Thermal shock behavior of multilayer and functionally graded micro- and nano-structured topcoat APS TBCs

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Thermal Barrier Coating
Thermal shock
Multilayer coating
Nano-YSZ
YSZ
CSZ

ABSTRACT
Performance of air plasma sprayed (APS) thermal barrier coatings (TBCs) with multilayer and functionally graded topcoat were investigated in thermal shock conditions. Ceria-yttria stabilized zirconia (CSZ) and micro- and nano-structured yttria stabilized zirconia (YSZ and YSZ-N) were used to produce coating samples. The samples were classified into four families, namely single-layer, double-layer, triple-layer and functionally graded (FG). To measure thermal shock resistance, the heating/water quenching cycles were repeated 70 times and 30% destruction of the coating was considered its functionality limit. Thus, cycles did not continue for those coatings that were destroyed more than 30%. At the end of each cycle, the surface and edge damage were determined from the photos of samples. Furthermore, scanning electron microscope (SEM) images and energy-dispersive spectrometer (EDS) analysis of samples’ cross-section were taken before and after the test. After collecting the experimental data, effects of various factors on outputs were investigated. The results showed that YSZ-N single-layer coating and triple-layer with CSZ as a top layer, has less thermally grown oxide (TGO) thickness and best performance in thermal shock conditions.

1. Introduction
Thermal barrier coatings (TBCs) are applied to those components of gas turbine that work in high temperature (more than 1000 °C). This high temperature environment causes many damages to these components and application of TBCs has shown to have a significant effect on preventing such damages. Some results of using TBCs include: fatigue and creep resistance improvement, better performance against foreign particle damage, reducing fuel consumption and increased operating temperature and components’ life [1–8]. Improving TBCs leads us towards the next generation of turbines that require more efficiency and reliability [9, 10].

Thermal barrier coatings have a multi-layer structure. The base layer is the substrate which in high-temperature components, usually produced from nickel-base superalloy. This layer has a limitation in working temperature and is subjected to fatigue and creep [11]. The next layer is the bondcoat (BC) that works as an intermediate layer between the ceramic topcoat and the metallic substrate. Coefficient of thermal expansion (CTE) amount of this layer -that is between the substrate and the topcoat (TC) - causes coating to have a better strain compliance in the thermal cycles. Compound of bondcoat is rich in Al and has a thickness of about 50–150 µm [3]. The outer layer that is known as the topcoat, is made from ceramic materials and has a thickness in range of 250–600 µm. This layer should have a low thermal conductivity, a CTE close to the bondcoat, a good resistance to sintering and a phase change at high temperatures [12].

After a couple of coating cycles, some amount of oxygen, infiltrated in the structure of topcoat and at the BC/TC interface, reacts with the aluminum and forms a thin layer of α-Al2O3 (thermally grown oxide -TGO). The thickness of this layer, which increases with time, is in the range of 0.1–10 µm. TGO protects the substrate from oxidation and hot corrosion. However, its thermal mismatch with other layers causes large compressive residual stresses. With TGO thickening, the amount of stresses will increase. Thus the TGO thickness plays an important role in the destruction of coating [11–14].

The most common material for the topcoat layer is Yttria Stabilized Zirconia (YSZ). Superior properties of YSZ, such as high CTE, low thermal conductivity and high thermal shock resistance, has pronounced it as the first choice for TBCs material; however some features, such as phase change and sintering at temperatures above 1200 °C and high oxygen permeability (Which causes the substrate oxidation and TGO thickening), led to restrictions on working condition [15–19]. Hence there is always a need for solutions that can fix the above limitations. One of the obtained results is adding CeO2 to YSZ and...
production of Ceria-yttria coStabilized Zirconium oxide (CSZ) [9]. This compound has a higher CTE than YSZ and also better resistance to hot corrosion and oxygen penetration. However, its performance under thermal shock and sintering condition is weaker than YSZ [4,20].

Using nano-structured materials in the coatings’ composition is another sound method towards improving the quality of TBCs. Research has shown that nano-structured coatings have lower thermal conductivity and better thermal shock resistance than conventional coatings [21–24].

