EVALUATION OF NANOSTRUCTURED BOND COAT IN THERMAL BARRIER COATING SYSTEM WITH NANO ALUMINA LAYER DURING OXIDATION

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To my beloved parents and wife thanks for all your affectionate caring and supporting, and above all your sacrifices and prayers accorded to me until the successful completion of this project.

“My Success Is Yours Too”

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ABSTRACT

A thermal barrier coating (TBC) system usually consists of a ceramic top coat (yittria stabilized zirconia or YSZ) and a metallic bond coat (MCrAlY) (M = Ni, Co or mixture of these two) on the nickel-based superalloy as a substrate. A thermally grown oxide (TGO) layer can be easily formed on the bond coat which plays an important role in the spallation of TBC due to its growth during oxidation. Hence, the principal purpose of this research is to provide a new coating to significantly lessen the TGO growth and to suppress the growth of detrimental mixed oxides (CSNs) on the Al_2O_3 (TGO) layer during oxidation. Therefore, air plasma sprayed normal and nano TBC systems including, Inconel 738/normal NiCrAlY/normal YSZ, Inconel 738/normal NiCrAlY/normal YSZ/normal Al_2O_3, Inconel 738/nano NiCrAlY/normal YSZ, Inconel 738/nano NiCrAlY/normal YSZ/nano Al_2O_3 (as a novel system), and Inconel 738/normal NiCrAlY/nano YSZ were prepared then evaluated by pre-oxidation at 1000°C for 48h, high temperature oxidation at 1000°C for 120h, cyclic oxidation (thermal shocks) at 1150℃ and finally hot corrosion test at 1000°C. Microstructural characterization of coatings was also performed using SEM, FESEM, XRD and EDX. The results showed that both TGO growth and CSNs were considerably reduced with the use of nano NiCrAlY/YSZ/nano Al_2O_3 coating compared to the other coatings. It was found that pre-oxidation treatment and particularly TBC system microstructure can influence the evolution of TGO layer and TBCs durability during service at elevated temperatures.

ABSTRAK

Sistem salutan halangan haba (TBC) biasanya mengandungi satu lapisan seramik sebagai lapisan atas (YSZ atau yittria distabilkan zirconia) dan satu lapisan logam sebagai lapisan pengikat (MCrAlY) (M = Ni, Co atau campuran kedua-duanya) di atas substrat superaloi berasaskan nikel. Satu lapisan oksida tertumbuh haba (TGO) akan terbentuk dengan mudah di atas lapisan pengikat yang memainkan peranan yang penting dalam proses serpihan TBC yang disebabkan oleh pertumbuhan lapisan TGO semasa pengoksidaan. Jadi, tujuan utama penyelidikan ini adalah untuk membentuk satu salutan baru untuk mengurangkan kadar pertumbuhan lapisan TGO dan mengurangkan dengan berkesan pembentukan campuran oksida yang merosakkan (CSNs) di atas lapisan Al_2O_3 (TGO) semasa pengoksidaan. Oleh itu, beberapa sistem TBC iaitu normal dan nano disediakan melalui kaedah semburan plasma iaitu Inconel 738/normal NiCrAlY/normal YSZ, Inconel 738/normal NiCrAlY/normal YSZ/ normal Al_2O_3, Inconel 738/nano NiCrAlY/ normal YSZ, Inconel 738/nano NiCrAlY/normal YSZ/nano Al_2O_3 (sistem *novel*) dan Inconel 738/normal NiCrAlY/nano YSZ yang kemudiannya dinilai melalui kaedah pra-pengoksidaan pada suhu 1000^oC selama 48 jam, pengoksidaan pada suhu tinggi pada suhu 1000^oC selama 120 jam, pengoksidaan berkitar (kejutan suhu) pada suhu 1150^oC dan seterusnya ujian kakisan panas pada suhu 1000^oC. Pencirian microstruktur terhadap salutan yang terbentuk telah dilakukan melalui beberapa kaedah SEM, FESEM, XRD dan EDX. Keputusan kajian ini mendapati kedua-dua pertumbuhan TGO dan CSN telah berkurangan dengan begitu ketara bagi salutan nano NiCrAlY/YSZ/nano Al_2O_3, berbanding dengan salutan-salutan lain. Didapati juga, mikrostruktur dari rawatan pra-pengoksidaan terutamanya sistem TBC yang digunakan boleh mempengaruhi evolusi pembentukkan lapisan TGO dan kebolehtahanan sistem salutan semasa digunakan pada suhu tinggi.

