THE BEHAVIOUR OF TURBO ENGINE ASSOCIATED THERMAL BARRIER COATING STRUCTURES FROM A TRIBOLOGICAL PERSPECTIVE

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Abstract

Adjustable nozzles, shutters, cover plates and other turbo engine "hot parts" (combustion chamber, diffuser, etc.) are subject to a number of wear factors-high temperature, thermal shock, corrosion, erosion-which can act simultaneously in complex manner. Dry friction due to the relative motion of the shutters and cover plates is also present. This paper underlines the properties of protective ceramic structures. Information on the behavior of the developed coatings, together with thermal testing results, will enable a more comprehensive evaluation of the protective solutions.

Key words: *TBC, thermal shock testing, friction coefficient, block-on-ring*

1. INTRODUCTION

Turbo engines are operating at high temperatures. Turbines are driven by exhaust gasses that exceed for commercial aircrafts 1200°C. Simultaneously, pyrolyzed particle erosion - sulfur compounds contained by the hot gas - at velocities above Mach 3, chemical corrosion and adhesion in the adjustable nozzles are encountered in gas turbine engines acting as wear factors. Extreme functional conditions of turbo engines (fig. 1) such as take-off, in-flight engine stop, landing failure, etc. could occur leading to sudden changes of temperature. From all these wear factors, the thermal shock is the most disturbing [1]. In this respect, having to perform under increasing firing temperatures and excessive contamination in the operating environment, it has become difficult to design super alloys which have the necessary creep strength on one side and the required resistance to corrosion/oxidation on the other side. The solution for this issue was to bring coatings on to the surface of the blades in order to provide them the necessary protection against the above mentioned wear factors.

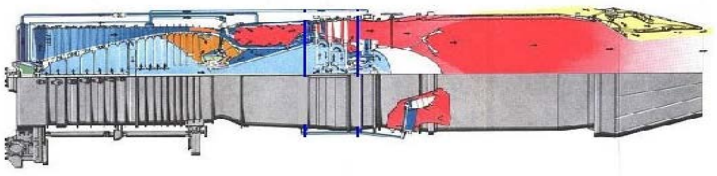


Fig. 1 Thermal fields in a turbo engine. Blue-cold section; red-hot section

During the last two decades many efforts have been done to improve and develop ceramic structures as thermal barrier coatings (TBC) for gas turbine parts in order to increase their efficiency in terms of service life and working temperatures [2].

The configuration of a multilayer TBC (fig. 2) consists of a ceramic top coat which lowers the temperature of the substrate by 150÷200°C, a thermal grown oxide (TGO) layer mainly composed of alumina whose thickness extends as the temperature is raising and an MCrAlY (where M=Ni, Co) bond coat deposited directly on the substrate alloy whose main characteristic is to provide a better chemical bond between the top coat and the substrate.

