Combustion flame spray of 7YSZ powders followed by corrosion in molten salts of the coating

Melquisedec Vicente Mendoza, Ricardo Cuenca Alvarez and Fernando Juárez López

Instituto Politécnico Nacional-CIITEC Cd. Mx, Mexico City, México

ABSTRACT

7YSZ coating was manufactured by combustion flame spray process of 7YSZ powders on MCrAlY substrate. Set parameters of combustion flame spray were used to build up an YSZ coating. Coating thickness in the range of 40–50 μm was obtained having microstructure of lamellar-splat morphology. Afterward, hot corrosion tests of the 7YSZ coating were performed in molten salts at 1050°C. Scanning electron microscopy and X-ray diffraction analysis was used to identify changes in the microstructure of the 7YSZ coating. It was identified as the main failure mechanism developed during spallation of YSZ coating.

1. Introduction

Yttria stabilized zirconia (7YSZ) has been widely used in thermal barrier coatings (TBCs) as a protective layer at high-temperature (top-coat) [1–5]. For YSZ coatings that work at high temperature up to 1000°C to increase their properties, it has been needed to develop new characteristics to be able to work in extreme conditions [6–9].

7YSZ-based TBC systems have been used extensively in gas turbine industry, although the manufacture processes are associated with complex dispositive to build up a coating [1–10]. Thus, Electron Beam Plasma Vapor deposition (EB-PVD) could be used to deposit a dense and enhanced tolerance capacity coating from the vapor phase [11–13], but with lower deposition rate and higher operating cost restrict its application to small surfaces. Atmospheric Plasma Spray (APS) has been used extensively; however, high temperatures associated with the deposit process prove a mass evaporation and therefore a resultant anisotropic microstructure [9]. Today both high costs and times associated with these techniques limit their use in the preparation or/and maintenance in-situ of the coating [7].

In regard to the combustion flame spray (CFS) technique has been proposed, due to the simple hardware configuration related to repair some components that they cannot be transported [14–17]. Besides the 7YSZ coatings are susceptible to corrosion at high working temperatures caused by molten salts, such as Na, S and V, contained in low-quality fuels [18–21]. Thus, two main ways have been involved to search alternative coating materials other than the stabilizers to Y2O3 for ZrO2-based systems notably type rare-earth zirconate ceramics [22–26], or/and alternative techniques of ZrO2-based systems processing. To best knowledge, few studies have been reported on the hot corrosion of YSZ coating manufactured by CFS [15,16]. Since the coatings manufactured by CFS are associated to a low temperature of processing, the resultant microstructure can promote minor changes in their initial properties, including hot corrosion resistance [9,14–16]. Moreover, some studies have shown that to have fine YSZ microstructure could increase the resistance to the corrosion in molten salts [7–9,21]. Thus, it has been promoted the use of sub-micrometric size powder to build up thermal barriers of YSZ base coating [9]. Such YSZ materials have proved to have finer grain and to exhibit unusual structure, e.g. dense or porous, also thinner than conventional thermal spraying coatings [7–9].

The aim of this paper was to assess under Na2SO4 + V2O5 mixture at an engine representative temperature of 1050°C the coating obtained by CFS process from 7YSZ sub-micrometric powder. Thus, the present work was firstly devoted to build up the coating from YSZ sub-micrometric powder, and restricted to discuss some corrosion problems brought up by the microstructure manufactured by the combustion flame spray (CFS) process. In order to deposit the 7YSZ coating, a MCrAlY alloy (NiCo) was previously manufactured as the substrate to deposit the 7YSZ powders. Afterward, tests of corrosion in Na2SO4 + V2O5 molten salts were carried out at a temperature of 1050°C. The particle size distribution of the 7YSZ powder was determined by a Malvern Masterziser X Laser Disperse apparatus granulometer equipped with a 300 mm lens, 2.4 mm ray length. The microstructural characteristics of the 7YSZ coating were evaluated in cross
section samples both before and after corrosion test using a JEOL-7800 high-resolution scanning electron microscope (HR-SEM) with detector XL-EDAX Ametek-Apolo, windows 30 mm, normally 10 Kv, WD 10–12 mm. Also, an X-ray diffraction (XRD) was carried out with the X’PertPro (Bruker D8-ECO Advance), with a Bragg-Brentano set-up, equipped with an X’Celeratrimina 2θ range of 20–80° using a 0.021 step size, 20 s time per step and Cu-Kα radiation with a λ 1/4 of 1.541.

