TRIBOLOGICAL PROPERTIES OF THERMAL SPRAY COATINGS

Prof. Ph.D. Virgil Geaman
Lecturer Ph.D. Mihai Alin Pop
Assoc. Prof. Ph.D. Dana Luca Motoc
Prof. Ph.D Irinel Radomir
Transilvania University of Brasov, Romania

Abstract

Thermal spraying techniques are coating processes in which melted or heated materials are sprayed onto a surface. Thermal spray coatings have a wide range of applications, for instance, by repairing machine parts damaged in service or by the production of parts with high wear resistance. Coating quality is usually assessed by measuring its porosity, oxide content, macro and microhardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.
The present paper analyses the thermal spray coatings by their tribological properties.

Keywords: Coatings, plasma spray, wear, adhesion, pin-on-disc

Introduction:

Thermal spraying is the process of applying coatings of high performance materials, such as metals, alloys, ceramics, cermets, and carbides, onto more easily worked and cheaper base materials [1].

Plasma spraying is part of thermal spraying, a group of processes in which finely divided metallic and non-metallic materials are deposited in a molten or semi-molten state on a prepared substrate. Plasma spraying is also the most common method for preparing ceramic coatings which are widely used for structural applications in order to improve wear resistance, corrosion, oxidization and erosion [2,3,4,5].

Plasma sprayed Al_2O_3/TiO_2, for example, have been widely used as wear-resistant coatings in textile, machinery, and printing industries [6]. Aluminum oxide (Al_2O_3) is a well-established and relatively inexpensive material, which is used in many tribological applications in the form of sintered monolithic components (as wear inserts) or as coatings [7].

Al_2O_3 ceramic coatings, having superior hardness, chemical stability and refractory character, are commonly utilized to resist wear by friction and solid particle erosion [8,5]. Applications of these materials vary widely but encompass cutting tools, grinding wheels, and certain critical automotive components like piston rings [7].

Ceramic coatings based on alumina are a good alternative in applications where good tribological properties, elevated hardness and high thermal resistance are required. Alumina is brittle and the addition of titanium oxide leads to a balanced equilibrium of properties maintaining enough hardness and increasing considerably the coating toughness.

Titanium oxide has a lower melting point and plays a role of binding alumina grains to achieve coatings with a higher density [9].

During the past 10 years, many research groups have prepared successfully nanostructured ceramic coatings using plasma spraying and other thermal spraying methods. Recently, the studies on nanostructured materials have shown that they could present excellent properties that differ markedly from their conventional bulk materials [10].

2. Materials

Many researchers reported that the Al_2O_3–TiO_2 coatings containing 13 wt.% of TiO_2 showed the most excellent wear resistance among the Al_2O_3–TiO_2 ones. They interpreted the excellent wear resistance of the nanostructured Al_2O_3-13 wt.%TiO_2 coating than that of conventional Al_2O_3-13 wt.%TiO_2 coating as the presence of partially melted regions inside the nanostructured coatings [3].

Tribological behaviour of Al_2O_3-13%TiO_2 nanostructured and conventional coatings deposited by atmospheric plasma spray has been experimentally analysed by A. Rico et al. [9].

Conventional coatings were obtained from commercial powder METCO130 and modified. Nanostructured Al_2O_3-13%TiO_2 coatings were prepared from agglomerates. The agglomerates, constituted by nanometric particles with average size of 200 nm, were prepared by spray drying. In both cases, conventional and nanostructured coatings, a bond coat type: Ni-Al-Mo 90/5/5 (%wt) was inserted between substrate and ceramic coating to enhance the adherence.

