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# Evaluation of hot corrosion behavior of plasma sprayed thermal barrier coatings with graded intermediate layer and double ceramic top layer

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ABSTRACT

In the present work, the hot corrosion behavior of two types of multilayer plasma sprayed TBC were investigated and compared with functionally graded and conventional TBCs. These kinds of multilayer coatings consisted of nano/μ alumina as a top coat on YSZ layer, a metallic bond coat and a functionally graded intermediate layer deposited between YSZ and bond coat layers. All the layers were sprayed on the Ni-base super alloy substrate. The hot corrosion resistance of the plasma sprayed coatings was examined at 1050 °C for 40 h, using a fused mixture of 45 wt% $Na_2SO_4$ + 55wt%$V_2O_5$. Before and after hot corrosion, the microstructure and phase analysis of the coating were studied using scanning electron microscope and X-ray diffractometer. The results showed that, the $Al_2O_3$ top layer acted as a barrier against the infiltration of the molten salt into the YSZ layer during exposure to the molten salt mixture at the high temperature and the multilayer coatings of zirconia/alumina with the nanostructured alumina as a top coat showed higher hot corrosion resistance. Also, the failure mechanisms of the functionally graded coating and duplex TBC were investigated. The spallation occurred between the graded layer and the bond coat/top coat in functionally graded TBC and duplex TBC, respectively.



## 1. Introduction

Thermal barrier coatings (TBCs) are currently used to provide thermal insulation against hot gasses in advanced gas turbines and diesel engines in order to improve their performance and efficiency, or to extend the life capabilities of these machines [1–3]. Typical TBC system includes $Y_2O_3$ stabilized $ZrO_2$ (YSZ) top coat as a thermal insulation layer and a bond coat layer, which is typically MCrAlY (M = Ni, Co, Fe or a combination of these elements) as an oxidation resistant layer. Bond coat is often first deposited onto a metallic substrate to protect the substrate from high temperature corrosion and oxidation [4–5]. TBCs are usually deposited either by electron beam-physical vapor deposition (EB-PVD) or air plasma spraying (APS). However, because of the high deposition efficiency and comparatively cost-effective deposition conditions, APS is a popular one [6–7].

There are some important factors affecting TBCs life time, including high temperature oxidation, infiltration of detrimental factors such as molten salts, which lead to spalling upon thermal cycling, and formation of thermally grown oxide (TGO) [2]. Because of the need to increase the efficiency of gas turbines, engines and energy generating systems, there has been a growing interest in the use of novel TBC materials with advanced structures [2,8]. Recently, multilayer TBCs with the double ceramic top coat system have been suggested [8–9]. In such coatings, the dense structure of the top layer prevents the infiltration of oxygen or other detrimental factors such as vanadium salt and also, retards the phase transformation of zirconia and formations of TGO, thereby increasing resistance to hot corrosion and TBCs life time [2,7–10]. Saremi et al. [2,11] have studied YSZ–$Al_2O_3$ composites and multilayer coatings. In such coatings, the $Al_2O_3$ layer, due to its good physical and chemical properties, is regarded as an oxygen barrier structure in comparison with $ZrO_2$, thereby making the coating more resistant in thermal cycles [11–12]. The study carried out by Wu et al. [13] revealed that the TBCs, by employing $Al_2O_3$ as a top layer, could resist the hot corrosion attack of molten salt for a longer time, as compared to the conventional TBC. It should also be noted that the spallation of the ceramic layer from the bond coat is an important problem for multilayer and conventional TBC systems [11–13]. To increase spallation resistance, the coefficient of thermal expansion (CTE) mismatch between ceramic and metallic layers should be minimized [5]. The use of a functionally graded coating is an important attempt toward improving the spallation resistance and coating properties [3–5]. Graded interfaces can be valuable for increasing fracture toughness and eliminating stress because of gradual changes in the properties of materials [14]. Recent studies have shown that functionally graded thermal barrier coatings (FG-TBCs) can exhibit higher properties when compared with coatings without the graded structure [14–15].

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Recently, nanostructured coatings fabricated by APS method have been widely used due to some superior properties, in comparison with conventional TBCs [16]. Sprayed nanostructured coatings exhibit improvements in resistance to corrosion, wear, erosion and mechanical properties, as compared to their conventional counterparts [7,16].

The aim of the present research was to investigate the structure and the hot corrosion behavior of conventional TBC and two types of functionally graded coatings comprising micro $Al_2O_3$ and nano $Al_2O_3$ as a top layer on the YSZ layer. In this regard, the dense alumina top coat with high hot corrosion resistance and low Oxygen conductivity was sprayed as a top layer to prevent the infiltration of salt into YSZ layer. Also, failure mechanism and degradation part of graded and ungraded coatings were compared and studied by the observation of microstructural and chemical analysis.

## 2. Materials and method

### 2.1. As-received materials

Ni-based superalloy (Inconel 738LC, Ni-15Cr-8.5Co) in the shape of disks 20 mm in diameter and 20 mm in thickness were grit blasted with alumina particles and used as the substrate. Four types of commercial feedstock powders were used: NiCrAlY (Metco 442, Ni–9Cr–6Al–5Mo–2Fe) commercial powders as the bond coat, Metco 204NS trade mark YSZ powder, Metco 105 NS $Al_2O_3$, and US 3008 nano $Al_2O_3$ as a ceramic top layer. Fig. 1 shows the XRD patterns of as-received alumina powders. As can be seen, both nano and micro alumina powders identically contained pure α-$Al_2O_3$ phase. It should be noted that before plasma spraying, nano $Al_2O_3$ powders must be granulated to micron-sized granules. For this reason, spray drying method was used to granulate the nano $Al_2O_3$. After granulation, granules in the size range of 30–100 μm were used by passing them through a sieve. In this regard, granulated powders could be fed in APS system. The use of granulated particles was due to their better flowability, as related to nanostructured powders. Fig. 2a shows the cross-section morphology of the agglomerated particles of nanostructured $Al_2O_3$ powders after spray drying process and Fig. 2b illustrates a high magnification view of the granulated powder. It is clearly observed that nano $Al_2O_3$ particles are the components of $Al_2O_3$ granulated particles. The picture of the granulated powder shows a semi- spherical shape suitable for the plasma spray process.