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LIST OF ABBREVIATIONS

APS	-	Air Plasma Spray
BC	-	Bond Coat
CZ	-	Columnar Zone
CVD	-	Chemical Vapor Deposition
CTE	-	Coefficient of Thermal Expansion
EDX	-	Energy Dispersive Spectroscopy
EZ	-	Equiaxed Zone
EB-PVD	-	Electron Beam- Physical Vapor Deposition
EBSD	-	Electron Backscatter Diffraction Analysis
FESEM	-	Field Emission Scanning Electron Microscope
PSZ	-	Partially Stabilized Zirconia
SEM	-	Scanning Electron Microscope
TEM	-	Transmission Electron Microscope
TGO	-	Thermally Grown Oxide
TBC	-	Thermal Barrier Coating
TC	-	Top Coat
XRD	-	X-ray Diffraction
YSZ	-	Yttria Stabilized Zirconia
TBCs	-	Thermal Barrier Coating System
FGM	-	Functionally Graded Materials
LPHS	-	Laser Plasma Hybrid Spraying

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Gas turbines have been claimed to be one of the most important systems for generating energy at the present and the future. Most research activities on gas turbines have been carried out, in order to enhance the thermal efficiency and durability of gas turbines components. The efficiency and durability of turbine blades can be increased by using high strength materials and protective coatings at high temperature applications [1, 2].

Ni or Co based superalloys were developed during 1950-1970. The Ni-based superalloys are usually used in fabrication of turbine blades and hot sections of gas turbines. Depending on the type of turbine, the temperature of external gases from the combustor can range between 800-1200°C. Under these conditions, superalloy would be reacted by high temperature oxidation and corrosion at elevated temperatures [3].

Additionally, Ni- based superalloys do not have adequate resistance at above ambient condition [4]. So, surface protection of gas turbine blades is very important using highly resistant ceramic coatings. The following coatings could improve high temperature oxidation and corrosion resistances of gas turbine blades at elevated temperatures:

(1) Diffusion coatings: the aluminum can diffuse into the substrate surface. These coatings are usually applied on substrate using Diffusion – Slurry, Powdery Sementasion and CVD methods.

(2) Overlay coatings: the principal chemical composition of these coatings is: MCrAlY (M=Ni, Co or both of them) which is usually applied on the blades via plasma spray or EB-PVD methods.

(3) Thermal barrier coating (TBC): these coatings have low thermal conductivity. They could significantly reduce the overall substrate (Ni- based superalloy) temperature [4-6].

TBCs could significantly increase the efficiency and durability of hot sections of gas turbines because zirconia has lower thermal conductivity in comparison with other ceramics [4]. If this coating is applied on the substrate, then the temperature of internal gases inside the combustor of gas turbines will be increased. It means that, the substrate temperature would not be altered [5].

The first TBC was applied on the engine components of aircraft in 1960. This coating had several problems such as ZrO_2 instability and poor bonding between the substrate and the ceramic thermal barrier coating [2]. These problems were then solved during 1970 – 1980 using (a) YSZ as a thermal barrier layer due to its low thermal conductivity, and (b) metallic bond coat MCrAlY (M = Ni, Co or mixture of these two) which was employed to improve the adhesion between the ceramic top-coat and the substrate. MCrAlY layer is an oxidation-resistant material.

Additionally, MCrAlY plays a major role in providing a rough and adherent surface for applying thermal barrier coatings and provides protection for the alloy (substrate) from further oxidation [7]. Other researches were carried out by some investigators during 1980-2007, which are: (a) FGM (Functionally Graded Materials) coatings: this coating increased the mechanical properties of coating [8, 9], (b) CeO_2 stabilizer that can be added to the ceramic thermal barrier layer, in order to improve

thermal shock resistance, and (c) remelting the ceramic layer using laser which reduced the oxygen infiltration into the TBCs [10].