2. Materials and methods

2.1. Materials

An YSZ sub-micrometric (7 wt.%) (464228 Sigma-Aldrich) size 700 nm powder with specific surface 9.0 × 10⁻³ m²/kg and melting point 2600°C. To deposit 7YSZ coating MCrAlY (20 Co, 18 Cr, 6 Al, 0.3 Y, 2 Ta (wt.%)) substrates were prepared by Spark Plasma Sintering (SPS) following an established process reported by [27] with dimensions 20 × 4 mm diameter × thickness, and grit-blasted with Al₂O₃ grit (d50 of 250 μm), with Ra 2.4 ± 0.2 μm surface roughness.

2.2. YSZ coating synthesis

The 7YSZ coatings were deposited on sintered MCrAlY substrates. A prototype TeroDyn 2000 Eutectic-Castolin gun was used as hardware to spray the 7YSZ powders. An axial injection mode was selected instead of radial injection mode in order to improve the energy exchange between the flame jet and the sprayed material in form of sub-micro powder. Before YSZ deposit the substrate was preheated at 400°C, using above mentioned flame torch, and previous feeding of the powder. Substrate temperature was measured through a laser pyrometer marc LT Lutron “instruments digital” model TM – 949. To prepare the 7YSZ coating on the MCrAlY substrates CFS set parameters are presented in Table 1.

2.3. Hot corrosion in molten salts

Upon synthesis of 7YSZ coating, hot corrosion tests using Na₂SO₄ and V₂O₅ mixtures were conducted on the surface at a temperature of 1050°C. For the above mixture preparation, Na₂SO₄ (96.0% purity) and V₂O₅ (99.9% purity) compose from Sigma Aldrich were used. To perform an accelerated high-temperature corrosion test on the sample, a mixture of Na₂SO₄ 50 wt.% and V₂O₅ 50 wt.% was deposited evenly onto the surface of each specimen with a mass ratio of 20 mg/cm² [28]. These specimens were then set in an electric furnace (TZF 1050 Carbolite) at atmosphere pressure under a maximum temperature of 1050°C during 8 h, by cycle. Since the typical working temperature on the surface of the TBC is around 1050°C (top-coat). This hot corrosion testing temperature (1050°C) is higher than that melting point of V₂O₅ (690°C), Na₂SO₄ (884°C), respectively. At the beginning of each cycle (8 h), the V₂O₅ + Na₂SO₄ mix was recharged on the surface of each specimen to provide more stoichiometric salts and to cause a severe corrosive environment. After one cycle by 8 h of testing at 1050°C, the samples were allowed to cool down inside the furnace, and later these samples were inspected to identify for possible crack formation. At end of each cycle, the samples were re-charged with Na₂SO₄ + V₂O₅ salt mixture, and the heating profile was repeated to reach the failure of the coating. Hence, corroded samples were obtained as follows: 3 cycles (A), 4 cycles (B), and 8 cycles (D) respectively. After hot corrosion tests microstructure of each 7YSZ sample was analyzed by HR-SEM and XRD.

3. Results and discussion

3.1. 7YSZ coating characteristics

Initial 7YSZ powder morphology is presented in Figure 1(a). The as-received 7YSZ powder has a particle fine-size of 700 nm, though agglomerates with sizes above 10 μm are also visible, Figure 1(b). An analysis of size distribution of the 7YSZ powder shows particle fine-size with size bimodal distribution at ~1 μm corresponding to 30%, a second peak indicates size of 46 μm at 60% as is observed in Figure 1(c). This measurement shows that submicrometric 7YSZ powder tends to form strong agglomerates.

