NASA Technical Memorandum 81742

Prolonging Thermal Barrier Coated Specimen Life by Thermal Cycle Management

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Prepared for the
International Conference on Metallurgical Coatings
sponsored by the American Vacuum Society
San Francisco, California, April 6-10, 1981

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E-795

ABSTRACT

Measurements have been made of the rate of increase in temperature of a ZrO_2-$8Y_2O_3$ thermal barrier coated (TBC) specimen for various values of fuel/air (F/A) ratios when the specimen is exposed to a 0.3 Mach burner flame.

For rod specimens in a carousel, the heating rates increased with (F/A) ratio and were higher at the inward facing surface for a given (F/A). Plate specimens were more sensitive to burner variations.

Calculated results are given for the radial stress in the coated rod specimens for variations in (F/A) ratios from 0.04 to 0.065. Over this range, the radial stress varies from 4.3 to 5.3 MPa (0.62 to 0.77 ksi).

The results indicate that controlling the heating rate of a TBC by controlling the (F/A) ratio offers a potential method to prolong TBC cyclic life; uncontrolled (F/A) ratios will produce scatter in experimental results. Geometric arrangement can have an equivalent effect, but is usually fixed by design.

INTRODUCTION

Thermal barrier coatings applied to the heated side of engine components such as seals, combustor and blades of a gas turbine offer a potential increase in efficiency through the use of higher gas temperatures or less cooling air or benefits arising from extended component life by reducing component metal temperatures (refs. 1 to 5).

Extensive research has been carried out to determine the properties of thermal barrier coatings (TBCs) and to improve their durability (refs. 6 to 11). Of major concern, however, are the large deviations in TBC life data. Satisfactory and consistent performance under cyclic heating and cooling is essential if TBCs are to be used by industry in major component design (refs. 12 and 13).

In a previous study (ref. 13) the calculated TBC detachment stress in the initial phase of the heating cycle was found to be greater than the allowable range given in reference 6 and quite sensitive to the rate of hea input. Methods were suggested to reduce the heat flux dependence such as varying the fuel-air ratio (F/A) since there is an equivalence between (F/A and the driving temperature potential.

The purpose of this paper is to show that while a TBC specimen can be brought to a fixed temperature using various (F/A) values, lower calculated stresses are associated with lower (F/A) values. This implies that control of (F/A) values (i.e., rates of heat input) during the starting transient and to a lesser extent during shutdown and operation, offers a potential method of improving TBC lifetime through thermal cycle management. Such control methods would be more readily applicable to industrial and some commercial turbomachinery rather than military turbines, where time to achieve maximum power is at a premium. One would, however, most likely continue to design for the most adverse conditions which would affect such things as allowable TBC thickness, cooling, strain isolation systems or other strain accomodation features, and use thermal cycle management to gai lifetime.

APPARATUS AND PROCEDURE

Methods of assessing the cyclic life of TBC specimens in a rotating carousel with a 0.3 Mach burner flame are described in reference 13.

In the manual operating mode, the burner (F/A) ratio can be fixed and the resulting free stream temperature then attains an equilibrium value. In the automatic operating mode the free stream temperature as well as the initial maximum (F/A) value are pre-selected. In this latter case the burner initially heats at close to the maximum (F/A) value and then (F/A) is dynamically adjusted by a controller (thermocouple feedback) to attain the preset free stream temperature. Both techniques were used in taking the free stream temperature surveys and specimen time-temperature data at various (F/A) values. The free stream temperature was surveyed using a K-type thermocouple (chromel-alumel) suspended at carefully calibrated locations along and off the burner centerline and corroborated using a radiation pyrometer. The agreement was within ±50° F at 1800° F (1256 K).

To determine the specimen time-temperature data, a K-type thermocouple was imbedded in a rod and placed in the carousel and rotated in the flame. The time-temperature data were recorded on strip charts.

The specimen bond coat was Ni18Cr12Al0.3Y, nominally 0.13 mm, which was coated by ZrO_2-$8Y_2O_3$, nominally 0.38 mm thick.

