NASA
TP
1322
c.1

NASA Technical Paper 1322

LOAN COPY: RETURN
AFWL TECHNICAL LIB
KIRTLAND AFB, N.
0134424
TECH LIBRARY KAFB, NM

Low-Cycle Fatigue of Thermal-Barrier Coatings at 982° C

Albert Kaufman, Curt H. Liebert,
and Alfred J. Nachtigall

DECEMBER 1978

NASA

TECH LIBRARY KAFB, NM

0134424

NASA Technical Paper 1322

Low-Cycle Fatigue of Thermal-Barrier Coatings at 982° C

Albert Kaufman, Curt H. Liebert,
and Alfred J. Nachtigall
Lewis Research Center
Cleveland, Ohio

NASA

National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1978

SUMMARY

Low-cycle fatigue lives of thermal-barrier coatings applied to TAZ-8A strips were investigated by means of cyclic flexural tests at 982° C in air and compared to those of uncoated TAZ-8A. Nonlinear, three-dimensional stress-strain analyses were performed to calibrate the imposed test specimen displacements against calculated strains in the various coating layers.

Three coating systems were studied: a single-layer NiCrAlY (Ni-16Cr-6Al-0.5Y, in wt %) coating, a two-layer ZrO_2-NiCrAlY coating, and a three-layer Al_2O_3-ZrO_2-NiCrAlY coating. The ZrO_2 was stabilized with nominally 12 weight percent of yttria. Fatigue curves of strain range against cycles to failure were constructed from the cyclic test and stress analysis results for the ZrO_2 and Al_2O_3 layers and for the uncoated and NiCrAlY-coated TAZ-8A. Failed specimens for each of the three coating systems and uncoated TAZ-8A were metallographically inspected to determine the sources of crack initiation, fracture mechanism, material microstructure, and uniformity of coating application. Additional stress-strain analyses were performed for the two-layer ZrO_2-NiCrAlY-coated specimens to evaluate the effects on the strain levels in the coating layers of different assumed coating to metal bonding temperatures.

The results show that the low-cycle fatigue lives of the ZrO_2 coatings applied to the TAZ-8A strips were about four times greater than those of the uncoated and NiCrAlY-coated TAZ-8A alloy. Furthermore, at temperatures up to the melting point of the TAZ-8A, the resistance of the ZrO_2 to low-cycle fatigue was expected to exhibit little or no deterioration. The results also indicate that adding an outer layer of Al_2O_3 to the two-layer thermal-barrier coating was neither beneficial nor detrimental to the coating fatigue strength of ZrO_2. Analyses of the effect on strains in the zirconia of increasing the bonding temperature showed that the mean strain levels decreased but the multiaxial component strain ranges were not changed.

INTRODUCTION

Ceramic thermal-barrier coatings have shown promise in reducing the metal temperatures of cooled turbine blades in tests on a research gas turbine engine at the NASA Lewis Research Center (ref. 1). A two-layer coating system was plasma sprayed on the blades. This system consisted of a NiCrAlY (Ni-16Cr-6Al-0.5Y, in wt %) bond coat initially applied to the metal substrate followed by an outer coat of nominally 12 weight percent yttria-stabilized zirconia. No significant deterioration to the coatings was observed after 500 engine cycles between turbine inlet gas temperatures of 1371° and 727° C at a gas pressure of 3 atmospheres. However, in more advanced engines with higher gas pressure levels and heat fluxes, the temperature levels and gradients in the coatings would be much higher. The high thermal strains that would be imposed on the coatings under these conditions, combined with the relatively low strength and ductility reported in the literature (ref. 2) for zirconia, cause some concern as to the low-cycle fatigue capability of the thermal-barrier coatings.

The primary purpose of this study was to investigate the low-cycle fatigue lives at elevated temperatures of the zirconia thermal-barrier coating. A secondary purpose was to investigate the low-cycle fatigue strength of an aluminum oxide coating which is being considered as an outer coat to the zirconia to provide increased surface hardness and erosion resistance.

Two methods for low-cycle fatigue testing of thin-wall specimens are employed at the NASA Lewis Research Center. One method involves axial strain cycling of tubular specimens with controlled diametral strains (ref. 3). This method was not applicable to testing specimens with thermal-barrier coatings because the coating could not be applied to the internal surface of the specimen where failure would be initiated. A second method that has been successfully used to determine low-cycle fatigue properties of superalloy materials is to conduct cyclic flexural tests of thin-sheet metal strips (ref. 4). In these tests, the U-shaped specimens are self-resistance heated and strain cycled by applying displacements at the ends. Because the thermal-barrier coatings could be applied easily to the surfaces of the test section of the specimens, the cyclic flexure method was used for low-cycle fatigue testing in this program.

TAZ-8A was selected as the base material because it was a material of blade superalloy quality which was available in sheet (thin section) form. Three types of coating systems applied to the surfaces of the TAZ-8A base material were studied: (1) a NiCrAlY bond coat, which was considered equivalent to an advanced coating of a conventional type and was used as a basis of comparison for the thermal-barrier-coated specimens; (2) a two-layer NiCrAlY-ZrO_2 thermal-barrier coating as was used for the blades of reference 1; and (3) a three-layer NiCrAlY-ZrO_2-Al_2O_3 thermal-barrier coating. The coating layers were applied symmetrically to both sides of the TAZ-8A sheet metal strips. In addition, a pair of uncoated TAZ-8A specimens was tested. Cyclic flexure testing was conducted in air at a specimen metal temperature of 982° C, which was about the highest temperature practicable for the TAZ-8A material.

Stress-strain analyses were performed for the uncoated and coated test specimens using a three-dimensional, nonlinear, finite-element computer program in order to construct strain-displacement calibration curves from which the imposed displacements could be related to strain ranges. The low-cycle fatigue lives were correlated with the computed strain ranges and comparisons were made for the three coating systems. Analyses were also performed to evaluate the effects of bonding temperature (coating to metal surface joining temperature) on the specimen strain levels.

EXPERIMENTAL APPARATUS AND PROCEDURE

Test Specimen

The geometry of the flexural test specimen is shown in figure 1. The base material was TAZ-8A, a nickel-base superalloy developed for turbine blades by NASA Lewis Research Center. A sheet of the alloy was hot rolled from an initial cast thickness of 2.79 to 1.02 millimeters and then ground to a final thickness of 0.84 millimeter. The specimen was machined from the TAZ-8A sheet so that the loading direction would be parallel to the sheet rolling direction and then formed to a 38-millimeter-semicircular arc. The ends of the specimen were straightened slightly to permit clamping. The surfaces of the specimens to be coated were cleaned and roughened after forming by grit blasting with alumina.