Additionally, other researchers also investigated other aspects of TBCs during 2002-2011 which are: (a) to replace zirconia (ZrO_2) with other ceramic materials in order to obtain lowest thermal conductivity and highest stability [11, 12], (b) to reduce oxygen diffusion and fused salts infiltration into the YSZ layer using normal Al_2O_3 as a third layer over the YSZ coating [11-19], and (c) to reduce the TGO growth and internal oxidation of the bond coat using nano crystalline NiCrAlY layer as bond coat in a TBC system [20-23]. In this research, it is expected that oxidation and hot corrosion resistances of TBCs at elevated temperatures will be considerably increased. This involves the use of nanostructured NiCrAlY layer as bond coat (via formation of continuous Al_2O_3 layer) in a TBC system with nanostructured Al_2O_3 as a third layer (as an infiltration barrier on the YSZ coating).

1.2 Problem Statement

Listed are the current major problems associated with conventional TBCs:

(a) TGO formation and growth in TBCs: an oxidized scale can be formed on the bond coat (BC) which is termed thermally grown oxide layer which is mainly related to the oxygen diffusion through the top coat towards the bond coat at elevated temperatures by micro-cracks and interconnected pinholes inside the top coat (TC) (via gas infiltration mechanism) [24]. It was found that the growth of the TGO layer plays an important role in the failure of TC during thermal exposure in air [25], (Figure 1.1).

The increase in TGO thickness during the oxidation process is accompanied by the evolution of stress at the BC / YSZ interface. This stress would cause the delamination of the coating at the interface of the BC / YSZ. It was found that the stresses in TBC will increase with a growing TGO layer [26].

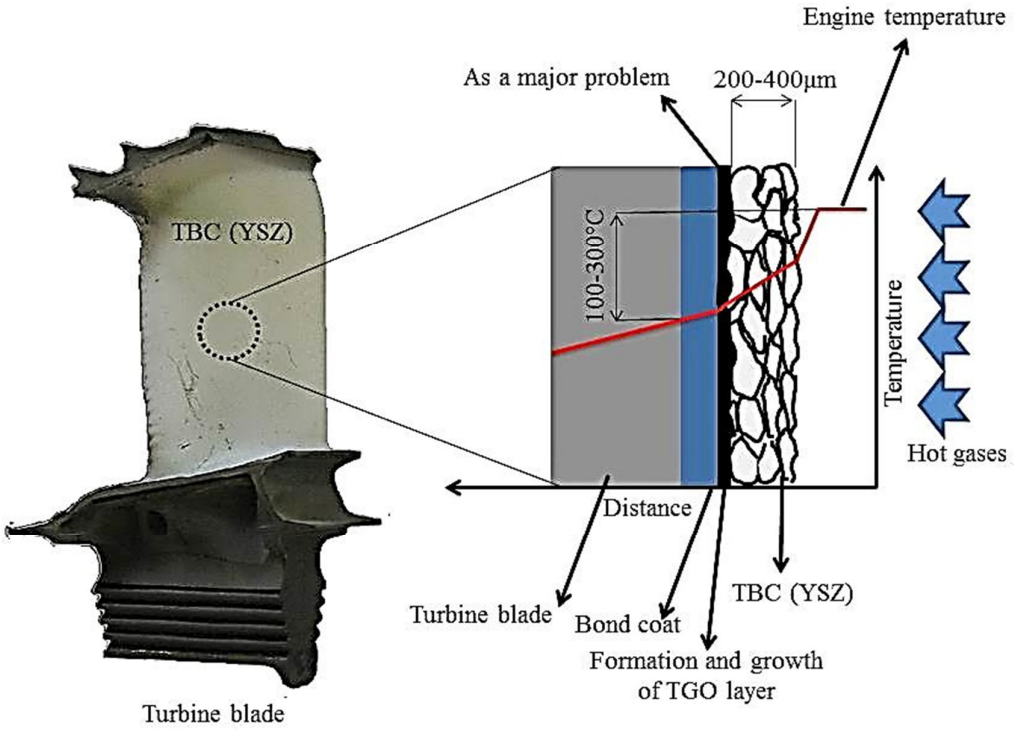

Figure 1.1: Schematic illustration of a normal thermal barrier coating system in addition to thermally grown oxide (TGO) layer. The temperature gradient during engine operation can be also observed.