Another solution to improve coating performance is using the multilayer topcoat TBCs. Increased operating temperature, better tolerance compliance in thermal cycles, more resistance to hot corrosion and reduction of oxygen penetration and thermal conductivity are some advantages of these coatings [9]. To improve mentioned properties of multilayer coatings, Functionally graded (FG) coatings, in which changing from one layer to another occurs gradually, can be used [10].

To apply topcoat on the surface, commonly air plasma spray (APS) and electron-beam physical vapor deposition (EBPVD) methods are used. The structure of coatings produced by each of these methods is different from the other but APS is less expensive and more used in industry, especially in the coatings of fixed turbine components [5,15]. The coating produced by APS method has a defected structure (includes cracks, micro-cracks, voids, porosity, etc.) that in addition to decreasing the thermal conductivity, leads to improved tolerance performance in thermal cycling [18]. In the APS method, powders are fed into plasma stream and after melting, impact to the surface at high speed and quickly solidified [25].

Some of the main reasons of TBCs damage are the thermal expansion mismatch of coating layers and thermal shocks. Low thermal compliance of topcoat with beneath layers, were resulted of crack initiation in the TGO region and into the topcoat [10,13,26]. Moreover, thermal shocks can be a source of many damages because in this situations coating temperatures suddenly drop from more than 1100 °C to the ambient temperature in a very short time [27–29]. In these circumstances, in order to evaluate the coating performance, usually two methods are used: laboratory burner rig and furnaces test. The latter is more time consuming, but is more compatible with the real conditions [30,31]. Recently, several papers have been published about coatings thermal behavior [32–42].

In this study, performance of single-layer, double-layer, triple-layer and FG coatings in thermal shock situations were investigated with furnace method. The design of the experiments has resulted in determining the role of the number of layers (based on the performance of single-, double- and triple-layer coatings), the boundary of the layers (according to the performance of FG coatings), the type of structure (micro or nano) and location of the layers on the coating behavior.

2. Materials and methods

2.1. Materials

The substrates of the samples were made of IN738LC disks with dimensions of 30 × 3 mm. Amperit®415.006 CoNiCrAlY also was applied as bondcoat material with APS method. 8YSZ (Metco 234A-8%), CYSZ (Metco 205NS) and YSZ-NANO (Inframat Sprayable Nanox™ S4007) powders were used for ceramic topcoat.

2.2. Air plasma spraying

In the first step, to increase the roughness of surface and coating adhesion, the substrates were sand blasted by 25 grain mesh Al2O3 particles and then samples were preheated at 200 °C. After the pre-process preparation, plasma spraying was performed using Metco 3MB in atmosphere. For primary and secondary plasma gases, argon and hydrogen were used, respectively. The related spraying parameters are shown in Table 1.

CoNiCrAlY coating with a thickness of 150 µm was applied on the top surface of samples as the bondcoat by APS. Then the samples were coated according to Table 2.

2.3. Thermal shock test

In order to investigate coating performance in thermal shock conditions, furnace tests were conducted. During this test after reaching the furnace temperature to 1100 °C, the samples were placed in the furnace. After 25 min in the furnace, samples were directly quenched in water for 5 min. The quenching process was repeated for each sample and stopped when a coating had more than 30% delamination. Three parallel tests were carried out for each condition.

2.4. Coating characterization

Investigations of sample’s performance in thermal shocks were done by observation of the coated disks’ section with a scanning electron microscope (SEM) and analyzed by an energy-dispersive spectrometer (EDS) before and after the test.

2.5. Calculating coating parameters

At the end of each cycle, photographs were taken from all samples, and then surface and edge damage (%SD and %ED) were quantified with Digimizer software with calculation the ratio of the damaged area

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>YSZ</th>
<th>CSZ</th>
<th>YSZ-N</th>
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<tr>
<td>Current</td>
<td>A</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Voltage</td>
<td>V</td>
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<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Primary gas flow (Ar)</td>
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<td>Spray distance</td>
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<td>100</td>
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<td>rotation speed</td>
<td>RPM</td>
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<td>120</td>
<td>120</td>
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<td>Surface roughness</td>
<td>µm</td>
<td>0.67 ± 0.1</td>
<td>0.67 ± 0.1</td>
<td>0.67 ± 0.1</td>
</tr>
<tr>
<td>Preheat and afterheat temperature</td>
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<td>200</td>
<td>200</td>
</tr>
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</table>

* Normal Liter Per Minute.
to the whole disk area (Eqs. (1) and (2)).