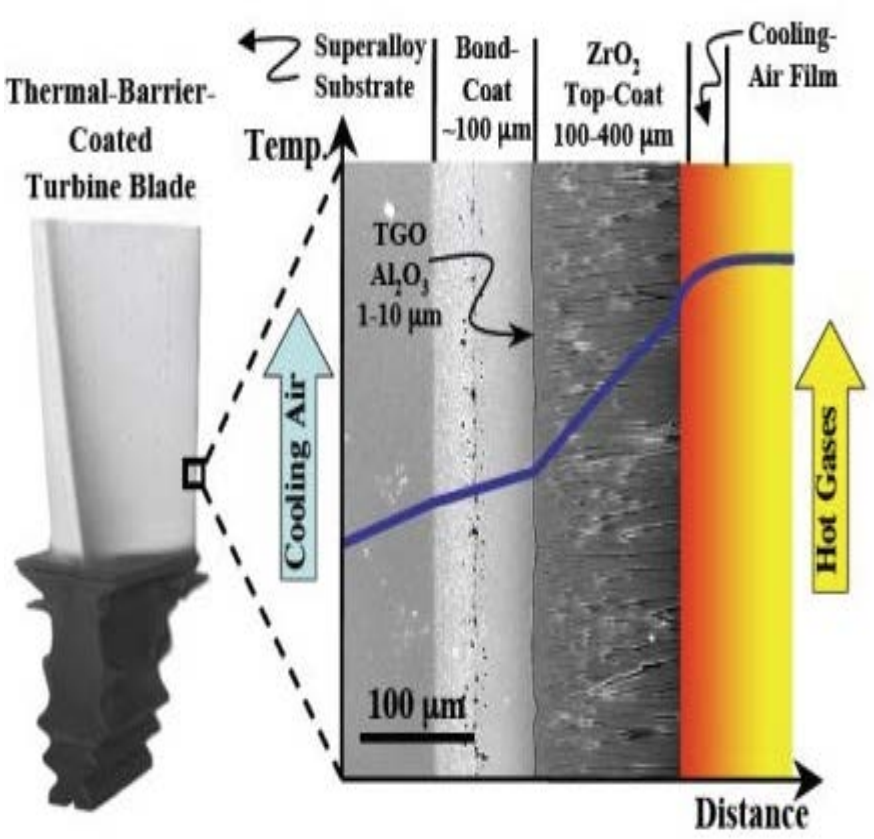


Fig. 2 Basic configuration of a TBC multilayer system from a turbine blade [3]

Due to low thermal conductivity (2.5-3.0 $Wm^{-1}K^{-1}$) ZrO_2 - Y_2O_3 ceramic coatings are widely employed to protect high temperature components in gas turbines from thermal degradation as well as to increase the resistance to environmental wear factors.

The goal of the current study was to investigate the wear behavior of plasma-sprayed $ZrO_2$8%Y_2O_3/ZrO_2 24%$CeO_2$2.5%Y_2O_3+Co/NiCrAlY triplex coatings under thermal shock testing and of $ZrO_2$8%Y_2O_3 (8YSZ), $ZrO_2$7.5%Y_2O_3-nano (7.5YSZ) and $ZrO_2$24%$CeO_2$2.5%Y_2 O_3 (CSZ) from a tribological perspective under dry conditions.

2. EXPERIMENTAL DETAILS

2.1 Thermal shock test

The QTS2 installation (fig. 3) was conceived by INCAS and designed and achieved within a partnership between INCAS and COMOTI research institutes teams [4]. The installation allows a quick ranking of multilayered materials submitted to quick thermal shock tests. The testing system ensures the reproducibility of the testing outcomes by operating in a semi-automatic regime. Some of its functional parameters are: maximum testing temperature – 1500°C, variable heating speed and quick cooling speed of tested specimen up to 70°C/sec, continuous measurement of specimen and oven temperatures during thermal cycle (fig. 4). Monitoring of key parameters was performed using the data acquisition software CompactDAQ NI LabVIEW. During a thermal cycle the specimen is exposed for 5 minutes to elevated temperature and then is cooled down by 8-9 bars pressurized air for 1 minute.



