial wear debris layers could have greatly influenced wear and friction of the system considered in the current study, as reported previously.[10,11] Thus, TiC-Fe coatings obtained from sintered reactive micropellets, because of their fine grain microstructure, may have generated minute debris that is entrapped by the surface porosity and acts as solid lubricants, thus reducing friction and wear rate. Such debris entrapment has been exploited in self-lubricating bushings.[12]

Conversely, TiC-Fe coatings obtained from blended TiC and iron powders contain large angular (irregular-faceted) particles unevenly distributed within the iron matrix. These TiC particles when liberated from their matrix, or fragments of these particles, constitute tough abrasive materials. Because the detailed mechanisms of debris formation, communition, migration, and consolidation into compacts with different structures and properties are still unknown in tribology, it is not appropriate to detail the role of debris when TiC-Fe coatings are subjected to sliding wear.

Except for its questionable role in entrapping debris and subsequently reducing the coefficient of friction, porosity adversely affects the wear properties of TiC-Fe coatings, regardless of their fabrication process.

4. Conclusion

Plasma sprayed synthesized TiC-Fe coatings obtained by spraying sintered reactive micropellets exhibit good wear behavior while sliding against steel. The low coefficient of friction and wear rate is thought to result from the fine grain microstructure of these coatings. Without sintering, reactive micropellets generate coatings with higher wear rates because of their higher porosity. TiC-Fe coatings obtained after spraying agglomerated TiC and iron, although the least porous, do not exhibit as good behavior as those obtained from sintered reactive micropellets, because of their coarser microstructure consisting of angular TiC particles within an iron matrix. Therefore, the sliding wear resistance of TiC-Fe coatings can depend on the size, shape, and cohesive strength of TiC particles dispersed within the iron matrix. Improvement in the tribological properties of TiC-Fe coatings obtained by spraying reactive micropellets would be achieved by increasing the coating density even at the expense of reducing the hard phase content within these coatings.

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