Characterization of Wear Properties of Plasma Sprayed Ceramic Coatings

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The paper presents experimental results of the structural and tribological characteristics of various zirconia and alumina based ceramic coatings. Ceramic coatings with the thickness up to 60 μm were prepared by plasma-spray technique on the titanium steel substrates employing non-equilibrium plasma spray technology at atmospheric pressure. The effect of alumina addition up to 85 wt.% on the morphology and wear behavior of yttria stabilized zirconia coatings was investigated. The hardness and tribological characteristics of plasma deposited ceramic coatings have been determined in relation with the microstructure of the coatings. The wear properties of sprayed ceramic samples were investigated under water lubricated conditions.
Keywords: ceramic powder, plasma spraying, coating, microstructure, wear properties.

1. INTRODUCTION

Amongst a huge variety of solid materials with improved wear resistance, high temperature oxide ceramic materials gained an increased interest in the last years for their physical and chemical natures and are often used for many applications to extend the lifetime and reliability of the metallic components. Alumina and zirconia materials are widely used due to their superior properties. Alumina shows a very high hardness, wear resistance and an extreme chemical stability [1]. Zirconia based ceramics are characterized by good physical and chemical properties such as high chemical, thermal, and mechanical stability [2]. The combination of the positive properties of alumina and zirconia seems to be desirable for the preparation of durable ceramic coatings [3, 4].

Plasma technologies are widely used for surface hardening of materials in order to improve wear, corrosion resistance and performance parameters [5 – 8]. The use of coatings can improve the properties of substrate materials. Plasma spraying is well-developed technique for preparation of metals, ceramic or composite coatings with improved wear resistance and surface hardness [8, 9]. Plasma spray deposition is a new technique for near-net-shape fabrication, especially suitable for near-net-shape fabrication of hard-to-form ceramic or metallic objects with layered structure and thin walls [10, 11].

A lot of works have been done to study the formation process and properties of hard protective coatings and understand the mechanisms of wear of coated surfaces. The thickness, hardness and adhesion of the coating, the roughness of the coated surfaces are main tribologically important properties of the coated surface [12]. The presence of wear debris in the tribological contact intensifies the wear process of the material. The size and hardness of the loose particles or debris affect the wear behaviour of the surfaces [9, 13].

Many investigations have been carried out to improve the microstructure and properties of yttria stabilized zirconia (YSZ) thin films by the addition of alumina (Al_2O_3) [14, 15]. The Al_2O_3 added to 8YSZ improves the sinterability of the deposited layer and reduces the sintering time [14]. A small addition of Al_2O_3 (about 3 wt.% – 4 wt.%) allows producing of plasma sprayed YSZ layer with higher value of bulk density [15, 16]. Doping the zirconia with alumina eliminates degradation phenomena due to zirconia phase transformation resulting in micro/macro cracking and degradation of the properties [17].

Aluminum oxide and zirconium oxide are ceramic materials very widely utilized in plasma spray processes to produce parts of machines for numerous industrial applications [15 – 17]. Typical applications of plasma-sprayed alumina coatings are thermal barrier coatings and wear resistance coatings for biomedical components [18]. High purity alumina coatings are used in load-bearing hip prostheses for improved osseointegration of the implants and protection the substrate metal against corrosion from the body fluids [18]. The increasing requirements of wear resistant materials and coatings for total hip replacement (THR) requires new ceramic materials and combinations [17]. Nanostructured zirconia – 30 vol.% alumina composite coatings were deposited by atmospheric plasma spraying using nanosized ZrO_2 and Al_2O_3 powders in [19]. Compared to pure zirconia coating, the microhardness of the as-sprayed coating increased from 5.7 GPa to 8.4 GPa, and the roughness increased from 3.74 μm to 6.03 μm with the addition of alumina into feedstock. The investigation of the mechanical properties of 10 vol.% zirconia/alumina composite pointed to crack-free composites with increased fracture toughness [20]. The development of plasma sprayed zirconia coatings by atmospheric plasma spray technology requires better understanding of both mechanical and thermal behaviour of the coating materials to ensure the durability and stability of the coated components.

