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# Evaluation of Wear Resistance of Plasma Sprayed Ceramic Coatings

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Various ceramic coatings based on yttria stabilized zirconia (YSZ), deposited by atmospheric plasma spraying technique on stainless steel substrates were studied for investigation of their tribological behaviour. Materials selected for this investigation were tetragonal zirconia and alumina. The wear properties of plasma sprayed coatings were investigated by sliding test under conditions of dry contact with reciprocating and scratch test. To identify the wear mechanism, optical and scanning electron microscopes, surface roughness tester and scratch tester were used. Alumina-zirconia composite coatings with 15 wt. % and 85 wt. % of alumina exhibited improved wear resistance under unlubricated conditions. Microstructural characterization of the worn surfaces was performed and the wear of coated surfaces was explained in terms of their morphology. The wear resistance under dry conditions for plasma-sprayed ceramic coatings was determined by the composition of the material. Morphological study of worn surfaces indicated that abrasion is dominant mechanism of wear investigated.

*Keywords*: plasma spraying, coatings, alumina, zirconia, tribological characteristics.

## 1. INTRODUCTION

Damage of materials in engineering systems due to wear is very undesirable and leads to the repair or replacement of worn details and finally to the failure of mechanical components. A lot of works are done to study and understand the mechanisms of wear and to improve the wear properties of the materials. The surface modification with the use of hard protective coatings can increase the wear resistance of many metallic substrates.

Plasma spraying is well-developed technique of thermal spraying for preparation of metals, ceramic or composite coatings with improved wear resistance [1 – 2]. Plasma sprayed coatings can improve wear, corrosion resistance and performance parameters of metallic substrate materials [3]. Structural ceramic materials such alumina, zirconia, titania are increasingly used for tribological applications as surface coating materials of working metal surfaces [4 – 6]. These engineering ceramics have been focused on the tribological applications due to their superior properties. Alumina shows a very high hardness, wear resistance and an extreme chemical stability [6, 7]. Alumina coatings are widely used to resist wear by solid particle erosion and friction [7, 8]. Zirconia ceramics were extensively studied as wear resistance materials for engineering applications [4, 9]. Zirconia is one of the structural ceramic materials characterized by good physical, chemical and mechanical properties because of the range of possible microstructures [1, 5, 10].

Development of the advanced ceramics has introduced ceramic-ceramic composites for many engineering applications due to the improvement in their microstructure and properties. The properties of the ceramics are strongly influenced by the structural features of the materials, such as grain size and morphology, crystal structure, porosity, etc. [2, 7, 8]. By the results of study of wear properties of plasma sprayed alumina [7] the denser alumina coatings presented higher wear resistance than the more porous ones. The analysis of worn surfaces of plasma sprayed zirconia [4] revealed that the wear properties of plasma sprayed zirconia coating were not only dependant on its lower porosity, homogeneous microstructure, higher microhardness, but also dependant on the size of wear debris. Based on the experimental results, the finer the wear debris size, the better the wear properties of plasma sprayed zirconia coating [4].

The combination of the positive properties of alumina and zirconia seems to be desirable for the preparation of durable ceramic coatings [1, 2, 5]. Many investigations have been carried out to improve the microstructure and properties of yttria stabilized zirconia (YSZ) thin films by the addition of alumina ($Al_2O_3$) [11]. 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 [12]. Doping zirconia with alumina eliminates degradation phenomena due to zirconia phase transformation resulting in micro/macro cracking and degradation of the properties [12]. For these reasons the system alumina-zirconia was investigated for the deposition of ceramic coatings on stainless steel substrates.

The interaction of solid surfaces in tribosystem can cause different types of wear – abrasive wear, erosive wear corrosive wear, thermal wear, etc. [13]. The wear process depends on the surface properties, such as morphology, composition and hardness [9 – 11]. The morphological features of the surface are important factors affecting the wear behaviour of the material [13]. The microscopical study of the grain, grain boundaries and porosity contributes to the prediction of wear behaviour of the ceramics. The development of ceramic coatings plasma sprayed by atmospheric plasma spray technology requires better understanding of both mechanical and tribological behaviour of the coating materials to ensure the durability and stability of the coated components [4, 6, 7]. Wear test procedures adapted for ceramics should be related to the practical application [14]. The simplest and most widely applied test is a scratch test. Scratch test offers relatively

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easy and quick comparison of different materials on abrasive wear, with good reproducibility of the results [15].