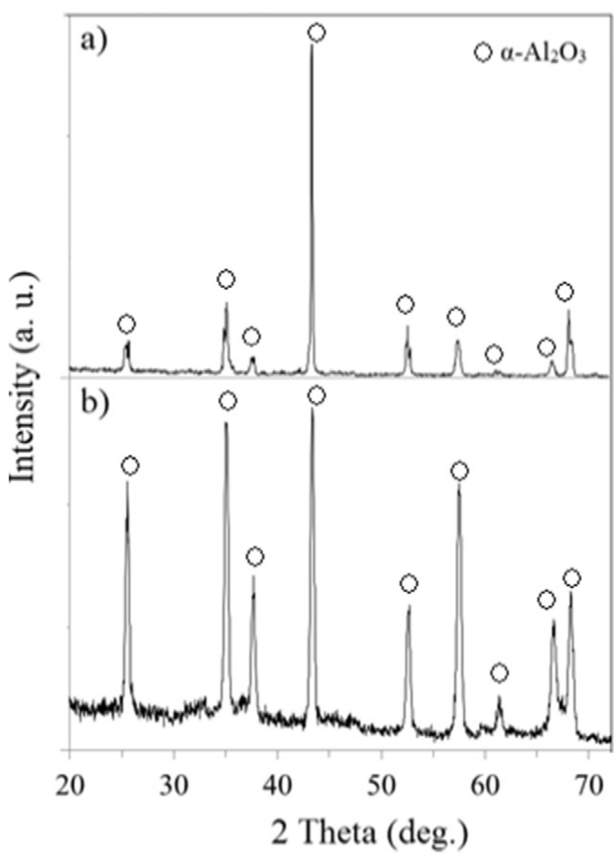


**Fig. 1.** XRD patterns from Alumina feedstock (a) micro $Al_2O_3$, and (b) nano $Al_2O_3$.

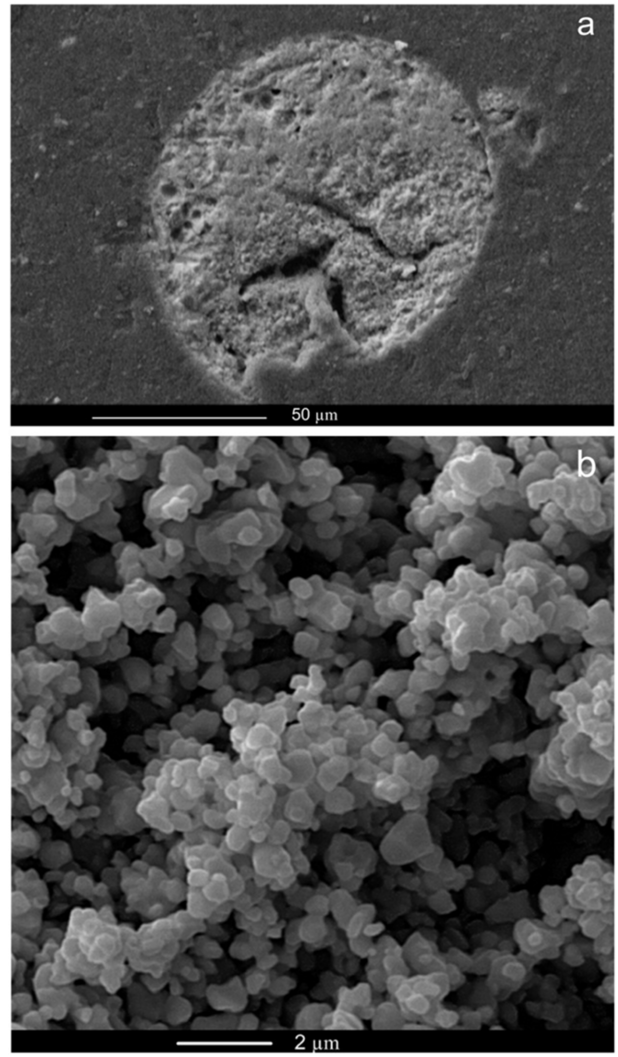


**Fig. 2.** (a) The cross-section morphology of nano $Al_2O_3$ granulated powder, and (b) high magnification view of the granulated powder.

### 2.2. Air plasma spraying

Prior to plasma spray deposition, in order to increase the specimen surfaces roughness and coatings adhesion, the substrates were grit

**Table 1**
Parameters of air plasma spraying.

| Parameter | NiCrAlY | YSZ | Graded layer | Nano $Al_2O_3$ | Micro $Al_2O_3$ |
|---|---|---|---|---|---|
| Current (A) | 450 | 550 | 550 | 500 | 550 |
| Voltage (V) | 75 | 70 | 70 | 70 | 70 |
| Primary gas, Ar (l/min) | 55 | 36 | 36 | 36 | 36 |
| Secondary gas, $H_2$ (l/min) | 17 | 17 | 17 | 17 | 17 |
| Powder feed rate (g/min) | 35 | 30 | 30 | 30 | 30 |
| Spray distance (cm) | 12 | 8 | 8 | 8 | 8 |