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The influence of plasma spraying parameters on microstructure and hardness of aluminium-bronze-polyester-YSZ composite coatings for plain bearings applications

Wpływ parametrów natryskiwania plazmowego proszku brązu aluminiowego z poliestrem oraz dodatkiem tlenków cyrkonu stabilizowanego tlenkiem itru na mikrostrukturę i twardość powłok do zastosowania na łożyska ślizgowe

The article presents the results of preliminary tests of a composite coating of aluminium bronze with additions of polyester and zirconium oxide stabilized with yttrium oxide. The coating was sprayed at variable parameters of hydrogen flow rate (0 NLPM, 4 NLPM, 8 NLPM) and burner current (300/500/700 A). The microstructure of the produced coating, regardless of the process parameters, was characterized by the presence of large porosities constituting polyester residue. The obtained porosity was approximately 20–30 vol. %. The analysis of the chemical composition showed a uniform distribution of YSZ oxides in the structure of the coating in the form of lamellar bands. There was no significant impact of process parameters on the coating hardness in the range of 160–170 HV02.

Keywords: plasma spraying, aluminium bronze-polyester-YSZ coating, YSZ

W artykule przedstawiono wyniki badań wstępnych kompozytowej powłoki brązu aluminiowego z dodatkami poliestru oraz tlenku cyrkonu stabilizowanego tlenkiem itru. Powłokę natryskiwano przy zmiennych parametrach natężenia przepływu wodoru (0 NLPM, 4 NLPM, 8 NLPM) oraz natężenia prądu palnika (300/500/700 A). Mikrostruktura wytworzonej powłoki, niezależnie od parametrów procesu, charakteryzowała się obecnością dużych porowatości, stanowiących pozostałość poliestru. Uzyskana porowatość wynosiła około 20–30% obj. Analiza składu chemicznego wykazała równomierne rozmieszczenie tlenków YSZ w strukturze powłoki w postaci lamelarnych pasm. Nie stwierdzono istotnego wpływu parametrów procesu na twardość powłoki mieszczącą się w zakresie 160–170 HV02.

Słowa kluczowe: natryskiwanie plazmowe, powłoka brąz aluminiowy-poliester-tlenek cyrkonu stabilizowany tlenkiem itru, YSZ

1. Introduction

One of the basic issues in the design of rotating machines is the problem of appropriate selection of the type of bearings and the material from which they are made [1]. In the case of sliding bearings, apart from polymeric materials, copper and aluminium alloys are mainly used [2]. Copper alloys are commonly used in the technology of regenerating bearings of this type [3]. One of the most used

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methods for deposition bearing material such as aluminium bronze is thermal spraying [4]. This type of coating is commonly obtained using wire flame or wire-arc-apray methods [5]. Tan, Wood, and Stokes [6] proposed the using of HVOF (high velocity oxygen fuel) method for aluminium bronze coating production. As research has shown [7], their erosion and corrosion resistance is similar to solid bronze. More advanced thermal spraying methods are also used: cold spray [8] and low-pressure plasma spraying [9].

Atmospheric plasma spraying (APS) is widely used to produce a wide range of coating types including bronzes. The high temperature of the plasma and the addition of polymer to the bronze powder cause its decomposition and increase the porosity of the coating [10]. The other idea in development of thermal-sprayed copper alloys is using of composite powders. Aissou et al. [11] proposed the addition of graphene to plasma-sprayed copper coating and production of anti-bacterial coatings. Döring et al. [12] developed the tungsten-copper composite coatings for heat flux components formed using vacuum plasma spraying process. The other modification of copper coatings is addition of hard particles – Ti_3SiC_2 [13]. In our previous research [14] we proposed the addition of yttria-stabilized zirconia nanopowder to WC-CrC-NiCr plasma-sprayed coating. The selection of plasma spraying parameters of pure aluminium-bronze-polyester we also investigated [15]. In present article we use the YSZ powder as an additive to aluminium-bronze-polyester powder for increasing its wear resistance and its potential application for bearing remanufacturing technologies. The aim of the study was to determine the effect of introducing a small amount of YSZ oxides on the hardness of the bronze coating. On the other hand, the presence of porosity caused by the decomposition of the polyester powder contained in the coating should allow for oil pockets that improve lubrication. The realization of spraying processes at different parameters was aimed at verifying these assumptions.