\[
\%ED = \frac{\text{edgedamagedarea}}{\text{wholediscaarea}} \times 100
\]

(1)

\[
\%SD = \frac{\text{surface damaged area}}{\text{whole disc area}} \times 100
\]

(2)

Comparison between samples, which have been destroyed in different cycles, was needed a common criterion, and thus the performance factor (PF) that is defined according to the Eq. (3), was used. The design of PF is such that in the initial cycles and small amount of damage, its value is about 100 and then decreases when the damage increases.

\[
PF = 10 \times \ln \left( \frac{\text{endcycle number}}{\%ED} \right) \times 100
\]

(3)

Cracks like honeycomb formed on samples' surface in the few first cycles, and examples are illustrated in Fig. 1. Surface crack size (CS) is the average of 10 measurements and calculated for all samples.

TGO thickness was determined from cross-section SEM image, after the thermal shock test was carried out and the samples were destroyed. Since TGO growth rates linearly related to the square root of time [43], the thickness of TGO in the cycle 70, is determined by the Eq. (4):

\[
C = C_0 + \frac{R}{(T/\sqrt{t})}
\]

(4)

Table 2

<table>
<thead>
<tr>
<th>Family name</th>
<th>Short code</th>
<th>Short code name</th>
<th>L1 (μm)</th>
<th>T1 (μm)</th>
<th>L2 (μm)</th>
<th>T2 (μm)</th>
<th>L3 (μm)</th>
<th>T3 (μm)</th>
<th>L4 (μm)</th>
<th>T4 (μm)</th>
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</tr>
<tr>
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<td>D28</td>
<td>F2YC225</td>
<td>Y</td>
<td>225</td>
<td>C</td>
<td>225</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<tr>
<td></td>
<td>D37</td>
<td>F3YC150</td>
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<td>Y</td>
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<tr>
<td></td>
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<td>F2YC225</td>
<td>Y</td>
<td>225</td>
<td>C</td>
<td>225</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>D49</td>
<td>F3Y(Y1C1)C</td>
<td>Y</td>
<td>250</td>
<td>Y1C1</td>
<td>150</td>
<td>C</td>
<td>150</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>D52</td>
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<td>Y</td>
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<td>112</td>
<td>Y1C2</td>
<td>112</td>
<td>C</td>
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<tr>
<td></td>
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<td>–</td>
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<td>–</td>
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<tr>
<td></td>
<td>D37</td>
<td>F2YC225</td>
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<td>Y1C1</td>
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<td>–</td>
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<td>D61</td>
<td>F4Y(Y2C1)YN1C2C</td>
<td>C</td>
<td>112</td>
<td>Y2C1</td>
<td>112</td>
<td>Y1C2</td>
<td>112</td>
<td>C</td>
<td>112</td>
</tr>
</tbody>
</table>

* L: Layer.
** T: Thickness.
Where TGO\textsubscript{70} is the estimated TGO thickness in cycle 70 and TGO\textsubscript{ES} is TGO thickness in the end cycle.

2.6. Effect of coating parameter

According to the experimental data, the main effects of the coating parameters were determined with MINITAB software.

3. Results and discussion

The porosity and defects in the structure of the APS coatings play an important role in strain compatibility. To calculate coating porosity, the cross-section images of coatings were converted to binary using Adobe Photoshop and then ratio of black pixels to total pixels was calculated. Binary images of three coatings are shown in Fig. 2. Calculated porosity for YSZ, YSZ-N and CSZ is 18.44%, 14.24% and 9.61%, respectively.

3.1. Single-layer coatings

Best performance and lowest damage in single-layer family were belonged to YSZ-N and then YSZ. Damage in the two mentioned coatings grows with low rate and in a linear manner, but in CSZ, growth is parabolic and has a high rate. Damage curves and performance data of this family are shown in Fig. 3 and Table 3, respectively.
When samples were placed inside the furnace, according to the CTE of layers, because of enough time, all parts of the coating uniformly expanded; however, in the quenching stage and due to limited time, the outer parts of the coating contracted, while the inner parts were still expanded. In these conditions, shrinkage stress prevails on the integrity of the coating, and vertical cracks appear on top and outer surface of samples. These cracks have a positive role on the performance of coatings in thermal cycling. According to coating material(s) and structure, sizes of cracks are different. However, the shape and arrangement are random.

