

Dilapidation of the TBC system during the Burner Rig Test

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Abstract—Substrate of Inconel 718 was deposited with a bond coat of nickel cobalt chromium aluminium yttrium (NiCoCrAlY). A top coat of thermal barrier coating of 8% Ytria stabilised zirconia (YSZ) was sprayed over the bond coat by an air plasma spray (APS) technique by employing standard process parameters.

Static oxidation test conducted at 1000 °C and for 120 hours (h) revealed that main degradation modes of the TBC system were connected with formation of porous NiAl₂O₄ oxides in the thermally grown oxide area followed by formation of micro-cracks, delamination of ceramic layer and spallation of ceramic top-coat.

Keyword- Inconel, APS Technique, High temperature oxidation, Thermally grown oxide (TGO), YSZ

I. INTRODUCTION

Gas turbine's efficiency is dependent on the temperature at the entry to the turbine (TET). The concept of TET motivates the designers to find ways to increase this temperature. Research is being focused on developing new materials that enhance TET, but at present nickel based super alloys are the choice of designers. These nickel based super alloys are coated with thermal barrier coatings (TBCs) to enhance the turbine's efficiency. TBCs are widely used in land-based or aero gas turbines. TBCs are applied to the combustor liners, nozzles, blades of the turbines for providing thermal, oxidation and hot-corrosion protection. TBCs comprises of two distinct coated layers called bond coat and top coat. These coatings offer insulation to metallic structures in the hot section of turbine engines and promote some advantages like, enhanced operating temperature of the engine, increased durability of the components of the turbine subjected to high temperature and hence high stresses. The TBC coatings are deposited by air APS or electron-beam physical vapour deposition (EB-PVD) processes. The APS is most preferred over the EB-PVD process due to the reason that it's simple and cost effective.

TBC technology has developed and found applications in various sectors [1]. It is often observed that TBCs undergo impulsive failure and this often limits their application range. Aircraft engines using TBC systems consist of a thermally insulating ceramic layer of 120 - 250 µm thickness and a 50 - 120 µm metallic bond coat layer between the ceramic layer and the metal substrate. These are commonly referred to as 'duplex TBCs'. Duplex TBCs often fail due to the thermal expansion mismatch between the ceramic and metal coating layers of the systems [2-5]. The bond coat is an oxidation and corrosion resistant layer and is used to improve the bond strength and to reduce the effect of thermal expansion mismatch between the ceramic and metal coating layers [6-8]. It is reported that, at elevated temperatures oxygen in the combustion chamber gets transferred through the top coat to the bond coat via the microcracks and voids present inside the top coat. As a result, an oxide layer forms on the bond coat which is known as thermally grown oxide (TGO) layer. This TGO plays a vital role in degradation of TBC system [9, 10]. During the oxidation process, it has been reported that the TGO thickness increases and this in turn generates residual stress at the interface of coated layers. The residual stress leads to delamination of coated layers [11, 12]. Literature indicates that stresses in TBC increase with a growing TGO layer and thus, higher TGO layer has larger stress than the thinner one [10, 13]. Many of the previous studies have dealt with the failure mechanism of TBCs due to TGO growth. Investigations on TBC systems by chen wr et al. [13, 14] have reported that Ni(Cr,Al)₂O₄ (as spinel) and NiO were formed at the Al₂O₃ layer/ceramic coating (YSZ) interface in TBC systems with MCrAlY (where M is Ni, Co) bond coat, during thermal exposure at temperature higher than 1000 °C. The Ni(Cr,Al)₂O₄ is a complex oxide which causes high

porosity in the TGO sublayer. These two oxides were found to be preferred nucleation sites for crack initiation, leading to premature top coat separation from the bond coat [1].

