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PRELIMINARY STUDY OF CYCLIC THERMAL SHOCK RESISTANCE OF PLASMA-SPRAYED ZIRCONIUM OXIDE TURBINE OUTER AIR SEAL SHROUDS

by Robert C. Bill
Propulsion Laboratory
U.S. Army R&T Laboratories (AVRADCOM)
Cleveland, Ohio 44135

and

Donald W. Wisander
Lewis Research Center
Cleveland, Ohio 44135

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Robert C. Bill and Donald W. Wisander

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U.S. Army R&T Laboratories (AVRADCOM)
Cleveland, Ohio 44135

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16. Abstract

Several experimental concepts representing potential high pressure turbine seal material systems were subjected to cyclic thermal shock exposures similar to those that might be encountered under severe engine start-up and shut-down sequences. All of the experimental concepts consisted of plasma-sprayed yttria stabilized ZrO_2 on the high temperature side of the blade tip seal shroud (outer air seal). Between the ZrO_2 and a cooled, dense metal backing, various intermediate layer concepts intended to mitigate thermal stresses were incorporated. Performance was judged on the basis of the number of thermal shock cycles required to cause loss of seal material through spallation. The most effective approach was to include a low modulus, sintered metal pad between the ZrO_2 and the metallic backing. It was also found that reducing the density of the ZrO_2 layer significantly improved the performance of specimens with plasma-sprayed metal/ceramic composite intermediate layers.

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INTRODUCTION

Gas turbine engine efficiencies are sensitive to the operating clearance between the tips of the turbine blades and the stationary gas path seal component over the blade tips. Studies have indicated that in high reaction turbine designs, approximately 3 percent turbine efficiency loss is suffered for each 1 percent increase in blade tip clearance to blade span ratio (ref. 1). In terms of fuel consumption, this is roughly equivalent to a savings of 2×10^6 BBl/yr in the commercial U.S. jet fleet for each reduction in turbine blade tip clearance of 1 percent that can be maintained.

Current state-of-the-art in turbine tip sealing technology is based on metallic material systems. Cast superalloy seal shroud segments, sintered or hot pressed powder metal shroud seals, and thermal sprayed metallic systems are employed in various turbine seal applications. To cope with the high turbine gas temperatures, these metallic systems require substantial amounts of cooling air with an associated engine efficiency penalty. Furthermore, these materials are prone to gradual clearance degradation through erosive and corrosive mechanisms.

An attractive alternate turbine sealing approach, especially considering the overall trend of increased turbine inlet temperatures in gas turbine technology, is to employ ceramic materials. As a class, ceramics retain their mechanical properties to significantly higher temperatures than metals, and, especially in the case of oxide ceramics, are chemically stable with

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*Propulsion Laboratory, U.S Army R&T Laboratories (AVRADCOM).

respect to the turbine operating environment. These considerations lead to improved turbine seal performance from the standpoints of both reduced cooling air requirements and the potential to maintain small turbine tip clearances.

In order for ceramics to survive turbine operating conditions, however, they must be able to withstand the thermal shock conditions imposed on them as the engine goes through its cycle of operation. Brittle as they are when compared to metals, care must be taken in the design of ceramic components to ensure that they not be subject to excessive tensile stresses. Some methods of controlling thermal stresses and improving cyclic thermal shock resistance of a plasma-sprayed ZrO_2 turbine seal system are explored experimentally in this paper.

All of the turbine seal system concepts evaluated included a thick plasma-sprayed ZrO_2 layer, a fully dense metal substrate, and various types of intermediate layers between the ZrO_2 and the substrate. The intermediate layers, depending on structure and composition, are characterized as belonging to one of two broad categories. Graded thermal expansion coefficient layers, prepared by plasma-spraying mixtures of metal and ceramic powders, mitigate thermal stresses by smoothing the thermal expansion mismatch between the ceramic layer and the metallic backing. The other type of intermediate layer concept evaluated was a low modulus thermal strain isolator, or cushion, composed of high porosity sintered metal. These concepts incorporated into the entire seal system, are shown schematically in figure 1.

An oxygen-acetylene torch system was employed as a test device, to heat the specimens which were alternately held directly in the torch flame, removed from the flame and subjected to a cooling air blast. In this way, severe thermal shocks similar to what would be imposed on the seal during sudden engine start-up - shut-down sequences were simulated. The various turbine seal system concepts were judged on the basis of the number of cycles required to cause spallation of material from the ceramic surface.