(b) CSNs formation and growth on the Al_2O_3 oxide scale (as pure TGO): The mixed oxides formation on the Al_2O_3 oxide scale (as pure TGO) has been reported by the other investigators [25-27]. These complex oxides (CSNs) contain chromia $(Cr,Al)_2O_3$, spinel $Ni(Cr,Al)_2O_4$ (CS) and nickel oxide NiO [28-31] which may be formed via a solid state reaction along with this TGO (Al_2O_3) layer in plasma sprayed TBC systems [32, 33].

CSNs are also believed to be detrimental to TBC durability during service at higher temperatures [26]. In this regard, it was reported that the maximum radial stress of bi-layered TGO (Al_2O_3 /detrimental mixed oxides) is about five times and the difference of maximum axial stress is about 10 times larger than mono-layered TGO (Al_2O_3) [26]. The formation of harmful oxides would provoke micro-cracks

nucleation during thermal exposure in air, leading to premature TBC failure during extended thermal exposure in air [26, 29-31].

The majority of previous researches described the failure mechanisms of TBCs due to TGO growth especially internal oxidation of BC during high temperature oxidation [30, 34]. Therefore, the main purpose of this research is to obtain a new coating to reduce the growth of the TGO layer during pre-oxidation (as a thinner and continuous Al_2O_3 layer) and to suppress the formation and growth of detrimental mixed oxides on the Al_2O_3 (as pure TGO) layer during thermal shocks.

(c) TC (TBC) deterioration during hot corrosion process: Low quality fuels usually contain impurities such as Na and V which lead to the formation of Na_2SO_4 and V_2O_5 corrosive salts on the coating of turbine blades [14]. These corrosive fused salts can penetrate into the entire thickness of YSZ through splat boundaries and other YSZ coating defects such as micro-cracks and open pores during hot corrosion process [34]. The penetrated salts can then react with yttria (the stabilizer component of YSZ). So, the depletion of the stabilizer and phase transformation of tetragonal zirconia to monoclinic zirconia and followed by YVO_4 crystals formation can occur in a very rapid and effective manner during cooling [14, 34]. This phase transformation is accompanied by 3–5% rapid volume expansion, leading to cracking and spallation of TBC [35]. So, the reduction of hot corrosion products (by using nanostructured Al_2O_3 coating) in the YSZ layer can be expected as a major factor for increasing the lifetime of TBCs during hot corrosion process.

1.3 Purpose of the Study

In this research, it is anticipated that the aforementioned problems to be considerably decreased using a TBC system consisting of nanostructured NiCrAlY (manufactured using planetary ball mill) as bond coat (BC) and YSZ/ nano Al_2O_3 (using granulated nano Al_2O_3 powders) coating as top coat (TC). In this regard, the nanostructured NiCrAlY layer would create a continuous and dense layer of Al_2O_3 on the BC which is a strong barrier for the oxygen penetration into the NiCrAlY

layer [20]. Nanostructured Al_2O_3 top coat over the YSZ layer will significantly lessen the oxygen diffusion and corrosive molten salts infiltration into the YSZ layer at higher temperatures. This phenomenon may be originated from the compactness of the nanostructure that was observed in the nanostructured YSZ coating which was mainly composed of nano zones and fully molten parts [36].

It is worth mentioning that the Al_2O_3 crystal lattice on the YSZ layer would resist the oxygen diffusion into the YSZ layer [13, 15]. Previous studies also showed that the dense alumina layer over the YSZ coating can lessen the oxygen partial pressure at the BC/YSZ interface and can prevent further formation of deleterious oxides within the BC [16, 18].

In later studies [32, 37], it was found that a continuous Al_2O_3 layer could develop at the ceramic/bond coat interface in air plasma-sprayed normal TBC systems under a low oxygen pressure conditions (furnace with low oxygen pressure). This continues and thin Al_2O_3 (TGO) layer could diminish the growth of CSNs in the normal TBC system during subsequent thermal exposure in service [37]. In this research, a new TBC system is required to create a dense, continuous and thinner Al_2O_3 layer on the BC during pre-oxidation in air, in order to diminish the formation and growth of Ni $(Cr,Al)_2O_4$ (spinel) and NiO oxides on the alumina oxide scale during thermal cycles in air. In other words, it is expected that nano TBC systems after a pre-oxidation could considerably improve oxidation behavior of normal TBC systems at elevated temperatures.

