TECHNICAL NOTE

LIFE ANALYSIS OF TBC ON AN AERO ENGINE COMBUSTOR BASED ON IN-SERVICE FAILURES DATA

R. Raghupathy, R.K. Mishra
Scientist
Centre for Military Airworthiness and Certification, DRDO
Bangalore - 560 037, India
Email : ragu.ur@gmail.com

R.D. Misal
Head, Department of Mechanical Engineering
Defence Institute of Advanced Technology (DU), DRDO
Pune - 411 025, India

Abstract

TBC (Thermal Barrier Coatings) mostly find application in the combustion sections of aircraft turbine engines. With the demand for fuel economy and increased power, combustion temperatures are approaching the design limits of the metal alloys from which hot end components are made. Modern TBCs are required to not only limit heat transfer through the coating but to also protect engine components from oxidation and hot corrosion. When a TBC fails, it exposes the underlying substrate to very high gas temperatures and the life of the component gets reduce drastically. With a failed TBC, a component can even fail within its prescribed service life. This is an airworthiness issue. So it is essential to estimate the TBC life accurate possibly to ensure airworthiness of the aircraft at any given time.

Premature failure are observed in the TBC applied over combustion section of a turboprop engine. The engine is 800 shp class and it powers a commuter aircraft. The objective of this paper is to find out mean life of the coating by life data analysis. The data has been fitted to Weibull distribution. The Weibull parameters have been discussed which highlights the dominating cause for TBC failure and hence suggestion for life improvement of TBC system has also been made. The need for TBC system redesign has been emphasized. In addition to this, it also presents a comparison between different users/ operators.

Nomenclature

β = Shape parameter
η = Scale parameter or characteristic life
t = Time

Introduction

TBCs are widely used in aero gas-turbine engines to protect the hot end components from hot combustion gases. TBCs consisting of ceramic layer over a metallic bond-coat layer offer a significant increase in engine efficiency and fuel economy by allowing increased inlet gas temperatures. TBC components generally operate in adverse engine environments involving high temperatures, cyclic thermal loading, and high stress conditions and are expected to survive thousands of cycles. One of the primary concerns regarding the use of TBCs is their premature failure during service, thereby exposing the base or parent material to very high gas temperatures. This leads to drastic reduction in component life. It can also pose a potential hazard to aircraft and its crew. Therefore accurate and reasonable estimation of TBC life under engine environment has become very important.

There are a number of techniques and methodologies developed by investigators for life estimation of TBC [1] [2]. In the present paper an attempt has been taken to ascertain the mean life of the TBC applied on the transition

Paper Code : V63 N2/715-2011. Manuscript received on 05 April 2010. Reviewed and accepted as a Technical Note on 21 Oct 2010

liner of a reverse flow combustion chamber based on data available from in-service failures. Weibull distribution has been used for this exercise and it is found to be in good agreement with the data. The mean life of the TBC so obtained from all failure cases as well as life estimated based on nature of operation for various operators will be a useful input for amending or specifying engine maintenance/overall schedule. Decision to withdraw the engine can be taken at right time for the operator based on this input and any undesirable incident can be avoided. The paper also highlights TBC failure modes and emphasizes any redesign of TBC needed.

Hardware Configuration

The subject engine has 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 [3]. 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 Fig.1.

In this TBC, both Top coat and Bond coat are Air-Plasma sprayed and have porosities around 10%. 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 = 2000 microns
- Bond Coat thickness = 150microns
- Top coat thickness = 250microns

Failure Modes

One of the primary leading causes of TBC degradation leading to failure is the presence of residual stresses in TBC systems. The presence of residual stresses in TBC systems play a dominant role in the behavior, performance, and durability of TBC coated components. The residual stress-state in the coated components undergoes a gradual change during service. There are two different origins for the residual stresses in the TBCs [2]. The first one is the coating deposition process, and the second one is the service conditions of the coated components. Stresses that arise from the coating deposition process such as plasma spraying are associated with the quenching effect of the splashed molten droplets sticking to the cold substrate or with the lower temperature of the solidified coating during the coating growth. The other contributing factors for residual stresses are the thermal expansion mismatch between different constituents of the TBC and temperature gradients across the top layers, the bond coats, and metallic components. In addition, the presence of thermally grown oxide (TGO) layer is another critical source of stress and strain at the interface of the bond coat/TBC. Though the thickness of the TGO layer is typically only a few microns, but the stress in the TGO layer can be very high due to its thermal expansion mismatch with the bond coat [4]. However, the detail analysis based on stresses on different layers is beyond the scope of the present paper.