To perform YSZ powder spray parameters, Figure 2 shows the surface coating formed by CFS process for spraying distance of (a) 60, (b) 80 and (c) 120 mm. A combination of fine microstructure and small spherical particles constitute the microstructure of the YSZ coatings sprayed to 60 mm (Figure 2(a)). It is discovered spherical particles with a dimension in the range of 1.0 μm upon the deposit at a spraying distance of 60 mm, denoted by yellow arrow in Figure 2(a). Hence, it can be deduced that strong agglomerate powders were destroyed to form nanostructured particles during

| Table 1. Thermal spray parameters. |
|-----------------------------------|
| Pressure O₂                          | 3.45 × 10⁵ Pa                        |
| Pressure C₂H₂ diluted                | 1.03 × 10⁵ Pa                        |
| Flow Rate Range O₂                  | 35–55%                               |
| Flow Rate Range C₂H₂                | 50–75%                               |
| Flow O₂                             | 2.08 m³/h                            |
| Flow C₂H₂                            | 1.85 m³/h                            |
| Spraying distance                    | D₁ 60, D₂ 80, D₃ 100 mm              |
| YSZ size particle                    | 700 nm                               |
the CFS process; however, high porosity is observed on the surface coating. Besides this last microstructure differs of the coating sprayed to 80 mm (Figure 2(b)), where the deposition of “splits” is persistent on the surface to form the YSZ coating, though a few small spherical particles can be observed disperse on the surface. These splats corresponds in the range of size of 10 um, and are distributed homogeneously on the surface sprayed from 80 mm. Besides Figure 2(c) shows a micrograph of the coating deposited to a spraying distance of 120 mm. This last micrograph also shows the presence of intersplat and relaxation cracks, both possibly generated by residual stress relaxation mechanisms during powder deposition [5]. The presence of both relaxation cracks and spherical particles can be appreciated in a single splat in Figure 2 (c) yellow arrow. Here spherical particles in the previous case would correspond to a higher presence of unmolten material, which constitutes uneven areas for the successive impact of incoming particles, generating porosity. In resume the
Figure 2. Splats in the surface coating formed by CFS process for spraying distance of (a) 60, (b) 80 and (c) 120 mm.

Microstructure composes mainly by splats would correspond to the presence of molten material, which reveals the building of the coating layer by layer during the CFS process. Moreover, it has been established by the literature [5], that typical like-splats morphologies shaped during the impact with the surface substrate, represent the conventional building of the coating produced by thermal spray techniques. Therefore, this set parameter of 80 mm (Table 1) was used to spray the YSZ powder, and to build the coating.

In addition to the spraying distance parameter of 80 mm, Figure 3(a,b) shows micrographs of the YSZ coating where is observed a smooth surface formed by splats with a homogeneous size distribution of 10 µm, though some pores with the size around 1 µm among splats can be located. Figure 3 (c) represents the HR-SEM analysis that shows close-up from a single splat where can be identified a morphology formed by the grain of size around 1 µm. This columnar YSZ grain has been reported to increase the thermal properties [29,30], such as ionic conductivity, and/or mechanical resistance across lamellar coating, which could be enhanced by the mean of the lamellar interface bonding ratio. Xing et al. reported that the columnar grain growth across lamellar interfaces could be enhanced by means of increasing deposition temperature, which results in the improvement of the lamellar interface bonding ratio and eventually the ionic conductivity of YSZ deposits [29]. Such improve lamellar interface bonding ratio again could be attributed to the nanometric structure present in the coating. Moreover, it was found that with the use of nano-sized powders, an improvement in thermal shock resistance could be obtained due to the lower tensile stress in plane and higher fracture toughness of nanostructured layers [31,32].

To determine other characteristic of the YSZ coatings, Figure 4(a) shows a micrograph of the YSZ coating in a cross-section before corrosion test, where coating thickness is measured in the range of 40 µm, and its microstructure is mainly formed by lamellas (before named splats) without visible cracks, though some pores are present. Also, Figure 4(b) shows a close-up from 7YSZ coating where is observed that lamellar morphology of size around 10 µm. This last observation is in accord with that splat size above shown in Figure 3(b), where splats sizes around 10 µm were identified.