It was observed that the protective Al_2O_3 layer on the YSZ coating can remarkably reduce the molten salts infiltration into the YSZ layer and can substantially lessen the depletion of stabilizer (Yittria) from this layer during the hot corrosion process. So, the percentage of monoclinic ZrO_2 and YVO_4 crystals (as hot corrosion products) was reduced in YSZ/ normal Al_2O_3 coating compared to that of conventional YSZ coating [14, 38]. In this research, it is expected that the usage of nanostructured Al_2O_3 layer over the YSZ coating could significantly reduce the corrosive molten salts penetration within the YSZ layer and could lessen hot

corrosion products in the YSZ as inner layer of YSZ/nano Al_2O_3 coating during the hot corrosion process.

Recently, NiCrAlY/nano YSZ coating showed better high temperature oxidation (according to the TGO thickness) and corrosion (according to hot corrosion products values) resistance compared to NiCrAlY/normal YSZ coating [36, 39]. This is because of the presence of nanostructured YSZ layer (with lower pinholes and micro-cracks) in the nano TBC system. But, the formation and growth of CSNs (NiO. Ni $(Cr,Al)_2O_4$. $(Cr, Al)_2 O_3$) have not been studied yet in the NiCrAlY/nano YSZ coating during extended thermal exposure in air. Therefore, it can be speculated that the CSNs formation and growth in NiCrAlY/nano YSZ coating to be considerably suppressed in comparison with NiCrAlY/normal YSZ coating during cyclic oxidation (thermal shocks).

1.4 Objectives of the Study

The main objectives in the present research are as follows:

1) To lessen the oxygen diffusion (getting TGO (Al_2O_3) layer with lowest thickness) and also molten corrosive salts infiltration (according to hot corrosion products values) into the YSZ layer by using nanostructured Al_2O_3 top coat over the YSZ layer during high temperature oxidation and corrosion.

2) To further reduce oxidation effect (bi-layered TGO thickness) using nanostructured NiCrAlY as bond coat (BC) and YSZ/ nano Al_2O_3 coating as top coat (TC) in a TBC system, simultaneously during cyclic oxidation (thermal shocks).

1.5 Scopes of Work

- In order to prepare the nanostructured NiCrAlY powders, commercial Ni22Cr10Al1Y powders would be milled using planetary ball mill device for 36h [20, 21, 40 and 41].

● The nanostructured NiCrAlY powders (as bond coat) will be then applied on the base metal by APS method.

● In order to produce nano NiCrAlY/normal YSZ/nano Al_2O_3 coating (Figure 1.2), normal YSZ layer will be sprayed on the nanostructured NiCrAlY layer and followed by granulated nano Al_2O_3 powders will be then deposited on the YSZ layer.

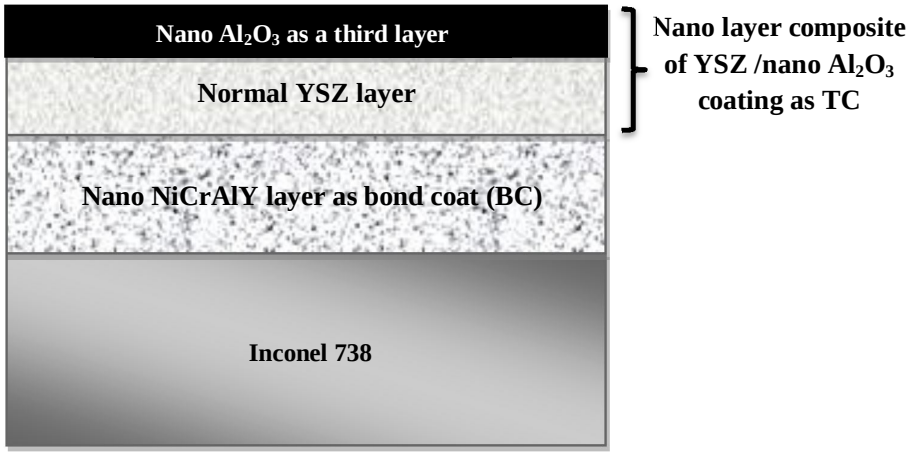

Figure 1.2: Schematic illustration of cross section of air plasma sprayed nano NiCrAlY/normal YSZ/nano Al_2O_3 coating on the Ni-based superalloy (as a novel TBC system) in this research.