Research works carried out by NASA GLENN RESEARCH CENTER, GE, DRDO – GTRE, NAL etc. have reported that these delaminated layers later on cause severe damage to turbine blades, combustor walls, injectors and thus deposits carbon which later breaks off as “carbon balls” that can strike the turbine blades [15]. Therefore in order to understand these effects burner rig testing is carried out. Burner rig testing also helps in understanding the behaviour of high temperature materials for gas turbine applications. The jet fuel and preheated air are mixed in the burner and are directed onto the substrates with the help of a nozzle. In the present work a top coat thickness of 200 μm , 400 μm , 600 μm and 800 μm has been employed and the time of exposure in the burner rig has been limited to 120 h. Studies with respect to the temperature gradient at different coating thicknesses have also been carried out.

II. EXPERIMENTAL

2.1 Materials and Methodology

Nickel base super alloy (Inconel 718) was used as a base material. Inconel 718 was chosen for the reason that it is an industrial accepted material used for aero gas turbine engine parts. The powdered NiCoCrAlY (Particle size: 125 +16 μm) material was chosen as a bond-coat material for plasma thermal spraying. Ytria-stabilized Zirconia (Particle size: 150 +22 μm) powder was chosen for production of ceramic coatings. Microstructure and composition analyses were carried out by means of a field emission electron scanning microscope (FESEM, Quanta 200 FEG) with Ultra thin window EDS System (EDAX) using 30 kV of accelerating voltage.

2.2 Sample Preparation

The substrate material was cut to the dimensions of 50 x 30 mm using wire cut EDM technique. The EDM machine and the optimized cutting parameters used in the study are depicted in Fig.1 and Table I respectively.



Fig. 1. EDM wire cutting machine

Table I. Optimized EDM wire cutting parameters

Wire Material	Wire Dia, mm	Wire Tension, g	Wire feed rate, m.min ⁻¹	Resistivity x 10 ⁴ , Ω cm,	Cutting Speed, mm.min ⁻¹
Brass	0.25	1300	10	5	4.3
Water flow, L.min ⁻¹	Water pressure, Bars	Water flushing rate, L.min ⁻¹	Current, A	Voltage, V	Dimensional accuracy, μm
10	13	10	52	4.5	5

2.3 Air Plasma spraying procedure

The coatings were applied on to the Inconel substrate strips. The strips were of 50mm x 30mm x 4mm dimensions. Substrate strips were silica grit blasted (grit mesh size 24) and bond coated using NiCoCrAlY metallic powder to a thickness of 100 μ m. The bond coated samples were coated with ZrO₂ × 8% Y₂O₃ (8% Yttria Stabilised Zirconia, YSZ) powder as a top coat (Fig. 2a, b and c).