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In D4, damage was started from the edge and has grown with a short distance from the edge. Damage growth in different cycles for this family can be seen in Fig. 4. Type of damage is separation pieces of the coating from the edge, and in separated areas, lower part of coating remains on the disk. Surface damage in this sample is small (around 1%), but deep. In YSZ coatings, because of high porosity, there are areas that are surrounded by porosities and defects (Fig. 5), thus have the lower mechanical bond, and in face of stress, are seamlessly separated.

In D13, edge damage was very low and surface damage was not observed. This sample has shown very good performance in thermal shocks, and unlike YSZ in locations where edge damage was happened, the whole thickness of the coating was washed away, and nothing was left on the disk surface. Appropriate performance and absence of surface damage are due to the nano-zones and their uniform dispersion. These zones are shown in Fig. 6-a, act as springs inside the coating which helps to expand and contract without damage. In other words, nano-zones have spring-like behavior. Examination of the cross-section SEM image of these coatings was showed that three different behavior of nano-zones in the area of meeting cracks to nano-zones can be occurred (Fig. 6-b, -c and -d): (1) redirecting the crack, (2) stopping the crack and (3) branching crack into two or several smaller and weaker cracks. All these phenomena help to increase the coating life.

<table>
<thead>
<tr>
<th>Name n</th>
<th>%Sid</th>
<th>%Ed</th>
<th>SC</th>
<th>EC</th>
<th>TGO70</th>
<th>Cs</th>
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<td>D28</td>
<td>2</td>
<td>18.7</td>
<td>34.8</td>
<td>32</td>
<td>52</td>
<td>1.8</td>
<td>965</td>
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<tr>
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<td>62</td>
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<td>33</td>
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<tr>
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<tr>
<td>D37</td>
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<td>34.2</td>
<td>26</td>
<td>43</td>
<td>1.9</td>
<td>482</td>
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Fig. 9. SEM image of separated CSZ coating after thermal shock test.

Fig. 10. Cross-section SEM image of double-layer family.

Fig. 11. Damage curve of double-layer coatings.
Performance of CSZ coating was different from two preceding cases (i.e. D4 and D13). In this sample, in cycle 42, the huge cracks were observed abruptly, and then a large part of the coating was separated. The structure of CSZ coating is denser than YSZ and YSZ-N, and its porosity can be seen, as very small areas and cracks with high dispersion.

With close examination of the structure of the CSZ coatings, two points attract the attention: (1) since there is the little barrier against crack growth on the structure of the coating, the length of the cracks is high and usually different cracks meet each other, and (2) horizontal cracks with intervals about 90 µm in thickness direction can be seen that exist almost in whole width of the coating (Fig. 7). These are the main reasons of coating behavior; the first one led to dislodging small fragments from the surface and edges of the sample and the latter causes the lower part of coating to remain on the disk surface. In the Fig. 8, the images of three samples with CSZ coating, at the end cycle of destruction, are shown. The end cycle of samples, is 41, 43 and 44 and in all cases, lower layers of coating remain on the disk surface.

The image of separated section of the coating after the thermal shock test is shown in Fig. 9. Areas created from joining cracks are well visible in this image.

3.2. Double-layer coatings

Despite poor performance of CSZ in comparison with the other two...
coatings in terms of thermal shocks, it has convenient features such as high resistance to hot corrosion and oxygen penetration, which are convincing enough to look for ways to improve it and make it a worthwhile candidate for thermal coating. In this section, performance of double-layer coatings, which have a CSZ layer, was investigated. CSZ on one hand has more CTE than YSZ, which places it on the lower layer in coatings architectural (for better strain adaptation) and on the other hand, has better resistance to hot corrosion and oxygen penetration that makes it a good choice for the top layer. Therefore, in two samples of this family, CSZ is top layer (D28 and D31) and in two others, is the lower layer (D34 and D37). In each sample, the thickness of layers is constant and equal to 225 µm (Fig. 10).

Damage curves and performance data for double-layer family are shown in Fig. 11 and Table 4, respectively. Damage curves shown that all samples had a good performance up to C35, then D28 and D37 (with CSZ as a first layer) exponentially with high rate have been destroyed. In two other samples, the damages were less than 5% to C45 and less than 15% to C57, but in C59 a big part of D34 coating separated at once. Presences of YN in D31 and D34 were resulted in a linear behavior. It is an important feature because in these samples, rate of delamination progress is not exponential.