Fig. 3 QTS-2 Installation for material testing in extreme thermal conditions

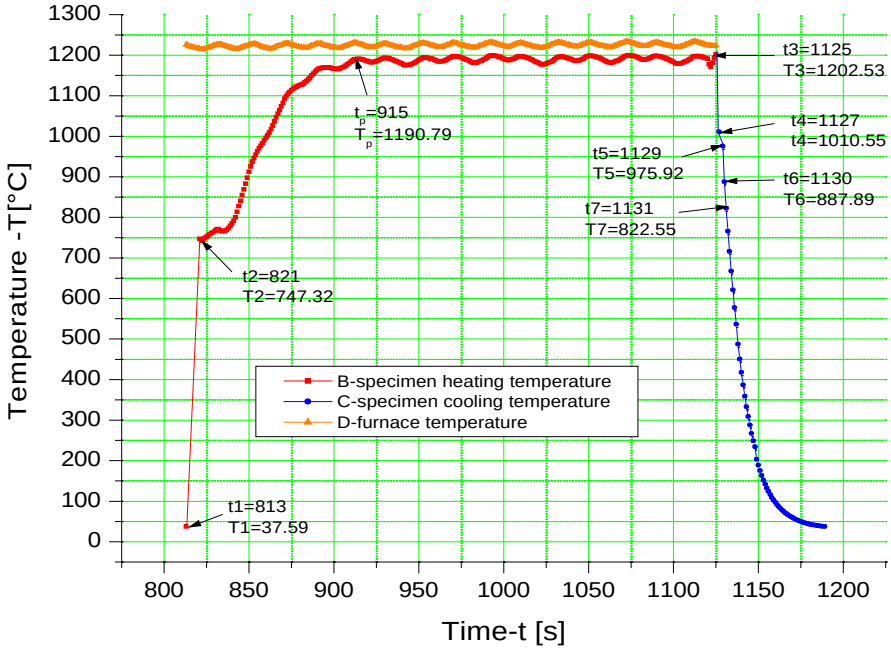


Fig. 4 Thermal shock test recording temperatures

2.2 Coating specimen

The samples to be tested were made of a sandwich structure consisting in

- nickel-chromium-cobalt super alloy substrate, NIMONIC 90
- bond coating layer NiCrAlY, deposited by high-velocity air-fuel (HVAF) method
- intermediate layer ZrO_2 24CeO_2 2.5Y_2O_3+Co
- ceramic zirconia-based layer (TBC) partially stabilized with yttrium oxide M222A (ZrO_2 8%Y_2O_3) deposited by air plasma spray technique (APS).

The sample geometry is 30x50x2 mm. The thickness of the TBC deposition was about 20÷45 μm for the bond coat (BC), 45-70 μm for the intermediate layer (IL) and 270-310 μm for the top coat (TC).

The bond coating has two main features. Firstly, the occurrence of a protective oxide layer at the interface between bond coat and ceramic layers is leading to slowing down of the substrate oxidation; secondly, the oxide layer improves the adhesion of the TBC ceramic during coating processing. Experimental studies had demonstrated that composition, microstructure and thickness of the bond coat have an impact on the overall performance in terms of endurance of the TBC system.

The sample has been isothermally shock cycled in air at 1200ºC until failure. The failure criterion i.e the critical number of cycles to spalling has been chosen as the number of thermal cycles immediately prior achieving 30% percent ratio of delamination of the specimen coating surface, according to ISO 14188 standard [5]. In this particular case the sample withstood 64 thermal cycles.

2.3 SEM -EDS investigations for thermally cycled and non cycled specimens

I) Non tested specimen characterization (fig. 5)

- The BC and TC layers are relatively uniform
- intermediate layer (IL) with micro cracks overall parallel to BC
- BC relatively uniform in terms of composition
- the intermediate layer with lamellar and punctiform concentrations point of lengths, shapes and sizes within a mass of zirconia
- Al is uniformly distributed except for some spotted areas at the S/BC interface, outline the BC geometry within TBC
- Cr, Mo, Co are uniformly distributed in BC
- Co as lamellar, with different shapes and sizes are generally oriented parallel to the BC/TC interface, and alternates with Zr and Y distribution in the IL

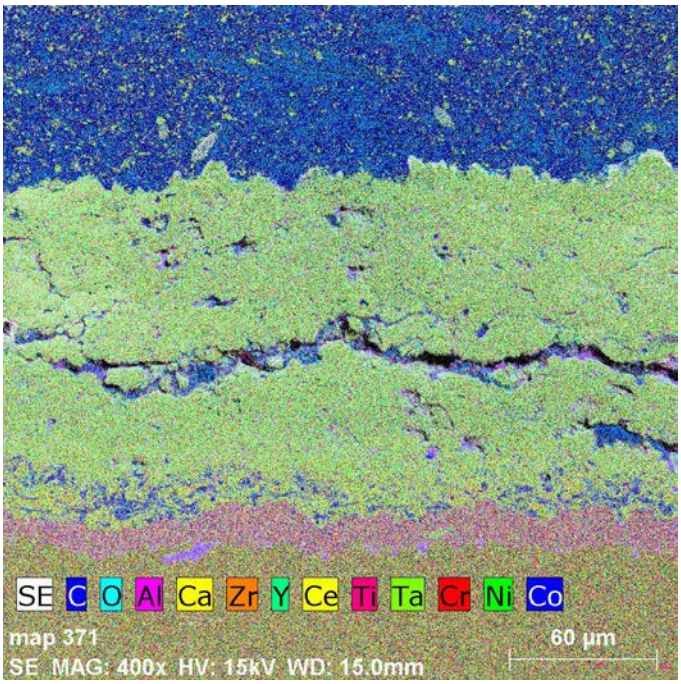


Fig.5 EDS spectrum of the non thermally tested triplex layer specimen

II) Thermally cycled specimen at 1200°C characterization (fig.6, 7, 8)

