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PROGRAM FOR DEVELOPMENT OF STRAIN TOLERANT THERMAL BARRIER COATING SYSTEMS

Informal Report

Task IV Coating Property Evaluation

30 January 1984

Prepared For:
National Aeronautics and Space Administration
Lewis Research Center

Under Contract NAS3-22548

Prepared By: N.P. Anderson

PWA-5777-30

UNITED TECHNOLOGIES
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Engineering Division
400 Main St.
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FOREWARD

This informal report provides results of coating property measurements made under Task IV of Contract NAS3-22548, "Development of Strain Tolerant Thermal Barrier Coating Systems." Results of Tasks I through III of this program, which led to the selection of two candidate optimized thermal barrier coating systems, were presented in a previously published Final Report, NASA CR-168251. The goals of Task IV are to measure various coating properties and to conduct a comparative experimental engine evaluation of the two selected coatings. Results of the property tests are reported herein; engine evaluation currently is awaiting the availability of a suitable test engine.

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PROGRAM SUMMARY

This report presents the results of thermal conductivity, thermal expansion and high cycle fatigue tests conducted on coating systems 3 and 8 identified in NASA CR-168251. These results show that the thermal conductivity of coating system 8 at approximately 982°C (1800°F) is substantially higher than system 3 while no significant differences were observed in the thermal expansion measurements up to approximately 1316°C (2400°F). High cycle fatigue (HCF) testing, which was conducted at room temperature and several stress levels, showed both coatings to be extremely resistant to spallation in HCF.

INTRODUCTION

The objective of this program is to develop and verify the methodology necessary to improve the resistance of thermal barrier coating systems to spallation during aircraft gas turbine engine operation. The program focuses on increasing thermal barrier coating strain tolerance and thus life through innovative improvements in coating chemistry, processing, process control and through procedures other than plasma spraying such as electron beam vapor deposition of ceramics. Specifically, two strain tolerant thermal barrier coating systems selected from cyclic thermal oxidation and hot corrosion tests of a large number of candidate strain tolerant coatings will be evaluated through engine testing to verify the potential durability of strain tolerant ceramic coatings in advanced turbine applications.

To accomplish these objectives, a four task technical effort is being performed:

- Task I - Sixteen experimental thermal barrier coating systems based on structural concepts which have been shown to increase the strain tolerance of ceramic coatings will be deposited on test specimens and subjected to burner rig screening tests. Based on the ranking tests and post test evaluation, four coating/process systems will be selected, subject to NASA Project Manager approval, for further improvement and evaluation in Task II.

- Task II - A system improvement study will be conducted for the four systems selected in Task I and four variations of each coating/process combination will be selected for burner rig testing subject to the approval of the NASA Project Manager. Burner rig testing of specimens coated with the selected coating/process systems will again be performed and evaluated as in Task I. Based on the post-test evaluation results, four coating/process system will be selected subject to NASA Project Manager approval, for further improvement and evaluation in Task III. Three specimens will be coated with each selected system and delivered to NASA-Lewis within 30 days after the evaluation of Task II results are completed.

- Task III - The four coatings selected in Task III will be subjected to cyclic oxidation exposure and to cyclic hot corrosion exposure. Post-test evaluation will be as in Tasks I and II. Two coating/process systems will be selected, subject to the approval of the NASA Project Manager, for evaluation in Task IV.

DISCUSSION

The first three tasks have been completed and results are reported in NASA-CR-168251. Task IV, described below, currently is in progress.

- o Task IV - The two candidate optimized coating/process systems selected in Task III will be evaluated to determine thermal conductivity, coefficient of thermal expansion and resistance to spalling during high cycle fatigue life of the turbine alloy substrate material. In addition, each of the selected coating systems will be applied to first stage turbine blades and subjected to endurance testing and evaluation in a ground based test engine. Results of these tasks will lead to selection of an optimized strain tolerent thermal barrier coating system for advanced turbine application.

This informal report presents results of property measurements on the two candidate optimized coating systems. Engine evaluation currently is awaiting the availability of a suitable test engine.