Performance data shown that samples with CSZ on top, have better performance than the other two. These samples were endured to C59 and C70 while last cycle for D28 and D37 is C52 and C43, respectively. Surface damage in D28 and D31 was very severe but in D34 and D37, nothing observed (Fig. 12). The reason behind this can be traced in the CSZ layer structure. As mentioned in the single-layer coatings, horizontal cracks have the capability of growth in the CSZ because of more dense structure and fewer defects; so surface cracks were grown in thermal cycles and joined to the horizontal cracks which were at the distance of about 90 µm from the surface, and then, small pieces of coating were separated. In YSZ and YSZ-N, because of structural defects
and also nano-zones, horizontal cracks could not grow easily, and their progress mostly was vertical due to the strain adaptation in thermal cycles.

Comparison between the edge damage of D28 and D31, were specified the roles of nano-zones in coating performance. With increasing distance from the center of the disk, thermal strain becomes greater; thus, the most critical part is the outer perimeter of sample. Vertical cracks on the edge of D28 and D31 started and continued to reach the interface. In D28 crack growth continues in YSZ to reach the BC/TC interface and consequently, in this sample, coating near the edge, separated completely. However, in D31, nano-zones in interface, were resisted against more grew and crack continued its path at the interface (Fig. 13).

Presence of nano-zones near the BC/TC interface and creating powerful mechanical bonds, is one of the other reasons for remaining parts of YN layer on the disk surface. Indeed, nano-zones resisted against oxygen diffusion, and thinner TGO was formed in interface, so less stresses created and cracks could not grew easily in interface and redirected among the coating or layer boundaries. As mentioned before, nano-zones have the main responsibility to control crack path. SEM images of different interfaces are shown in Fig. 14.

As can be seen in Fig. 15, damage was started in D31 earlier, but progress rate in D28 is more. It shows that YN controls the coating separation and resists against its propagation; therefore, surface damages are more visible in this sample.

In D34, vertical cracks grew to BC/TC and then a large part of the coating was separated (Fig. 18). However, in D37, firstly, crack grew vertically in YN layer and after reaching the CSZ layer, was redirected and moved in a diagonal manner towards the edge (Fig. 16). Damage progress of D37 in the last six cycles can be seen in Fig. 16. This trend indicates that after starting damage, CSZ disposed of more delamination.

SEM image after the thermal shock test of D34 shows that large crack was initiated from interface of two layers and grew obliquely in

![Fig. 18. Damage growth in D34.](image-url)

![Fig. 19. Damage curve of triple-layer family.](image-url)

![Fig. 20. Cross-section SEM image of triple-layer family; distinct boundary (red lines) in CSZ interface, plays an important role in crack control.](image-url)
Comparison between damage type in D37 and D34 indicates that in D34, horizontal cracks in BC/TC play main roles (Fig. 18) but in D37, functions of horizontal cracks in CSZ structure are more dominant. One of the other reasons behind this phenomenon is thickened TGO that caused very large compressive stresses in BC/TC interface and led to growing crack in this region.

3.3. Triple-layer coatings

In this section, in order to examine the performance of triple-layer coatings, four different samples were designed and produced. In two of them, CSZ is the top layer (D45 and D47) and in the other two, it is the bottom layer (D41 and D43). Damage curve and Performance data of these samples can be seen in Fig. 19 and Table 5, respectively.

According to performance data of this family, it was observed that layer boundary had a positive role in coating function and similar to the CSZ layer (Fig. 17).

Comparison between damage type in D37 and D34 indicates that in D34, horizontal cracks in BC/TC play main roles (Fig. 18) but in D37, functions of horizontal cracks in CSZ structure are more dominant. One of the other reasons behind this phenomenon is thickened TGO that caused very large compressive stresses in BC/TC interface and led to growing crack in this region.
double-layer coating, samples, which had CSZ as a top layer, performed better but had intense surface damage. TGO thickness is low in all samples which indicated the importance of layer boundary in preventing the penetration of oxygen.