APPARATUS AND PROCEDURE

The cyclic thermal shock apparatus is shown in figure 2. An oxygen-acetylene torch provides the means of heating the specimen when it is in the "heat-up" position, with the flame impinging directly onto the ceramic surface at a 90° angle. While the ceramic surface is being heated, cooling air is directed onto the specimen backing. The flame is positioned and tuned so that during the heat-up phase the ceramic surface reaches a stable temperature of about 1260° C within one minute for all seal configurations. Total duration of the "heat-up" phase is $3\frac{1}{2}$ minutes. Cooling air flow to the backing is controlled to 9.0×10^{-4} M^3/sec (2 ft^3/min) for all specimens, with associated backing temperatures of 480° to 540° C, depending on specimen configuration. Ceramic surface temperatures are monitored by an infra-red pyrometer, and cross-checked by chromel alumel thermocouples embedded in a few special calibration specimens. Temperatures at other locations in the seal and on the metallic backing are indicated by chromel-alumel thermocouples in all specimens.

After being held in the flame for $3\frac{1}{2}$ minutes, the specimen is moved by means of the pneumatic cylinder into the "cool-down" position. During the cool-down phase, lasting for one minute, a cooling air flow of 4.6×10^{-4} M^3/sec (1 ft^3/min) is directed onto the ceramic surface in addition to the 9.0×10^{-4} M^3/sec (2 ft^3/min) flowing over the back surface. The ceramic surface was thereby cooled from its maximum of 1260° C to about 450° C in several seconds. By the end of the cool-down phase the entire specimen is at about 350° C. The cycle is then repeated. A representative time-temperature schedule for the entire thermal cycle is shown in figure 3. Temperatures are indicated for the ceramic surface and the metallic backing.

MATERIALS

The turbine seal material systems evaluated in this study consisted of several functional components, or layers, as shown in figure 1. A plasma-sprayed yttria stablized zirconium oxide layer (ZrO_2 - 12% Y_2O_3) comprised the side of the specimen exposed to the hot gas. Directly beneath the ZrO_2 - 12% Y_2O_3 layer were various arrangements of thermal stress control intermediate layers. Finally, the entire seal material system was supported on a 304 stainless steel backing.

In all cases, the zirconium oxide ceramic layer was prepared from pre-stablized ZrO_2 - 12% Y_2O_3 powder, -200 + 325 mesh size (henceforth referred to as ZrO_2). Standard spray conditions (for Plasmadyne SG-1 gun) included a 550 ampere arc current, a 7.5 cm to 10 cm standoff distance, and argon as the powder carrier and arc gas. The arc gas flow rate was 4.6×10^{-4} M^3/sec (60 ft^3/hr), and the powder gas flow rate was 9.3×10^{-5} M^3/sec (12 ft^3/hr). The powder feed setting employed was 3.0.

Two thermal stress control intermediate layer concepts were evaluated. The first consisted of a pair of plasma sprayed metal/ceramic layers. Directly beneath the ZrO_2 layer was a 750 μM thick layer of 85% ZrO_2/15% NiCrAlY (volume percent) composition. In turn, beneath the 85/15 layer is a 40% ZrO_2/60% NiCrAlY layer, again 750 μM thick. Between the 40/60 layer and the 304 stainless steel substrate is a NiCrAlY bondcoat, about 50 to 75 μM thick. Although the properties of these particular layer compositions were not measured, they are believed to be similar to the properties of ZrO_2/CoCrAlY plasma sprayed layers described in reference 2.

The other type of intermediate layer studied in this investigation was a low density sintered NiCrAlY fiber pad, approximately 2500 μM thick. The pad is brazed directly to the 304 stainless steel backing, and 75 to 125 μM of NiCrAlY bondcoat is applied to the pad surface before the plasma-sprayed ZrO_2 is applied. It is estimated that the sintered pad is 70 to 80 percent porous, and the elastic modulus is about 1000 MN/m^2 (150 000 psi).

RESULTS

The number of thermal shock cycles required to cause spallation for each of the seal systems evaluated is summarized in figure 4. In all cases, specimens without intermediate low modulus or graded layers underwent complete spallation of the ceramic layer during the first heating cycle, indicating the necessity of providing some means of mitigating thermal expansion mismatch between the ceramic and the metal substrate.

Specimen with Sprayed Metal/Ceramic Intermediate Layers

Two variations on this particular seal system concept were experimentally evaluated. The first variation incorporated a ceramic layer 2300 μM thick (0.090 in.) sprayed under the conditions described in the Materials Section. These specimens were able to survive the first heat-up cycle, but complete loss of the ceramic layer occurred a few seconds into the first cool-down. The fracture surface was near the interface between the ceramic layer and the first intermediate layer. Such failures occurring on the first cycle are more correctly considered stress rupture failures rather than cyclic thermal shock failures.