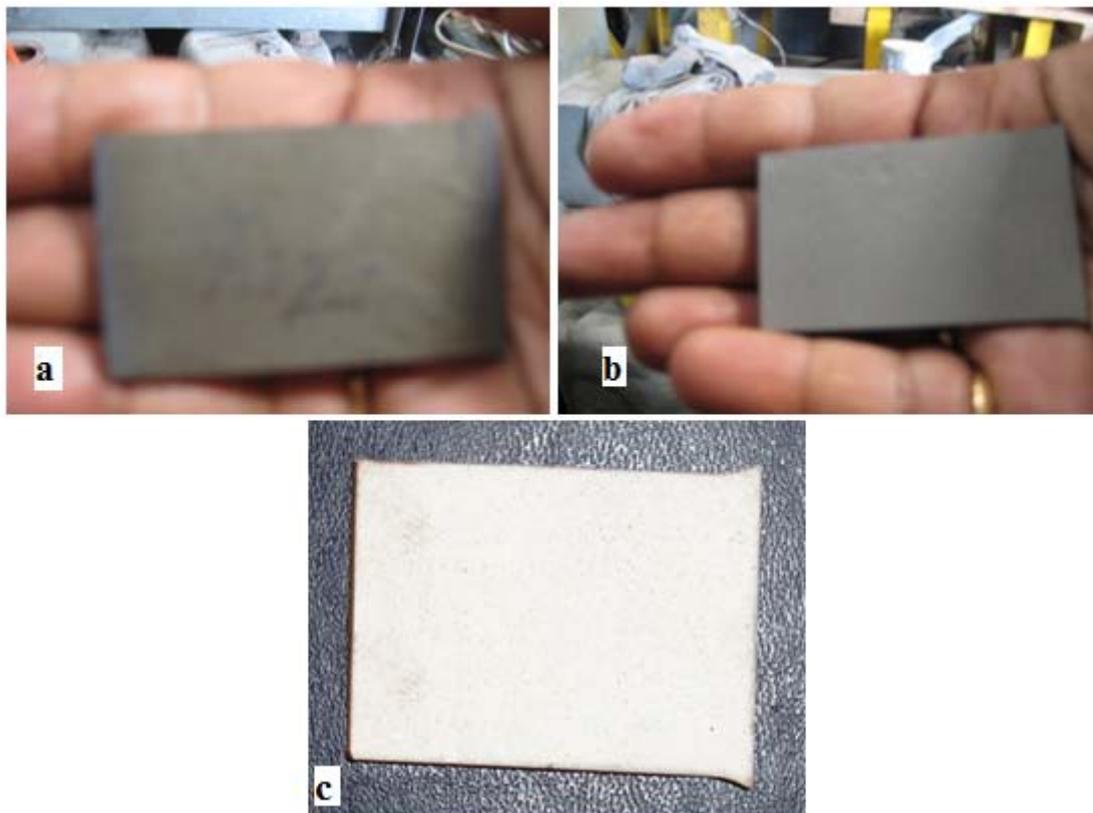


Fig. 2. Specimen preparation and coating: (a) Before grit blasting (b) After grit blasting (c) As sprayed TBC sample

The thickness of top coat was varied in the range of 200 μ m to 600 μ m, whereas the bond coat thickness was restricted to 100 μ m. The parameters of atmospheric plasma spraying are shown in Table II.

Table II. Optimized parameters of air plasma spraying

TBC	Current, A	Voltage, V	Primary gas flow (Ar), L.min ⁻¹	Secondary gas flow (H ₂), L.min ⁻¹	Powder feed rate, g.min ⁻¹	Spray distance, mm
NiCoCrAlY	450	65	6.5	4.5	120	110
YSZ	500	70	6.5	4.5	45	90

APS was carried out using Metco Sulzer machine of capacity 100 kW power supply. The Inconel substrate was initially preheated using the plasma gun without any particles being injected. Then a bond coat of approximate thickness of 100 μ m was sprayed on it (constant bond coat thickness was maintained for all samples), these bond coated samples were then top coated with varying thicknesses (200 μ m, 400 μ m, 500 μ m, 600 μ m) on different samples.

2.4 Burner Rig Test

Burner rigs are torches that burn fuel and preheated air. They are generally used to evaluate, rank, and understand the behaviour of high-temperature materials for gas turbine applications. With burner rigs, gas and preheated air are mixed within the burner, and the combustion products exit through a nozzle to accelerate the

gases to Mach 0.3 or higher subsonic velocities [15]. In the present work the coated samples were subjected to TGO and conductive mode of heat transfer studies via the use of Burner rig test method (Fig.3).