The purpose of this study was to find out the effect of alumina addition on mechanical properties and microstructural characteristics of plasma sprayed yttria stabilized

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zirconia coatings. The influence of different feed stock materials prepared from alumina and zirconia on the Vickers microhardness and roughness of plasma sprayed coatings was investigated. The wear properties of samples were tested under demineralised water.

2. EXPERIMENTAL

The test substrates of 2 mm thickness were made from titanium steel. The surface of substrates was hand-polished to 0.5 µm finishing, cleaned by acetone and dried in air.

Plasma sprayed coatings were deposited employing non-equilibrium plasma spraying technology at atmospheric pressure [21], suitable for various engineering applications. A distance of 70 mm was chosen between the reactor exit and substrate fixed on a cooled plate. The coatings were formed moving plasma torch in horizontal direction. The main operating parameters of the plasma torch were: power – 49 kW – 51 kW, total gas flow rate – 5.13 gs^{-1}, additional hydrogen flow – 0.13 gs^{-1}, the average velocity – 1450 ms^{-1} and temperature – 3750 K – 3800 K.

Microscopy of deposited coatings was performed using scanning electron microscopy (SEM, JSM 5600) and optical Olympus BX51 microscope and high-resolution digital color camera Go-21 with QCapture software. The hardness of plasma coatings was measured on polished surface by means of Vickers microhardness tester PMT-3 (Russia) using a load of 100 g. The surface roughness of coating layers was measured by surface analyzer-profilometer HOMMEL TESTER T500 (Germany). The wear tests of deposited coatings were carried out using home made test bench with sliding surfaces [22]. Sliding velocity during the experiments was 0.3 ms^{-1}, the load applied was 3 N. Distilled water was used as a lubricant.

3. RESULTS AND DISCUSSION

The powders applied in the investigations are characterized in Table 1. Zirconia powder stabilized with 8 wt.% yttria (YSZ) was used as zirconia precursor. The composition of investigated feed stock materials for plasma spray deposition is presented in Table 2.

Table 1. Some characteristics of the powders used

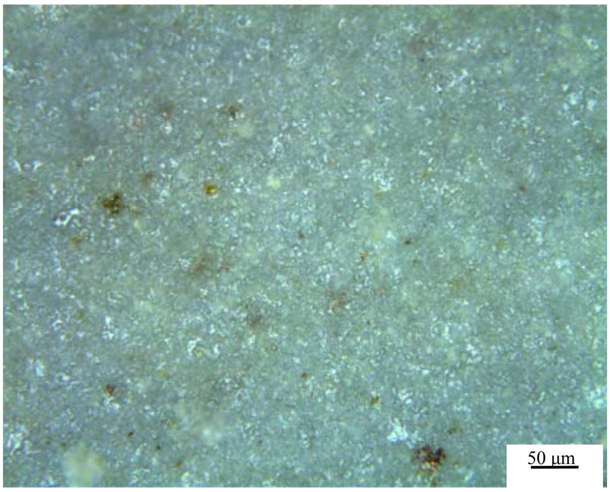
Notation	Powder	X-ray phases	Particle size, µm
Z	ZrO_2 + + 8wt.% Y_2O_3	Tetragonal	1.68
A	Al_2O_3	α-alumina	<10

Table 2. Composition of the powders used for plasma spraying

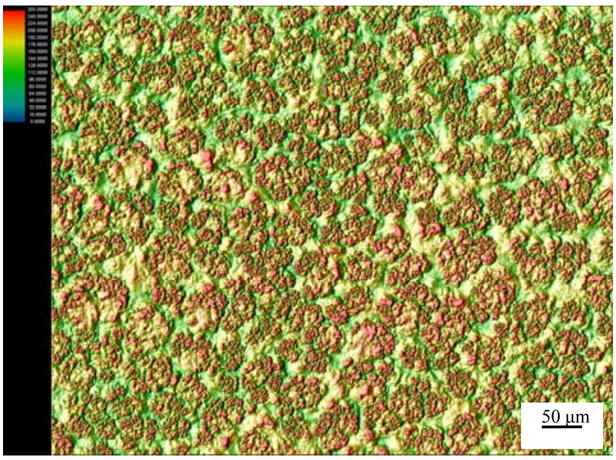
Notation	Alumina content, wt.%	Zirconia content, wt.%
Z100	0	100
ZA15	15	85
ZA85	85	15
A100	100	0

