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LIFE ESTIMATION OF TBC ON AN AERO GAS TURBINE COMBUSTOR: A FINITE ELEMENT APPROACH

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ABSTRACT

Thermal barrier coatings (TBCs) are used for the thermal protection of turbine engine hot end components to have increased life and or better performance. Due to extreme environments and cyclic loads experienced by these components, the TBC may also fail prematurely. Once the TBC fails, it exposes the underlying substrate to very high gas temperatures and the life of the component gets reduced drastically and it can fail within its prescribed service life. This has necessitated the accurate possible estimation of TBC life. The TBC coated transition liner of an aero engine reverse flow combustion chamber has been analysed using finite element approach for life estimation. Stress analysis followed by fatigue analysis is carried out based on a typical mission cycle of the component for life estimation. The approach focuses on the mismatch in thermo-physical properties, operational conditions, Thermally Grown Oxide (TGO) layer surface finish and its growth. Increase in TGO thickness leads to decrease in life – this fact is modelled appropriately and proved using this FEM based methodology. Actual failure data of service engines has also been analysed and compared with that of predicted. This approach can be extended for parametric studies and life evaluation of any TBC system. The present approach will be adopted for qualification of prime reliant TBC for Aero engine application.

INTRODUCTION

Gas turbine engines present a significant challenge to designers and manufacturers due to the severe conditions present in their operating environments. The hot section of a turbine engine is especially hostile to materials that make up the turbine blades and vanes [1]. Thermal Barrier Coatings (TBCs) are applied over metallic surfaces of gas turbine engine components to safeguard it from elevated temperature and associated degradations. These coatings are made of thermally insulating materials and serve to insulate metallic components from large and prolonged heat loads. These materials can sustain an appreciable temperature difference between the load bearing alloys or base metals and the coating surface. In doing so, these coatings allow the system to work at higher operating temperatures while limiting the thermal exposure of structural components and extending component life by reducing oxidation and thermal fatigue. There are number of instances where TBC has failed prematurely and thereby exposing the base or parent material to very high gas temperature. This causes drastic reduction in component life and failure during operation. This can be a potential hazard to the engine and aircraft. This necessitates the estimation of TBC life with reasonable accuracy in the working environment considering the mission cycle the engine is subjected to.

The objective of this paper is to present a methodology to estimate life of aero gas turbine thermal barrier coating (TBC) by FEM i.e. stress analysis followed by fatigue analysis. This methodology is focussed on the effects of mismatch in thermo-physical properties, operational conditions, TGO layer surface finish and its growth. A life data analysis has been carried out and mean life of the coating has been obtained which has been used as a base-line to compare the result obtained by FEM methodology. In this paper, factors contributing for TBC failure, proposed life estimation methodology and In-service failure data analysis have been discussed.

BACKGROUND

A typical TBC system can be identified by its major constituents, i.e., base material, bond coat, thermally grown oxide layer and the thermal barrier coating itself as shown in figure 1 [2].

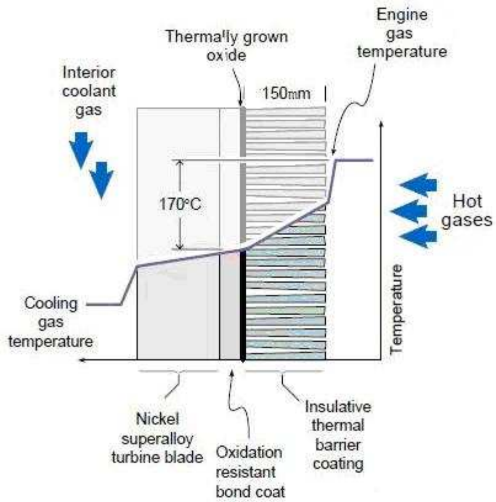


FIGURE 1.TYPICAL TBC SYSTEM

The thermal barrier coating is a thermal insulating layer with high thermal expansion coefficient and low thermal conductivity which experiences highest thermal load in the system. Yttria Stabilized Zirconia has become the preferred TBC layer material for gas turbine engine applications because of its low thermal conductivity and its relatively high (compared to many other ceramics) thermal expansion coefficient [3].