So, it is anticipated that the new coating (See Figure 1.2) to form a thinner and fully continuous Al_2O_3 layer at the BC/YSZ interface during pre-oxidation and to diminish the formation and growth of detrimental mixed oxides on the Al_2O_3 (as pure TGO) layer during cyclic oxidation (thermal shocks). In this research, it is also expected that the nanostructured Al_2O_3 layer over the YSZ coating could significantly reduce the corrosive molten salts penetration within the YSZ layer and could lessen hot corrosion products in the YSZ as inner layer of YSZ/nano Al_2O_3 coating during hot corrosion process. On the other hand, the reduction of hot corrosion products (YVO_4 crystals and monoclinic zirconia) in the YSZ layer is a major factor for increasing the lifetime of TBCs during hot corrosion process which was observed in the triple layered TBCs [38].

● Normal NiCrAlY layer (as bond coat), normal and nano YSZ layers (as top coats) will be eventually applied on the base metal (Inconel 738) using APS method. On the whole, five types of TBCs will be produced which consist of: (1) Inconel 738/normal NiCrAlY/normal YSZ (normal TBCs), (2) Inconel 738/normal NiCrAlY/normal YSZ/normal Al_2O_3 (normal TBCs), (3) Inconel 738/nano NiCrAlY/normal YSZ (nano TBCs), (4) Inconel 738/nano NiCrAlY/normal YSZ/nano Al_2O_3 (as a novel nano TBCs), and (5) Inconel 738/normal NiCrAlY/nano YSZ (nano TBCs).

● The air plasma sprayed normal and nano TBC systems will be evaluated by pre-oxidation (at 1000°C for 48h), high temperature oxidation (at 1000°C for 120h), cyclic oxidation (or thermal shocks at 1150°C) and hot corrosion (at 1000°C) tests.

● Microstructural characterization of the coatings before and after tests will be performed using SEM, EDS, FESEM, XRD, and X-ray mapping.

1.6 Organization of Thesis

This thesis consists of five chapters. Chapter 1 provides an introduction to the study. The background of the study, problem statement, objectives and scopes of the study and organization of thesis are presented in this chapter. In the Chapter 2, normal thermal barrier coating system and its problems in the service would be comprehensively introduced. In the meantime, recent research activities about improvement of TBCs at elevated temperatures are reviewed. Chapter 3 is concerned with the research methodology for this study. In this chapter, the experimental steps from providing feed stokes until microstructural characterization of samples are discussed in detail. There are 7 sub chapters in the Chapter 4. In this chapter, 1) microstructural characterization of the feed stokes and as-sprayed coatings, 2) improvement of thermally grown oxide layer in thermal barrier coating systems with nano alumina as a third layer during isothermal oxidation, 3) investigation of hot corrosion resistance of YSZ/ nano Al_2O_3 coating at 1000 $^{\circ}$C, 4) role of formation of continues thermally grown oxide layer on the nanostructured NiCrAlY bond coat during thermal exposure (pre-oxidation + cyclic oxidation) in air, 5) formation of a

thinner and continues Al_2O_3 layer in nano thermal barrier coating systems for the suppression of Spinel growth on the Al_2O_3 oxide scale during cyclic oxidation, 6) high temperature oxidation and corrosion behavior of thermal barrier coating systems with nanostructured YSZ as top coat, and 7) formation and effect of nearly continues but thinner thermally grown oxide scale in NiCrAlY/nanostructured YSZ coating during oxidation (pre-oxidation + cyclic oxidation) test would be comprehensively discussed. Chapter 5 summarizes all the results and discussion in this research and some recommendations for the future work are also made.

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