Coating Systems

Three coating systems were investigated: a single-layer NiCrAlY (Ni-16Cr-6Al-0.5Y, in wt %) coating, a two-layer NiCrAlY-ZrO_2 coating, and a three-layer NiCrAlY-ZrO_2-Al_2O_3 coating. The ZrO_2 was stabilized with nominally 12 weight percent of yttria. The results for the thermal-barrier coatings were compared against results for a NiCrAlY coating system which is representative of conventional coatings.

All coatings were applied with a hand-operated plasma-spray gun. The coatings were applied at a gun standoff distance of 11 to 15 centimeters for the NiCrAlY and 5 to 10 centimeters for the stabilized zirconia and alumina. Argon was used as the plasma gas. Measurements with a spot radiometer indicated that the metal surface temperature during the zirconia plasma spraying was about 427° C ± 3 percent; this bonding temperature affects the residual stresses and, therefore, has to be taken into account in the stress analyses of the thermal-barrier-coated specimens. Further details of the spraying process are given in reference 1. The effects of variations in bonding temperature will be discussed later.

A NiCrAlY bond coating was applied to a nominal thickness of 0.08 millimeter to all surfaces and edges of each specimen. One group was then set aside. A ZrO_2 coating was applied to a nominal thickness of 0.20 millimeter to all surfaces and edges of the remaining specimens. A second group was then set aside. Al_2O_3 was plasma sprayed to a depth of approximately 0.05 millimeter on the surfaces and edges of the specimens in the remaining group.

Cyclic Test Apparatus

An electrohydraulic servocontrolled fatigue testing machine using resistance heating of the specimens was used to perform the cyclic tests. This equipment is illustrated in figure 2 and is described in detail in references 3 and 4.

The ends of the test specimen were clamped to the ends of loading rods directly over the water-cooled electrical connectors supplying current for resistance heating of the specimen. The surface temperature of the specimen test section was measured with a disappearing-filament optical pyrometer focused on the midsection failure location (section A-A in fig. 1). This temperature was controlled by a closed-loop system employing feedback from a Chromel-Alumel thermocouple spot welded to the convex surface of the specimen near the gripped end where the strains would be small. The set point of the closed-loop controller was adjusted to obtain the desired surface temperature at the test section of the specimen as observed and measured through the optical pyrometer.

Cyclic displacements were applied through the lower platen of the machine while the upper platen remained stationary. The imposed vertical displacements were monitored by a dial gage. The cycling was conducted under closed-loop displacement control using a linear variable differential transformer as the platen displacement sensor.

Testing Procedure

After installation in the machine, the specimen was resistance heated until a temperature of 982° C was obtained in the TAZ-8A base material under the coating. This metal temperature was selected as being the highest practicable for the TAZ-8A base material and the NiCrAlY bond coat. For each coating system, the required surface temperature to obtain a metal temperature under the coating of 982° C was determined with an expendable specimen not used for testing. For each of these three specimens a small area of coating was removed on the concave midsection side of the test section so that a thermocouple could be spot welded to the bare metal and the temperature of the metal under the coating could be measured. The convex surface temperature for each coating system was observed and measured with the optical pyrometer when the thermocouple indicated a temperature of 982° C. The measured coating surface temperature for each coating system was 982°, 930°, and 916° C for the NiCrAlY, NiCrAlY-ZrO_2, and NiCrAlY-ZrO_2-Al_2O_3 systems, respectively. The resulting temperature gradients through the specimen thickness and the estimated maximum measurement error of 36° C are too small to have a significant effect on either the experimental or analytical results.

The desired alternating displacements were imposed in a triangular waveform with a zero mean value about the initial platen position. Cyclic testing was conducted in an air atmosphere until the machine shut off when the specimen failed and the electrical circuit was broken. All failures occurred at the specimen midsection (section A-A, fig. 1) and were usually initiated on the concave surface. The imposed displacement range and the number of cycles to total failure were recorded for each specimen.

THEORETICAL ANALYSIS

Stress and strain distributions and end displacements for the flexural specimens under various applied mechanical loads were calculated using the MARC nonlinear, finite-element, structural analysis program. The program capabilities, which include plasticity, are described in reference 5. Computations are based on incremental plasticity theory using the von Mises yield criterion (ref. 6). Three-dimensional, 20-node isoparametric elements were used to model the specimens. A three-dimensional model of a coated specimen with a two-layer coating system on each surface of the base metal is shown in figure 3; since this specimen is symmetrical about its midcenter, only half the specimen (an arc of a quarter of a circle) had to be analyzed.

Material properties for the stress analysis (table I) were obtained from reference 7 for the TAZ-8A alloy and from reference 8 for plasma-sprayed ZrO_2. Inconel alloy 702 properties from reference 9 were assumed for the NiCrAlY bond coat since the alloy has approximately the same nickel, chromium, and aluminum composition as the coating. At 982° C, both the NiCrAlY and Inconel alloy 702 would have little inherent strength and would simply act as a buffer to match the displacements between the zirconia and base materials in the thermal-barrier coated specimens.

The stress analysis results were used to construct effective strain range - vertical displacement range calibration curves for both uncoated TAZ-8A and the two-layer NiCrAlY-ZrO_2-coated flexural specimens. From these calibration curves and the cyclic test results, the effect of strain range on the number of cycles to failure could be determined. Since the coated specimens were composite structures with multiaxial loading, the calibrations were based on von Mises effective strains rather than the maximum normal strains.

Stress analyses were also performed for the single-layer NiCrAlY-coated specimen; however, these analyses were not used in this study as the coating is of little structural value and the stresses in the base material were not appreciably different from the analytical results for the uncoated specimens. Stress analyses were not performed for the three-layer coating system because the matrix bandwidth would have been too large for the core storage available on the Univac 1110 computer. All the analytical cases were run in double precision to reduce roundoff errors since the elements composing the NiCrAlY coating had an unavoidably large aspect ratio. Stress and strain values were calculated at 27 Gaussian integration points in each element; coating surface strains presented herein were actually calculated at stations inside the coating at a depth of about 11 percent of the coating thickness.

A parameter for the analyses of the thermal-barrier-coated specimens is the stress-free reference temperature. This temperature was assumed to be uniform through the specimen thickness and to be equal to the coating to metal bonding temperature. At any other temperature at which the specimens are tested, the differences in thermal expansion coefficients and elastic moduli between the ceramic and metal parts create residual stresses which have to be taken into account.