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 [5].

Combustor components after a certain period of operation were selected for study from which coating failure modes were analyzed. The failure of TBC is defined based on erosion beyond limit, coating crack, spalling, burns, and delamination, etc. Failure due to spalling is found to be a major cause in the cases studied. The location of spalling is almost near the outer curvature of the liner as shown in Fig.2. After 1800 hrs of life the coating is observed to have failed at several locations along the circumference.

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. Exact failure hours of the coating are not available as the data is interval censored / left censored. Interval censored means the coating might have failed somewhere between the inspection interval, left censored is a special case of interval censored data where lower limit of the interval is 0 hrs.

The data is analysed using Reliasoft Weibull++7 software [6]. 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. 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,

- 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.
- The components accounted in the interval censored data also had some degree of coating failure but below the acceptable limit, this greatly supports this assumption.
- This assumption also encourages convergence of iteration as it generates solid failure points from interval censored data.

Figure 3 shows the hour wise distribution of failures and survivals. The abscissa in Fig.3 has hours at which coating inspection is carried out. Hot Section Inspection (HSI) is scheduled at 1800 hrs but inspection can be carried out at an early stage whenever the engine visits the overhaul base due to any defect. Maximum failures of 78 cases (83%) are found to be in the interval of 1700-1900 hrs. The interval 1500-1700 hrs has 29 inspections carried out and about 93% of the HSI revealed coating failure. The population of inspections in the interval of 1100-1800 is clearly higher than in the interval of 1800-2500. This is due to the fact that being fixed an inspection cum preventive maintenance at 1800 hrs, carrying out early inspection is allowed to some limit. But operating beyond the scheduled inspection time is not allowable as it impairs the system's safety.

Weibull Distribution

Weibull distribution is an empirical distribution, which provides a flexible model for analysis of failure data in general [7] [8].

The probability density function (PDF) of Weibull distribution is represented by the following equation for the values of $t \geq 0$, $\eta > 0$ and $\beta > 0$.

$$f(t, \eta, \beta) = (\beta / \eta^{\beta}) \; t^{\beta - 1} \, e^{-(t/\eta)\beta}$$

A hazard function can also be called as instantaneous failure rate [9]. For the Weibull distribution it is represented by the following equation for value of $t \geq 0$, $\eta \geq 0$ and $\beta > 0$.

$$h(t, \eta, \beta) = (1/\eta)^{\beta} \; \beta \, t^{\beta - 1}$$

The mean life for a large number of cases considered for the Weibull distribution can be found out using is for values of beta (β) less than and greater than one is given by

Mean life = $(\eta/\beta) \Gamma (1/\beta)$ or $\eta \Gamma (\beta + 1/\beta)$

Since "Weibull" is a multi-shape distribution model, the shape mainly depends upon the value of shape parameter (β). Following references are generally drawn by these parameters.

$\beta < 1$ indicates a decreasing hazard rate (early failure regime)

$\beta = 1$ indicates a constant failure rate (chance failure)

$\beta > 1$ indicates an increasing hazard rate (the wear out failure regime)

In the case of scale parameter (η) the value is given by the age at which 63.2% of equipment population is expected to fail.

Results and Discussion

The segregated data has been fitted to 2 parameter Weibull distribution and the Weibull parameters found to be $\beta = 4.6758$ and $\eta = 1466$ hrs. The Weibull probability plot, Probability density function plot and Failure rate plot are shown in Fig.4, 5 and 6 respectively.

High β value of 4.67, safely rules out failures related to quality such as process and raw materials. So coating failures can be attributed mainly to operation which is severe than the design intend. From the Weibull parameters, the Mean life works out to be 1341 hrs.

Whereas the coating has to work for minimum 1800 hours to safeguard the substrate, this raises the necessity for improvement in TBC system life. From the discussion over the Weibull parameters it is evident that any further improvement required in TBC life can be addressed by better TBC system design. Different coating process shall also be considered such as EB-PVD (Electron Beam - Physical Vapor Deposition) which has higher spallation life compared to Air - Plasma Sprayed coatings.

Further analysis has been carried out over the mean life of TBC obtained for different operators. There are three operators for this engine / aircraft. The mean lives of the TBC system for different users are provided in Table-1.