In the present work, the influence of feed stock materials with various combinations between zirconia and alumina on the tribological properties of plasma sprayed coatings was investigated by sliding test and scratching them with diamond indenter under loading. The interaction between the coating and the indenter was studied. Worn surfaces were imaged by optical or scanning electron microscopy in order to provide more information about the wear mechanism.

## 2. EXPERIMENTAL

Plasma sprayed coatings were produced employing non-equilibrium plasma spraying technology at atmospheric pressure suitable for various engineering applications [16]. For the evaluation of wear characteristics of ceramic coatings they were subjected to the ball-on-plate sliding test under conditions of dry contact. The motion of the ball over stationary plate was linear and reciprocated. A ball made of 15X steel (GOST 9543-71) (14 mm in diameter, hardness HRC 62-65) was used as a counter-body. The applied load was 30 N. The wear tests were continued up to a total sliding distance of 108 m. A length of the stroke was 3 cm. The area of the sliding track and the wear track volume was derived from profilometric and optical microscopy measurements [17]. For reciprocating unidirectional sliding test the volume of the material removed from the surface in the wear track can be obtained by reporting maximum length and cross-sectional area of the wear scar [18]. For the linear reciprocating option, the wear volume of the linear track ($V_{track}$) is given by:

$$V_{track} = A \cdot L, \quad (1)$$

where $A$ is the average cross-sectional area of the track, $L$ is length of the stroke [17, 18].

Before the tribological testing and after the tests, the surface integrity of coatings was evaluated using standard metallographic methods, microhardness testing [19] and surface profilometry.

The microstructures were observed by scanning electron microscope (JEOL, JSM 5600) and optical microscope (OLYMPUS BX51TF) with image analysis software "QCapture Pro".

A scratch test was used to evaluate the wear resistance of plasma sprayed coatings. For the scratching experiments single scratch tests were carried out under the load 50, 100 and 200 g.

## 3. RESULTS AND DISCUSSION

Three groups of zirconia ceramic coatings with different amount of alumina (0, 15 and 85 wt.%) were plasma processed on stainless steel substrates using alumina and yttria stabilized (5.3 wt.%) zirconia (YSZ) powders [19]. The composition of investigated feed stock materials for plasma spray deposition and processing parameters are presented in Table 1 and Table 2.

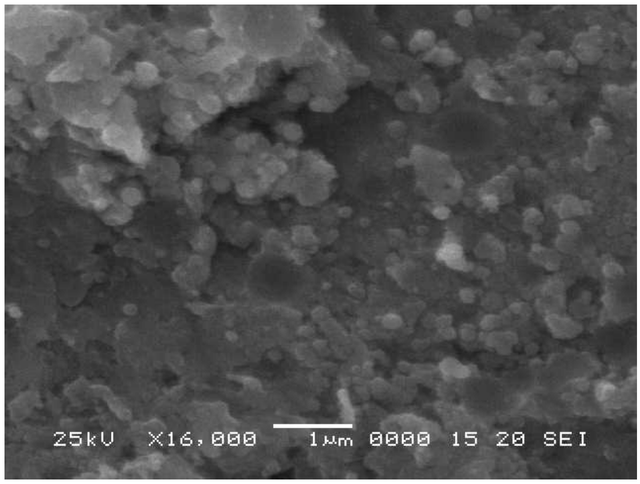
By the data of microstructural SEM characterization as well as analysis of surface roughness of as-sprayed coatings, the morphology of all samples is quite similar despite the different composition of initial powders. All ceramic coatings are characterized by small grained and homogeneous structure. Data of cross-sectional SEM analysis showed that sprayed coatings are well bonded to the substrates. Typical feature and surface profile of as-sprayed ZA85 coating are presented in Fig. 1. Average thickness of ceramic coatings estimated by image analysis was 40 μm – 45 μm.

**Table 1.** Composition of the investigated materials for plasma spraying

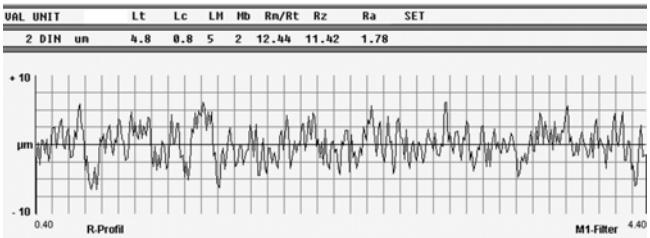
| Sample | Z100 | ZA15 | ZA85 |
|---|---|---|---|
| Alumina content % | 0 | 15 | 85 |
| YSZ, content % | 100 | 85 | 15 |