Cross-section SEM images of this family shown in Fig. 20. According to the sample’s image, in the last cycle of activity (Fig. 21), the integrity of the coating structure is evident in triple-layer family. It is because, in the time of damage, the entire coating separated and nothing remained on the surface. In D45 and D47, like other cases that CSZ is the top layer, widespread surface damages were observed.

According to the behavior of this family, it can be concluded that the TGO region, firstly, and layers' boundaries, secondly, are areas of coating prone to large damages. Hence, in the samples which have a thick TGO (e.g. D41), there is a complete separation of large parts of the coating. Thus, when the thickness of TGO is low, damage region shifted to the layer's boundary. The latter results in some parts of the coating remain on the disk surface after damage.

One of the points that must be considered within this context is that the more damages, were increased the penetration of oxygen and facilitated TGO formation conditions. For example, line scans analysis of D43 after C70 and close to TGO area (Fig. 22) shows that at a distance about 3.5 µm from TGO, oxygen and aluminum are sufficient for the formation of Al2O3. When this happens near the TGO, it thickens quickly and large flakes of coating are separated.

3.4. FG coatings

After investigation of double- and triple-layer coatings, it became clear that for better performance of multilayer coatings, CSZ should be as the top layer. Thus, in this section, FG coatings with CSZ as the top layer and YSZ or YSZ-N as the bottom layer were designed and produced. It is predicted that gradual change in these coatings, cause less damage in thermal strains. In all cases, the total thickness of coating was constant (450 µm) and thickness of all layers was equal. For middle layers, at first, powders mixed into a bottle with the specified ratio for one hour and then, the mixed powder fed in plasma spraying machine.

Cross-section SEM images of produced coatings are shown in Fig. 23. The growing of vertical cracks in the coatings is interesting. In the double-layer coatings, after reaching to the boundary, cracks have been stopped (Fig. 10). In the triple-layer coatings (D49 and D52), cracks in the layer boundary are weakened but continued their path. Finally, in the quadruple-layers (D52 and D61), layers have no distinct boundary and hence has not any effects on cracks’ path.

Damage curves for this family shown in Fig. 24, and clearly the damage growth in the YN-C class has been with less steep. According to performance data (Table 6), average life and PF of Y-C class is 54.67 and 50.1, and these are 67.67 and 58.5 for YN-C class. Triple-layer in both class has less TGO and better performance and surface crack size in both class is relatively large.

Another observation in this family is medium-sized horizontal cracks in the intermediate layers. These cracks mostly are seen in triple-layer. In these coatings, middle layers of topcoat consist of mixture of two powders and despite the uniformity of the coating structure, because of differences in materials' density, some areas are richer in A and some other areas are rich in B. In this situation, there are micro-boundaries that act as a source of micro-cracks. It seems micro-cracks due to the small size, only able to control and redirect the vertical cracks that are smaller than itself and larger cracks easily pass through them and continue their path. This phenomenon observed less strictly in quadruple coatings because, in these coatings, underlying intermediate layer is richer than A and therefore, behavior of A is dominant.

![Fig. 24. Damage curves of FG family.](image)

![Fig. 25. Y-C class of FG family in last cycle.](image)

### Table 6

<table>
<thead>
<tr>
<th>Name</th>
<th>n</th>
<th>%Sd</th>
<th>%Ed</th>
<th>SC</th>
<th>EC</th>
<th>TGO</th>
<th>Cs</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>D28 G2YC</td>
<td>2</td>
<td>18.7</td>
<td>34.8</td>
<td>32</td>
<td>52</td>
<td>1.8</td>
<td>965</td>
<td>50</td>
</tr>
<tr>
<td>D49 G3Y(Y1C1)C</td>
<td>3</td>
<td>37.9</td>
<td>36.3</td>
<td>23</td>
<td>56</td>
<td>1.5</td>
<td>985</td>
<td>50.4</td>
</tr>
<tr>
<td>D52 G4Y(Y2C1) (Y1C2)C</td>
<td>4</td>
<td>0.4</td>
<td>38.7</td>
<td>23</td>
<td>56</td>
<td>1.7</td>
<td>1103</td>
<td>49.8</td>
</tr>
<tr>
<td>D31 G2YNC</td>
<td>2</td>
<td>62</td>
<td>20.1</td>
<td>33</td>
<td>70</td>
<td>1.5</td>
<td>761</td>
<td>58.5</td>
</tr>
<tr>
<td>D58 G3YN(YN1C1)C</td>
<td>3</td>
<td>57</td>
<td>11.3</td>
<td>18</td>
<td>70</td>
<td>1.2</td>
<td>1026</td>
<td>64.3</td>
</tr>
<tr>
<td>D61 G4YN(YN2C1) (YN1C2)C</td>
<td>4</td>
<td>1.1</td>
<td>32.1</td>
<td>16</td>
<td>63</td>
<td>1.3</td>
<td>1218</td>
<td>52.8</td>
</tr>
</tbody>
</table>

