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Cyclic furnace testing and life predictions of thermal barrier coating spallation subject to a step change in temperature or in cycle duration

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ABSTRACT

Thermal barrier coatings (TBCs), used for thermal protection of gas turbine hot section parts in service are typically subjected to thermal histories that involve variations in both maximum temperature and hold time. The primary purpose of this work is to begin to study the durability consequences of non-constant thermal exposure and the associated life prediction challenges that such load histories present. Nearly all published TBC cyclic furnace tests have been conducted at constant temperature and constant cycle duration. In this work, two types of non-constant condition tests were run, tests in which the temperature was changed part way through the cyclic life and a second type of test where the high temperature hold time was changed part way through the cycle life. The validity of the linear damage rule was examined and found to work well for changes in maximum temperature and not as well for changes in cycle duration. In addition, the stresses in the thermally grown oxide (TGO) were recorded with the use of photoluminescence piezospectroscopy (PLPS) and the changes in stress were used to predict remaining cyclic life for non-constant condition tests.

1. Introduction

Thermal barrier coatings (TBC) were developed to insulate the surface of superalloys to allow gas turbine engines to operate at higher temperatures with increased efficiency and durability. The ceramic-based coatings insulate the superalloy from the gas path and provide a temperature difference across the coating as much as 175 °C [1]. Most production thermal barrier coatings consist of an yttria stabilized zirconia (YSZ) ceramic top coat, and an oxidation resistant bond coat on top of a superalloy base metal.

Many previous studies of the cyclic furnace durability of TBC systems have been carried out, including those on TBC specimens similar to those used in this study [2–4]. In virtually all of these studies, the temperature and cycle duration were held constant. It is not unusual in commercial aviation that an aircraft can be used on routes of different durations both from year to year or even on a single multi-destination flight. Military aircraft engines have even more varied operational history. The traditional method for dealing with non-constant conditions in durability estimation is to use the linear damage rule which is both simple and requires a minimum of input information. The experiments to be described will be used to examine the validity of the linear damage rule. In addition to testing the linear damage rule, we will examine the feasibility of using a non-destruction damage detection method based on measuring the stress in the thermally grown oxide (TGO) using photoluminescence piezospectroscopy (PLPS). This method has shown some success in remaining life prediction for lab samples tested at constant conditions [2]. The challenge for non-constant conditions is significantly greater even for lab samples as discussed here. The use of PLPS measurements to predict the lives of aircraft engine parts will be even more difficult, but this work seeks to see to what degree this method can be made to work for the more difficult case of non-constant cyclic conditions. Feasibility of such predictions, as will be shown, depends in part of what sort of information is available about the thermal history of the part. We include one case for which the information required is not currently collected in the event that rapidly growing condition monitoring technology may someday include the required information.

In this work, tests are carried out in which the temperature history is changed during the test. The peak temperature or the cycle duration was changed at roughly half of the expected life of the samples. This is a simplified load history designed to see if a simple linear damage rule applies. Baseline samples in this study were previously tested under constant conditions [2]. These constant condition test results were then used as input to test the accuracy of the linear damage rule. In addition, extensive measurements of TGO stress taken by photoluminescence piezospectroscopy (PLPS) of the constant history samples reported for these samples in Ref. [2] was shown to have

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Abbreviations: TBC, Thermal barrier coating; TGO, Thermally grown oxide; PLPS, Photoluminescence piezospectroscopy; YSZ, Yttria stabilized zirconia; EB-PVD, Electron beam physical vapor deposition; GPa, Gigapascal.

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potential for nondestructive prediction of remaining life. The technique, invented by Paton et al. [5] has been useful in non-destructively measuring the stress in the TGO and is based on the frequency shift in the Cr^{3+} ions within the TGO. The impact of non-constant temperature and cycle duration on PLPS data and life prediction was also examined [6].

Before presenting the results a few preliminary comments are in order. First we note that the linear damage rule takes no account of the physical damage mechanisms involved however it is widely used because it requires a very minimum amount of information. In contrast, mechanism based methods require extensive information. For example, in one recent study, life prediction required finite element modeling using an advanced constitutive model as well as measurements of rumpling and oxidation kinetics collected from over 1000 micrographs [7]. Mechanism based approaches such as in [7] are beyond the scope and intent of this experimental program and often infeasible in an industrial context. Second, with respect to using measured TGO stress to predict remaining life there are several challenges. Generally when measuring TGO stress on turbine blades there is some variation in stress with locations on a given component however as shown in [8,9] this variation is typically manageable. In the study conducted by Sohn et al. [9], stresses at the pressure, suction, and leading edge all dropped off significantly with thermal cycling. Initial stresses of 3.14 +/− 0.25 GPa at the pressure side, 3.15 +/− 0.12 GPa at the suction side, and 3.58 +/− 0.23 GPa at the leading edge dropped to 1.64 +/− 0.18 GPa, 1.41 +/− 0.21 GPa, and 1.47 +/− 0.32 GPa in those locations respectively indicating that the surface curvature and local bond coat roughness or other factors did not excessively change the stress decay during thermal cycling. Typically on an individual blade, the variation in measured stress is less than 15% [8] and to be conservative the location with the greatest stress drop would be used to characterize the blade.