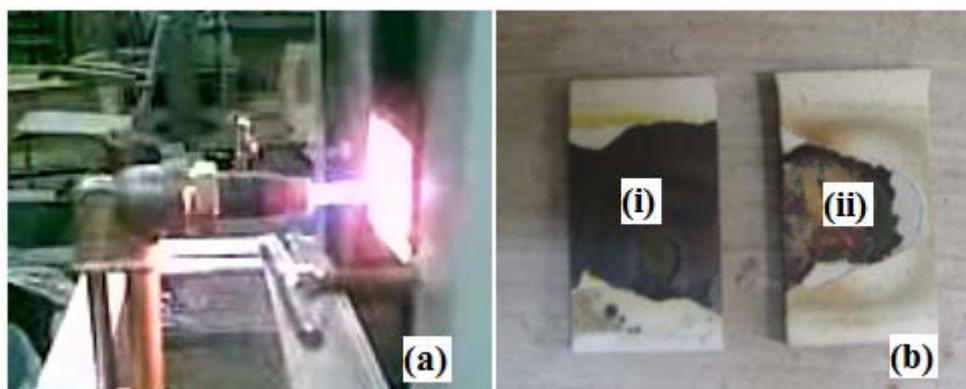


Fig. 3. Burner rig thermal test: (a) Samples subjected to rig test (b) failed samples during testing (i) 1BC5TC (ii) 1BC6TC

Table III. Observed temperature readings during burner rig testing

Bond coat thickness (μm)	Top coat Thickness (μm)	Temp on Top coat (experimental), $^{\circ}\text{C}$	Temp on Substrate rear side (experimental), $^{\circ}\text{C}$	Temperature drop in the specimen ΔT specimen, $^{\circ}\text{C}$	Sample Designation
100	200	1000	830	170	1BC2TC
100	400	1000	775	225	1BC4TC
100	500	1000	720	280	1BC5TC
100	600	1000	680	320	1BC6TC

Infrared ray thermometer was used to record the experimental values of temperature on top coat surface and substrate rear side surface. Samples with varying top coat thickness were used in the experiments. The values as recorded in Table III are for a period of 24 h. TBCs were exposed to isothermal high temperature oxidation test and microstructural characterization studies by heating the samples using the burner rig test setup at 1000°C for 120 h and then cooled to ambient temperature (natural air cooling), to study the growth of TGO. Micro structural characterization of the coatings before and after oxidation was carried out using field emission scanning electron microscopy equipped with energy dispersive spectrometer (EDS).

III. RESULTS AND DISCUSSIONS

The measured thickness of 1BC2TC sample's bond-coat (NiCoCrAlY) was approximately $100\mu\text{m}$, whereas the thickness of the ceramic layer was approximately $200\mu\text{m}$. Micro structural analysis was carried on only 1BC2TC samples (exposure time 120 h), for the reason that higher thickness (1BC6TC, 1BC5TC, and 1BC4TC) samples failed when exposed to 1000°C at 52 h, 68 h and 80 h of operation respectively. The failed 1BC5TC and 1BC6TC samples are as shown in the Fig. 3(b). Literature survey indicates that SEM methodology is an adequate tool for qualitative assessments of TBC system from the point of view of application in industry [1].

The SEM images of Inconel substrate, bond coat and top coat are shown in the Figs. 4(a), (b) and (c), respectively. Cross section of the coated substrate (Fig. 4(d)) shows that the coated layers are free from voids, cracks and delamination and this indicates that the bonding between metallic substrate and coated layers is satisfactory. Parameters like adhesion, defects, voids, porosity, and thickness of top coat play an important role in characterizing the quality of TBC. Volume fraction of porosity in the ceramic layer (top coat) was carried out by a metallurgical microscope equipped with an image analysis software. Analysis depicts presence of two zones of different volume fractions of porosity. Region adjacent to the bond coat displayed 15% volume fraction of porosity whereas region located on outer part of the ceramic layer displayed porosity volume fraction of about 12%. The main purpose of the study was to determine the impact of the oxidation of TBCs on the process of their degradation and also to understand the effect of coating thickness on the temperature gradient. From the Table III it is understood that with the increase in coating thickness there was a drop in temperature from top coat end to the uncoated substrate end. In order to determine the effect of oxidation, flat slabs (TBC coated end) were heated at 1000°C in air (with dimensions as addressed in section 2.2 and 2.3).

Micro structural analyses performed on 1BC2TC (top coat thickness 200 μm) samples prior to the burner rig test did not reveal the presence of the TGO. Besides, top coat and bond coat were found to be free from cracks and delamination (Fig. 4d). No spallation effect was observed in the ceramic layer.