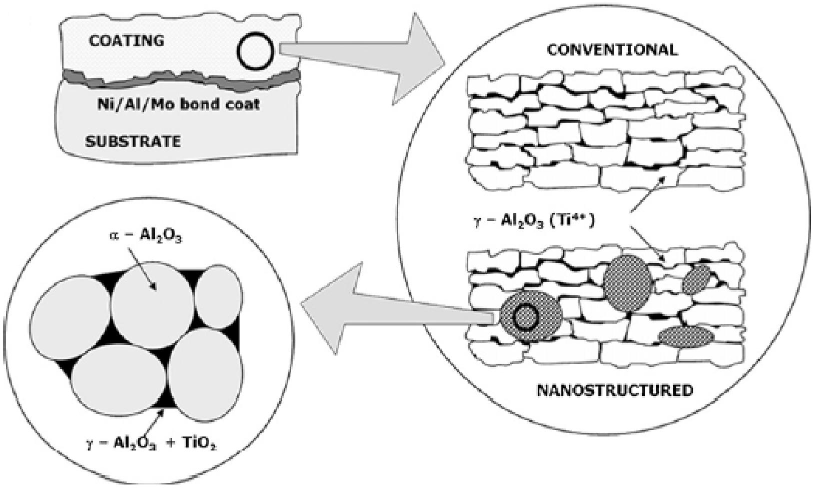


Fig. 1. Diagram showing the hierarchical microstructure of the nanostructured coating. A comparison with the conventional coating is also included [9].

3. Wear resistance

3.1. Dry sliding wear resistance of alumina-titanium coatings

Wear tests were carried out in a wear testing machine with a pin-on-disc configuration under dry sliding conditions without eliminating the debris formed. Both materials exhibit a transition between mild and severe wear regimes, given by an abrupt increment of the wear rate. The transition pressure is higher for the nanocoating, extending therefore, the mild wear regime. Both conventional and nanostructured coatings exhibit a typical splat microstructure, very commonly observed in thermal spray coatings.

In Fig. 1, a diagram showing the hierarchical microstructure of the nanostructured coating, and a comparison to the conventional one, is presented. The first microstructural level corresponds to the splat morphology. In this level, the cracks interact with the splat borders. The second microstructural level is related to the presence of the partially melted zones. In this level, the cracks can interact not only with the splat boundaries, but with the nanoparticles placed inside the partially melted zone. The second microstructural level is not present in the conventional coating.

The wear mechanisms identified in both coatings are predominantly related to brittle propagation of cracks, so the material fracture toughness could be considered the key parameter controlling the wear behaviour.

When the severity of the contact is low, for nominal pressures below the critical one (20MPa and 30MPa for the conventional and nanostructured coatings, respectively), the main wear mechanism is in both coatings the crack propagation through the splats boundaries, because these are the weakest regions. At high loads, for nominal pressures above the critical one (20MPa and 30MPa for the conventional and nanostructured coatings, respectively) transversal cracks growing from the top surface can be detected. These cracks tend to pass through the splats, easily reaching the boundary between the ceramic coating and the bond layer and multiplying the damage in the material by complete spalling. They are associated with a substantial increment in the friction coefficient and a huge rise of several orders of magnitude in wear rates [9].

3.2. Fretting wear resistance of alumina-titanium coatings

W. Tian et al. investigated the fretting wear behaviour of alumina-titanium fabricated also by plasma spray [11]. In this case a bond coating of NiCrAl was deposited on the metal substrate. Fretting is a small amplitude oscillatory movement occurring between contacting surfaces, which are usually nominally at rest. That movement may result from external vibration (fretting wear) or cyclic stress (fretting fatigue), and both cases may give rise to service failure due to the production of debris or the initiation and propagation of fatigue cracks.

Fretting wear tests of nanostructured and conventional Al_2O_3-13wt%TiO_2 coatings, were carried out on a PLINT fretting fatigue machine (Fig.2.) under unlubrication condition.

The wear scar of conventional coating was much deeper and wider than that of nanostructured coating under both C1 and C2 fretting wear conditions (Table 1). In addition, increasing the displacement amplitude, the depth of wear scar was not obviously increased for nanostructured Al_2O_3-13 wt%TiO_2 coatings. For the conventional coating, the depth and width of wear scars obviously increased when fretting displacement amplitude increased. It could be concluded that the nanostructured Al_2O_3-13 wt%TiO_2 coatings possess much better fretting wear resistance than the conventional Al_2O_3-13 wt%TiO_2 coatings [11].