2. Experimental

The base material was S235 grade carbon steel. Samples measuring 50 × 20 × 2 mm were used. The powder to produce the coating was prepared by mixing aluminium bronze powder with polyester type Metco 604 (8.5 wt.% Al, 1 wt.% Fe, 5 wt.% polyester, Cu-bal.) and zirconium oxide stabilized by yttrium oxide fine-grain powder type Metco 6700 (ZrO_2 + 7.5% Y_2O_3; Oerlikon-Metco, USA) typically used for PS-PVD process [16]. The mixing process of 80% by weight of Metco 604 powder and 20% of Metco 6700 was carried out in a ball mill for 8 hours at a speed of 100 rpm. The number of torch passes over the surface of the samples was constant at 45. Plasma spraying was performed using an A60 torch and the Thermico APS system (Germany). Variable values of power current (300/500/700 A) and hydrogen flow rate (0 NLPM, 4 NLPM, 8 NLPM) are used to select the parameters of the thermal spraying process. They were selected according to our previous research [15]. Detailed process parameters are listed in Table 1.

Observations of the microstructure of the obtained coatings were made using a Nikon Epiphot 300 light microscope (LM) using the bright field technique, at three different magnifications: ×25, ×100 and ×200. Micrographs of the coatings were recorded using the NIS-Elements software.

The porosity assessment consisted of taking a set of 10 images of the coating under a light microscope at equal magnification.

Table 1. The parameters of plasma spraying process of aluminium-bronze-polyester-YSZ composite powder
Tabela 1. Parametry natryskiwania plazmowego proszku brązu aluminiowego z dodatkiem poliestru oraz tlenku YSZ

Process no.	Ar flow [NLPM]	H_2 flow [NLPM]	Power current	Powder feed rate [g/min]	Ar-carrier gas flow [NLPM]
21	56	4	500	20	6
25	60	0	500	20	6
29	52	8	500	20	6
33	56	4	300	20	6
37	56	4	700	20	6

A magnification of ×200 was adopted during the porosity tests. To obtain accurate results, a series of 10 photographs were taken in different parts of the sample. The obtained binary photos were subjected to quantitative image analysis using the LAS Phase Expert software.

Detailed examination of individual components of the microstructure of the produced microscopic coatings was performed using a Phenom XL scanning electron microscope (SEM), using a backscattered electron (BSE) detector. A secondary energy dispersive X-ray spectrometer (EDS) was used to investigate the chemical composition of the microstructure components of the composite coating.

The hardness measurement of the composite coating was performed using the NEXUS 4303 device. During the study, a series of measurements was performed, taking 6 measurements for each sample in random places. The load assumed during the tests was 200 g.

3. Results

The microstructure of the coating, regardless of the spraying parameters used, was characterized by the same structure (Fig. 1). It was characterized by a lamellar structure typical of plasma-sprayed coatings [17]. On the other hand, the presence of polyester causes high porosity, which is typical for this type of coating [15, 18]. Its introduction is primarily aimed at increasing resistance to abrasive wear [19].

The coating thickness measured at a variable hydrogen flow rate indicate that it causes an increase in the average coating thickness from 186 µm (no hydrogen) to 215.5 µm and 267 µm, respectively, for hydrogen flow rates of 4 NLPM and 8 NLPM (Fig. 2). In the case of coatings without the addition of YSZ, no clear dependence of hydrogen flow rate on the thickness of the coating ranging from 144–215 µm was observed [15]. Porosity measurements do not show its dependence on the hydrogen flow in the plasma plume. The obtained values were in the range of 21–27 vol. % – similar to obtained using pure aluminium-bronze-polyester powder.

In the case of variable power current, both the thickness and porosity did not depend on it. The highest coating thickness was obtained for the lower (300 A) and the highest (700 A) power current, 317 µm and 313 µm, respectively (Fig. 3). Increasing the torch current when spraying aluminium bronze powder with polyester resulted in a reduction in coating thickness from 324 µm (for 300 A) to 243 µm [15]. The coating produced at a current intensity of 500 A was characterized by the lowest porosity (approximately 21%).