Table-1 : Mean Life for Different Operators

User/Operator	Mean Life (Hrs)
Operator 1	889
Operator 2	1285
Operator 3	1524

There is a notable variation in the mean life between different operators. This may due to different operational requirements and environmental conditions for every operator. In order to ascertain this, the operational conditions of all the operators are required to be studied and compared with each other. The Weibull probability plot for all the three operators is given in the Fig.7.

Conclusion

The life data analysis result indicates the necessity for redesign of TBC system for improved life. This has been substantiated by the Weibull shape parameter (β). The difference in mean life between different operators has been explained to be due to different engine operational requirements and environmental conditions, which can be ascertained by further study and comparison upon these aspects. An attempt is being made to establish TBC system life by stress analysis, the mean life obtained out of the current work will also be used to validate the life obtained out of the stress analysis.

References:

1. Kang, B. S. -J., Feng, C., Tannenbaum, M. and Alvin, M. A., "A Load-based Depth-sensing Indentation Technique for Damage Assessment of Thermal Barrier Coatings", Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air, GT2009-59985, 8-12 June, 2009, Orlando, Florida, USA.

2. Madhavrao Govindaraju, et al., "Development of Life Prediction Methodology for Thermal Barrier Coatings based on Nondestructive Piezo-spectroscopy Photoluminescence Measurements", Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air, GT2009-59570, 8-12 June, 2009, Orlando, Florida, USA.

3. Gas Turbine Combustors, A. H. Lefebvre, Second Edition.

4. Evans, A. G., He, M. Y. and Hutchinson, J. W., "Mechanics-based Scaling Laws for the Durability of Thermal Barrier Coatings", Progress in Materials Science, 46, pp.249-271, 2001.

5. Mats Eskner., "Mechanical Behaviour of Gas Turbine Coatings", ISBN 91-7283-786-1, 2004.

6. Reliasoft Weibull++7 Software Operating Manual.

7. System Software Reliability, Hoang Pham, ISBN-10:1852339500

8. Ragupathy, R., Sakthivel, A., Ramesha, H.P. and Gouda, G., "Analysis of In-service Failure Data for Continued Airworthiness Assurance - Case Studies", Globalization Of Engineering, Design, R&D Challenges and Opportunities, 9-11 August, 2007, Indian Institute of Science, Bangalore.