RESULTS AND DISCUSSION

Rod specimen time-temperature data were taken and replotted as figure 1. The temperature was controlled and the initial (F/A) varied from 0.051 to 0.059 (automatic mode). The slopes of the time-temperature curves increase with increasing (F/A) and represent the rate of heat input to the specimen. Despite differing initial heating rates (different slopes), the same specimen equilibrium temperature is achieved by the controller after approximately 3 minutes. In the manual mode of operation, with preselected fixed (F/A) ratios, both the slope and the steady state level increased as the (F/A) ratio increased.

Experimental values of free stream temperature variation with (F/A) (manual mode) are given along with the combustion temperatures in figure 2. These values represent the temperature 1.3 cm from the nozzle, along the centerline. Using the temperature- (F/A) values as input, the thermal stresses were calculated under transient heating using a combination of the programs SINDA (refs. 14 and 15) and FEATS (refs. 16 and 17). As anticipated from the results of reference 13, the higher the rate of heat input, the higher the resultant stresses, figure 3. Calculated thermal stresses are shown to be at a maximum in a TBC specimen near the stoichiometric (F/A) and less at other (F/A) ratios. Such stresses, of course, depend on the free stream temperature but more importantly on the rate of heat input to achieve that temperature. It is the (F/A) of initial heating which most affects the magnitude of the stresses,* since the gas temperature is the driving potential for heat input.

Since thermal stresses can cause TBC failure, to prolong TBC life specimens should be subjected to a low initial heating rate, gradually increasing to achieve the equivalent temperature. Testing which controls only the final temperature and dynamically varies (F/A) to achieve that temperature subjects the specimens to a variety of stresses which may produce significant life-cycle data scatter.

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*The major parametric groups are Material properties, Geometric configuration, Heat flux - thus other parts of the heating cycle can produce failures depending on the nature of these parameters (e.g., cooldown of some flat plate specimens).

Testing geometry can also have an effect. The heating rate for eight rod specimens in a carousel is higher for those surfaces facing one another (radially inward) than for those surfaces facing the environment (radially outward). This is in agreement with test data where failures nearly always occur at the more rapidly heated and ultimately hotter inward location, figure 4 and Appendix.

To further illustrate the consequences of high and low (F/A) values, flat plate test specimens were placed in a nonuniform, maldistributed burner flame. A temperature survey 5 cm from the nozzle exit plane indicated a hot zone in the lower quadrant of the burner and a relatively cool zone in the upper half; a surface temperature variation of 250° F at 1800° F (1256 K) was noted on the test specimen. Such a maldistribution can be considered as stratification or equivalently as variations in (F/A), from top to bottom of the burner. Surface oxidation, geometric distortion and TBC failure were closely monitored. With a constant (F/A) value of 0.061 (free stream temperature 1622 K (2460° F), fig. 2), the specimen shown in figure 5(a) failed in less than 370 thermal cycles of 2 min. heating and 1.5 min. cooling. However, with a (F/A) value of 0.047 (free stream temperature 1444 K (2140° F), fig. 2) the specimen did not really fail although a wedge shaped chip in the lower edge was noted at 4700 cycles and the test was terminated after 10,000 thermal cycles (fig. 5(b)). In both cases the upper portion of the specimen did not fail, but appeared degraded by products of combustion gas deposition.

SUMMARY OF RESULTS

Since the heating rate is controlled by the gas temperature which is directly related to the fuel-air ratio (F/A), the free stream temperatures associated with various (F/A) values for a Mach 0.3 burner rig were mapped to provide input for the transient thermal stress computations. The resulting stress computations for a TBC coated rod show increased stresses at higher (F/A). These results imply longer TBC cycle life for lower initial (F/A) in the 0.04 to 0.07 range of Jet A/air used herein.

Properly controlled (F/A), herein termed thermal cycle management, offers a potential method to prolong TBC life; uncontrolled (F/A) could produce substantial scatter in experimental results.

At a fixed (F/A) ratio and a mass flow rate, the heating rates of rod specimens are larger on the surfaces facing the inside of the carousel. These results imply the importance of geometry in both testing and practice.