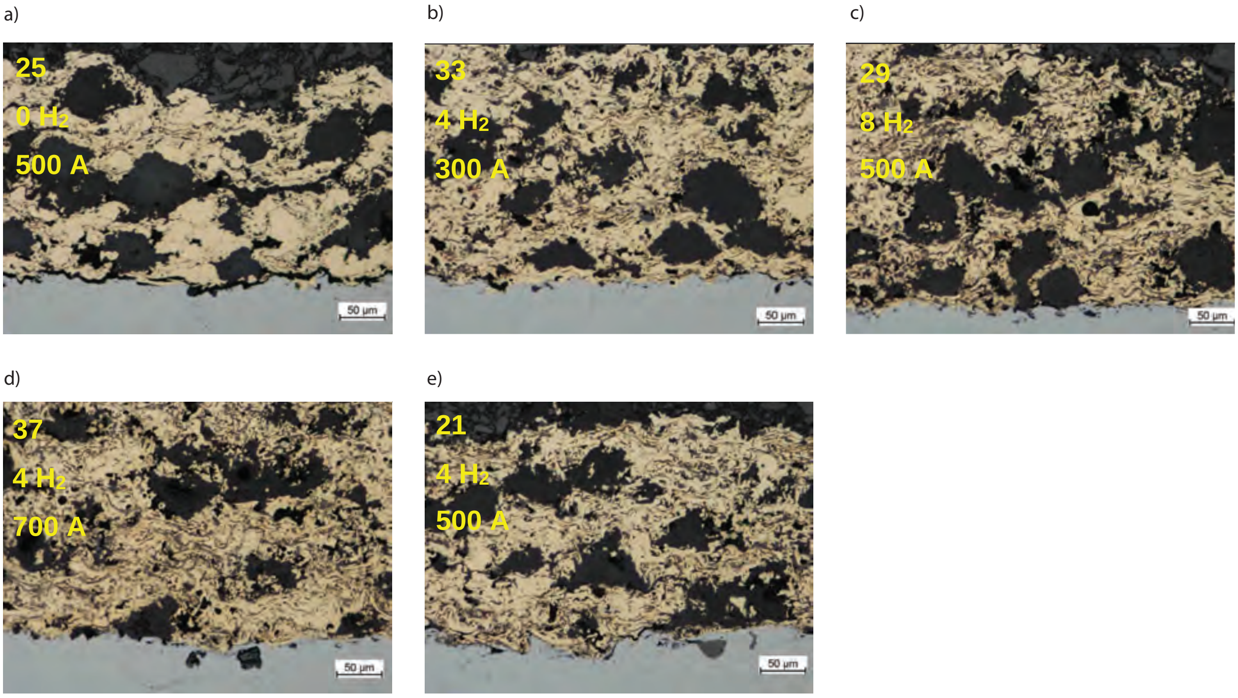

Fig. 1. The microstructure of plasma sprayed aluminium-bronze-poyester-YSZ coating obtained using different process parameters (process number/hydrogen flow rate/power current) – light microscope: a) 25/0 H_2/500 A, b) 33/4 H_2/300 A, c) 29/8 H_2/500 A, d) 37/4 H_2/700 A, e) 21/4 H_2/500 A

Rys. 1. Mikrostruktura natryskiwanej plazmowo powłoki brąz aluminiowy-poliester-YSZ uzyskanej przy użyciu różnych parametrów procesu (liczba procesowa/prędkość przepływu wodoru/prąd zasilania) – mikroskop świetlny: a) 25/0 H_2/500A, b) 33/4 H_2/300 A, c) 29/8 H_2/500 A, d) 37/4 H_2/700 A, e) 21/4 H_2/500 A

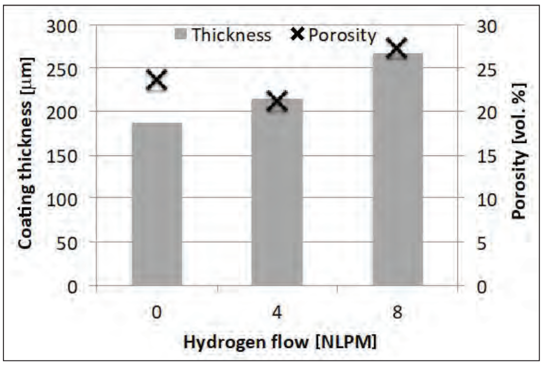

Fig. 2. The influence of secondary gas flow (hydrogen) on structure and porosity of aluminium-bronze-polyester-YSZ composite coating