**Table 2.** Plasma spray parameters for ceramic coatings deposition

| Spray regime | Coatings | | |
|---|---|---|---|
| | Z100 | ZA15 | ZA85 |
| $P$, kW | 48.90 | 49.08 | 51.30 |
| $G$, gs$^{-1}$ | 5.14 | 5.20 | 5.16 |
| $v$, ms$^{-1}$ | 1450 | 1447 | 1469 |
| $T$, °C | 3750 | 3753 | 3775 |
| Spray distance, mm | 70 | 70 | 70 |
| Spray duration, s | 20 | 20 | 20 |




a




b

**Fig. 1.** SEM micrograph (a) and surface profile (b) of as-sprayed ZA85 coating

Main averaged parameters of surface roughness measurements of as-sprayed coatings are presented in [19]. On comparison with the characteristics of alumina coating deposited by atmospheric plasma spray technique in [8], the obtained coatings are characterized by slightly lower values of mean arithmetic profile roughness parameter $R_a$.

By the data presented in [8] the surface roughness parameter $R_a$ of alumina ceramic coatings varies from 4.6 μm to 4.9 μm, while $R_a$ of plasma sprayed alumina coating deposited by plasma spray technique presented in this study is 1.38 μm [19].

The tribological characterization of plasma sprayed coatings included series of wear experiments using ball-on-plate sliding technique under constant load 30 N and total sliding distance 108 m. After the sliding test, the worn surfaces of ceramic coatings were analyzed by optical microscope and profilometry technique. The volumetric wear loss was evaluated by averaging the cross-sectional area of the wear track from wear scar profile. The wear rate was calculated by dividing the volumetric wear loss after the reciprocated sliding test by the sliding distance and the contact load. Fig. 2 displays the variation of wear rate for all studied samples.

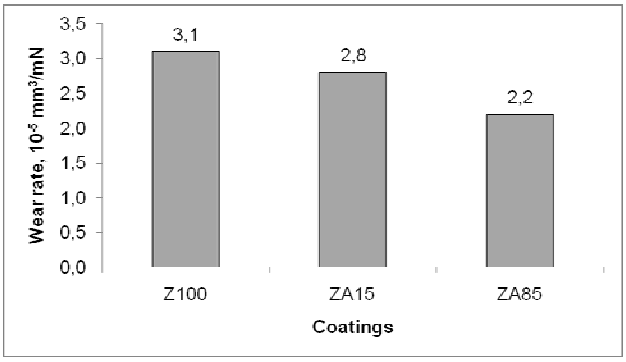


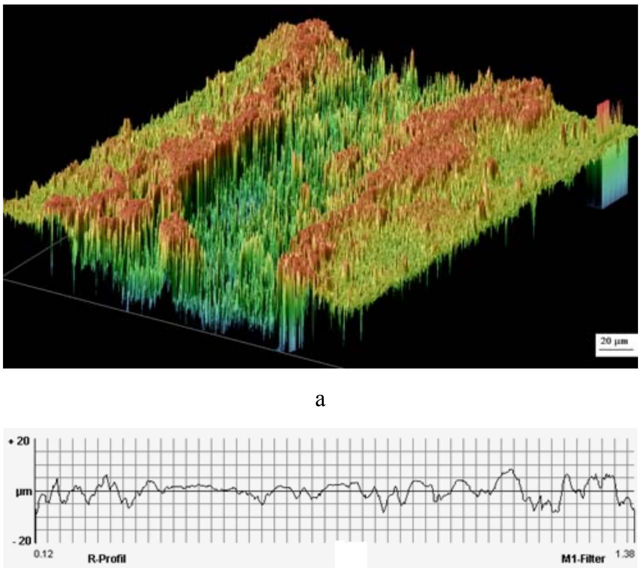

**Fig. 2.** The variation of wear rate of plasma sprayed zirconia coatings doped with different amount of alumina

According to the data obtained, wear rate of tested materials decreases with the increase of alumina content in the ceramic. Wear resistance of plasma sprayed coatings is higher for plasma sprayed coatings doped with high addition of alumina (ZA85). By the data of study of wear resistance of zirconia-alumina ceramics and ceramic coatings, wear rate of plasma sprayed alumina coating, performed on pin-on-disc apparatus (normal load 10 N), is $1.3 \cdot 10^{-5}$ mm$^3$/m [8], the specific wear rate of the $ZrO_2$ disk with a $ZrO_2$ ball, declared in [20], is $10^{-4}$ to $10^{-3}$ mm$^3$/Nm.

A micrograph and typical profilogram of worn surface of the coating ZA85 after the sliding test under the load of 30 N are presented in Fig. 3. Total sliding distance is 108 m.