Two candidate optimized 6 w/o Y_2O_3-ZrO_2 coating/process systems selected in Task III were evaluated to determine ceramic thermal conductivity and coefficient of thermal expansion and the resistance of each of the coating systems to room temperature high cycle fatigue induced spallation.

Thermal conductivity and thermal expansion were measured on bulk ceramic test specimens fabricated by plasma spray using deposition parameters identical to those used to fabricate the corresponding thin ceramic coatings. Photomicrographs obtained by metallographic examination of representative bulk specimens are shown in Figures 1 and 2. These structures are similar to those found in the respective thin coatings, as shown by comparison of Figures 1 and 2 with Figures 5-1 and 5-2 of CR-168251. The primary difference between system 3 and 8 is in the openness of the structure. Porosity in System 8 is larger and more heterogeneously distributed and appears to be linked by a larger and more open microcrack network. The influence of this structural difference on properties is discussed below.

As deposited specimens were machined to the configurations shown respectively in Figures 3 and 4 for conductivity and expansion testing. Testing was conducted at Dynatech R/D Company using the comparative method to measure 950°C (1742°F) thermal conductivity and an electronic automatic recording dilatometer to measure thermal expansion up to 1300°C (2372°F). Tests were conducted on duplicate specimens of each system.

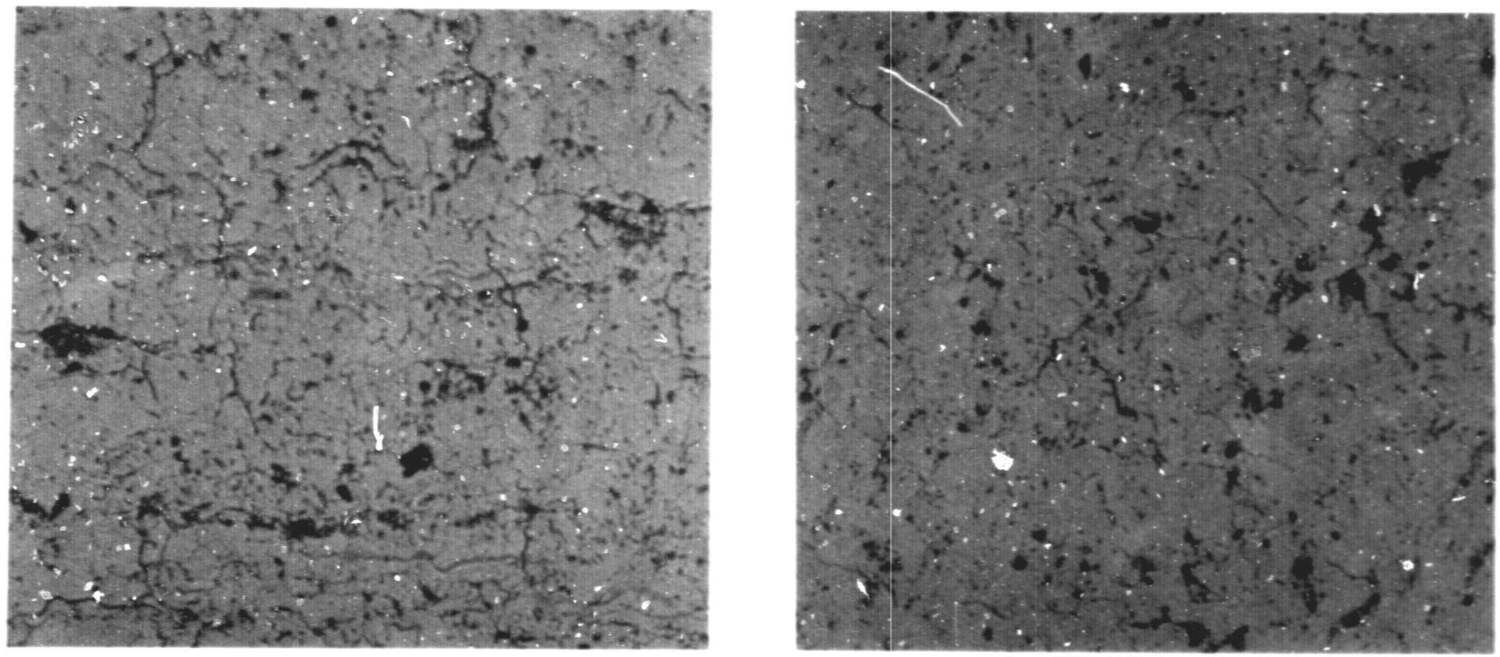
Results of thermal conductivity and expansion measurements are shown in Tables I and II, respectively. While there is little difference of expansion coefficient between the two systems, thermal conductivity values are significantly different, with the conductivity of System 8 being almost twice that of System 3. This difference is not fully understood. Conventional wisdom would suggest that the more open System 8 structure would be a better insulator due to "dead air space" entrapped on the ceramic. Apparently, however, the higher degree of connectedness in this structure provides a preferred path for transport of thermal energy at elevated temperature. Regardless of the explanation, these results indicate that System 3 will be a better insulator on turbine components than System 8.