9. A Handbook of Statistical Analysis Using SAS, Geoff Den, Brian Everitt, ISBN-1-58488-245X

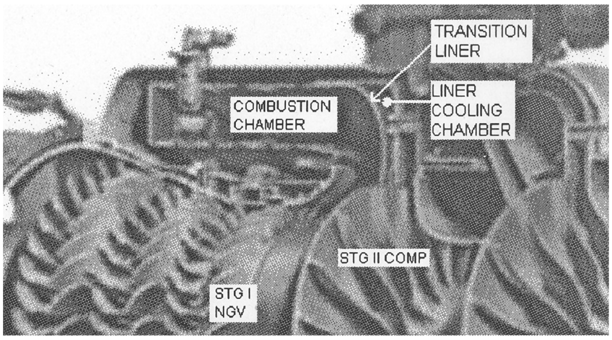

Fig.1 Typical Transition Linear Assembly

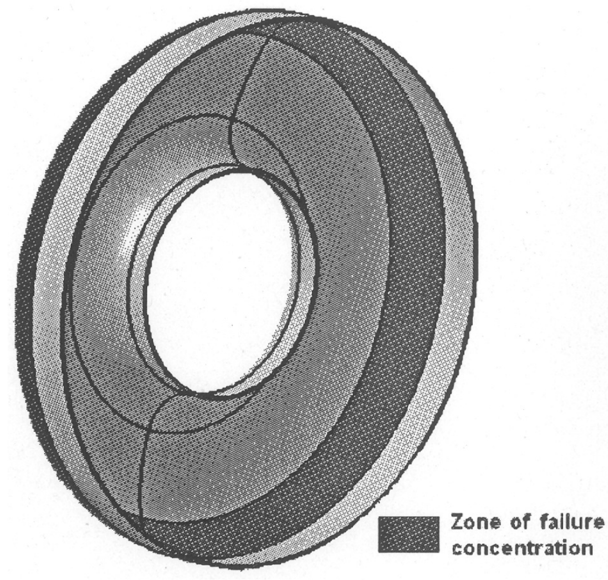

Fig.2 Transition Linear and Zone of Failure

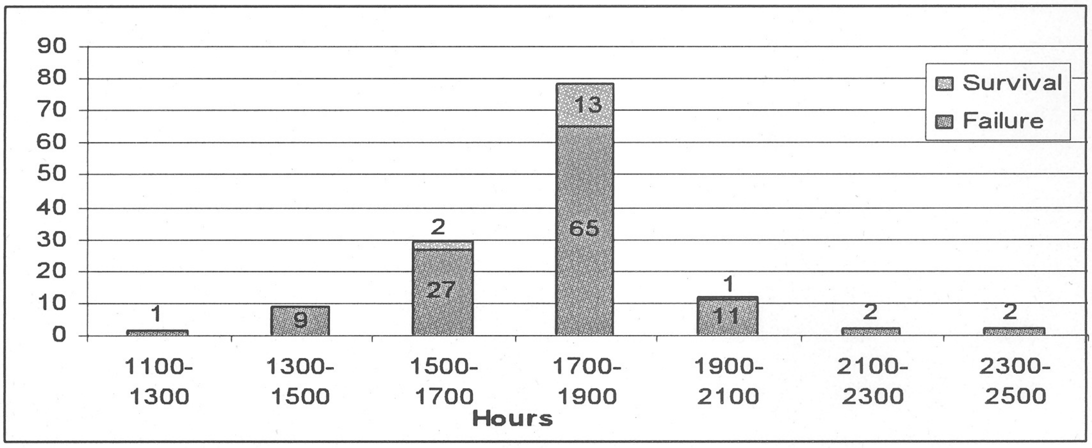

Fig.3 Hour Wise Distribution of Failures and Survivals