Table 1. Depth of wear scar (nm), [11]

	C1 fretting condition (D=60µm; P=50N; N=10.000)	C2 fretting condition (D=200µm; P=50N; N=10.000)
Nanostructured coating	6 7	
Conventional coating	12 >20	

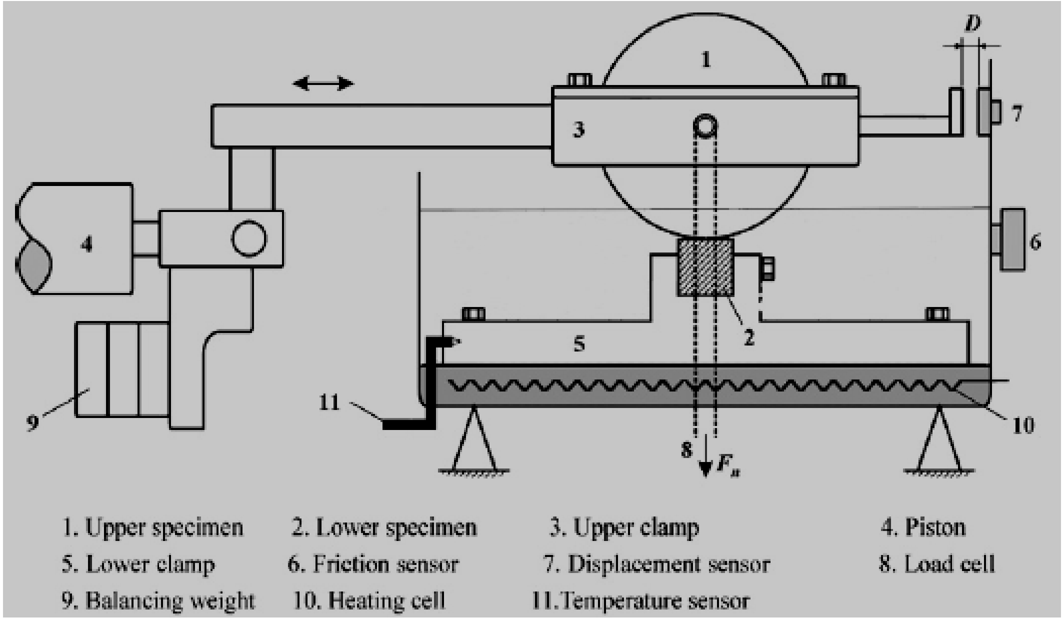


Fig. 2. Schematic illustration of fretting wear testing machine [11]

4. Effects of plasma spraying conditions on wear resistance

Previous studies have shown that the coating microstructure and properties are not only dependent of the characteristics of the feed powder, but also of the thermal spray condition [6]. Spraying conditions such as critical plasma spray parameter (CPSP) and distance between a spraying gun and a substrate can affect the final coating microstructure and consequently the wear resistance [3, 4].

4.1. Effects of CPSP on wear resistance

In the nanostructured Al_2O_3–TiO_2 coatings, the amount of partially melted regions varies with the CPSP [3]. The partially melted regions can play an important role in determining the overall hardness of the coatings because they are softer than the fully melted regions and their volume fraction is varied in the coatings. Thus, the overall hardness of the coatings increases as the volume fraction of partially melted regions decreases with increasing CPSP [4].

The hardness increase generally matched with the increase in wear resistance, although the hardness and wear resistance were not correlated in the coating fabricated with the low CPSP [3]. Anyway, the addition of 25 vol.% of partially melted regions as toughening reinforcements in the coating fabricated with the low CPSP provided the better wear resistance than that of the coatings fabricated with higher CPSP because the improved resistance to fracture might compensate a deleterious effect of the hardness decrease [3].

4.2. Effects of spray distance on wear resistance

If the spray distance is too short, nanopowders may be insufficiently melted, or the moving speed of nanopowders is not fast enough to form dense coating layers. Thus, the plasma spraying technique should be conducted at an appropriate distance or farther in order to enhance the deposition efficiency of nanopowders.

The temperature and speed of plasma flame or spray nanopowders are schematically plotted as a function of spray distance as shown in Fig. 3.