Results of room temperature high cycle fatigue (HCF) tests conducted on thermal barrier coated specimens show both coating systems to possess excellent resistance to HCF spalling (Table III). The specimen used for these tests is shown in Figure 5. The substrate was B1900 + Hf nickel base superalloy. Axially loaded fatigue tests were conducted at various stress levels with an R ratio of -1. As noted in Table III, no ceramic spallation was observed on any of the ten specimens tested, some of which accumulated over ten million applied strain cycles. Typical photographs of specimens which failed in fatigue with no coating loss are shown in Figures 6 and 7.

CONCLUSIONS

- The thermal conductivity and expansion coefficients of coating Systems 3 and 8 have been measured. Coating System 8 exhibits a conductivity approximately twice that of System 3; expansion coefficients of the two systems are approximately equivalent.

- Room temperature high cycle fatigue resistance of both coating systems is outstanding, with specimens surviving as many as ten million fully reversed stress cycles with no coating spallation.



a) Thermal Conductivity Specimen

b) Thermal Expansion Specimen

Figure 1 Microstructure found in bulk ceramic specimens fabricated to simulate the thin ceramic structure of coating system 3. Magnification: 250X.

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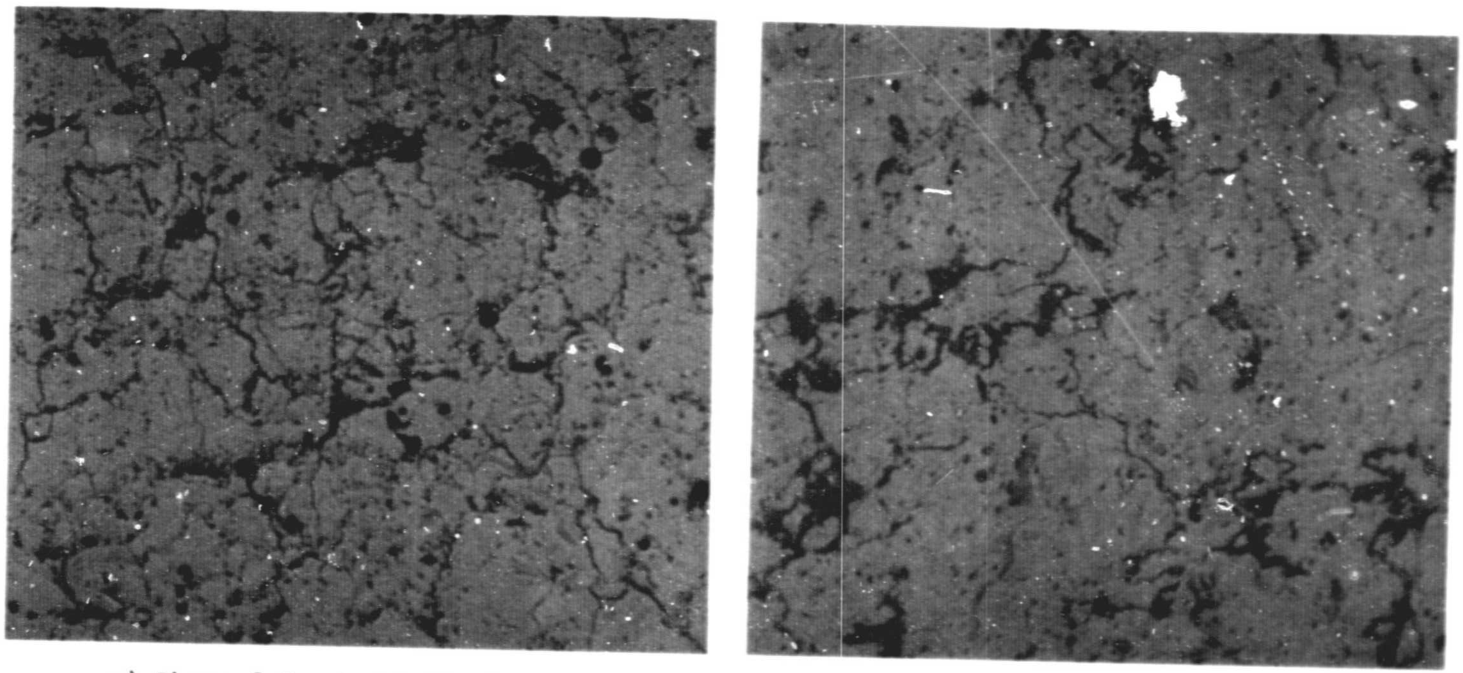