The bond coat is mostly deposited by either plasma spray or HVOF (High Velocity Oxygen Fuel) and is of the same type as overlay coatings, i.e. of MCrAlY designation. The bond coat is required to improve top coat adhesion by mechanical interlocking, and to prevent or delay oxidation of the substrate material by forming a dense oxide layer that acts as a oxygen diffusion barrier. [4]. During high temperature exposure, bond coat oxidises to form Al_2O_3 layer at top coat - bond coat interface, this layer is called as Thermally grown oxide (TGO) layer. Residual stresses are induced during the coating deposition process and in addition, TGO layer can cause a high compressive stress in the order of 3 to 6 GPa. These arise primarily on cooling because of its thermal expansion with the substrate. Smaller, yet significant stresses also arise during TGO growth [5].

In order to develop a methodology to estimate the life of TBC, the TBC applied over the combustion chamber transition liner a turbo prop engine has been chosen. This particular coating has suffered from high premature failure rate. In this coating, both Top coat and Bond coat are Air-Plasma sprayed and have porosities around 10% by volume. The top coat is 8% Yttria Stabilized Zirconia and bond coat is of NiCrAlY (31%Cr + 11%Al + 0.6%Y and balance is Ni). Substrate is of Hastelloy-X (AMS 5536).

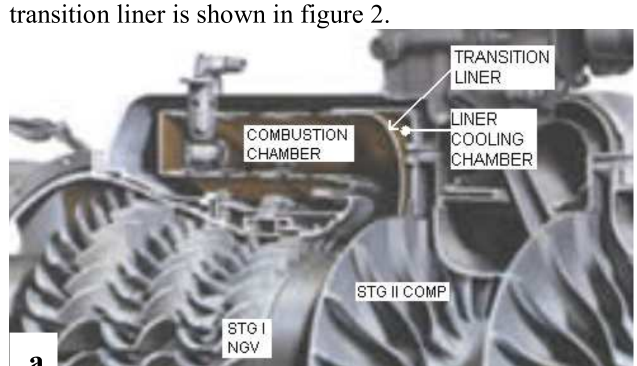
Thickness of the TBC system is as given below:

- Substrate thickness = 1400 µm
- Bond Coat thickness = 150 µm
- Top coat thickness = 250 µm

Study on failed TBC revealed that coatings mostly fail due to spalling rather than other modes of failure.

COMBUSTOR CONFIGURATION

The subject engine is a 620 kW class turboprop, it has a two-stage centrifugal compressor driven by a three-stage axial turbine and the combustion chamber is reverse flow type. The transition liner of combustion chamber reverses the direction of hot combustion products inwards to drive the turbine. This liner is always in direct contact with the hot gases and hence it is vulnerable to damages attributed to high temperature. TBC has been applied on the liner inner surface for its protection. The outer surface of the liner is convectively cooled by compressor delivery air. The typical component assembly of the engine and the transition liner is shown in figure 2.



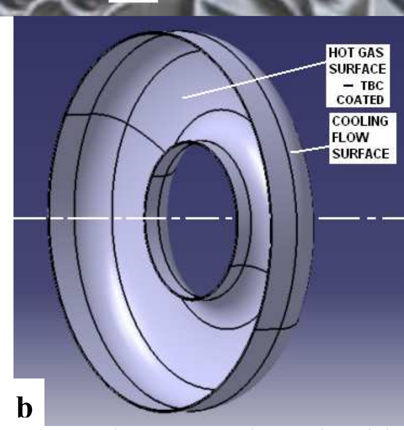


FIGURE 2 (a) TYPICAL REVERSE FLOW COMBUSTION CHAMBER SYSTEM; (b) TRANSITION LINER

FACTORS CONTRIBUTING FOR TBC FAILURE

In general, the Erosion, cracks, spalling, burns, de-laminations, etc beyond the specified limits are termed as TBC failure. Failures such as spalling or cracks mostly initiates at TGO interfaces [6]. The major factors contributing for TBC failure are mismatch in thermo-physical properties that gives rise to thermal stresses during heating and cooling cycle, bond coat oxidation and associated undulations which impose stresses onto the system in addition to thermal stresses and some other factors which degrades the TBC system performance such as ceramic sintering and chemical degradation of top coat.

Further, coating method employed, process parameters adopted, coating system related and operator related variables, preparation of the substrate do also influence life of TBC. Composition, microstructure, density, micro crack distribution, cohesive strength, thickness and phase distribution of the ceramic; density, thickness and surface roughness of the bond coat; thermal expansion and geometry of the substrate and finally the residual stresses in the coating system all have influence on the performance of thermal barrier coatings [7].