- BC is compact, adherent to substrate S and partially adherent to the intermediate layer (IL)
- IL with voids, porosity, poorly adherent to TC
- TC with cracks, porosity, small cracks
- the images reveal an homogeneous composition in BC and TC
- TGO composed of aluminum oxide very well defined at BC/IL interface and some punctual oxide concentration at BC/S interface
- C comes from the embedding resin of specimen located in the existing cracks of TC
- Co present in S, BC relatively uniform and less homogeneous in the intermediate layer (IL)
- Cr, Ni are homogeneous in S and BC; one notice the lack of these elements in areas where Al is present
- Zr and Y are relatively even distributed in TC and less uniform in the intermediate layer (IL); one notice the absence of these elements in the longitudinal crack as well as in the porous areas
- one notice a continuous layer of relatively uniform thickness (1.3 ÷ 2.0 μm) along the entire length analyzed at the BC/IL interface- TGO formation

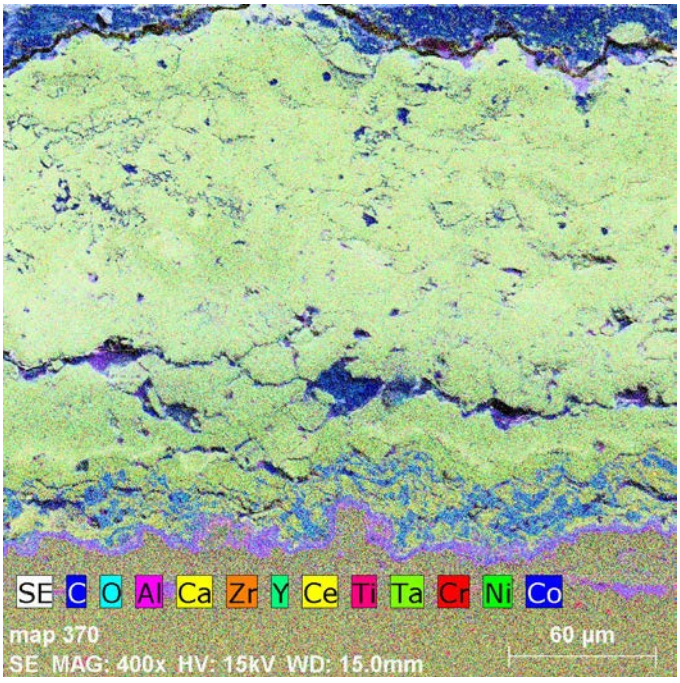


Fig.6 EDS spectrum of the thermally cycled triplex layer specimen

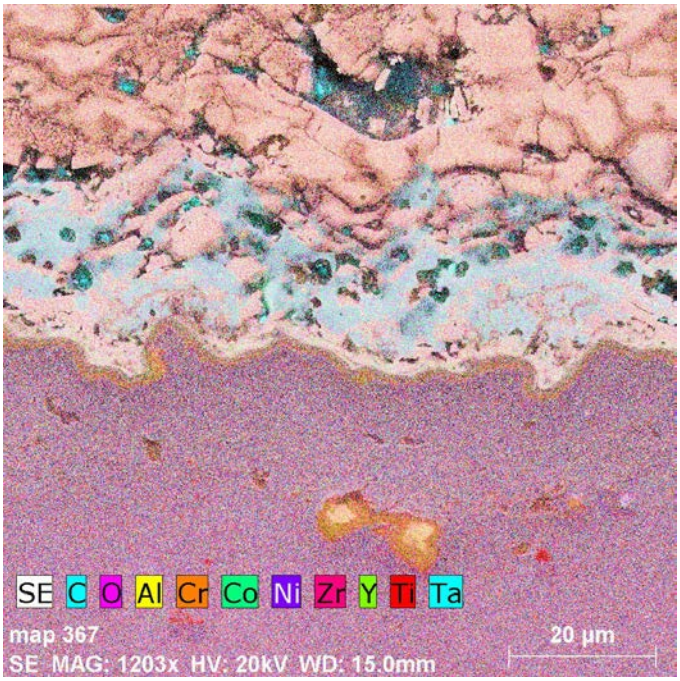


Fig.7 EDS spectrum of the bond coat layer

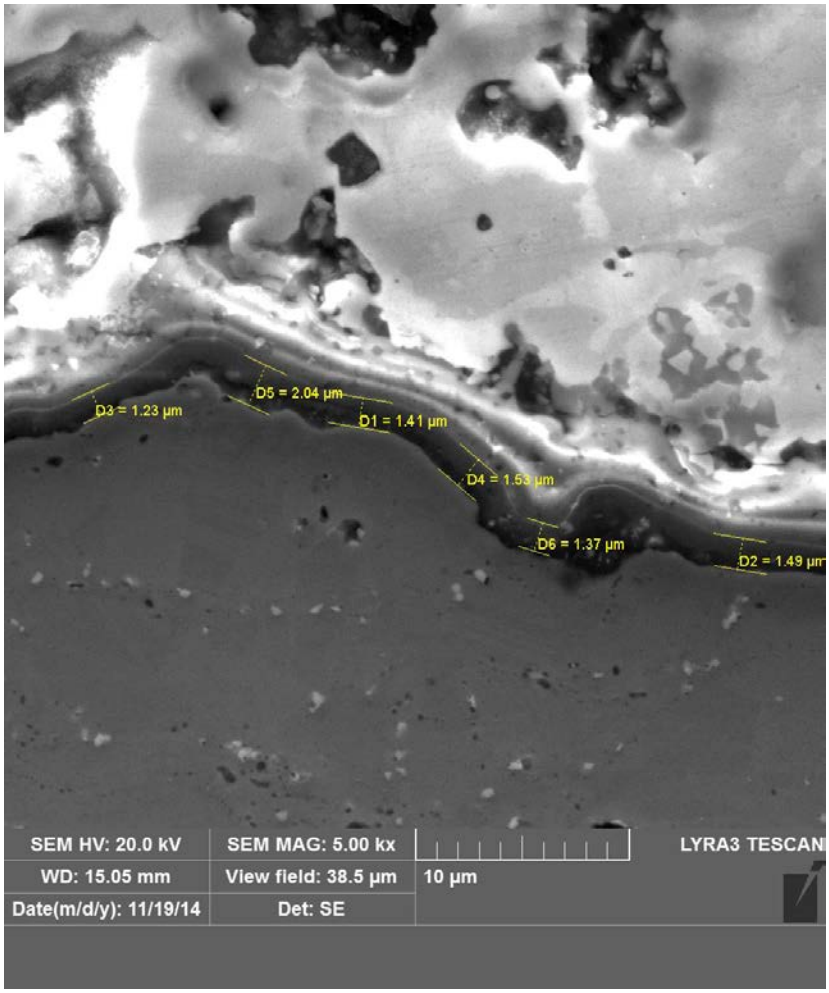


Fig. 8 SEM image of TGO formation after thermal testing