a) Thermal Conductivity Specimen

b) Thermal Expansion Specimen

Figure 2 Microstructure found in bulk ceramic specimens fabricated to simulate the thin ceramic structure of coating system 8. Magnification: 250X.

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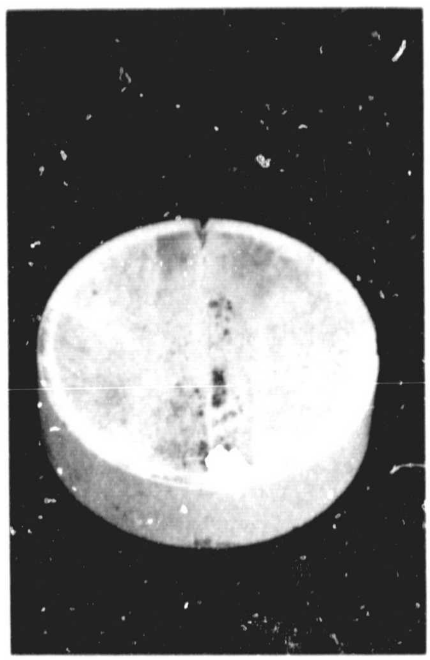

Figure 3 Photograph of thermal conductivity specimen. Specimen dimensions are 2.5 cm. diameter and .8 cm. thick (1.0 in. diameter by 0.3 in. thick). Wire leads, barely visible at the top of the photo, are for the measurement of thermal conductivity through the thickness of the specimen. Magnification: 1.75X

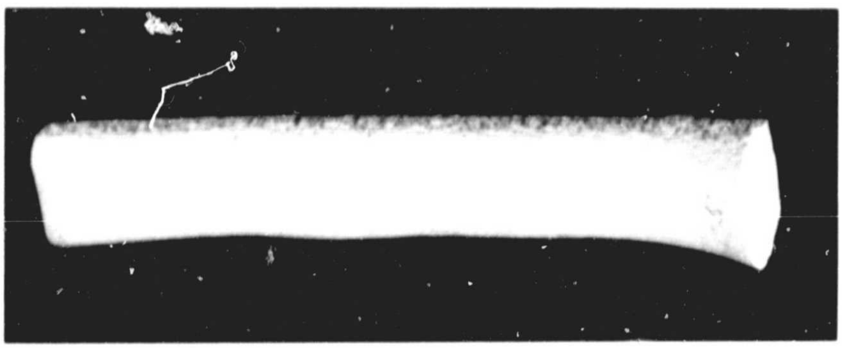

Figure 4 Photograph of thermal expansion specimen. Dimensions are approximately 0.5 by 0.5 by 4.8 cms. (0.2 by 0.2 by 1.9 in.). Magnification: 2X.