IN-SERVICE FAILURE DATA ANALYSIS

In-service failure data has been obtained over a considerable period of 8 years with engine serial number, type of operation, engine hours logged during coating inspection, engine hours during previous inspection, condition of the coating (whether spalled/ eroded/ cracked /normal etc) and whether re-coated after inspection, etc. A total of 133 cases have been studied for failure data of TBC. The data are interval / left censored (i.e) the exact time of failure of TBC is not possible from this data, it is always taken based on the previous inspection interval [8].

The data is analysed using Reliasoft Weibull++7 software [9]. There is a provision in Weibull++7 software to directly input interval / left censored data. The data is fitted to Weibull model; the Weibull parameters were obtained and discussed. Out of 133 cases, 16 cases were interval censored and the rest are left censored as shown in fig.3. Left censored data were considered as it is.

Lower limit of the interval censored data were considered as failures in the analysis. This is assumed because,

1. The upper limit of the interval is not available, so rather than taking any random upper limit, it is better to make this assumption and declare it as conserved estimation.
2. The components accounted in the interval censored data also had some degree of coating failure but below the acceptable limit, this greatly supports our assumption.
3. This assumption also encourages convergence of iteration as it generates solid failure points from interval censored data.

Weibull probability plot is shown in figure 3.

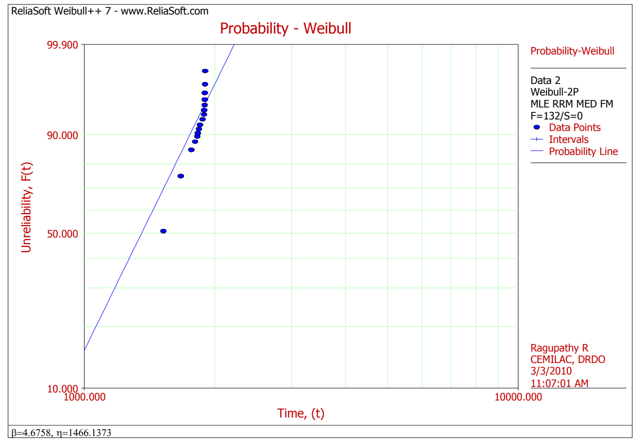


FIGURE 3: WEIBULL PROBABILITY PLOT

From the Weibull parameters, the mean life of the TBC system is worked out to be 1341 hours. When the low end data is considered, it gives about 1520 hours of life. Since the least mean life is critical from design point of view, it is considered for validation.

FACTORS CONSIDERED FOR LIFE ESTIMATION

Mismatch in thermo-physical properties leads to thermo-mechanical fatigue (TMF) which is the dominating factor as far as aero engine application is concerned [10]. Bond coat oxidation leads to TGO layer between bond coat and top coat. Moreover the surface finish of TGO will be wavy in nature which is generally known as undulation. These undulations will impose uneven stresses to the top coat coupled with TGO layer growth stress and cyclic stress derived from engine mission cycle. When the effects of property mismatch are combined with volumetric changes associated with the oxide formation, especially when the later are accompanied by a constrained expansion of the TGO, large stresses can develop upon cooling, which can lead to the nucleation of cracks at or near the interfaces of the oxide [11]. The influence of bond coat oxidation is normally described by the TGO thickness.

Engine mission cycle gives the true representation of actual operational condition. Hence, the temperature cycle that the component undergoes has to be derived from engine mission cycle and accounted in TBC life estimation

Hence, mismatch in thermo-physical properties, engine mission cycle, bond coat oxidation and TGO undulations have been considered for establishing methodology for life estimation. Other factors have been assumed to have less impact on life.

LIFE ESTIMATION METHODOLOGY

The methodology to arrive at life of TBC by FEM, i.e., stress analysis followed by fatigue analysis, adopted in the current exercise is discussed below.

- The exercise has to include the effect of TGO growth in life estimation. Here 'life' denotes the hours or cycles till failure of a new coating called as Category 'A' or Cat-'A'. Cat 'A' coating will have hardly any TGO, so when analysis is carried out without considering TGO then it will be an overestimated figure because TGO thickness is a major contributing factor for failure. Hence a trend of life for different TGO thickness is to be established. For this estimation three TGO thicknesses have been considered. Thicknesses (t) of 2, 3 and 4 µm are taken for which stress and fatigue analyses have been carried out.
- A small portion of Axi-symmetric 2D section has been considered for FE analysis. The thicknesses of Top coat, Bond coat and Substrate are 150, 250 and 2000 µm respectively.
- Idealized TGO undulation of 10 µm amplitude and 100 µm wavelengths has been considered in the FE model [12]. This introduces stress concentration to the system. Materials are assumed to be homogeneous.
- Temperature cycle that the top coat of TBC system faces was derived from respective engine mission cycle and it is presented in figure 4. This cycle is of 1.5 h duration and is applied over the top coat.