Rys. 2. Wpływ natężenia przepływu gazu dodatkowego (wodoru) na strukturę i porowatość powłoki kompozytowej brąz aluminiowy-poliester-YSZ

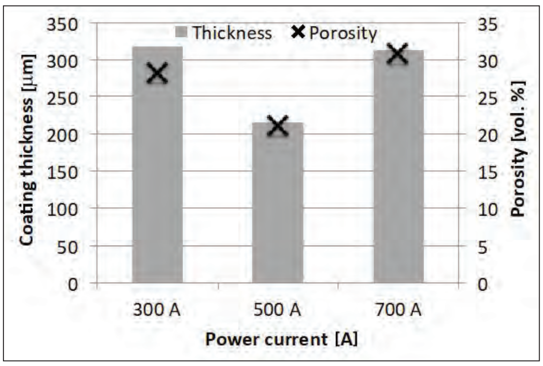

Fig. 3. The influence of power current on structure and porosity of aluminium-bronze-polyester-YSZ composite coating

Rys. 3. Wpływ natężenia prądu palnika na strukturę i porowatość powłoki kompozytowej brąz aluminiowy-poliester-YSZ

For the remaining current values, the porosity of the coatings reached approximately 30%. This was a similar value to that obtained for the coating without the addition of YSZ.

Analysis of the distribution of elements on the cross-section of the coating showed that the dominant component of the matrix is copper (Fig. 4). The presence of its second component, aluminium, was also found. When comparing the area of aluminium and oxygen, it should be concluded that there is a probable presence of aluminium oxide in the matrix. Zirconium, which is the main component of YSZ powder, is distributed throughout the entire cross-section of the coating. Together with yttrium, zircon forms local lamellar bands in the matrix. There was no significant influence of spraying parameters on the microstructure of the coating.

The analysis of the chemical composition in micro-areas allowed for the indication of the distribution of zirconium oxide and yttrium oxide introduced into the thermally sprayed powder in the structure (Fig. 5). A high content of Zr (approximately 50%) and oxygen was found in areas 2 and 4 of the coating, while stabilizing yttrium oxide was found in area 1 (Table 2). The content of copper and aluminium in area 6 is the same as the metal matrix of the powder. The results of the analysis of the chemical composition in the porosity areas (areas 3 and 5) do not allow drawing clear conclusions regarding the phase components present in them (Fig. 5, Table 2).

The results of hardness measurements in the coating area showed that the introduction of 4 NLPM as a secondary plasma gas allows obtaining a hardness of approximately 170 HV02. The lack of hydrogen in the plasma stream, as well as increasing its flow rate to 8 NLPM, resulted in a decrease in hardness (Fig. 6). However, there was no significant effect of the power current on the hardness of the coating (Fig. 7). A minimal decrease in hardness was found from 170 HV02 to 162 HV02 at 300 A and 700 A current, respectively.