2.4 Block-on-ring test

The tribological behavior of the Zr based ceramic coatings was investigated using a CETR-UMT3 block-on-ring machine (fig.9). The ring was the external ring of the tapered rolling bearing made of stamped steel (Timken A4138 ring – Φ35.0mm x 8.7mm). The specimen was the steel block (15.9mm x 6.6mm x 10.6mm) coated by thermal spraying. For the first layer, the bond coat, we used the M450 powder. This type of powder which is mechanical clad composites of aluminium and nickel exhibit an exothermic reaction during the spray process and is considered self-bonding to steel substrates. Then, three different coating ceramics were used as top coat namely M204XCL ($ZrO_2 8\% Y_2O_3$ - 8% yttria stabilized zirconia powder = 8YSZ), $ZrO_2 7.5\% Y_2O_3$ - nano (7.5% stabilized YSZ nanostructured powder = 7.5YSZ) and M205NS ($ZrO_2 24\% CeO_2 2.5\% Y_2O_3$ – ceria stabilized zirconium oxide powder = CSZ). Three specimens were tested at different loads comprising four load levels (10/25/50/100N). The test parameters were selected as below: unlubricated condition, wheel speed of 100 rpm, testing time duration of 480 sec. For a complementary result, one test run for 720 sec. One disk revolution corresponded to about 110 mm of sliding distance.