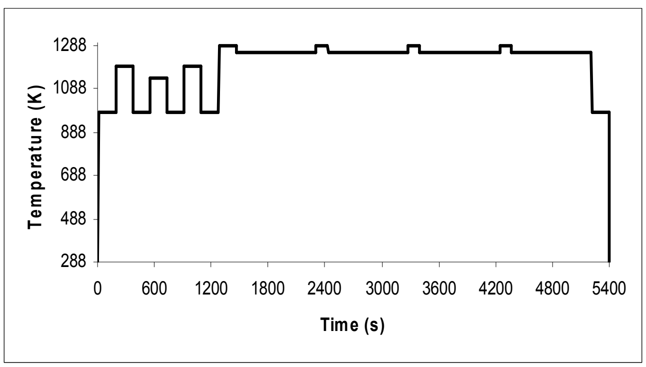


FIGURE 4: TBC TEMPERATURE CYCLE - HOT GAS SIDE

- The substrate side is convectively cooled by compressor delivery air. The convective heat transfer co-efficient has been calculated to be 431 W/m^2K using Sieder-Tate equation and it is applied on the substrate side of the TBC system [13].
- To capture the initial compressive stresses, an initial step has been considered in FEA wherein the initial temperature of the system assumed to be 1223K and then it is cooled down to room temperature (288K) with appropriate convective heat transfer coefficient. This step is followed by the temperature cycle derived from engine mission profile as shown in figure 4.
- Material properties considered for the analysis is presented in table 1 [12][14].
- Yanar et al (2000) have found that failure occurs in TGO-bond coat interface [15]. As failure is generally not likely to occur at TBC-TGO interface, the stress-life relation of TBC can even over-estimate the life locally. This will not bring in any considerable deviations in the estimated life. Moreover, in the absence of an exact stress-life relation, Seeger's approximation is used for stress-life relation of top coat in addition to bond coat [16].
- Axi-symmetry model has been considered for the FE analysis as shown in figure 5(a).
- The element type used for the analysis is CAX4T and CAX3T. The meshed model is shown in figure 5(b). Number of elements maintained along the thickness of each layer is given below.

Substrate	:	70 elements
Bond Coat	:	40 elements
TGO	:	2 elements
TBC	:	60 elements

There are a total of 158370 elements in the model.
- A stress analysis has been carried out over this model using the commercial FEM software ABAQUS. The output of stress analysis (stress cycle) is then fed to the commercial fatigue analysis software FESAFE to obtain life [17][18]. Radial and Axial stress contours at the end of loading cycle for all three TGO thickness are shown in figure 6, 7 and 8 respectively.

TABLE 1: MATERIAL PROPERTIES

Layer	Temperature (^{0}C)	Thermal Expansion (CTE) in 10E-6 1/K	Thermal conductivity (λ) in W/mk	Density (ρ) in Kg/ m^3	Specific Heat (cp) in J / Kg K	Modulus of Elasticity (E) in GPa	Poisson's Ratio
Top Coat	25	9.092	0.9	3610	505	85	0.1
	1000	10.5	0.3	3510	630	35	0.1
Bond Coat	25	9.375	10.8	7380	450	200	0.3
	1000	17.5	32.1	7030	980	120	0.3
TGO	25	4.29	33	3984	755	416	0.23
	1000	8.3	6.7	3868	1285	364	0.25
Substrate	20	15	9.1	8220	485	215	0.3
	1000	16.6	28.7	7760	850	139	0.3