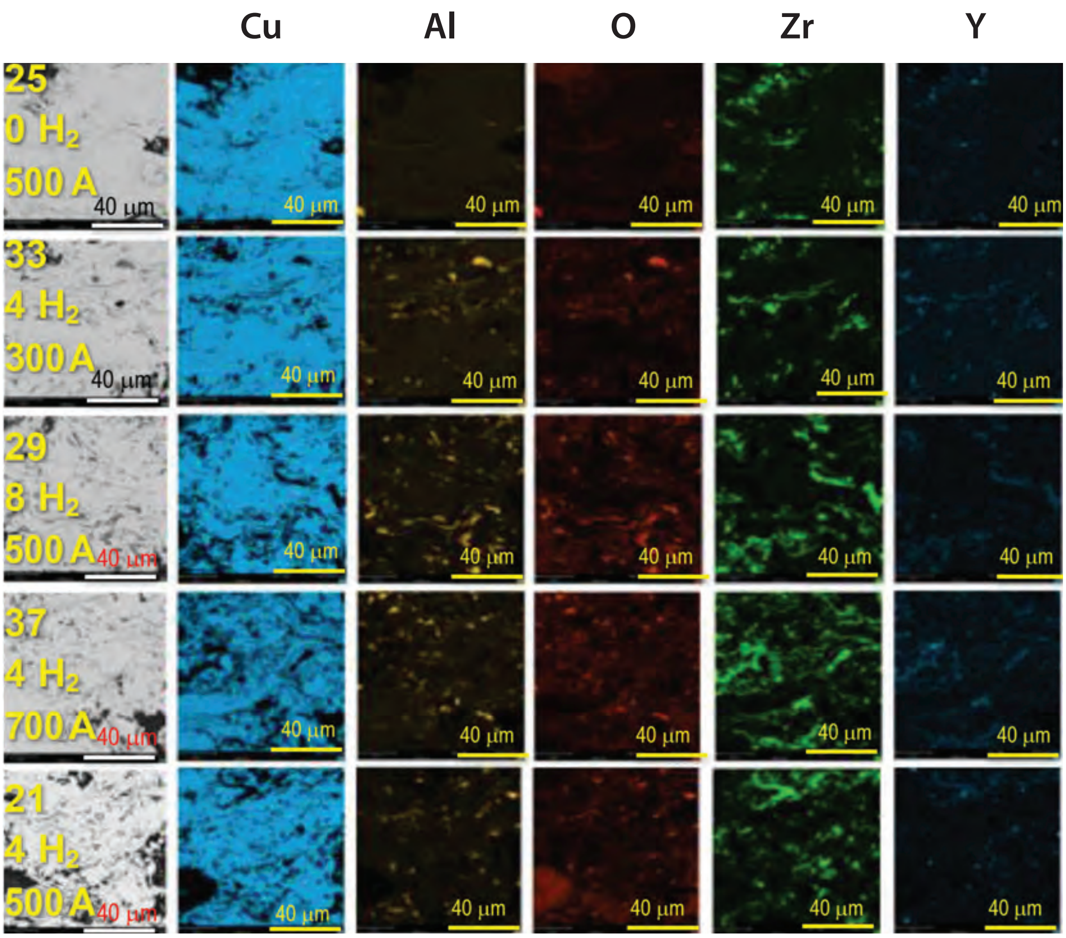

Fig. 4. Elemental mapping of cross-section of aluminium bronze polyester with the addition of YSZ coating obtained with different plasma spraying process parameters (process number/hydrogen flow rate/power current) – SEM

Rys. 4. Stężenie względne pierwiastków na przekroju powłoki kompozytowej brąz aluminiowy-poliester-YSZ uzyskanej przy różnych parametrach procesu (liczba procesowa/prędkość przepływu wodoru/prąd zasilania)

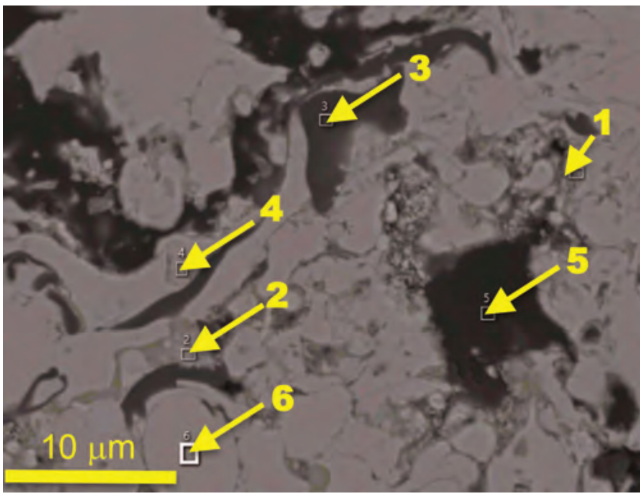

Fig. 5. The SEM microstructure of cross-section of aluminium bronze-polyester--YSZ composite coating formed by plasma spraying using following parameters: power current – 500 A, hydrogen flow – 4 NLPM, argon flow – 56 NLPM, powder feed rate – 20 g/min with marked areas of chemical composition analysis

Rys. 5. Mikrostruktura SEM przekroju poprzecznego powłoki kompozytowej brąz aluminiowy-poliester-YSZ utworzonej przez natryskiwanie plazmowe przy użyciu następujących parametrów: natężenie prądu palnika – 500 A, przepływ wodoru – 4 NLPM, przepływ argonu – 56 NLPM, szybkość podawania proszku – 20 g/min, z zaznaczonymi obszarami analizy składu chemicznego

Table 2. Results of chemical composition analysis in areas marked on Fig. 5
Tabela 2. Wyniki analizy składu chemicznego w mikroobszarach przedstawionych na rys. 5