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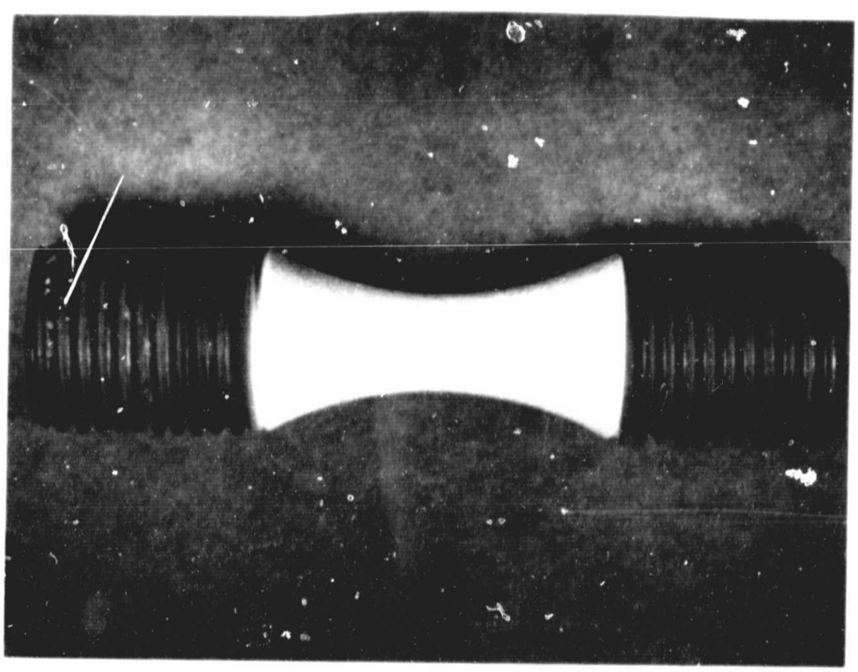

Figure 5 Photograph of thermal barrier coated high cycle fatigue specimen. Magnification: 1.9X.

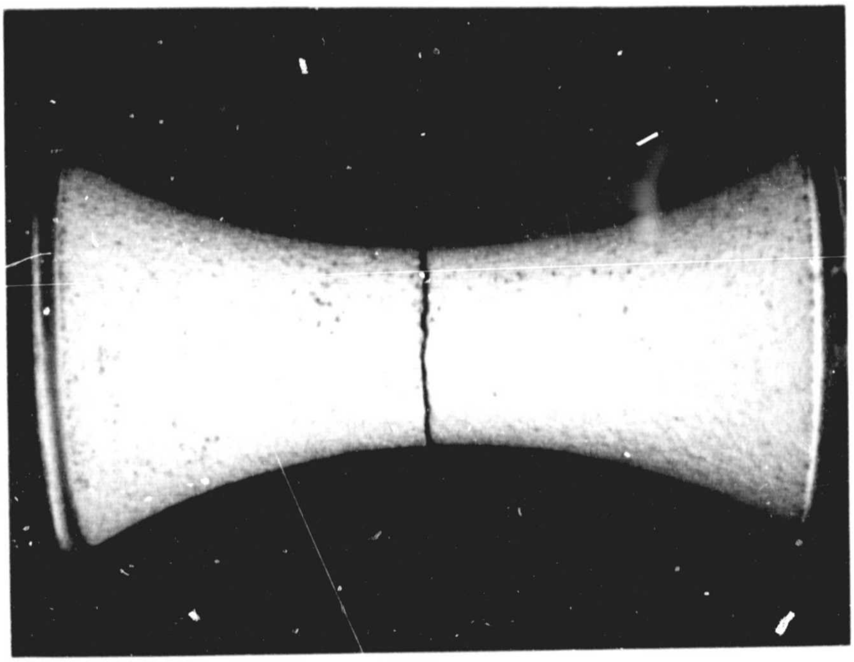

Figure 6 Photograph showing the excellent condition of ceramic thermal barrier coating system 3 on a high cycle fatigue specimen which failed after 1,006,300 cycles at $\pm$ 262 MPa ($\pm$ 38 ksi). Magnification: 3.8X.