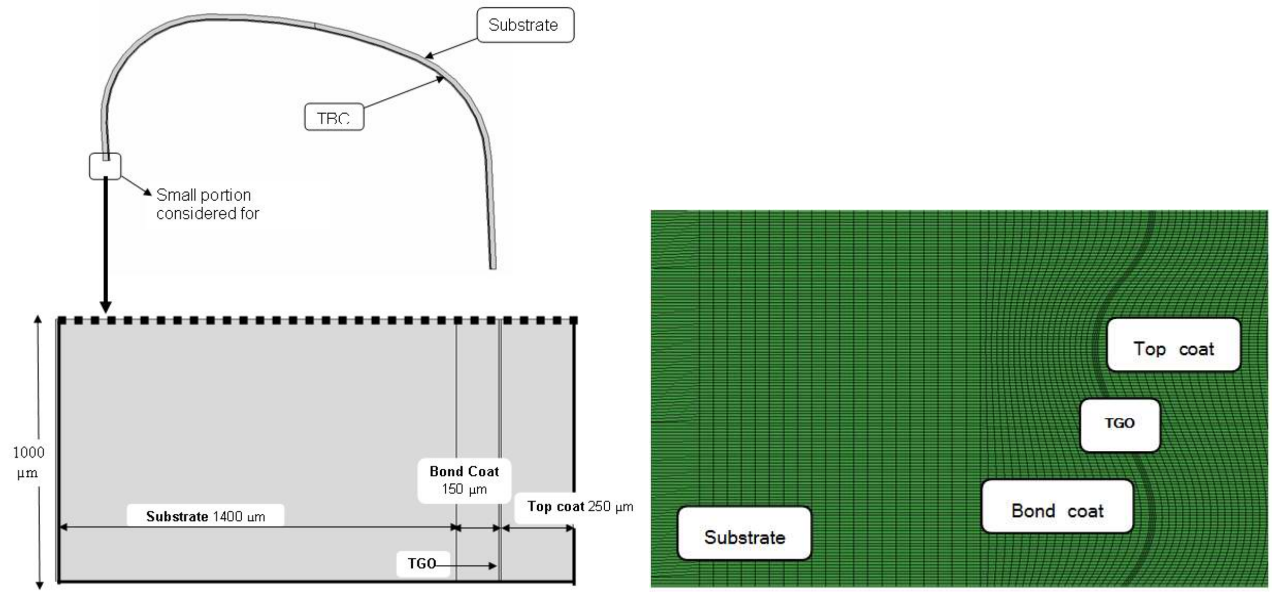


Figure 5: (a) Axi symmetric model for analysis (b) Meshed model

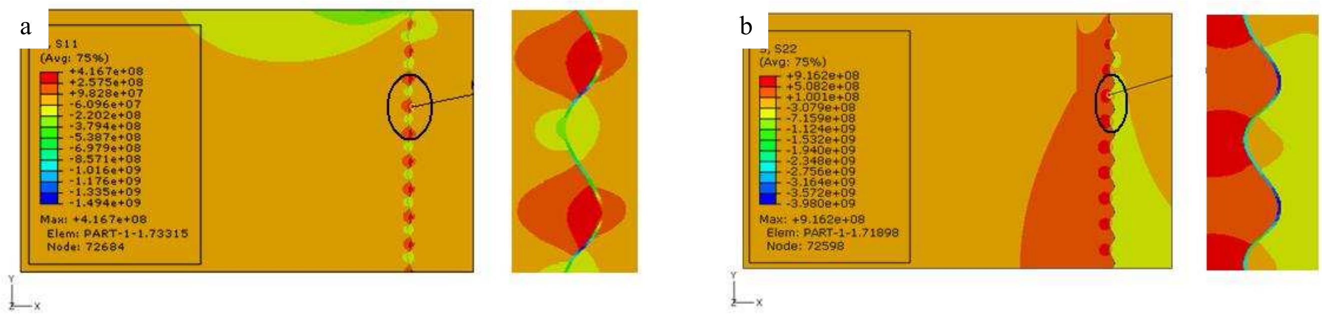


Figure 6: TGO thickness=2µm: (a) Radial stress contour (b) Axial stress contour

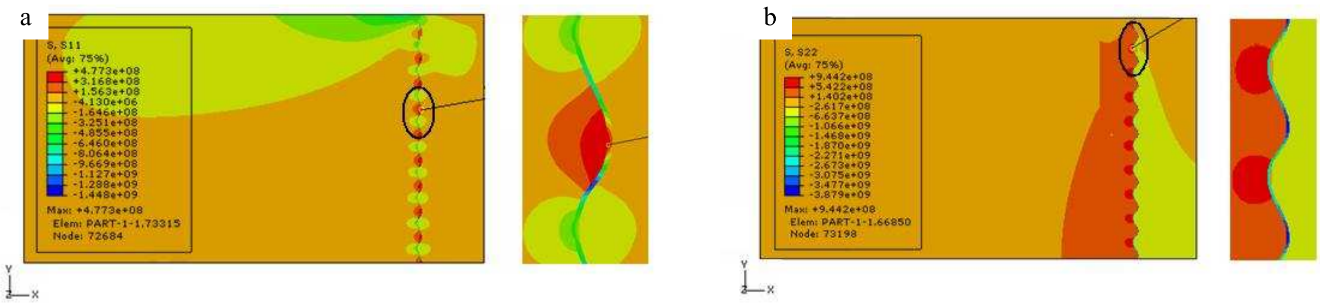


Figure 7: TGO thickness=3µm: (a) Radial stress contour (b) Axial stress contour

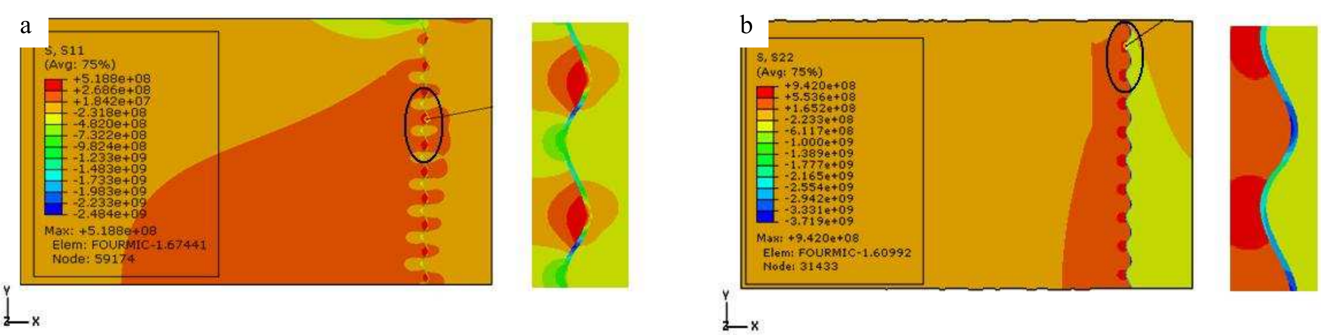


Figure 8: TGO thickness=4µm: (a) Radial stress contour (b) Axial stress contour

With these FE Analysis results, fatigue life is computed for all the three cases using FeSafe software. Several researchers have found the failure to occur at TGO interfaces but not in TGO. Generally