Analysis of SEM and optical views of plasma sprayed coatings showed, that all coatings are characterized by homogeneous and dense structure (Fig. 1). The distribution of pores and voids is quite homogeneous. The morphology of all samples is quite similar despite of the different composition of started powder. The thickness of sprayed samples evaluated from the cross-sectional SEM observation is about 60 µm.

a



b



c

Fig. 1. Typical SEM (a) and optical views (b and c) of as-sprayed coatings: a – Z100; b, c – A100

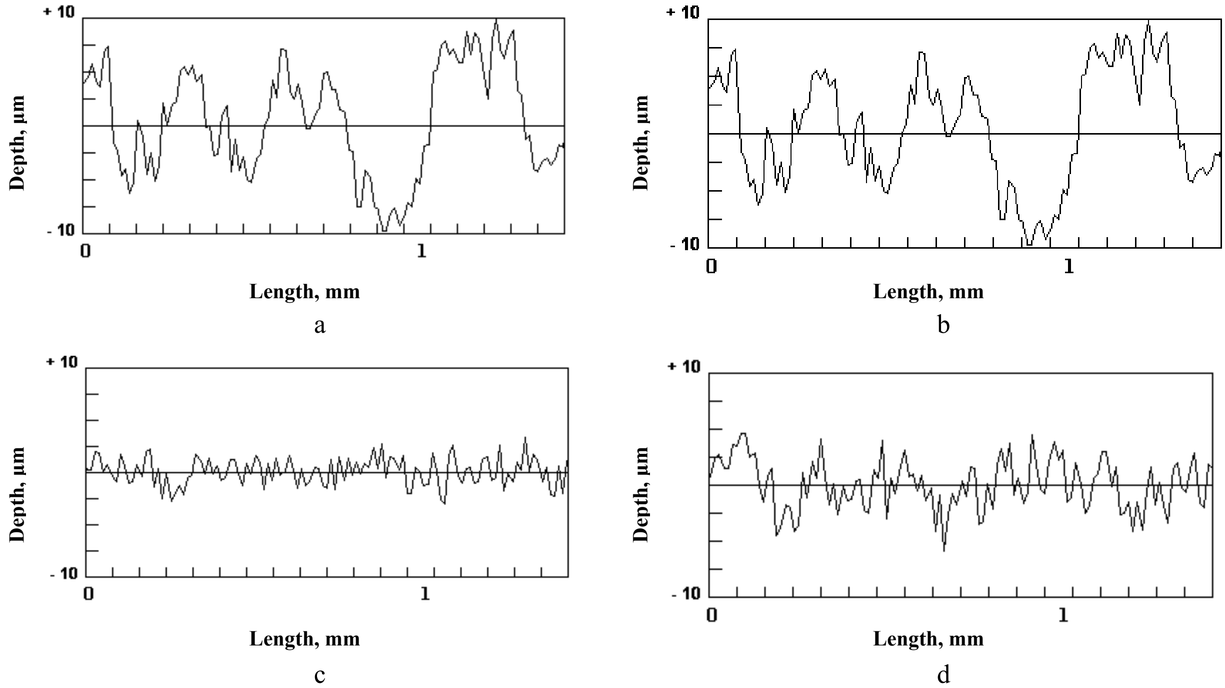


Fig. 2. Surface profiles of plasma sprayed ceramic coatings: a – Z100, b – AZ15, c – ZA85, d – A100

The roughness profiles of the as-sprayed surfaces obtained by traversing across the test surfaces using a profilometer are rather divers (Fig. 2). The less roughness is typical for ceramic coatings with higher content of alumina (Fig. 2, c and d). The main parameters of surface roughness *Ra* of as-sprayed ceramic coatings are presented in Table 3. Typical surface plot profile of plasma sprayed coating with wear track under the load of 100 g is shown in Figure 3.

In order to identify the wear mechanism, the worn surfaces of plasma sprayed samples were examined after the wear test by optical microscopy and profilometer. The values of parameter *Ra* after wear test are presented in Table 3. The coatings based on alumina ceramics (A100 and ZA85) revealed higher wear resistance.