In addition there tends to be considerable consistency as to where on a blade the spallation occurs in a given engine and blade row. We have had the opportunity to study 100 turbine blades from five different engines each with a different number of operational hours. The majority of blades examined had spallation in only three different locations with the most frequent being in the center of the pressure side. Accordingly, in practice it is expected that measurements would be taken from a limited number of known critical locations for which there is some but not extreme variation in measured stress.

In carrying out this study there were many possible choices as to the nature of non-constant condition tests to carry out. Since non-constant conditions tests are new we choose the conditions based on what generally is the most challenging for the linear damage rule in metal fatigue, namely a change from test condition A to condition B at an estimated life fraction of 0.5. Actual service is likely to involve mixed conditions for which sequence effects if any would tend to average out compared to the tests involving only two conditions applied in sequence making the tests run likely to be strong tests for the linear damage rule.

2. Experimental setup

2.1. TBC specimens

In this study, two types of TBC samples were utilized (Fig. 1). Both types consisted of 25.4 mm diameter disk-shaped coupons that were 3.2 mm in thickness with YSZ topcoats deposited by electron beam physical vapor deposition (EB-PVD). Type I TBC samples consisted of 150 μm 7 wt.% Y_2O_3 (YSZ) stabilized zirconia electron physical vapor deposited (EB-PVD) top coat, and a 75 μm grit blasted platinum nickel-aluminide bond coat [(Ni, Pt) Al]. The outwardly grown chemical vapor deposition single phase platinum aluminide coating was formed at 1080 °C and grit blasted prior to electron beam physical vapor deposition (EB-PVD) of the ceramic top coat.

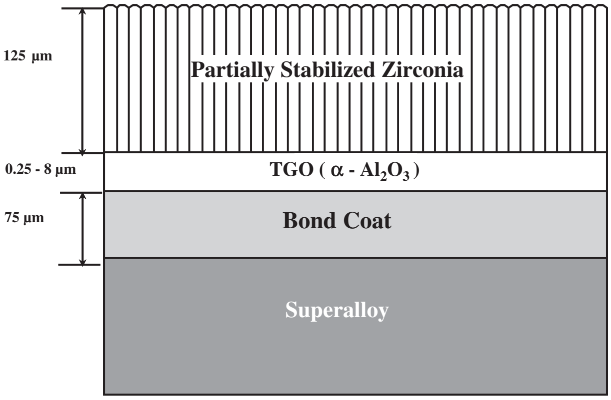

Fig. 1. Four layers in thermal barrier coating system [6].

Type II TBC consisted of 175 μm 7 wt.% Y_2O_3 (YSZ) stabilized zirconia EB-PVD top coat, and a 55–60 μm grit blasted platinum modified nickel-aluminide bond coat. The bond coat on Type II was inwardly grown at 982 °C using pack cementation. In addition, both types of TBCs also had contained an initial thermally grown oxide (TGO). This layer, typically 0.5 μm prior to cycling, consisted of an alpha aluminum oxide that forms during heat treatment. The compositions of these bond coats are shown in Table 1.

2.2. Furnace cycling tests

Furnace cycling tests were conducted in bottom-loading thermal cycling furnaces made by CM Furnaces Inc. The type S thermocouple that controlled the furnace temperature was welded to the back of a superalloy dummy sample in the center of the furnace. Three additional thermocouples were mounted in three of the four corners of the furnace and agreed at steady state with the control thermocouple within 5 °C.

The 1-hour cycles consisted of a 10-minute heat-up to the cycle temperature, followed by a dwell for 40 min at the maximum temperature. The final step was a 10-minute forced-air cool. The 24-hour cycle test consisted of the same 10-minute heat up to temperature, followed by a 1430-minute hold and then a 10-minute forced air quench. The samples subjected to the two-stage cyclic tests were first cycled at a test condition which will be referred to as condition A until approximately 50% life, and then tested at a second test condition to be called B until failure. The order in which the conditions are applied is likely to matter and this is consistently designated as condition A first followed by condition B.

Initial baseline testing, reported in [2] involved cycling separate sets of samples at 1121 °C and 1151 °C using 1-hour and 24-hour hold times to determine the average failure life of specimens. For Type I TBCs, eleven specimens were cycled at 1121 °C and nine at 1151 °C all using 1-hour cycles. In addition, eight were cycled at 1121 °C using 24-hour

Table 1
Composition and thickness of the two TBCs studied [6].

Type	Superalloy substrate	Bond coat		Ceramic (7 YSZ)	
		Type	Thickness (μm)	Type	Thickness (μm)
I	Single crystal CMSX-4	Grit blasted on outward diffusing single phase platinum modified nickel aluminide	75	EB-PVD	150
II	Single crystal CMSX-4	Grit blasted on inward diffusing type single phase platinum modified nickel aluminide	55–60	EB-PVD	175