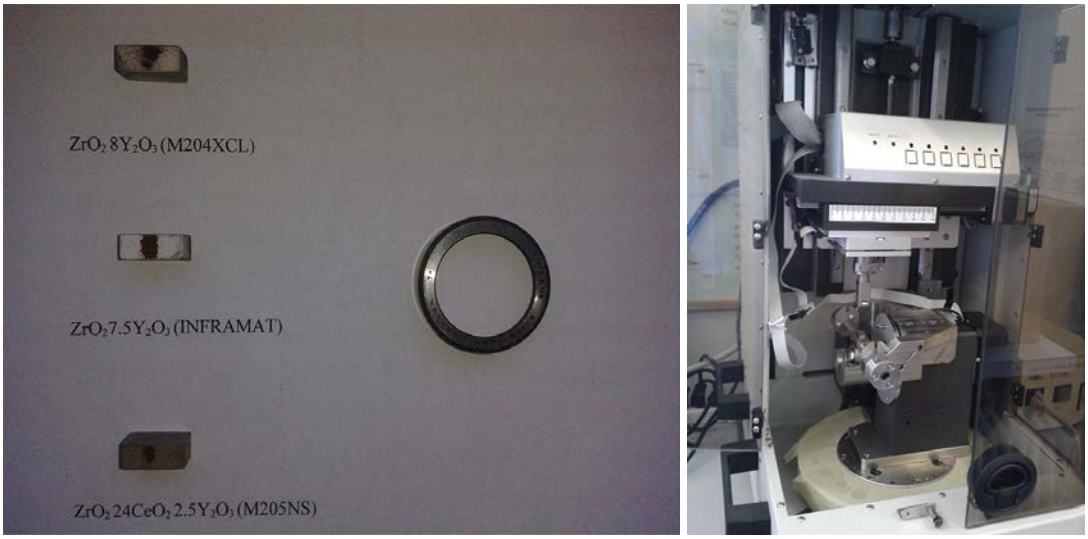


Fig.9 a) Stamped steel ring and coated block specimens after testing. b) Block-on-ring tribotester

During the test the stationary block specimen was pressed with a constant force against a rotating ring specimen at 90° to the ring's axis of rotation. Friction between the sliding surfaces of the block and ring resulted in loss of material and material transfer mainly from the steel ring to the block. The test was run at ambient temperature, and a software control unit was employed to allow for monitoring during the test the actual dynamic normal load and friction force thus computing friction coefficient in real-time (fig.10).

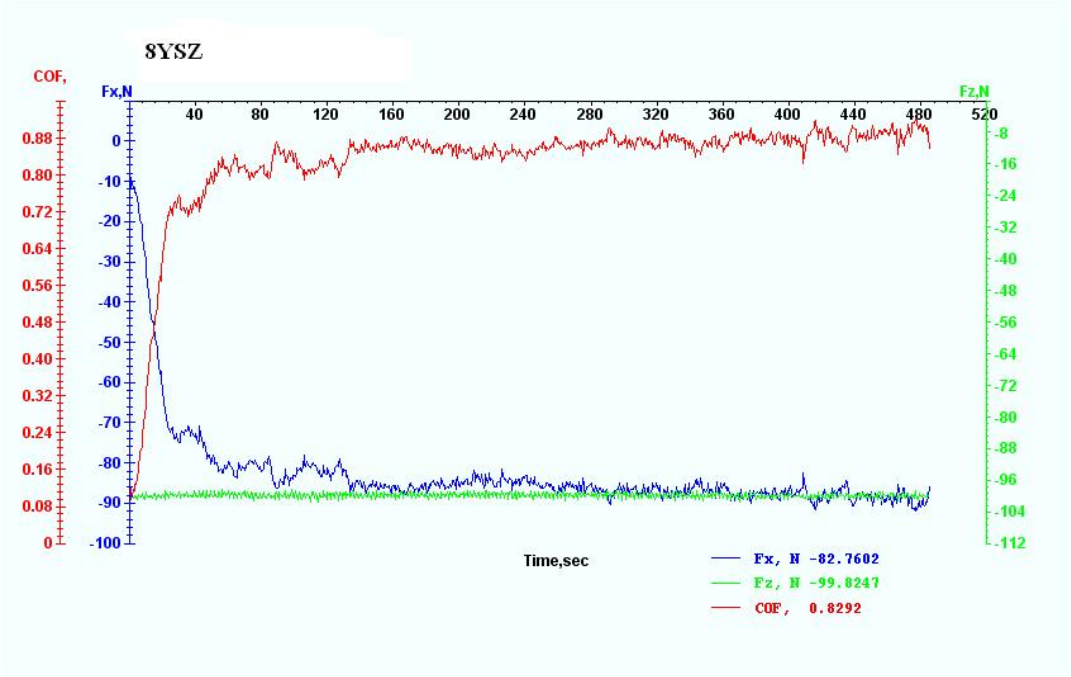


Fig.10 Test run characteristics: normal load (Fz), friction force (Fx) and friction coefficient (COF)

8YSZ material (fig. 11, 12)

For a 10 N load a larger scattering interval of the friction coefficient had resulted. There are prevailing the micro-cutting process and events involving overrunning of the hard asperities either of the coating or of the metallic ring which lead to a rise of the COF value after 280 sec. When increasing the normal load, the friction coefficient increases revealing a steady-state value.