![Fig. 26. Regions prone to damage.](image)
and in the other layer conditions are vice versa.

In quadruple-layer coatings, CSZ was presented at the bottom of coating and close to BC layer. As previously mentioned, the existence of CSZ in the bottom, causes downfallen coating performance.

3.4.1. Y-C class

Images of this class in the last cycle of their activity are shown in Fig. 25. With a close look to the areas that coatings are separated, it can be percept that damage mainly occurred in the top boundary of a layer and in some parts this happened in the lower boundary of this layer (Fig. 26). The first mode caused remaining parts on the surface, and the latter was the reason of the complete separation from the surface. In this class, triple and quadruple layer endured more but best PF is belonged to triple-layer.

Absence of surface damage in D52 was due to a low thickness of top layer (CSZ) that does not allow the formation of horizontal cracks. In this situation, relatively strong mechanical bonds with the next layers prevented separation parts of the coating. Damage progress for D52 shown in Fig. 27 and indicate that crack formed in previous cycles in lower layer and growth to the top surface. Also presence parts of the coating on the disk surface indicate that damage happened in region 1 (Fig. 26) and then travels in the direction of thickness obliquely.

3.4.2. YN-C class

Growing of damage in YN-C class shows that presence of YN prevents horizontal cracks and coating separation. In this class, also, surface damage is severe (except D61) and appearance of surface damage in different samples is similar to the corresponding members in Y-C class. The latter confirms that the surface damage in CSZ layer was depended on the thickness (Fig. 28).

Best performance in this class was belonged to triple-layer, and it was concordance with Y-C class; so in can be conducted that specified and soft layer boundaries are effective and helpful for thermal shock behavior improvement.

3.5. Effect of parameters

In last section of discussion, to investigate the effect of different factors on test outputs, their fitted line graph was drawn (Fig. 29). Summaries of results are as follows:

- TGO: it has a strong inverse effect on PF and believable effect on %ED, but has a little effect on surface damage. The effect of TGO is more tangible than other factors.
- CS: crack size has an only small effect on surface damage, and is ineffective on the other factors.
- %Y: This factor has almost no effect on outputs and only has a small positive effect on the PF.
- %YN: This has a good positive effect on the PF.
- %C: this factor has a significant inverse impact on PF and the effect on %ED also become apparent.

It must be noted that locations of materials are also affected on the mentioned outputs, but above analysis only considered percentage of materials.

In the right side of Fig. 29, effect of the layer number investigated. The greatest effect of N is on the CS and then TGO; it also has a positive effect on the PF.

4. Conclusions

Performance of single-layer, double-layer, triple-layer, and functionally graded (FG) topcoat APS TBCs were investigated using the furnace test. Results shown that:

- In single-layer family, YSZ-N has the best performance; YSZ, while has a high performance factor, but its TGO was thick.
- In double-layer family, best performance belonged to D31 (with YSZ-N and CSZ as a first and top layer). Furthermore, it was founded that coatings with CSZ as the top layer had better performance and less TGO thickness.
- In triple-layer family, coatings with CSZ as a top layer have better performance, but surface damage was seen in these coatings. TGO thickness is relatively low in this family that can be a verification for positive roles of layer's boundaries in oxygen diffusion resistance.
- In FG family, YN-C (with nano-structured YSZ and CSZ) class has better performance than Y-C (with micro-structured YSZ and CSZ) class and in each class, triple-layer was the best. This shows that specified layers' boundaries had a positive effect on coating performance.
- Among all coatings, YSZ-N single-layer and then triple-layers with CSZ as a top layer had best performance.
- The most obvious effect of experimental factors was belonged to the effect of TGO thickness on performance factor and edge damage.
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References