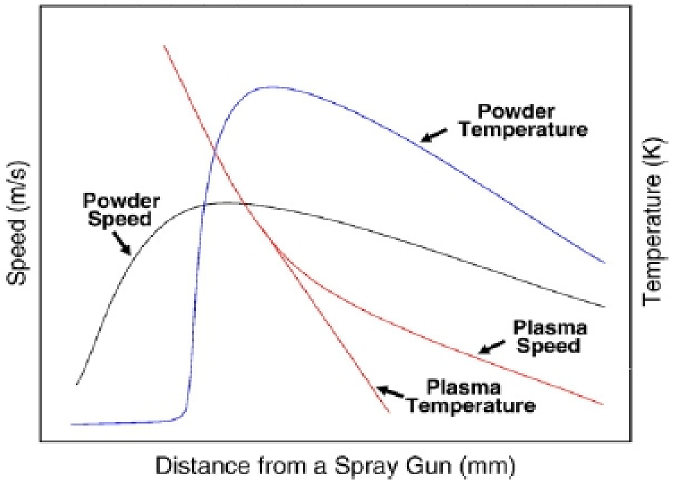


Fig. 3. Temperature and speed of plasma flame, as a function of spray distance from spray gun [3].

According to Eun Pil Song et co. the coatings fabricated at the long spray distance contained a considerable amount of pores and partially melted regions resulting the deterioration of the wear resistance [3]. When the spray distance decreases, dense coatings could be fabricated. In these coatings, cracks or spelled-outs of oxides were hardly found on the smoothly worn surface.

4.3. Coefficient of friction

Results of coefficient of friction measurement by pin-on-disc technique, are summarized in the figure 4. For all coatings, the coefficient of friction reaches the highest values for the lowest pin load. With increasing load, the coefficient of friction tends to a steady-state value [12].

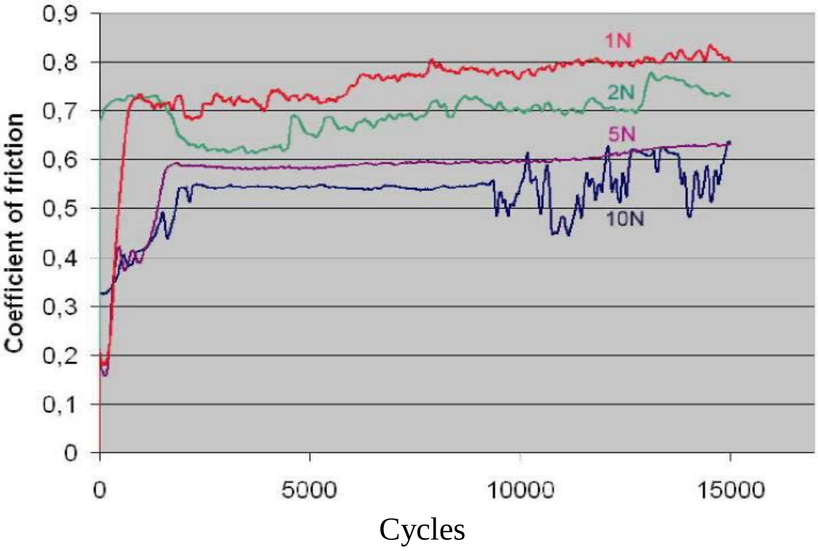
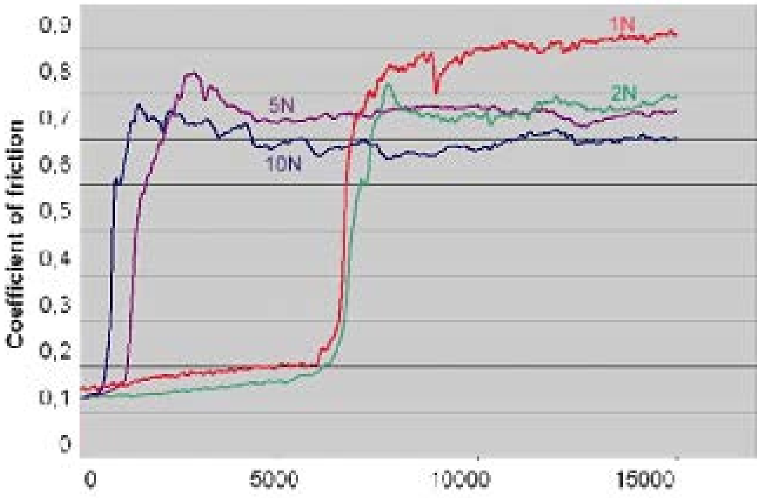


Fig. 4. Coefficient of friction records for Cr_3C_2-NiCr coating

In the Fig. 5, the coefficient of friction records for Cr_3C_2-NiCr can be seen.