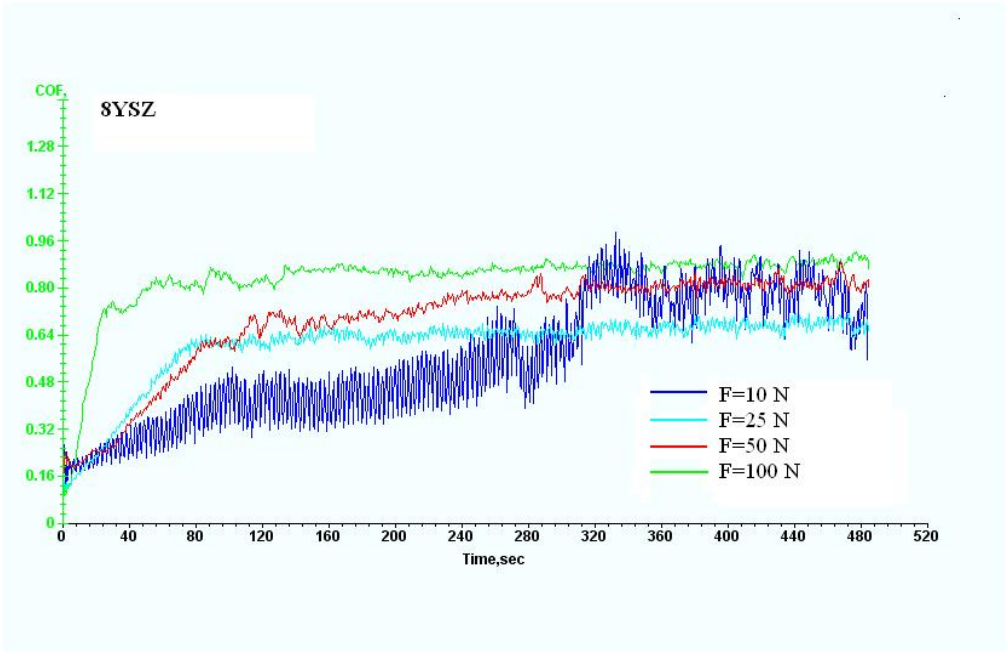


Fig.11 Friction coefficient variation with duration time of 8YSZ coating against steel ring under different normal loads

For normal load of 100N the friction coefficient value tends asymptotically with the sliding distance to a steady-state value of 0.9 due to material transfer.

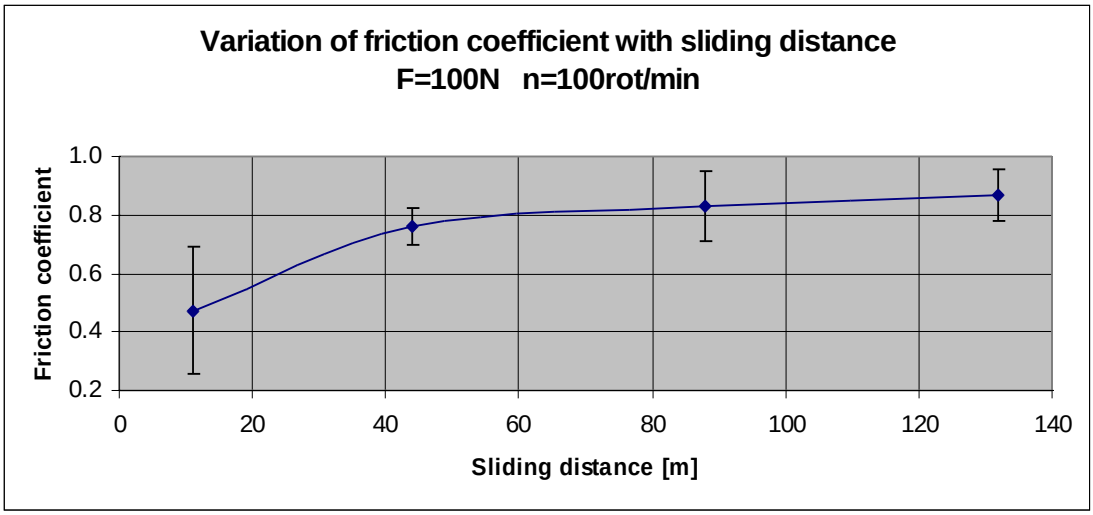


Fig. 12 Variation of friction coefficient average value with the sliding distance under 100 N load