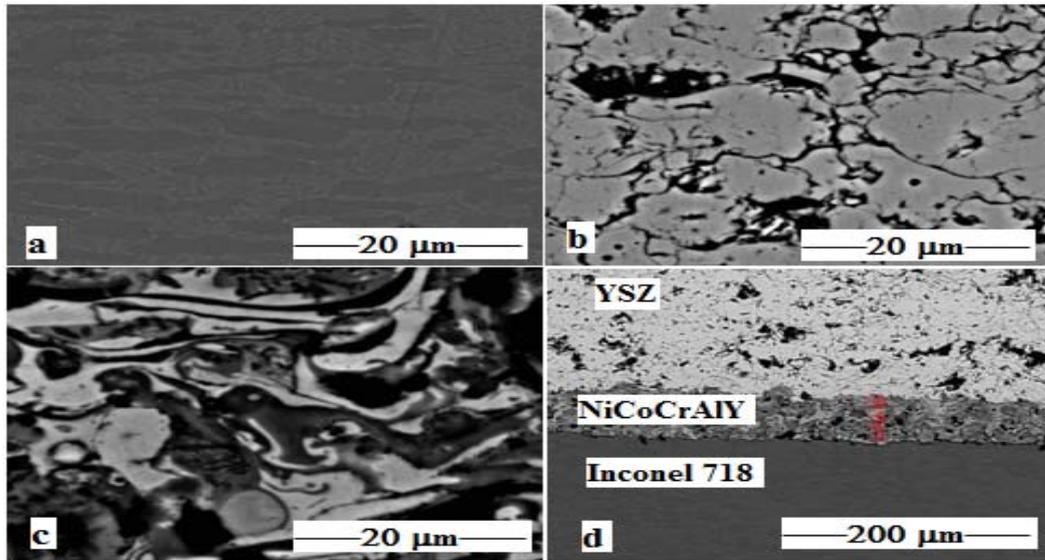


Fig. 4. SEM micrographs of cross section of as-sprayed TBCs: (a) Inconel 718 substrate (b) Top coat YSZ (c) Bond coat NiCoCrAlY (d) NiCoCrAlY / YSZ coating

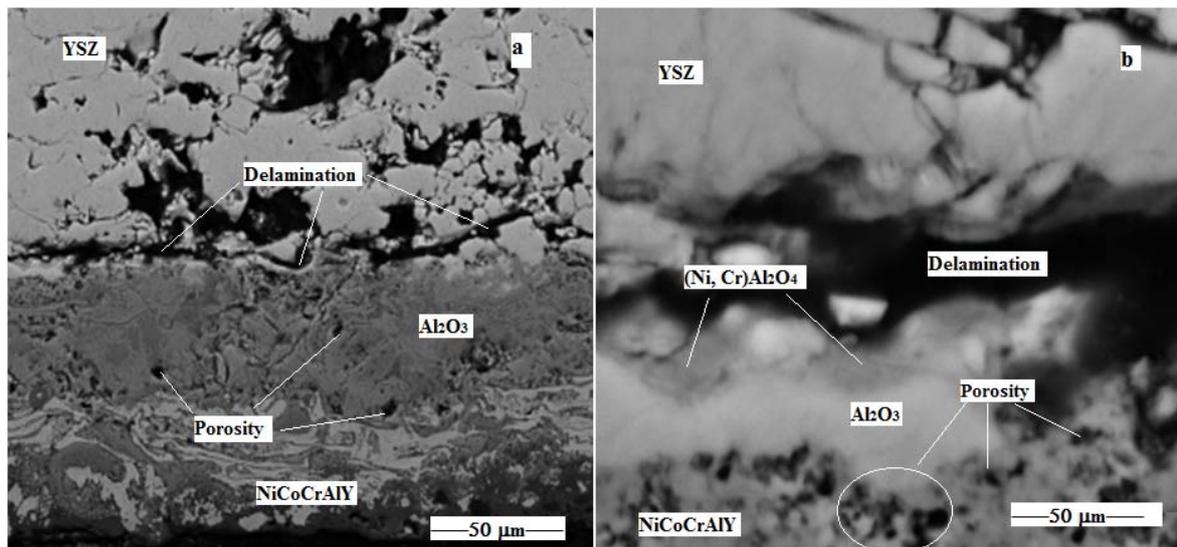


Fig. 5. SEM micrographs of cross sections of TBCs subjected to burner rig test: (a) 48 h exposure (b) 120 h exposure