RESULTS AND DISCUSSION

Cyclic Flexure Test Results

The cyclic test results for TAZ-8A flexural specimens without coatings and with the three coating systems considered in this investigation are summarized in table II in terms of the vertical displacement ranges and cycles to failure. All but one of the specimens were cycled about a zero mean displacement so that, for example, a total displacement range of 2.54 millimeters means that the displacement of the end attached to the moving platen varied from +1.27 to -1.27 millimeters. The exception was a two-layer thermal-barrier-coated specimen which was cycled between 0 and 2.54 millimeters with a mean displacement of 1.27 millimeters in order to evaluate the effect of mean strain level on cyclic life; the results (11 584 cycles against 12 886 cycles for the comparable test with 0 mm mean displacement) indicate that these specimens undergo sufficient plastic flow, especially in the NiCrAlY, so that initial differences in mean strain level do not significantly affect the cyclic lives.

In order to interpret the relative fatigue strengths of the different types of specimens, the displacement ranges presented in table II have to be converted to strain ranges for the failure location which usually occurs on the concave surface at midcenter. The strain in the loading direction for the uncoated specimens can be calculated from formulas given in reference 10, and the strains in the coated specimens for the same displacements can be approximated by making a ratio of the specimen thicknesses. However, this procedure neglects the multiaxial effects introduced by constrained plastic flow and leads to unrealistically high fatigue resistance for the zirconia. Therefore, the strain calibrations were based on curves of effective strains as functions of vertical displacements from the stress-strain analysis results for the thermal-barrier-coated specimens.

Stress-Strain Analysis Results

Results of the stress-strain analyses of the uncoated and thermal-barrier-coated specimens are shown in figure 4. Effective stress and strain ranges at midsection for calculational locations 0.02 and 0.09 millimeter below the concave surfaces in the zirconia layer and the TAZ-8A base material, respectively, are plotted against the vertical displacement range at the specimen ends.

In figure 4(a), the stresses calculated from the finite-element stress analysis are compared to predicted stresses from reference 10 for an uncoated flexural specimen. Good agreement between the two analytical solutions is shown in the elastic range. Because the results from reference 10 are only applicable to an elastic case, agreement between the two curves becomes worse as the displacement increases because of plastic flow. The strain range as a function of displacement range curve of figure 4(a) was also used to determine the strains in the single-layer NiCrAlY specimens since the NiCrAlY has relatively minor structural strength at 982° C.

Stress analysis results are shown in figure 4(b) for NiCrAlY-ZrO_2-coated flexural specimens at a stress-free reference temperature of 982° C. A reference temperature of 982° C represents the condition where the bonding and test temperatures are identical and no residual thermal strain would occur. The reasons for using 982° C as the reference temperature rather than the approximate measured bonding temperature of 427° C are discussed in the next section.

Analysis of Coating Bonding Temperature

Bonding temperature effects on the strains in the zirconia coat of a two-layer thermal-barrier-coated specimen are presented in figure 5. The calculations were based on a specimen subjected to a maximum displacement of +1.42 millimeters and a minimum displacement of -1.42 millimeters at 982° C. Normal strains computed slightly below the midsection concave surface are compared for assumed bonding temperatures of 427° and 982° C.

The results show that, for the three normal strain components, the strain ranges remain constant but the mean strain levels decrease with increasing bonding temperature; similar results were obtained for the three shear strain components. The decrease in mean strain level with increased bonding temperature is due to the greater compressive residual stresses induced in the zirconia because of its lower coefficient of thermal expansion compared to the metal.

The tensile mean strains associated with the 427° C reference temperature will result in tensile mean stresses relative to the 982° C reference temperature condition. However, under repeated cycling there will be a tendency for the mean stresses associated to the mean strains to relax toward zero. This conclusion is supported by the experimental results shown in table II for the NiCrAlY-ZrO_2-coated specimens in the 11 000 to 13 000 cyclic life range; these results demonstrated that the low-cycle fatigue life for this coating system was not sensitive to mean strain level. Fatigue life is probably also insensitive to the mean strain differences between the 427° and 982° C reference temperatures; this assumption is made in the ASME pressure vessel code (ref. 11) where fatigue damage is evaluated on the basis of equivalent strain range without any consideration of the mean strain level. Since the initial residual stresses and strains due to a bonding temperature of 427° C can be neglected, the computation of the effective strain range can be based on the strain analysis for the assumed stress-free 982° C bonding condition. Therefore, the strain-displacement curve for the zirconia coat in figure 4(b) was used to determine the effective strain range shown in table II for the NiCrAlY-ZrO_2 coating system.

No stress analyses were performed for the NiCrAlY-ZrO_2-Al_2O_3-coated specimens since this would be a prohibitively large problem which would have exceeded the storage capacity of the computing system. Strain values are not shown in table II for the uncoated and coated specimens with the largest imposed displacements because the strain levels were becoming so high that the ceramic would crack immediately and most of the experimentally determined cyclic lives would probably be due to crack propagation.

It would normally be expected that the crack propagation time in a ceramic would be negligible compared to the time to crack initiation. However, in a thermal barrier-coated structure it is possible that the ceramic undergoes microcracking with some of its load component being transferred to the base metal, thus slowing the crack propagation rate. This would explain the anomalies in references 12 and 13 which show calculated strains in thermal barrier coated turbine blades greatly in excess of the fracture strain data for zirconia.

Analysis of Experimental Results

The cyclic lives of the uncoated and NiCrAlY-coated TAZ-8A and the ZrO_2 coat are plotted against the calculated effective strain range based on a 982° C reference temperature in figure 6. These results show that the low-cycle fatigue life of the plasma-sprayed zirconia is about four times greater than the uncoated or NiCrAlY-coated TAZ-8A base material for the same strain range at the test temperature of 982° C. Furthermore, the fatigue characteristics of the zirconia will probably appear better relative to TAZ-8A or any other nickel-base superalloy at temperatures higher than 982° C. At a temperature of 1316° C, which is about the melting point of most turbine blade superalloys, the tensile strength of the zirconia is only slightly reduced compared to room temperature as shown in table I. The somewhat higher elongation at failure at 1316° C implies that the zirconia has greater fatigue resistance at 1316° C than at lower temperatures. The zirconia cyclic lives shown in figure 6 undoubtedly include an unknown proportion of crack propagation time. The ZrO_2 curve in figure 6 was not extended above a strain range level of 0.6 percent for the reasons discussed in the previous section.

Although effective strains were not computed for the three-layer coating system, the effect of adding an Al_2O_3 outer layer can be assessed from the Al_2O_3 material properties in table I (ref. 11) and the experimental results of table II. Based on the low fracture strains shown in table I, the Al_2O_3 coat must have cracked on the first cycle for all the Al_2O_3-coated specimens, and the cyclic lives represent crack propagation through the ZrO_2 and TAZ-8A. If the elongation data are assumed to be incorrect and are ignored, the strain in the Al_2O_3 coat can be estimated for a given displacement by multiplying the calculated zirconia strains in figure 4(b) by the ratio of the overall thicknesses of the three- and two-layer-coated specimens. The result for one Al_2O_3 data point shown in figure 6 falls on the ZrO_2 fatigue curve and indicates no apparent benefit or detriment in using an outer Al_2O_3 coat.