The wear mechanism was studied analyzing the worn surfaces of coatings after the sliding test and scratch test. Microscopic observation of the worn surfaces after sliding tests indicated that the wear is caused mainly by abrasion. The scratch tests were conducted with three different loads – 50, 100 and 200 g. After the scratching tests at different loads, the worn surfaces of scratched samples were observed by optical microscope and scanning electron microscope in order to determine which wear mechanism occurred during testing. The morphology of worn surface with wear tracks of ZA15 and ZA85 samples at a load of 100 g is presented in Fig. 4.

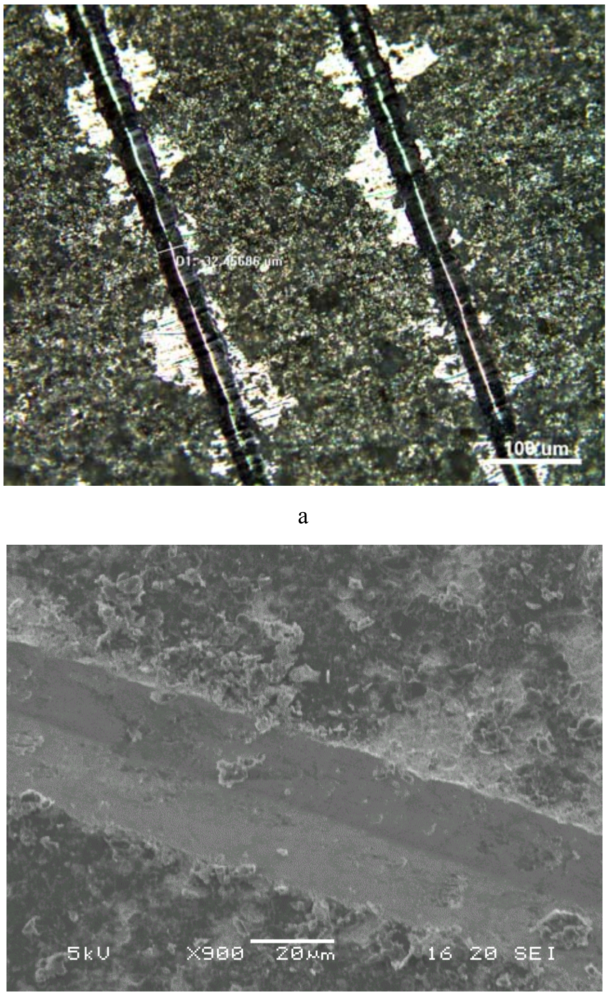
SEM examination of the scratched profiles revealed that with the increase of normal load the width of scratches is increased (Fig. 5). A small load produces plastically deformed groove.




a

b

**Fig. 3.** Partial plot of scar surfaces of plasma sprayed coating ZA85 (a) and typical surface profile (b) of worn surface of ZA85 after the sliding test




a

b

**Fig. 4.** Optical view (a) and SEM image (b) of the scratches on plasma sprayed coating. Scratch direction from top left to bottom right: a – ZA15, b – ZA85

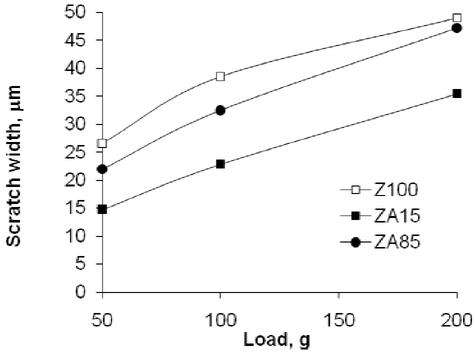



**Fig. 5.** Scratch width of plasma sprayed coatings at different loads

It is difficult to point the main reason of the failure in the scratch track of such coatings. Image analysis of worn scratched surfaces shows that dominant mechanisms of wear process of plasma sprayed coatings may be plastic deformation, partial delamination and brittle fracture in the investigated conditions.

## 4. CONCLUSIONS

The tribological characteristics of plasma sprayed ceramic coatings based on zirconia were examined using reciprocated ball-on-plate sliding test and scratch method.

The results of these experiments indicated, that wear properties of the coatings are determined by the composition of the material.

The addition of alumina to zirconia reduces wear rate of sprayed samples and can improve the tribological properties of the coatings. Plasma sprayed coating doped with 85 wt. % alumina is characterized by lower value of wear rate ($2.2 \cdot 10^{-5}$ $mm^3/mN$) and higher microstructural homogeneity.

Microscopic examination of worn surfaces indicated that abrasion is dominant mechanism in initial stage of wear process.

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