Microscopic analysis (Figs. 5a and b) on 1BC2TC samples revealed the effects of degradation after 48 and 120 h of exposure to burner rig in the form of macro-cracks, delamination and spallation in the ceramic layer. Micro-cracks in the $(\text{Ni,Cr})\text{Al}_2\text{O}_4$ oxide zone appears as result of coalescence of pores and voids.

Exposure to 120 h burner test (Fig. 6b) showed larger amounts of Al and O besides other elements like Ni and Cr. This reveals that TGO layer predominantly contains alumina (Al_2O_3). The presence of approximately 7.8 μm -thick TGO oxide layer was detected. TGO thickness was measured on each cross-sectional SEM micrograph at more than 10 different locations and the average value was reported as TGO thickness. The variations of TGO thickness as a function of oxidation time are plotted in Fig. 7. As can be seen, the thickness of TGO layer increases with increasing oxidation time up to 120 h for the different samples under study.

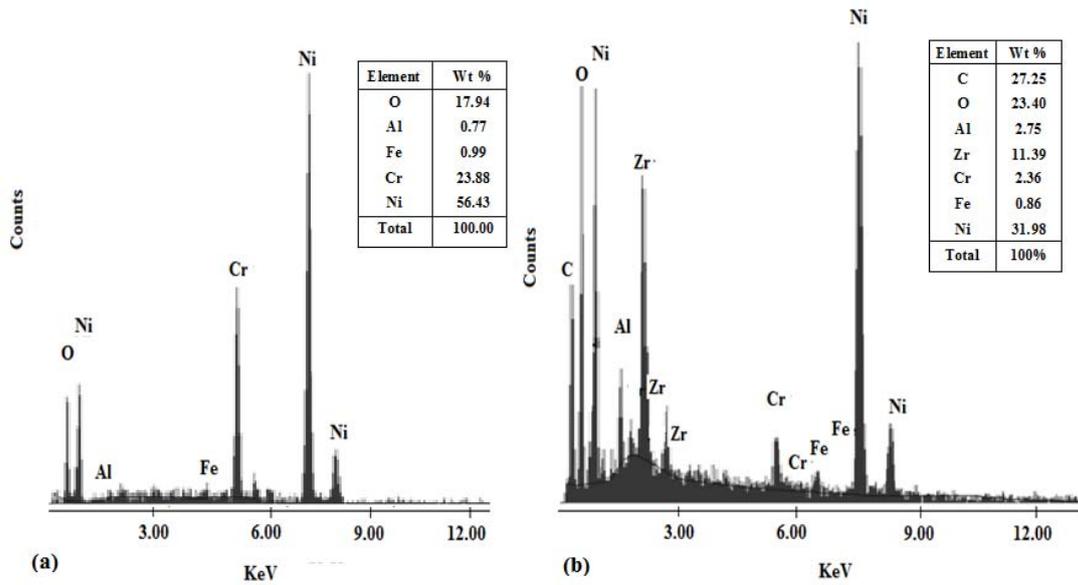


Fig.6. Energy Dispersion Spectrum (EDS) of TGO: (a) 48 h exposure (b) 120 h exposure