Metallographic Results

One failed specimen for each of the three coating systems and one of bare TAZ-8A were metallographically investigated. Photographs of the failure surfaces are shown in figure 7. The photomicrographs in figure 8 were taken at the specimen edges to exhibit coating and edge cracks.

The bare TAZ-8A (fig. 7(a)) shows cracking initiating from a number of sites along the concave surface. The cracking was transgranular up to the neutral axis where final fracture occurred. Other cracks initiating from both convex and concave surfaces are seen in figure 8(a).

The single-layer NiCrAlY-coated specimen (fig. 7(b)) exhibited crack initiation at the center of the concave surface. The fracture was transgranular through most of the failed section. Severe oxidation of the NiCrAlY layers is indicated in figure 8(b), particularly within the coating and along the metal interface. The fewer initiation sites seen in the NiCrAlY-coated specimen (figs. 7(b) and 8(b)) as compared to the bare TAZ-8A (figs. 7(a) and 8(a)) suggest that the cracking in the TAZ-8A substrate was initiated from cracks in the coating and that propagation was rapid in the substrate. It also appears that much of the NiCrAlY coating spalled off during the test.

The photographs of the fracture surfaces of the two-layer ($NiCrAlY+ZrO_2$) and the three-layer ($NiCrAlY+ZrO_2+Al_2O_3$) coated specimens (figs 7(c) and (d), respectively) show that the coating thicknesses around the specimen surfaces were significantly nonuniform and that transgranular fatigue failure tended to start from the side that had the thickest ceramic coating. Failure in the two-layer coated specimen (fig. 7(c)) was initiated on the concave surface at the edge where chipping occurred (upper right corner). Failure in the three-layer coated system (fig. 7(d)) was initiated at several sites along the convex surface where the ceramic layer was thickest. Both the two- and three-layer coating systems exhibited substantial oxidation of the NiCrAlY layer, as can be seen in figures 8(c) and (d).

SUMMARY OF RESULTS

Low cycle fatigue lives of thermal barrier coatings applied to TAZ-8A flexural specimens were determined from cyclic tests at 982° C in air. Nonlinear, three-dimensional, stress-strain analyses were performed in order to calibrate the imposed displacements against calculated strains in the coating layers. The results of this investigation can be summarized as follows:

1. The cyclic lives of the ZrO_2 coatings, including some crack propagation time, were about four times greater than those of the uncoated and NiCrAlY-coated TAZ-8A material at 982° C for the same strain ranges. Based on the material properties of ZrO_2, the low-cycle fatigue lives of ZrO_2 are expected to show little or no deterioration up to 1316° C, which is approximately the melting point of most turbine blade materials; therefore, ZrO_2 coatings should be even more beneficial at these very high temperatures.

2. The limited data indicated that the addition of the Al_2O_3 coating did nothing to improve or harm the coating fatigue life.

3. Cyclic life over a given displacement range was insensitive to the mean strain level for the conditions studied in this report. This indicates that, regardless of the coating to metal bonding temperature, the proper stress-free reference temperature to use for stress analysis of the thermal barrier coated specimens is the test temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 3, 1978,
505-04.

REFERENCES

1. Liebert, C. H.; and Stepka, F. S.: Ceramic Thermal-Barrier Coatings for Cooled Turbines. NASA TM X-73426, 1976.
2. Engineering Properties of Selected Ceramic Materials. The American Ceramic Society, 1966.
3. Hirschberg, M. H.: A Low Cycle Fatigue Testing Facility. Am. Soc. Test. Mater. Spec. Tech. Publ. (465), 1969, pp. 67-86.
4. Hirschberg, Marvin H.; Spera, David A.; and Klima, Stanley J.: Cyclic Creep and Fatigue of TD-NiCr, TD-Ni, and NiCr Sheet at 1200° C. NASA TN D-6649, 1972.
5. MARC-CDC Non-Linear Finite Element Analysis Program, Vol. I, User Information Manual. Publ. 17309500, Control Data Corp., 1977.
6. Kaufman, Albert; and Gaugler, Raymond E.: Cyclic Structural Analyses of Air-Cooled Gas Turbine Blades and Vanes. SAE Trans., vol. 85, Sept. 1977.
7. Fritz, L. J.; and Koster, W. P.: Tensile and Creep Rupture Properties of (16) Uncoated and (2) Coated Engineering Alloys at Elevated Temperatures. (Rept.-931-21300, Metcut Research Associates, Inc.; NASA Contract NAS3-18911.) NASA CR-135138, 1977.
8. Shiembob, L. T.: Development of a Plasma Sprayed Ceramic Gas Path Seal for High Pressure Turbine Applications. (PWA-5521, Pratt & Whitney Aircraft; NASA Contract NAS3-19759.) NASA CR-135183, 1977.
9. High Temperature High Strength Nickel Base Alloys. International Nickel Company, Inc., 1964.
10. Timoshenko, S.: Strength of Materials, Part I. Third ed., D. Van Nostrand Co., Inc., 1955.
11. ASME Boiler and Pressure Vessel Code, Class 1, Components in Elevated Temperature Service - Section III, Division 1. Case 1592-7, Dec. 1975.
12. Andress, D. E.: An Analytical Study of Thermal Barrier Coated First-Stage Turbine Blades in a F100 Engine. (PWA-FR-9609, Pratt & Whitney Aircraft; NASA Contract NAS3-21032.) NASA CR-135359, 1978.
13. Sevcik, W. R.; and Stoner, B. L.: An Analytical Study of Thermal Barrier Coated First Stage Blades in a JT9D Engine. (PWA-5590, Pratt & Whitney Aircraft; NASA Contract NAS3-21033.) NASA CR-135360, 1978.

TABLE I. - DESIGN PROPERTIES OF TAZ-84 AND COATING MATERIALS

Temperature, °C	Ultimate tensile strength, MN/m^2	Yield strength (0.2 percent offset), MN/m^2	Modulus of elasticity, GN/m^2	Elongation of failure, percent	Mean coefficient of thermal expansion from 21° C, mm/m-°C
TAZ-8A					
21	996	818	207	3.8	12.4
850	848	743	174	3.0	----
925	650	515	148	4.4	15.3
1000	472	366	137	6.5	15.7
NiCrAlY					
21	1020	579	217	35	12.1
760	496	427	171	4	----
871	331	193	157	12	----
982	76	48	143	75	18.0
ZrO_2					
21	56	---	47	0.12	----
93	----	---	---	-----	7.6
982	----	---	---	-----	8.6
1316	51	---	16	.33	----
Al_2O_3					
21	262	---	393	0.07	----
587	----	---	---	-----	7.9
1093	234	---	310	.08	8.2
1316	41	---	221	-----	----

TABLE II. - CYCLIC FLEXURAL TEST RESULTS

Coating system	Vertical displacement range, mm	Calculated effective strain range, percent	Cycles to failure
Uncoated TAZ-8A	2.54	0.325	24 581
	7.62	-----	1 215
NiCrAlY	1.52	0.193	[a]>500 000
	2.54	.325	16 593
	5.08	.740	1 825
	7.62	-----	715
NiCrAlY+ZrO_2	1.52	0.322	95 570
	2.54	.578	12 886
	5.08	-----	824
	7.62	-----	958
	[b]2.54	.578	11 584
NiCrAlY+ZrO_2+Al_2O_3	2.54	[c]0.619	8 180
	5.08	-----	883
	7.62	-----	556

[a]Test stopped without specimen failing.