3.2. YSZ coating after hot corrosion

Afterward, corrosion test each 7YSZ-coating sample was prepared for observation microstructural. Figure
5 shows a shared image that corresponds to all samples corroded by molten salts at a temperature of 1050°C to cycles of: 0 (A), 3 (B), 4 (C), and 8 (D) respectively, where SEM micrographs (left), and visual image (right) are showed. Figure 5(a) shows initial 7YSZ coating surface.

Figure 5(b) (right) shows the 7YSZ coating after 3 cycles in molten salts with a charge of 5 mg-cm⁻². At this cycles, number of yellow zones were formed on the surface and that would correspond to 7YSZ coating zones attacked by reaction with vanadium oxide + sodium sulfate. SEM micrograph (left) shows the formation of small pores could be channels developed during corrosion process. EDS elemental analysis, showed yellow rich zones in V and Y elements, nevertheless at this cycles number the 7YSZ coating is kept without some spallation.

After four cycles in molten salts, Figure 5(c) shows the 7YSZ coating surface. It is observed two zones (right); again light yellow zones correspond to 7YSZ coating attacked by molten salts, however in this case SEM micrograph shows the growth of small cracks on the 7YSZ coating surface. It is beginning to see small black zones that could correspond to MCrAlY substrate. Moreover, a close-up from the yellow zone is observed the growth of rod-like (yellow arrow) structures that appear to grow from splat morphology. It is suggested that initial cracks were promoted by the growth of rod-like structures and extended through the coating. In addition, EDS analysis (Table 2) shows that these rods-like morphologies are rich in Y, Na and V elements.

Figure 5(d) shows the surface coating after 8 cycles by 8 h in molten salts at 1050°C. It is observed a diminution of yellow zones that correspond to 7YSZ coating attacked by molten salts; however, larger black zones correspond to substrate are identified to have increased. Moreover, it is evident the YSZ coating detachment from MCrAlY substrate. SEM analysis in the yellow zone shows the growth of larger crack on 7YSZ coating, moreover this analysis revealed the growth of acicular-like morphologies (yellow arrow) of size around 20 µm on the 7YSZ coating surface. EDS analysis from these zones shows rich zones in Yttrium and Vanadium elements (Figure 5(d)). After 8 cycles by 8 h in molten salts, it was already noted 7YSZ coating spallation.

**Figure 3.** SEM micrographs of the 7YSZ coating, spraying distance of 80 mm: (a) smooth surface, (b) morphology splats and (c) close-up from a single splat shown in (b).
The kinetic model of the 7YSZ system in Na₂SO₄ + V₂O₅ molten salts has been characterized by rapid degradation of the protective layer (top coat), indeed NaVO₃ salt condensed on and/or into the 7YSZ coating during corrosion test YVO₄ as reaction product has been reported by [19–21]. The Na₂SO₄ + V₂O₅ reaction with ZrO₂-Y₂O₃ has been studied by Habibi et al. [19–21] having as product yttrium vanadates (YVO₄). Therefore, the growth of acicular-like morphologies well corresponds to YVO₄ chemical composition, as shown in Figure 5(d).