APPENDIX

WATER TABLE SIMULATION OF THE TEST CAROUSEL

For the rod specimen analysis it is expedient, but incorrect, to assume an average heat flux over the specimen surface. The effects of circumferential heat flux variation and pressure for cylinders in crossflow can be found in most heat transfer texts and are Reynolds number dependent.

The burner-carousel arrangement was simulated on a water table, see figure 6(a), and dye was used to define the flow field. For times when the cylinders are inline, the incident turbulence intensity of the second rod is the wake intensity of the first rod, figure 6(b). When the flow is between cylinders or the first is at some angle of attack, the flow between the two leading cylinders is accelerated. As a result, surface B is "fanned" by an augmented jet. In some cases the augmented jet is directly inline with surface B, figure 6(c).

Thus for the carousel ensemble rather than a single cylinder in cross flow, the flow characteristics are such as to indicate, (1) an increase in incident turbulent intensity, (2) "fanning" by an augmented jet and (3) possibly a higher suction force at surface B over that of surface F. Since friction factor and heat transfer are directly related, it follows that surface B should heat at a higher rate. This in turn implies a higher average stress at surface B.

The preceeding discussion applies to either heating or cooling of the specimen.

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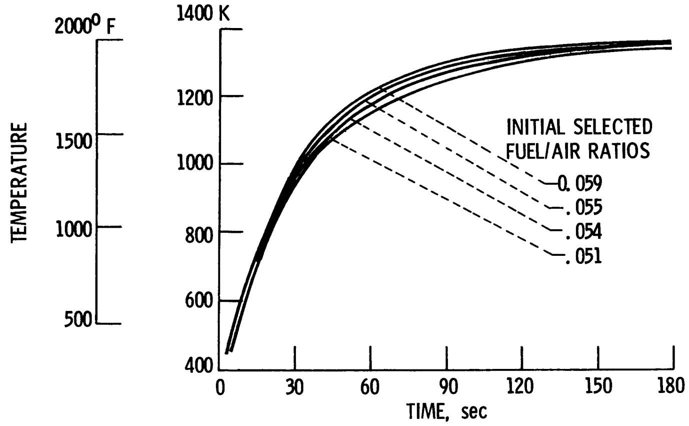


Figure 1. - Time-temperature response of a 2.6 cm diameter TBC rod for selected initial fuel/air ratios for a pre selected equilibrium temperature (automatic operation mode). Eight carousel positions occupied, one rod instrumented.

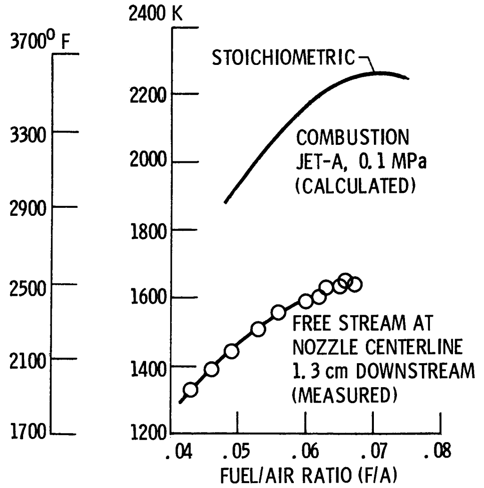


Figure 2. - Variation of free-stream temperature and combustion temperature with fuel/air ratio along the center line and at 1.3 cm downstream of the nozzle.

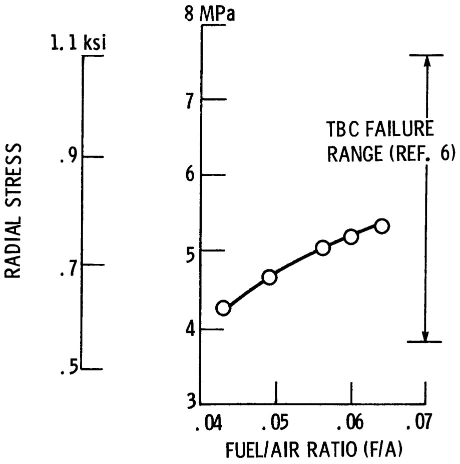


Figure 3. - Calculated radial stress for various fuel/air ratios compared to the measured adhesive/cohesive stresses of reference 6.