[b]Cycled about mean displacement of 1.27 mm. All other specimens were cycled about 0 mm mean displacement.

[c]Estimate based on thickness relationships between three- and two-layer coated specimens.

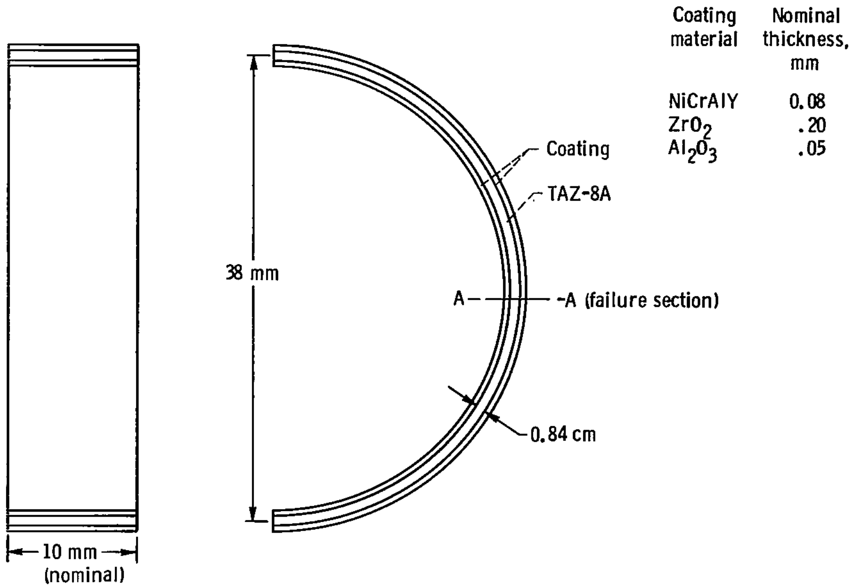


Figure 1. - Coated flexural test specimen geometry.

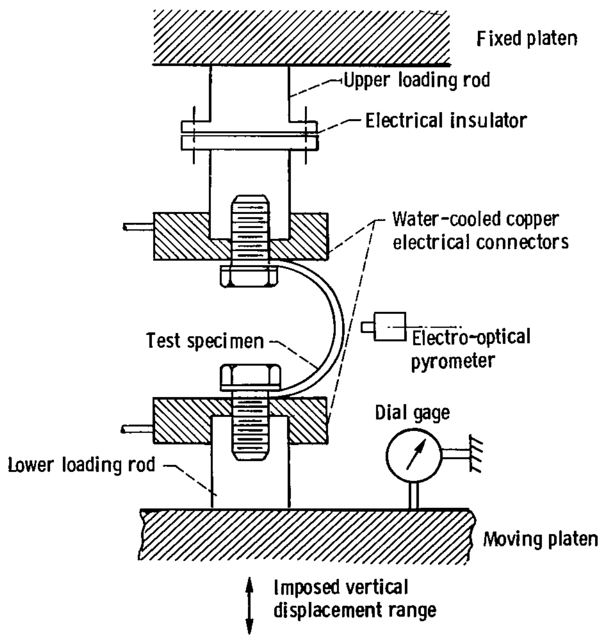


Figure 2. - Apparatus for strain cycling of resistance-heated flexural specimen.