A second variation of the sprayed metal/ceramic intermediate layer concept incorporated a 2300 μM ZrO_2 layer sprayed under conditions intended to promote increased porosity. From the literature (refs. 3 to 5) it appeared that improved performance could be achieved by increasing the porosity and number of microcracks in the ceramic layer. Through experimentation with the plasma spray process, it was discovered that significantly increased porosity and increased density of microcracks could be consistently obtained by reducing the plasma-spray gun current from 550 to 500 Å, and increasing the gun-to-workpiece distance from 7.5 cm (3 in.) to 15 cm (6 in.). Comparison of the increased porosity microstructure thus obtained and the standard microstructure is shown in figure 5. In fact, the cyclic life of specimens prepared with the increased porosity ceramic layer is dramatically increased, as shown in figure 4. As many as 51 cycles were accumulated on one such specimen before spallation occurred.

Low Modulus Sintered Intermediate Layer

Three specimens incorporating the sintered NiCrAlY fiber intermediate layer were evaluated, and all were still intact after the numbers of cycles indicated in figure 4. Surface, or "mudflat" cracks were seen on all specimens, as shown in figure 6. Sectioning revealed that the cracks did extend nearly down to the ceramic/intermediate layer interface, as may be seen in figure 7. One of the specimens showed no evidence of laminar cracking (cracks propagating parallel to the ceramic/intermediate layer interface) after 160 thermal shock cycles, while another specimen, after 150 cycles, did show some localized laminar cracking as in figure 7(b). It is believed that spallation is caused by the propagation and coalescence of such laminar cracks. A third specimen was subjected to 455 thermal shock cycles without spallation.

CONCLUSIONS

Results of cyclic thermal shock tests conducted on specimens representing potential high pressure turbine seal concepts lead to the following conclusions:

1. The most effective way of reducing thermal stresses, thereby increasing thermal shock life, is to provide a highly porous, low modulus "cushion" between the ceramic layer and the fully dense metal substrate.
2. The effectiveness of the sprayed metal/ceramic intermediate layers was probably masked by the severity of the cool-down portion of the thermal shock cycle. These intermediate layers were beneficial in that the ceramic layer was retained through the heat-up portion of the cycle.
3. Increasing the porosity of the ceramic layer proved to be an effective means of improving the cyclic thermal shock life of specimens incorporating sprayed metal/ceramic intermediate layers.

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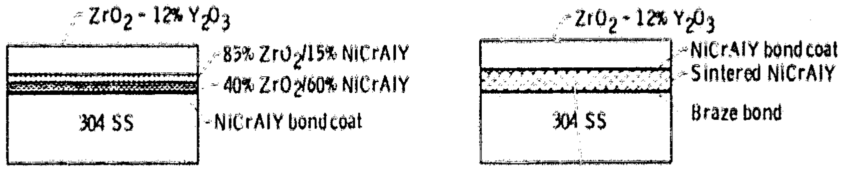

(a) Plasma-sprayed metal/ceramic intermediate layer concept.

(b) Sintered metal, low modulus intermediate layer concept.

Figure 1. - Schematic representation of the two major turbine seal concepts evaluated.

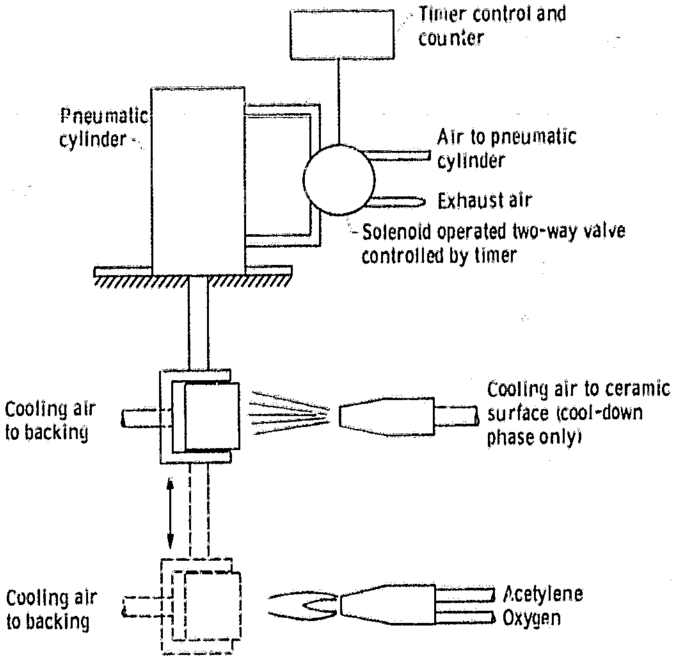

Figure 2. - Thermal shock apparatus.