XRD pattern analysis of the 7YSZ coating after reaction with Na₂SO₄ and V₂O₅ salts at 1050°C, is shown in Figure 6. The evolution of the 7YSZ-coating phase can be identified; firstly, before corrosion test 7YSZ coating pattern with tetragonal and monoclinic phases presence, indexed according to JCPDS 00–050-1089 and JCPDS-9016714, respectively, is shown in Figure 6(a). After 3 cycles by 8 h of hot corrosion test, it was observed the attenuation in the peak intensity from a tetragonal pattern, whilst the peak corresponding to monoclinic pattern suffered light increment intensity (Figure 6(b)). In this sense, 7YSZ transition from tetragonal to monoclinic phase has been studied by several authors [18–21]. Thus, more tetragonal phase transforms to monoclinic phase after 4 cycles by 8 h, as can be shown by diffraction pattern in Figure 6(c), where indexed peaks of zirconia monoclinic phase are highest (intensity) than that corresponding to 7YSZ tetragonal. Thus, most tetragonal zirconia transformed to monoclinic phase after hot corrosion at 8 cycles...
Indeed, it was identified a YVO₄ phase indexed by JCPDS-0160250 corresponding to the peaks at 25, 32 and 50 2θ position. At this end cycles number, the 7YSZ coating was wholly detached from the MCrAlY substrate due to the reaction produced by Na₂SO₄ + V₂O₅ corrosives salts at temperature 1050°C. In addition, at this 8 cycle number XRD analysis shows the presence of nickel chromate (NiCrO₄), sodium sulfate (Na₂SO₄) and nickel disulfide (NiS₂) phases, last phases as products of the molten salts with MCrAlY substrate [33]. Rietveld refinement analysis revealed an increment in ZrO₂ baddelite (monoclinic structure) and YVO₄ phases of 52.9% and 20.7% respectively. To determine the monoclinic phase volume-percent (M%), it is possible to

![Figure 5](image_url)
use the following equation [34,35]; where “T” is the peak intensity of tetragonal ZrO$_2$ from (101) plane, “M1” is the peak intensity of monoclinic ZrO$_2$ from (111) plane and “M2” is the peak intensity of monoclinic ZrO$_2$ from (111) plane after hot corrosion test.

$$M\% = \frac{M_1 + M_2}{M_1 + M_2 + T} \times 100$$  \hspace{1cm} (1)

Using Equation (1), the volume of monoclinic phase in YSZ coatings for B and C was calculated to be 63.3% and 98%, respectively. But complete delamination YSZ coating was marked, and both NiS$_2$ and NiCrO$_4$ phases were detected at 8 cycles number (D) as a reaction-products with Nickel and Chromium substrate, and NaSO$_4$ crystals as the residue of mix salts.

Furthermore, Figure 7(a) shows a micrograph of the corroded 7YSZ coating surface after 8 cycles by 8 h in molten salts at a temperature of 1050°C. It is identified on the coating surface the presence of morphologies of type acicular with homogenous distribution (Figure 7(b)). Mapping EDS elemental of the corroded 7YSZ surface shows rich zones in Y and V content from acicular morphology (Figure 7(c)), this chemical composition would correspond to YVO$_4$ compound, as was indexed by XRD. Indeed, it is observed some acicular morphology seems to be anchored to MCrAlY substrate (Figure 7(a), yellow arrow).

To deepen analysis 7YSZ coating cross-section after 4 cycles number of corrosion in molten salts at a temperature of 1050°C is shown in Figure 8. EDS maps elemental shows the presence of rich

Figure 6. XRD analysis of the YSZ coatings after hot corrosion test for each cycle in molten salts: (a) without molten salts, (b) 3 cycles, (c) 4 cycles and (d) 8 cycles.
zones in O, V, Y, Zr, Na and S elements, this chemical distribution confirms the diffusion of salts through 7YSZ coating. Thus, during diffusion and condensation of salts, the NaVO$_3$ reacts with the YSZ layer promoting depletion of Y$_2$O$_3$ and the formation of the YVO$_4$ phase. This YVO$_4$ growth has been reported in hot corrosion by [18–20], the YVO$_4$ compound was identified as a product of the reaction between 7YSZ with molten salts, promoting the depletion of Y$^{3+}$ from YSZ, consequently the transition of YSZ tetragonal to YSZ monoclinic phase. Since YSZ monoclinic phase has a minor cell-volume that YSZ tetragonal phase, such a shift volumetric increases the stress among lamellar microstructure, contributing to the cracking and the spallation of the 7YSZ coating. It is expected that cell-volume shift promotes the cracks growth, subsequent to the diffusion of molten salts during cyclic cool-down and heating test, thus the growth of YVO$_4$ through the 7YSZ coating.