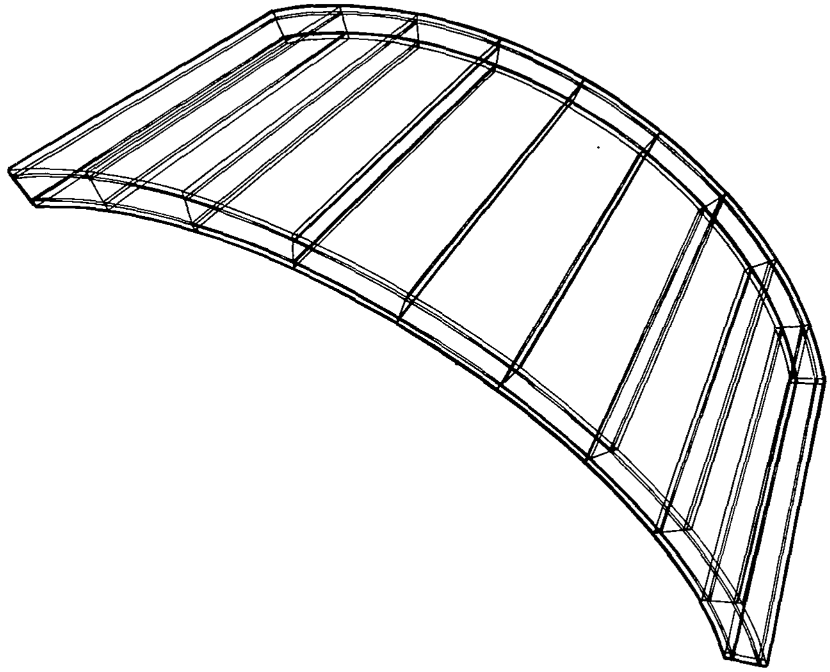
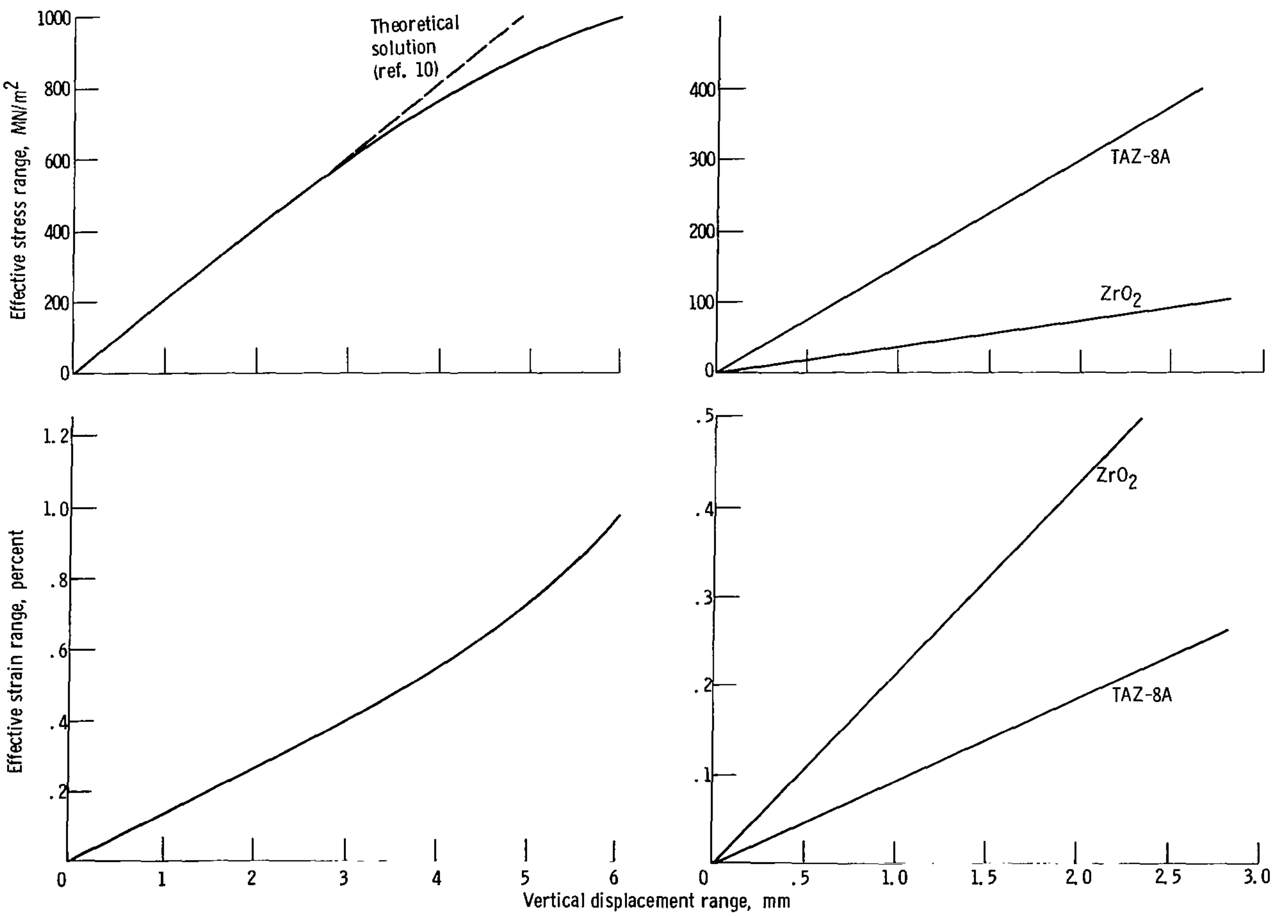


Figure 3. - Finite-element modeling for stress analysis of symmetrical half of coated flexure specimen.



(a) Uncoated. (b) NiCrAlY + ZrO_2 coating system (T_{ref} = 982° C).

Figure 4. - Stress analysis results for flexural specimens at 982° C.

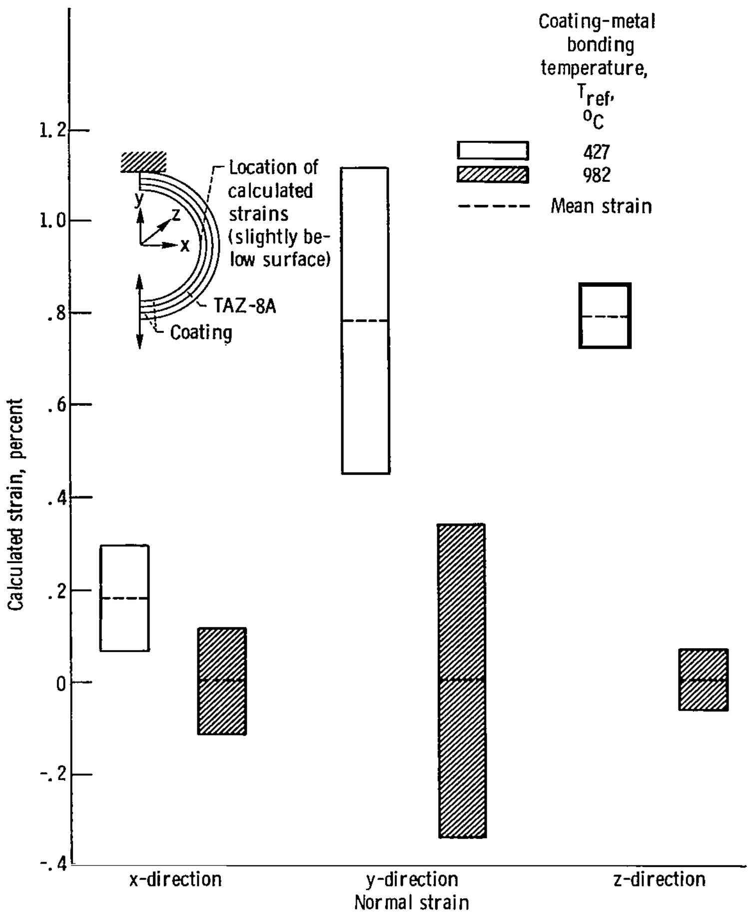


Figure 5. - Effect of bonding temperature on calculated strain levels and ranges in ZrO_2 (vertical displacement range, ±1.42 mm).