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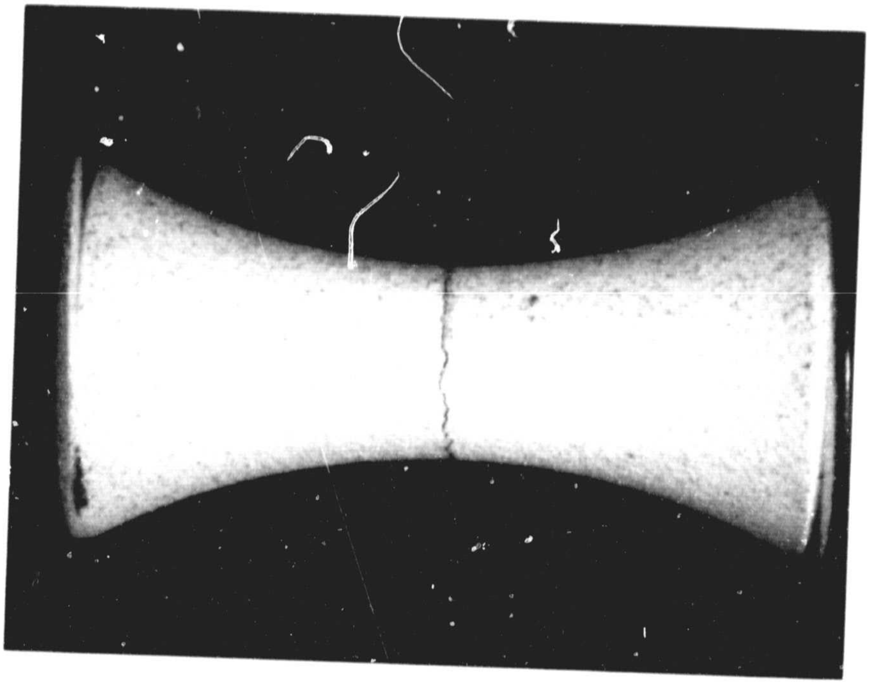

Figure 7 Photograph showing the excellent condition of ceramic thermal barrier coating system 8 on a high cycle fatigue specimen which failed after 2,383,100 cycles at $\pm$ 262 MPa ($\pm$ 38 ksi). Magnification: 3.8X.

TABLE I

RESULTS OF 950°C (1742°F) THERMAL CONDUCTIVITY MEASUREMENTS

Specimen	Thermal Conductivity W/mK	Thermal Conductivity Btu in/hr ft^2 °F
Baseline Coating System 3	0.82	5.69
2.5 cm (1 inch) Gun-To-Specimen Distance Coating System 8	1.53	10.61

TABLE II

THERMAL EXPANSION MEASUREMENTS

Temperature °C	Temperature °F	Thermal Expansion in L/L_0 x 100 (%): 2.5 cm (1 inch) Gun distance Coating System 8	Thermal Expansion in L/L_0 x 100 (%): Baseline Coating System 3
24	75	0	0
100	212	0.0506	0.0511
200	392	0.165	0.150
300	572	0.282	0.258
400	752	0.372	0.358
500	932	0.446	0.454
600	1112	0.527	0.547
700	1292	0.621	0.647
800	1472	0.725	0.754
900	1652	0.837	0.862
1000	1832	0.949	0.982
1100	2012	1.060	1.099
1200	2192	1.175	1.216
1300	2372	1.271	1.322

TABLE III

ROOM TEMPERATURE HIGH CYCLE FATIGUE TEST RESULTS

Specimen Number	Coating System	Stress MPa (KSI)	Cycles to Substrate Fatigue Failure	Comments
1	3	262 (38)	301,000	No coating failure
2	3	262 (38)	1,006,300	No coating failure
3	3	234 (34)	10^7	No coating failure
4	3	241 (35)	717,000	No coating failure
7	3	234 (34)	6,341,000	No coating failure
8	8	262 (38)	4,504,400	Failed in threads No coating failure
10	8	262 (38)	2,383,100	No coating failure
11	8	234 (34)	10^7	Specimen did not fail No coating failure
12	8	241 (35)	10^7	Specimen did not fail No coating failure
13	8	234 (34)	10^7	Specimen did not fail No Coating failure