TGO promotes failure rather than failing itself. Hence, the TGO layer has not been included for the life analysis. The fatigue analysis plots are as shown in figures 9, 10 and 11.

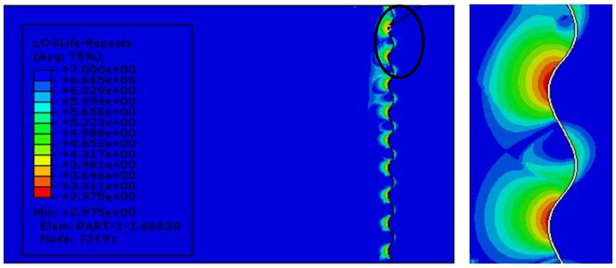


FIGURE 9: FATIGUE LIFE CONTOUR FOR TGO THICKNESS=2 μm

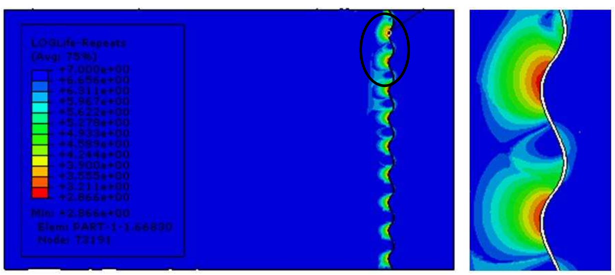


FIGURE 10: FATIGUE LIFE CONTOUR FOR TGO THICKNESS=3 μm

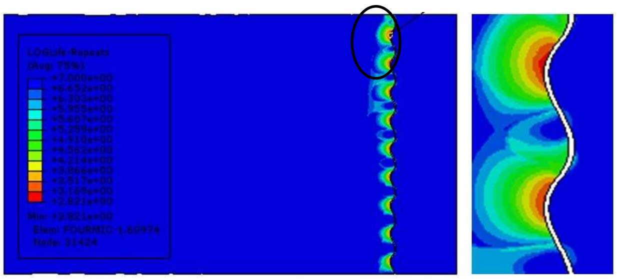


FIGURE 11: FATIGUE LIFE CONTOUR FOR TGO THICKNESS=4 μm

- Life obtained were 944, 734 and 662 cycles for 2, 3 and 4 μm thick TGO layers respectively. The failure is observed between TGO - bond coat interface. The trend obtained is shown in figure 12.