Single scratch tests were carried out on the coatings surfaces under the load of 100 g. Figure 3 presents the optical images of wear track. The results of scratch analysis revealed, that wear mechanism is similar for all investigated materials. Under the load investigated, it is noticed, that the intensity of wear of plasma sprayed Z100 coating is higher compare to other plasma sprayed samples. The line profiles of the optical view of wear tracks were used to evaluate the spacing between the two edges of the wear track. The x-axis represents the distance along the line and the y-axis is the pixel intensity. The typical optical views and line profiles of scratches perpendicular to the scratching direction were presented in Figure 4.

Vickers microhardness values of all tested samples are presented in Table 3. Plasma sprayed coatings based on alumina ceramics (ZA85 and A100) are characterized by higher microhardness.

Analyzing the optical view images of the worn surfaces of plasma sprayed coatings after wear test under water-lubricated conditions and images of wear tracks, it may be presume, that dominant wear mechanism is abrasive wear.

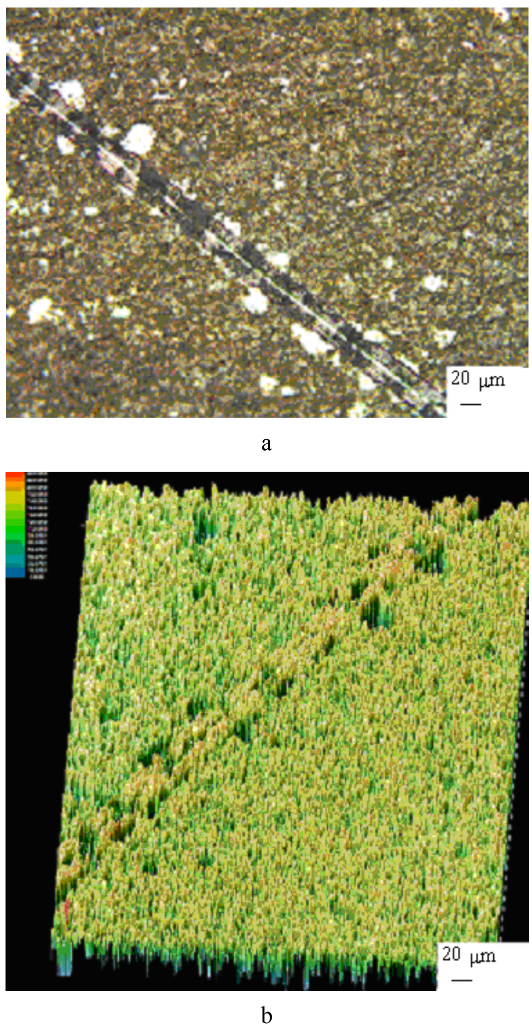
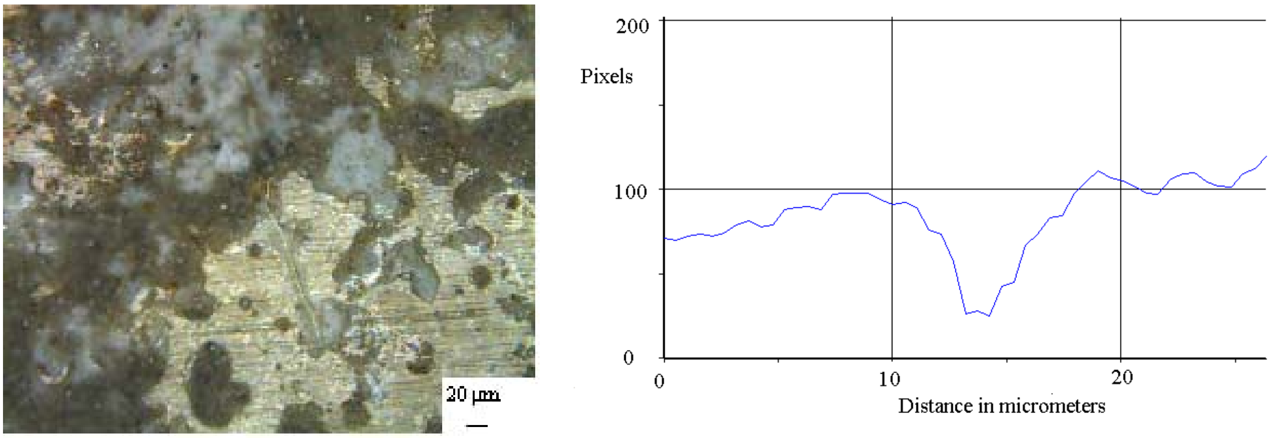
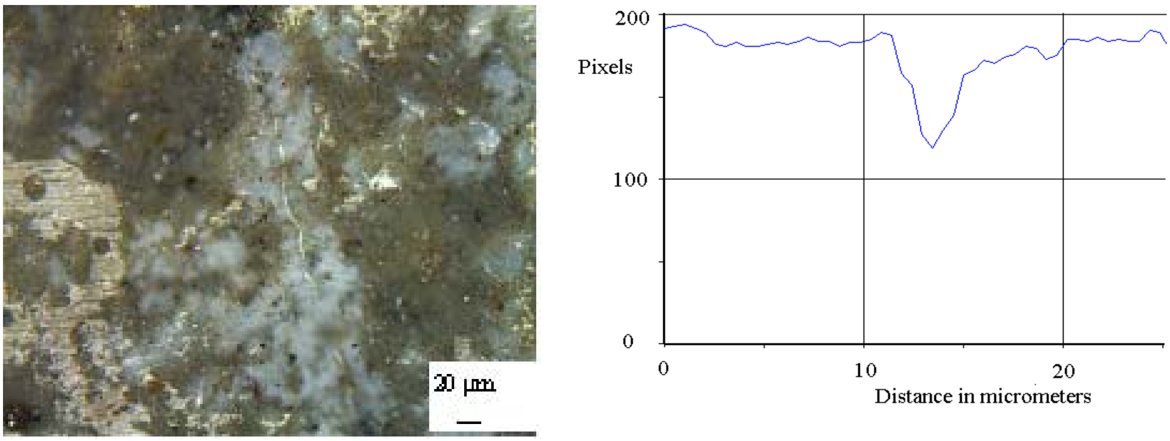