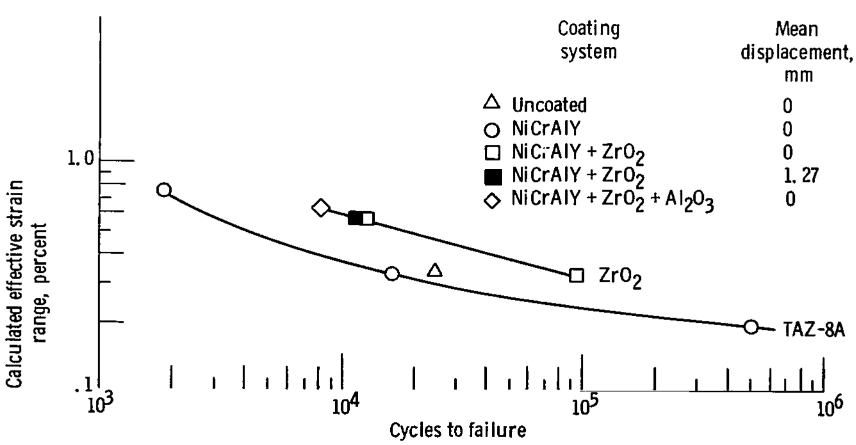
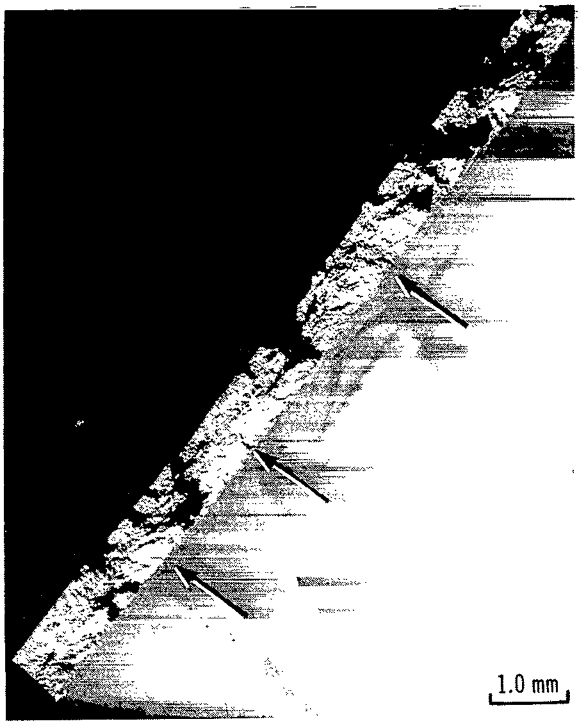
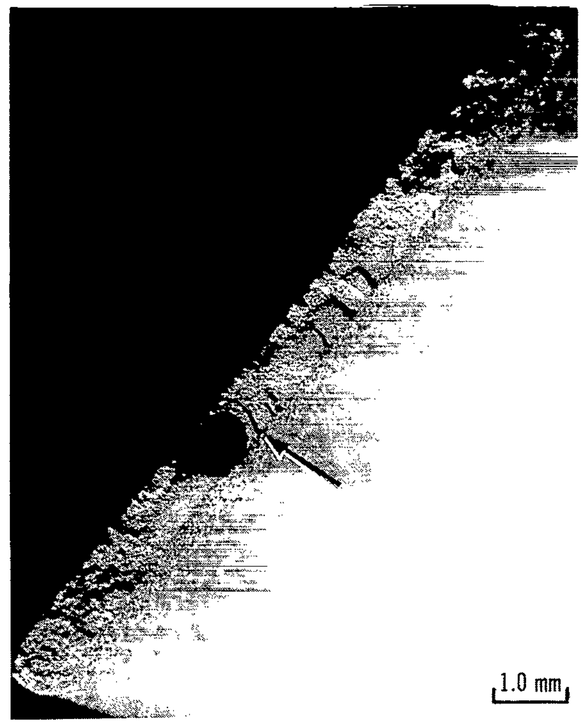


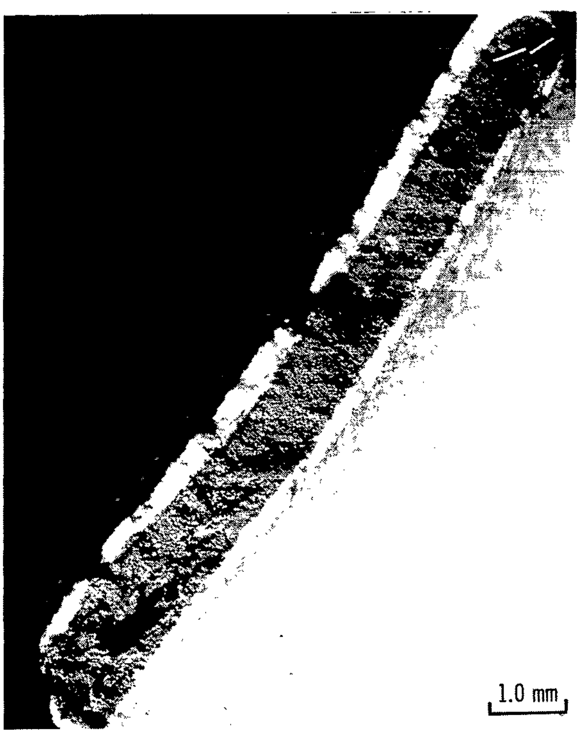
Figure 6. - Low-cycle fatigue characteristics at 982° C for TAZ-8A coated and uncoated flexure specimens.



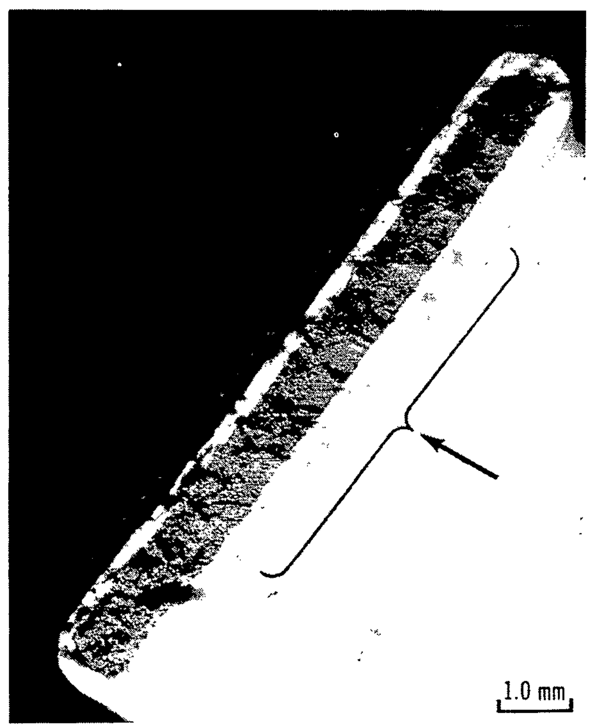
(a) Bare TAZ-8A.



(b) NiCrAlY-coated TAZ-8A.

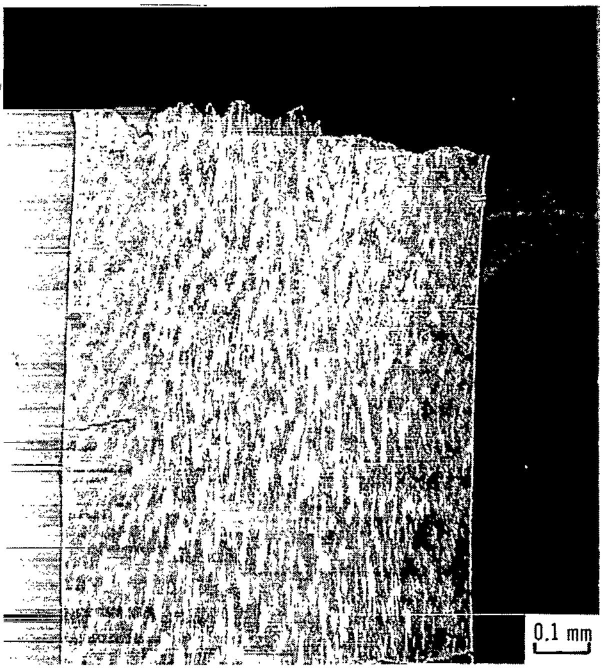


(c) NiCrAlY + ZrO_2 coated TAZ-8A.