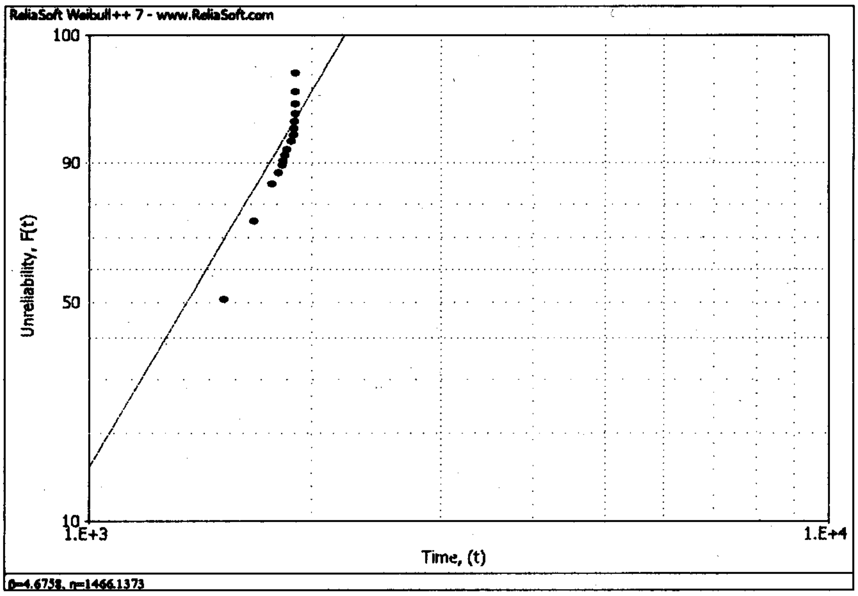

Fig.4 Weibull Probability Plot

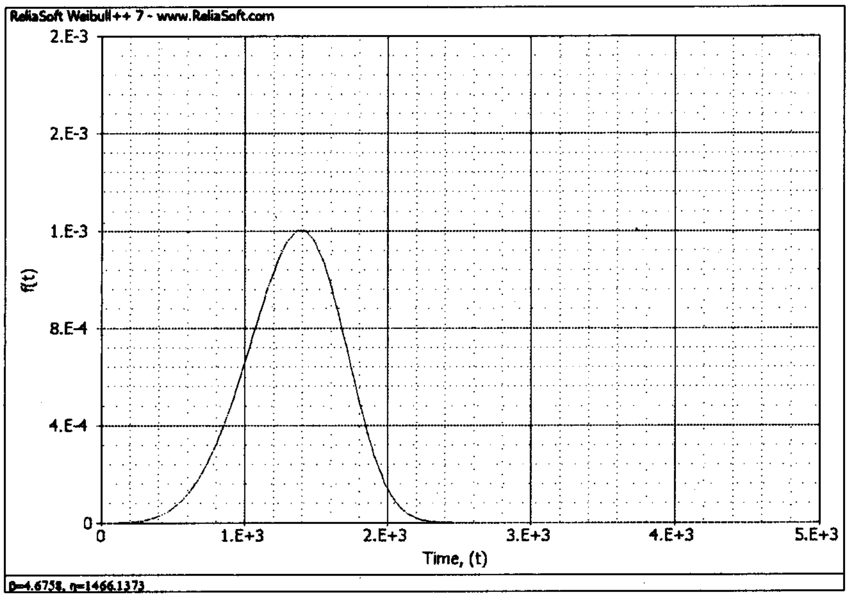

Fig.5 Probability Density Function Plot

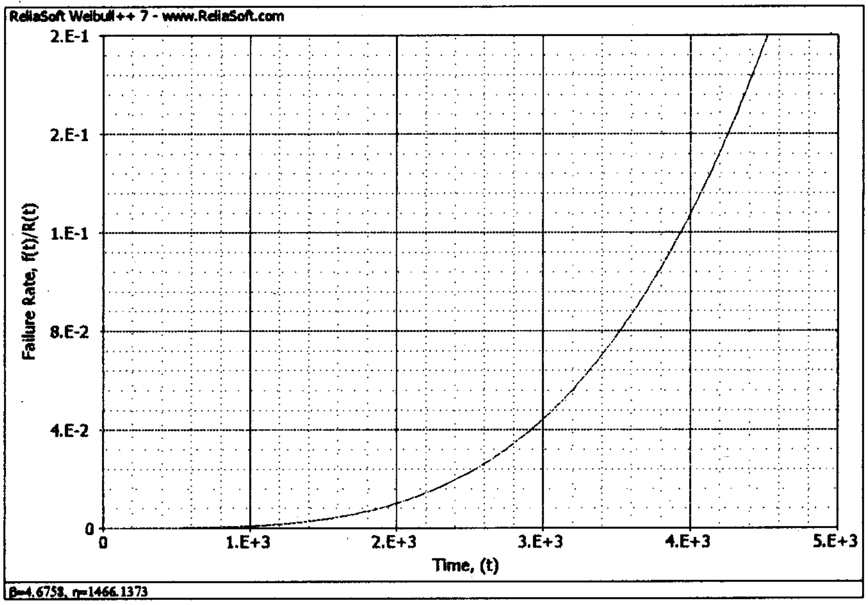

Fig.6 Failure Rate Plot

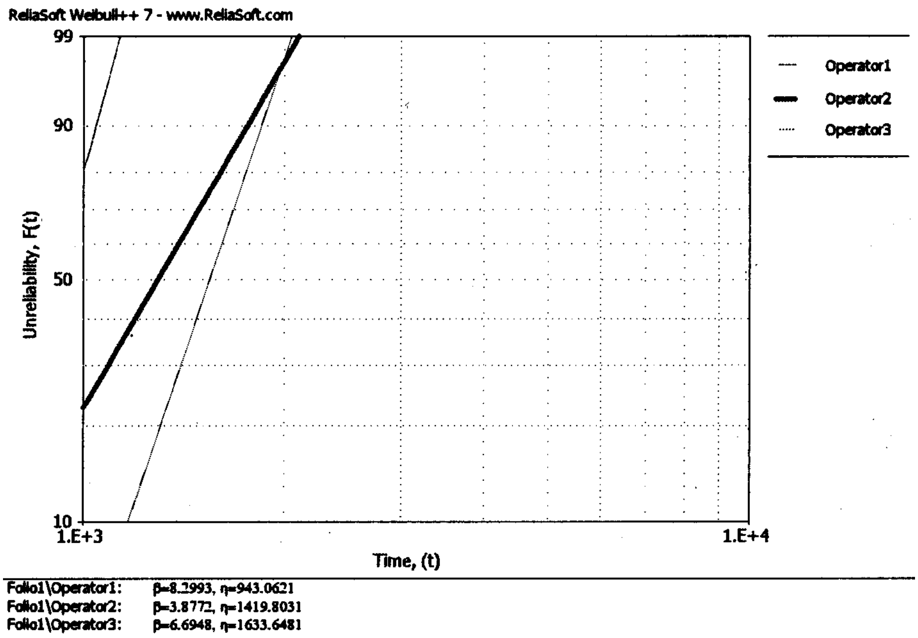

Fig.7 Probability Plot for Difference Operators