Comparison of tribological behavior (fig. 13)

The friction coefficient between steel and ceria stabilized zirconia coating (CSZ), due to material transfer runs uptrend rapidly and its value becomes similar to the friction coefficient of coatings sprayed using the conventional powder (8YSZ). The friction coefficient between steel and the nanostructured coating (7.5YSZ) is more unstable compared to the coating sprayed with the conventional powder.

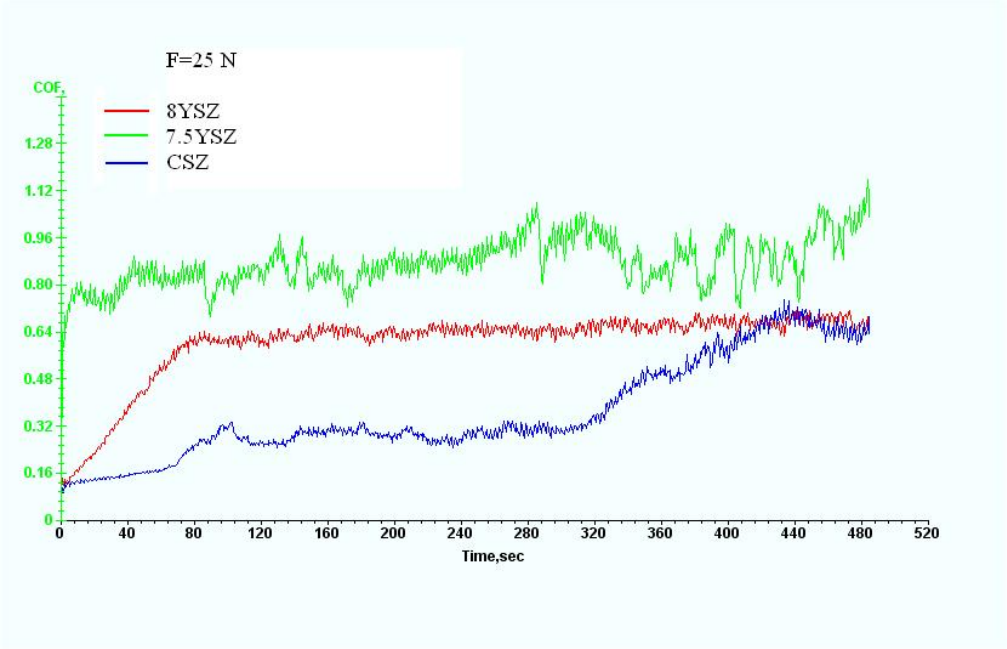


Fig. 13 Friction coefficient variation with duration time of 8YSZ, 7.5YSZ and CSZ coatings against steel ring under a load of 25 N

3. CONCLUSIONS/SUMMARY

1. Adjustable nozzles of turbo engine are additionally subjected to wear factors as hot parts respectively to sliding friction which is joining the current environmental wear factors such as temperature, thermal shock, wear, corrosion, erosion, etc.
2. In order to increase the performance of turbo engine protective coatings or of some parts/subsystems from the energy industry, the characteristics of triplex ceramic structures with higher potential of substrate/bond coat/intermediate layer/top coat type and duplex ceramic structures (without intermediate layer) were evaluated.
3. Evaluation of behavior of protective ceramic layers to high heating-cooling gradients was performed with a versatile thermal shock test facility - QTS2 designed and made by a joint partnership team from INCAS and COMOTI research institutes with superior performance compared to other European similar facilities.
4. SEM-EDS investigation reveals the inter- and intrafacial structural changes induced by high heating-cooling gradients and the mechanism of TGO formation – thermally grown oxide, located at the top coat / bond coat interface that may cause the damage of the ceramic layer.
5. The tribological testing performed on the duplex ceramic coatings highlights the friction behaviour under dry conditions of ceramic coating against steel using the block-on-ring tribotester. One notice the material transfer from the steel ring to the coated block, smooth surfaces process for materials in contact and friction coefficient variation with normal load, type of ceramic coating and sliding distance.

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