Area	Element concentration (at%)				
	O (S)	Al	Cu	Y	Zr
1	21.55	1.24	24.60	52.04	0.58
2	26.89	4.48	6.11	6.95	55.57
3	44.86	48.58	6.56	–	–
4	24.72	1.38	24.49	–	49.41
5	28.54	16.55	54.91	–	–
6	–	9.99	90.01	–	–

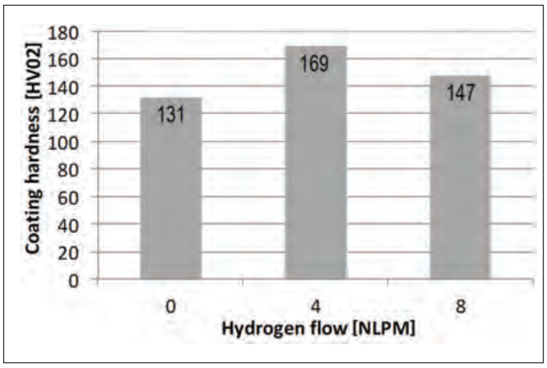

Fig. 6. The influence of hydrogen flow rate on hardness of aluminium-bronze-polyester-YSZ composite coating

Rys. 6. Wpływ natężenia przepływu wodoru na twardość powłoki kompozytowej brąz aluminiowy-poliester-YSZ

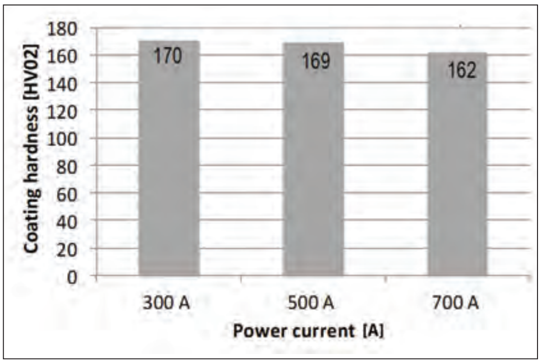

Fig. 7. The influence of power current on hardness of aluminium-bronze-polyester-YSZ composite coating

Rys. 7. Wpływ natężenia prądu na twardość powłoki kompozytowej brąz aluminiowy-poliester-YSZ

4. Conclusions

The experimental plasma spraying processes of aluminium-bronze-polyester-YSZ carried out indicate the possibility of obtaining a coating of uniform thickness in range 200–350 μm depending of process parameters. This thickness was analogous to that of coatings sprayed with yttrium oxide-stabilized zirconia powder for the same range of hydrogen flow rate and power current [15]. The obtained coating structure was characterized by a similar structure to the coatings without the addition of YSZ obtained by Yang et al. [19]. The coatings were characterized by the presence of large pores, which were the remains of the introduced polyester, which was decomposed in the plasma plume. The consequence was a high measured porosity of the coating in the range of 20–30 vol. % – similar to that obtained for pure aluminium-bronze-polyester powder [15]. This confirmed the assumptions of the experiment and points to the use of pores as oil pockets in a plain bearing application. The high porosity obtained is highly desirable in this case. The elemental mapping results indicate an even distribution of ZrO_2 and Y_2O_3 in the coating structure. They form lamellar areas between bronze strands. Hard oxide particles both introduced (YSZ) and generated during spraying, the presence of which was shown by the elemental mapping results, should increase the abrasion resistance of the coating matrix, which constitutes the sliding surface of the bearing. The hardness of the produced coatings depends primarily on the presence of large pores, which does not allow determining the influence of the addition of YSZ to the plasma sprayed powder. It can be observed that the presence of numerous porosities had a significant effect on the hardness measurement results – probably significantly underestimating its value. There was no significant influence of the spraying process parameters on the hardness, which was approximately 170 HV02. Further research should be focused on the use of powder that does not contain polyester, which will allow determining the influence of plasma spraying parameters on the properties of the coating. In the case of the powder produced, it should be assumed that the porosities will act as oil pockets, and the introduction of the YSZ additive increases the hardness of the matrix. However, this can only be confirmed by carrying out tribological tests [20].

CRediT authorship contribution statement

Marek Góral: Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.
Tadeusz Kubaszek: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation.
Barbara Kościelniak: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation.
Dorota Stawarz: Investigation, Resources.
Mateusz Woźniak: Investigation, Resources.

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