Fig. 3. Typical optical view and surface plot of plasma sprayed coating Z100 with wear track



a



b

Fig. 4. Optical views and wear track line profiles of plasma sprayed coatings ZA85 (a) and A100 (b) after wear test

Table 3. Vickers microhardness and variation of surface roughness parameter *Ra* for as-sprayed ceramic coatings and after wear test under the load of 3 N

Coatings	Vickers microhardness H_{100}	*Ra*, µm	
		As-sprayed	After wear test
Z100	9270	3.18	1.13
ZA15	10920	3.48	1.36
ZA85	12870	0.96	0.8
A100	14010	1.38	1.14

4. CONCLUSIONS

The wear properties of plasma sprayed coatings under water-lubricated conditions were authorized by the their microstructure. The homogeneous microstructure is relevant to higher microhardness and better tribological properties of sprayed ceramics. By the analysis of worn surfaces, the dominant wear mechanism for the plasma-sprayed coatings is abrasive wear.

The microhardness measurements data resulted that coatings formed from alumina based ceramics are characterized by higher microhardness values. The higher wear resistance is specific to the plasma coatings with high alumina content too.

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REFERENCES

1. Alpha Alumina Protective Coatings (Al_2O_3, Aluminum Oxide) with Excellent Adhesion from NextTechs Technologies. Online at http:/www.azom.com.
2. **Chen, H., Zhang, Y., Ding, C.** Tribological Properties of Nanostructured Zirconia Coatings Deposited by Plasma Spraying *Wear* 253 (7) 2002: pp. 885 – 893.
3. **Kurzweg, H., Heimann, R. B., Troczynski, T., Wayman, M. L.** Development of Plasma-sprayed Bioceramic Coatings with Bond Coats Based on Titania and Zirconia *Biomaterials* 19 1998: p. 1507.
4. **Liang, B., et al.** Nanostructured Zirconia – 30 vol.% Alumina Composite Coatings Deposited by Atmospheric Plasma Spraying *Thin Solid Films* 484 (1 – 2) 2005: pp. 225 – 230.