Moreover, Figure 9 shows the 7YSZ coating cross-section after 4 cycles number test. BS-SEM (backscattering scanning electron microscopy) micrograph identify both thickness 7YSZ coating and MCrAlY substrate in light gray contrast and gray color, respectively (Figure 9 (a,b)). In a close-up of the coating (Figure 9(c)), BS-SEM image shows light gray zones where can be identified YSZ columnar grains, and other gray zones identified as “shapeless” morphologies. EDS analysis (Figure 9(d)) shows this last gray zones are rich in Vanadium, Oxygen and Yttrium elements content, and would correspond to the YVO$_4$ compound. These rich V element zones confirm both diffusion and reaction of molten salts through the coating. Moreover, it is observed that columnar grain size well corresponds to that shown in Figure 3(c), where each splat is constituted by submicrometric grain size. Thus, these YSZ grains assembled layer by layer during the CFS process, now would promote the detachment layer by layer of the

Figure 7. SEM micrographs of the YSZ coating after 8 cycles in molten salts at temperature of 1050°C: (a) coating-substrate, (b) close-up microstructure and (c) mapping EDS analysis.

Figure 7. SEM micrographs of the YSZ coating after 8 cycles in molten salts at temperature of 1050°C: (a) coating-substrate, (b) close-up microstructure and (c) mapping EDS analysis.
YSZ coating. It is worth noting that the YVO$_4$ phase grew from these 7YSZ grains also contributed to the coating spallation.

4. Conclusions

A 7YSZ coating with a thickness of 40 µm was manufactured by the combustion powder flame spray process. Sub-micrometric columnar grains of 1 µm size constituted the lamellar microstructure of the coating. Afterward, 7YSZ coating was corroded in molten salts at a temperature of 1050°C. At this temperature, the molten salts reaction promoted both the 63% volume-percent of monoclinic phase transition, and the growth of compounds of YVO$_4$ with acicular morphology of size 25 µm through the YSZ coating. It was observed that YSZ coating suffered layer-by-layer delamination from the substrate, seems to be the main chemical damage. This last damage mode was attributed mainly to the lamellar characteristic.

Figure 8. 7YSZ coating in cross-section after 4 cycles of corrosion in molten salts at temperature of 1050°C: (a) SEM micrograph and (colors) mapping EDS analysis.
of the coating, which was built by stacking of splat by splat during the CFS process.

Acknowledgements
The authors acknowledge to COFAA, EDI-IPN and SNI-CONACYT for supporting this work. The authors are also indebted to Red de Nanociencias y Nanotecnologia of IPN.

Disclosure statement
No potential conflict of interest was reported by the authors.

References
[1] Padture NP, Advanced structural ceramics in aerospace propulsion. Nat Mater 2016;15: 804–809.
[2] Clarke DR, Oechsner M, Padture NP, Thermal-barrier coatings for more efficient gas-turbine engines. Ms Bull 2012; 37(10): 891–898.
[3] Padture NP, Thermal barrier coatings for gas-turbine engine applications. Sci 2002; 296(5566): 280–284.
[4] Clarke DR, Philpot SR, Thermal barrier coating materials. Mater Today, 2005; 86: 22–29.
[5] Fauchais PL, Heberlein JVR, Boulos MI, Thermal Spray Fundamentals. Springer Science + Business Media. 2014. DOI:10.1007/978-0-387-68991-3.
[6] Chaochui W, You W, Liang W, et al. Nanocomposite lanthanum zirconate thermal barrier coating deposited by suspension plasma spray process. J Therm Spray Technol 2014; 23: 1030–1036.
[7] Fauchais P, Vardelle M, Vardelle A, et al. What do we know, what are the current limitations of suspension plasma spraying? J Therm Spray Technol 2015; 24: 1120–1129.
[8] Fan W, Bai Y, Review of suspension and solution precursor plasma sprayed thermal barrier coatings. Ceram Int 2016; 42:14299–14312.
[9] Pengjiang H, Hui S, Yunfang G, et al. Microstructure and properties of nanostructured YSZ coating prepared by suspension plasma spraying at low pressure. Surf Coat Technol. 2015; 261(15): 318–326.
[10] Serrano PE, Martinez GH, Martinez GK, et al. Densification and microstructure of spark plasma sintered 7YSZ–Gd2O3 ceramic nano-composites. J Asian Ceram Soc. 2017;5(3): 266–275.
[11] Mishra SK, Pandey S, Mahato P, et al. Microstructural studies on EB-PVD deposited NiCrAlY-YSZ and lanthanum zirconate for thermal barrier applications Surf Coat Technol. 2012; 207(25): 143–148.
[12] Tyler RK, Andi ML, Ted DB, et al. Evolution of thermal properties of EB-PVD 7YSZ thermal barrier coatings with thermal cycling. Acta Mater. 2009; 57(8): 2583–2591.
[13] Jang B-K, Hideaki M, Microstructure of nanoporous yttria-stabilized zirconia films fabricated by EB-PVD. J Eur Ceram Soc. 2006; 26: 1585–1590.
[14] Bandypadhyay R, Nylén P, Computational Fluid A Dynamic analysis of gas and particle flow in flame spraying. J Therm Spray Technol 2003; 12:492–503.
[15] Fanicchia F, Axinte DA, Kell J, et al. Combustion flame spray of CoNiCrAlY & YSZ coatings. Surf Coat Technol 2017; 315: 546–557.
[16] Heel A, Vital A, Holtappels P, et al. Flame spray synthesis and characterisation of stabilised ZrO2 and CeO2 electrolyte nanopowders for SOFC applications at intermediate temperatures. J Electroceram 2009; 22: 1–3: 40–46.
[17] Cano C, Osendi MI, Belmonte M, et al. Effect of the type of flame on the microstructure of CaZrO₃ combustion flame sprayed coatings Surf Coat Technol. 2006; 201: 3307–3313.