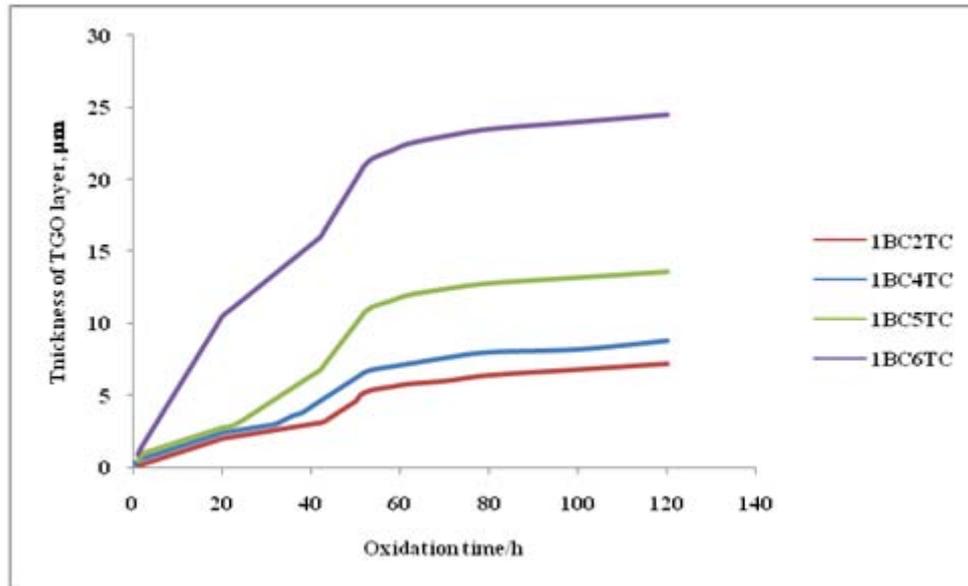


Fig. 7. TGO thickness vs oxidation time at 1000 °C for different samples under study

The EDS analysis (Fig. 6a) performed on samples exposed to 48 h in burner rig shows the intensity of Ni and Cr comparable to 120 h exposure test (Fig.6a). However low intensities of Al and O elements at 48 h exposure (Fig. 6b) indicates a lower extent of oxidation as compared to that at 120 h exposure (Fig.6a). This is substantiated by low thickness of TGO (3.1µm) at 48 h exposure as compared to that (7.8µm) at 120 h exposure to burner test.

The TGO area was made up of two types of oxides viz., aluminium oxide observed on the bond-coat side and NiAl₂O₄ observed on the YSZ layer side. The presence of two oxide layers has also been reported by Mohammadreza et al.[16]. Chen et al [17] have identified two more mixed oxides like NiO and ((Cr,Al)₂O₃) in the TGO region. These mixed oxides have also been reported by Liang et al. [18] and Seo D et al. [19]. The presence of higher concentration of Ni in the EDS (Fig. 6) may indicate the presence of NiO layer also.

Chen [20] and Lee [21] have reported that, when a Ni unit cell is transformed to NiO, an increase of 67% in volume can be expected at TGO/YSZ interface. The growth of TGO layer in the present work after 120 h exposure in burner test rig may possibly substantiate the presence of NiO layer. An increase in thickness of the TGO zone from 3.12µm to approximately 7.38µm for enhancement in exposure time during burner test from 48 to 120 h could also be attributed to the presence of both NiO and Ni-Cr oxides.

IV. CONCLUSIONS

- Study highlights the phenomena connected with the creation and growth of the TGO oxide layer, and also the study indicates that higher coating thickness helps in increased thermal barrier effect between the top coat end and substrate end.
- Typically, the bond coat with exposure to high temperature causes the growth of TGO. The role of alumina is to protect the substrate and bond-coat's surface. But conversely, the oxide growth is likely to result in the generation of large residual stresses during cooling due to the thermal expansion mismatch. The resultant delamination and spallation observed can perhaps be ascribed to this factor.
- Dilapidation of the TBC can be attributed to the formation and growth of complex oxides such as, $(\text{Ni,Cr})\text{Al}_2\text{O}_4$ and NiO in TGO oxide layer following thermal exposure.

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