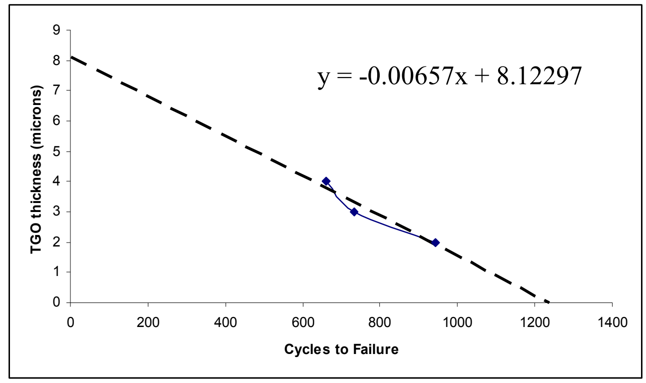


FIGURE 12: CYCLES TO FAILURE VS TGO THICKNESS

- From the trend shown in figure 12, critical TGO thickness (δ) is obtained to be 8.12 μm. A practical TBC system may fail before reaching the critical thickness due to the cumulative effect of TMF.
- Then the trend extrapolated for zero TGO thickness on abscissa brings out 'TMF life (N_{TMF})' in cycles. N_{TMF} is found to be 1237 cycles; this is the life of the TBC system excluding TGO growth effect. N_{TMF} is converted into hours by multiplying with mission duration (i.e.) 1.5 h to obtain 'TMF life (t_{TMF})' in hours, t_{TMF} is 1855 h.
- The time taken for TGO layer to grow till the critical thickness, i.e., 8.12 μm as in this case, can be defined as 'TGO life (t_{TGO})' in hours, this life of the TBC system excluding the TMF effect. An empirical relation for oxidation rate from literature has been used to obtain the duration for TGO to grow till critical thickness for all 7 temperature levels defined in the temperature cycle [19].

$$\text{Oxide thickness } (\delta) = C\,(A\,e^{-\Delta H/RT}\,t)^{1/2}$$

where,

C and A are constants
ΔH = activation energy
R = universal gas constant
T = temperature (K)
t = time (s)

- Further using Miner's rule with weight factor accounting for duration at each temperature level [20], t_{TGO} is worked out to be 3472 h, taking the constants as C = 0.5358 cm^3/g, A = 0.06760 g^2/cm^4-s and ΔH = 66430 cal/mol.
- Assuming TMF and TGO growth are two different life consuming factors of TBC system, Miner's rule has been applied to arrive at life of TBC system (t_{TBC}) as 742 hours.
- TBC system is modelled by a combination of compressive residual stress built up by cooling, stress-life relation, TGO undulations severity and surface finish. The result obtained is due to the combined effect of all these parameters.

- The methodology can be further extended to break the combination effect of these 4 parameters by analysing each parameter independently as well as combined which will lead to more reasonable TBC life estimation close to that obtained during service.
- Though the present study is based on single modelling with simplified boundary conditions of a single roughness profile, further analysis can be carried out with different coating thickness and varying the material properties. Specimen testing can be carried out to generate failure data bank which in turn will help in validation of the life prediction methodology and to minimise the uncertainties involved in this Finite Element approach.

CONCLUSION

From the present exercise for development of life estimation methodology for a TBC system, the following points have been arrived;

- Mismatch in thermo-physical properties, residual stress, TGO layer surface finish and growth are found to be the prime factors responsible for TBC failure.
- Top coat sintering/ageing and erosion are found to have lesser impact on coating degradation and are not considered for analysis.
- Tensile stress is found to increases and compressive stress to decrease at TGO interfaces with increase in TGO thickness.
- Over the time TGO thickness increases affecting adversely the life of TBC.
- The methodology is useful for predicting the base-line life of TBC system under service condition. However further study along with specimen test data is needed to make it a generalized approach.

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