[18] Guo L, Li M, He S, et al. Preparation and hot corrosion behavior of plasma nanostructured Gd₂Zr₂O₇-LaPO₄ thermal barrier coatings. J Alloys Compd. 2017; 698: 13–19.

[19] Habibi MH, Wang L, Guo SM. Evolution of hot corrosion resistance of YSZ, Gd₂Zr₂O₇, and Gd₂Zr₂O₇+YSZ composite thermal barrier coatings in Na₂SO₄+V₂O₅ at 1050°C. J Eur Ceram Soc. 2012; 32: 8: 1635–1642.

[20] Habibi MH, Wang L, Liang J, et al. An investigation on hot corrosion behavior of YSZ-Ta₂O₅ in Na₂SO₄ + V₂O₅ salt at 1100 °C. Corros Sci 2013; 75: 409–414.

[21] Flores FC, Morales RA, Martinez GH, et al. Hot corrosion behaviour of 7YSZ + Gd₂O₃ nano-composites in molten salts prepared by spark plasma sintering. Corros Eng Sci Technol. 2017; 52(3): 236–243.

[22] Xie L, Dorfman MR, Cipitria A, et al. Properties and performance of high-purity thermal barrier coatings. J Therm Spray Technol 2007; 16: 804–808.

[23] Ahmami S, Vuoristo P, Mäntylä T, et al. Thermal cycling resistance of modified thick thermal barrier coatings. Surf Coat Technol 2005; 190: 378–387.

[24] Chen X, Zhao Y, Gu L, et al. Hot corrosion behaviour of plasma sprayed YSZ/Al₂O₃ composite coatings in molten sulphate-vanadate salt. Corros Sci 2011; 53: 2335–2343.

[25] Sreedhar G, Raja VS. Hot corrosion of YSZ/Al₂O₃ dispersed NiCoAlYTa coating deposited on Inconel alloy substrate by high velocity oxy-fuel spraying upon exposure to molten V₂O₅-containing salts. Corros Sci 2016; 112: 696–709.

[26] Bahamirian M, Khameneh AS. An investigation on effect of bond coat replacement on hot corrosion properties of thermal barrier coatings. Iran J Mater Sci Eng. 2013; 10: 3: 12–21.

[27] Afrasiabi A, Saremi M, Kobayashi A. A comparative study on hot corrosion resistance of three types of thermal barrier coatings: YSZ, YSZ+Al₂O₃ and YSZ/Al₂O₃. Mater Sci Eng A 2008; 478: 264–269.