In the case of electric arc sprayed coatings 95 MXC, the coefficient of friction records for 1N and 2N had very long rise time (Fig. 5).



Cycles

Fig. 5. Coefficient of friction records for 95 MXC coating

The 95 MXC coating has, due to its heterogenous structure, worse friction and wear properties. For tribological application it could be recommended only if it could not be used for plasma sprayed coatings.

5. Conclusions

In this paper tribological behaviour of alumina-titanium nanostructured and conventional coatings has been analysed, leading to the following conclusions:

- In the low load regime (below the critical pressure) nanostructured coating wear rates are lower than those for the conventional coating in the same regime.

- The wear scar of conventional coating was much deeper and wider than that of nanostructured coating under both C1 and C2 fretting wear conditions. It could be concluded that the nanostructured Al_2O_3-13 wt%TiO_2 coatings possess much better fretting wear resistance than the same conventional coatings.

- The addition of 25 vol.% of partially melted regions as toughening reinforcements in the coating fabricated with the low CPSP provided the better wear resistance than that of the coating fabricated with the higher CPSP because the improved resistance to fracture might compensate a deleterious effect of the hardness decrease.
- When the spray distance decreases, the dense of coatings could be fabricated. In these coatings, cracks or spelled-outs of oxides were hardly found on the smoothly worn surface.

References:

Witherspoon, F.D., Massey, D.W., Kincaid, R.W., Whichard, G.C. & Mozhi, T.A. (2002). *High Velocity Pulsed Plasma Thermal Spray*. Journal of Thermal Spray Technology, Vol. 11(1), 2002, pp. 119-128.

Fauchais P, - *Topical review - Understanding plasma spraying*, Journal of physics and applied physics, vol. 37, 2004, pp. 86-108.

Eun P.S., Jeehoon A., Sunghak L., Nack J. K. - *Effects of critical plasma spray parameter and spray distance on wear resistance of* Al_2O_3*–8 wt.%*TiO_2 *coatings plasma-sprayed with nanopowders*, Surface & Coatings Technology 202 (2008) pp. 3625–3632.

Eun P.S., Jeehoon A., Sunghak L., Nack J.K. - *Microstructure and wear resistance of nanostructured* Al_2O_3*–8wt.%*TiO_2 *coatings plasma-sprayed with nanopowders*, Surface & Coatings Technology 201 (2006) pp. 1309–1315.

Jingde Z., Kangning S., Jiangting W., Baoyan T., Hongsheng W., Yansheng Y. - *Sliding wear behavior of plasma sprayed* Fe_3Al*–*Al_2O_3 *graded coatings*, Thin Solid Films 516 (2008) pp. 5681–5685.

Meidong W., Leon L.S. - *Effects of the powder manufacturing method on microstructure and wear performance of plasma sprayed alumina–titania coatings,* Surface & Coatings Technology 202 (2007) pp. 34–44.

Dearnley P.A., Kern E. and K L Dahm K.L.- *Wear response of crystalline nanocomposite and*
glassy Al_2O_3*–SiC coatings subjected to simulated piston ring/cylinder wall tests*, Proc. IMechE Vol. 219 Part L: J. Materials: Design and Applications (2005) pp. 121-137.

Zhijian Y., Shunyan T., Xiaming Z., Chuanxian D. - *Microstructure and mechanical properties of* Al_2O_3*–Al composite coatings deposited by plasma spraying,* Applied Surface Science 254 (2008) pp. 1636–1643.

Rico A., Rodriguez J., Otero E., Zeng P., Rainforth W.M. - *Wear behaviour of nanostructured alumina–titania coatings deposited by atmospheric plasma spray*, Wear 267 (2009) pp.1191–1197.

Huang C., Soowohn L., Xuebing Z., Chuanxian D. - *Evaluation of unlubricated wear properties of plasma-sprayed nanostructured and conventional zirconia coatings by SRV tester*, Wear 260 (2006) pp. 1053–1060.

Tian W., Wang Y., Yang Y. - *Fretting wear behavior of conventional and nanostructured* Al_2O_3*–13 wt%*TiO_2 *coatings fabricated by plasma spray,* Wear 265