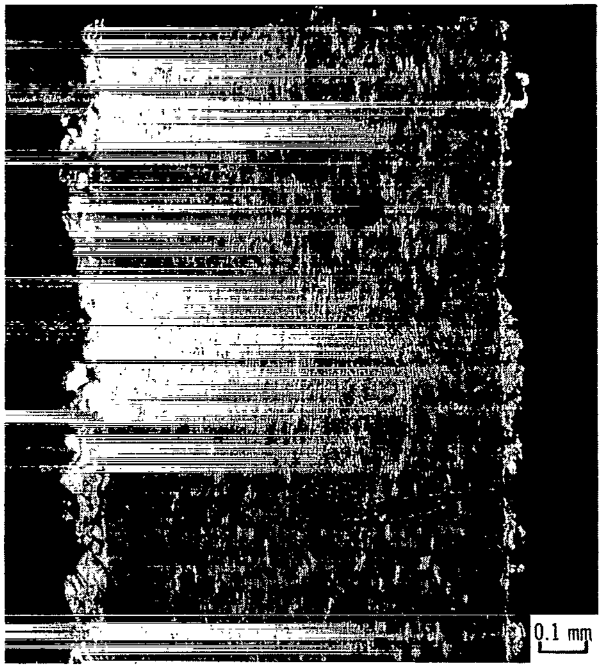


(d) NiCrAlY + ZrO_2 + Al_2O_3 coated TAZ-8A.

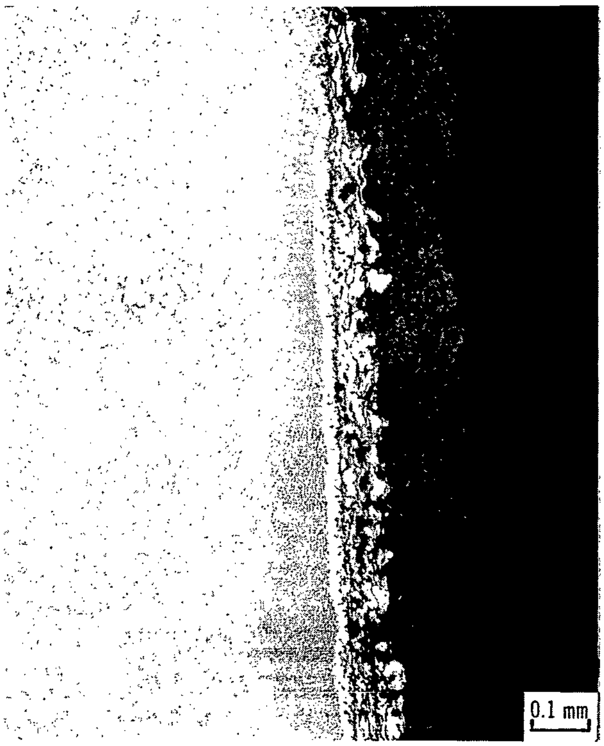
Figure 7. - Photographs of fracture surfaces of flexural fatigue specimens tested at 982° C in air. (Arrows indicate crack initiation sites.)



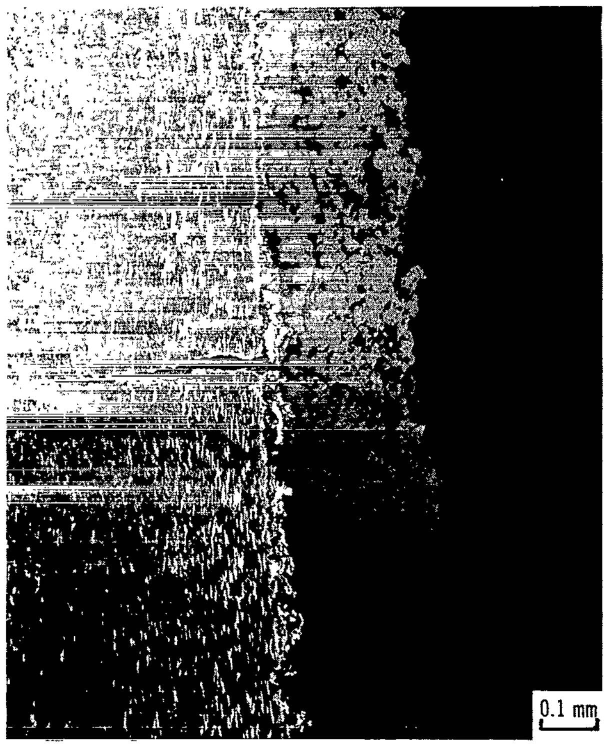
(a) Bare TAZ-8A.



(b) NiCrAlY-coated TAZ-8A.



(c) NiCrAlY + ZrO_2 coated TAZ-8A.



(d) NiCrAlY + ZrO_2 + Al_2O_3 coated TAZ-8A.

Figure 8. - Photomicrographs of edges of flexural fatigue specimens tested at 982° C in air.

1. Report No.
NASA TP-1322

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
LOW-CYCLE FATIGUE OF THERMAL-BARRIER COATINGS AT 982° C

5. Report Date
December 1978

6. Performing Organization Code

7. Author(s)
Albert Kaufman, Curt H. Liebert, and Alfred J. Nachtigall

8. Performing Organization Report No.
E-9688

10. Work Unit No.
505-04

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 Paper

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The low-cycle fatigue lives of ZrO_2-NiCrAlY and Al_2O_3-ZrO_2-NiCrAlY thermal-barrier coatings in air at 982° C were determined from cyclic flexural tests of coated TAZ-8A strips. Strains were computed as a function of specimen displacements from a nonlinear, three-dimensional stress analysis program. Fatigue resistances of thermal-barrier coatings applied to the strips were compared with those of uncoated and NiCrAlY-coated strips. The results indicate that ZrO_2 is about four times greater in fatigue life than TAZ-8A at 982° C, that ZrO_2 would probably retain that fatigue strength up to 1316° C, and that adding an outer coat of Al_2O_3 to ZrO_2 is neither beneficial nor detrimental to fatigue resistance.

17. Key Words (Suggested by Author(s))
Thermal barrier coatings
Low-cycle fatigue

18. Distribution Statement
Unclassified - unlimited
STAR Category 07

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
19

22. Price*
A02

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

NASA-Langley, 1978