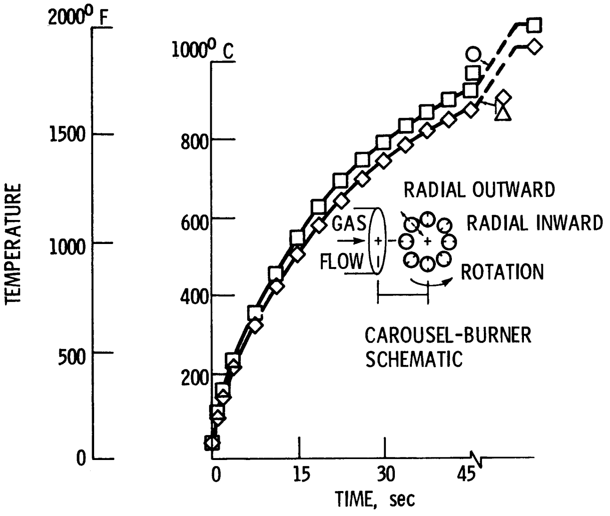
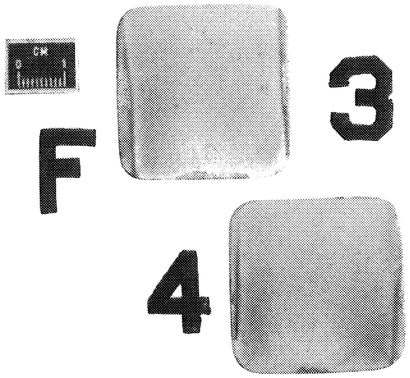
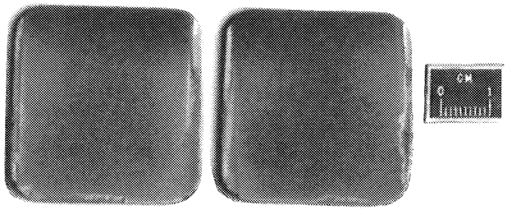


Figure 4. - Time-temperature characteristics for a TBC rod specimen for the radial inward or radial outward positions.



TBC FAILURE < 370 CYCLES)

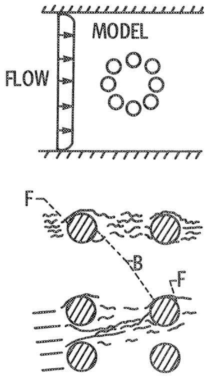
(a) FUEL/AIR RATIO = 0.061.



TEST TERMINATED AT 10^4 CYCLES;
WEDGE TYPE ZrO_2 FRACTURE AT LOWER EDGE,
SUBSTRATE STILL PROTECTED.)

(b) FUEL/AIR RATIO = 0.047.

Figure 5. - Cycle life comparisons for flat plate TBC specimens at fuel/air ratio in a Mach 0.3, Jet-A burner flame.



(a) WATER TABLE MODEL.

(b) DYE PATTERNS
CYLINDERS INLINE.

(c) CYLINDERS ROTATED
WITH ANGLE OF ATTACK
TO FLOW.

Figure 6. - Water table simulation of the carousel-burner.

1. Report No. NASA TM-81742	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PROLONGING THERMAL BARRIER COATED SPECIMEN LIFE BY THERMAL CYCLE MANAGEMENT		5. Report Date
		6. Performing Organization Code 506-53-12
7. Author(s) Robert C. Hendricks and G. McDonald, Lewis Research Center, and Nicholas P. Poolos, Harvard University, Cambridge, Massachusetts 02138		8. Performing Organization Report No. E-795
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the International Conference on Metallurgical Coatings sponsored by the American Vacuum Society, San Francisco, California, April 6-10, 1981.

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17. Key Words (Suggested by Author(s)) Fuel/air ratio Thermal cycle Thermal barrier coatings Cycle life	18. Distribution Statement Unclassified - unlimited STAR Category 34

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161