5. Surface Engineering for Corrosion and Wear Resistance. Ed. by J. R. Davis. Woodhead Publishing Limited: Cambridge, 2001.
6. **Liang, H., Shi, B., Fairchild, A., Cale, T.** Applications of Plasma Coatings in Artificial Joints: an Overview *Vacuum* 73 2004: pp. 317 – 326.
7. **Skoric, B., Kakas, D., Gredic, T.** Influence of Plasma Nitriding on Mechanical and Tribological Properties of Steel with Subsequent PVD Surface Treatments *Thin Solid Films* 317 1998: pp. 486 – 489.
8. **Kaufmann, H.** Industrial Applications of Plasma and Ion Surface Engineering *Surface & Coatings Technology* 74 – 75 1995: pp. 23 – 28.
9. **Holmberg, K., Matthews, A., Ronkainen, H.** Coatings Tribology – Contact Mechanisms and Surface Design *Tribology International* 31 1998: pp. 107 – 120.
10. **Shi, S., Hwang, J. Y.** Plasma Spray Fabrication of Near-net-shape Ceramic Objects *Journal of Minerals & Materials Characterization & Engineering* 2 2003: pp 145 – 150.
11. **Gopalakrishnan, M. V., Metzgar, K., Rosetta, D., Krishnamurthy, R.** Structural Characterisation and Strength Evaluation of Spray Formed Ceramic Composite Near-net Shapes *Journal of Materials Processing Technology* 135 (2 – 3) 2003: pp. 228 – 234.
12. **Voevodin, A. A., Rebholz, C., Matthews, A.** Comparative Tribology Studies of Hard Ceramic and Composite Metal-DLC Coatings in Sliding Friction Conditions *Tribology Transactions* 38 (4) 1995: pp. 829 – 836.
13. **Sue, J. A., Troue, H. H.** Friction and Wear Properties of Titanium Nitride Coating in Sliding Contact with AISI 01 Steel *Surface and Coating Technology* 43 – 44 1990: pp. 709 – 720.
14. **Hassan, A., et al.** Influence of Alumina Dopant on the Properties of Yttria-stabilized Zirconia for SOFC Applications *Journal of Materials Science* 37 (16) 2002: pp. 3467 – 3475.
15. **Ji, Y., et al.** Study on the Properties of Al_2O_3 – Doped $(ZrO_2)_{0.92}(Y_2O_3)_{0.08}$ Electrolyte *Solid State Ionics* 126 1999: pp. 277 – 283.
16. **Rizea, A., et al.** The Influence of Alumina on the Micro-structure and Grain Boundary Conductivity of Yttria-doped Zirconia *Solid State Ionics* 146 2002: pp. 341 – 353.
17. **Green, D. D., et al.** Preliminary Investigation of Al-doped Zirconia in Water for THR`s. Online at http://www.scientific.net.
18. **Yilmaz, S, Ipek, M., Celebi, G., Bindal, C.** The Effect of Bond Coat on Mechanical Properties of Plasma-sprayed Al_2O_3 and Al_2O_3–13wt% TiO_2 Coatings on AISI 316L Stainless Steel *Vacuum* 77 2005: pp. 315 – 321.
19. **Lianga, B., et al.** Nanostructured Zirconia – 30 vol.% Alumina Composite Coatings Deposited by Atmospheric Plasma Spraying *Thin Solid Films* 484 (1 – 2) 2005: pp. 225 – 231.
20. **Miyazaki, H., Yoshizawa, Y., Hirao, K.** Preparation and Mechanical Properties of 10 vol.% Zirconia/Alumina Composite with Fine-scale Fibrous Microstructure by Co-extrusion Process *Materials Letters* 58 (9) 2004: pp. 1410 – 1414.
21. **Kezelis, R., Mecius, V., Pranevicius, L. L.** Heat Energy and Technologies. Kaunas, 2002: pp. 253 – 258.
22. **Kezelis, R., Brinkiene, K.** Wear Resistance of Plasma Sprayed Zirconia Coatings *Proccedings of COST 533 Biotribology Workshop, ISBN: 978-84-932064-4-4,* Fundation Tekniker, Eibar, Spain, 2007: pp. 81 – 85.

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