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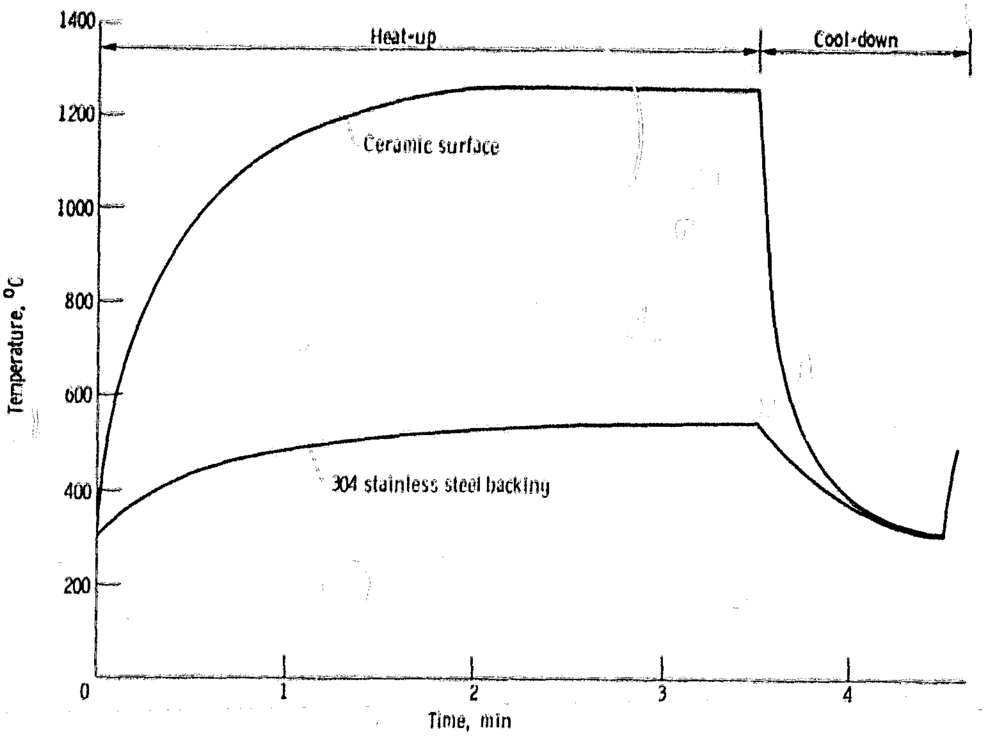


Figure 3. - Representative time-temperature plot for thermal shock cycle.

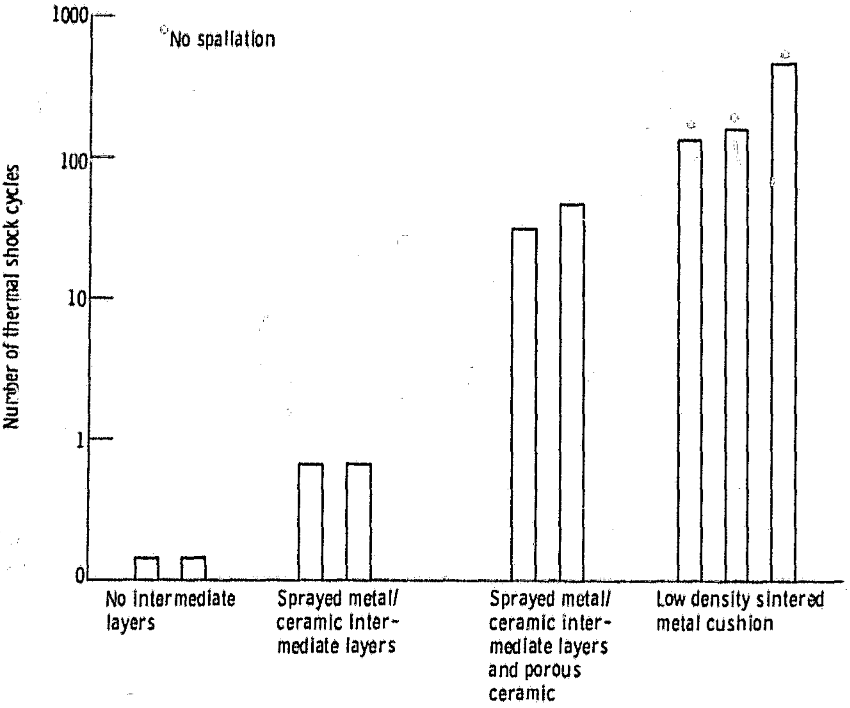
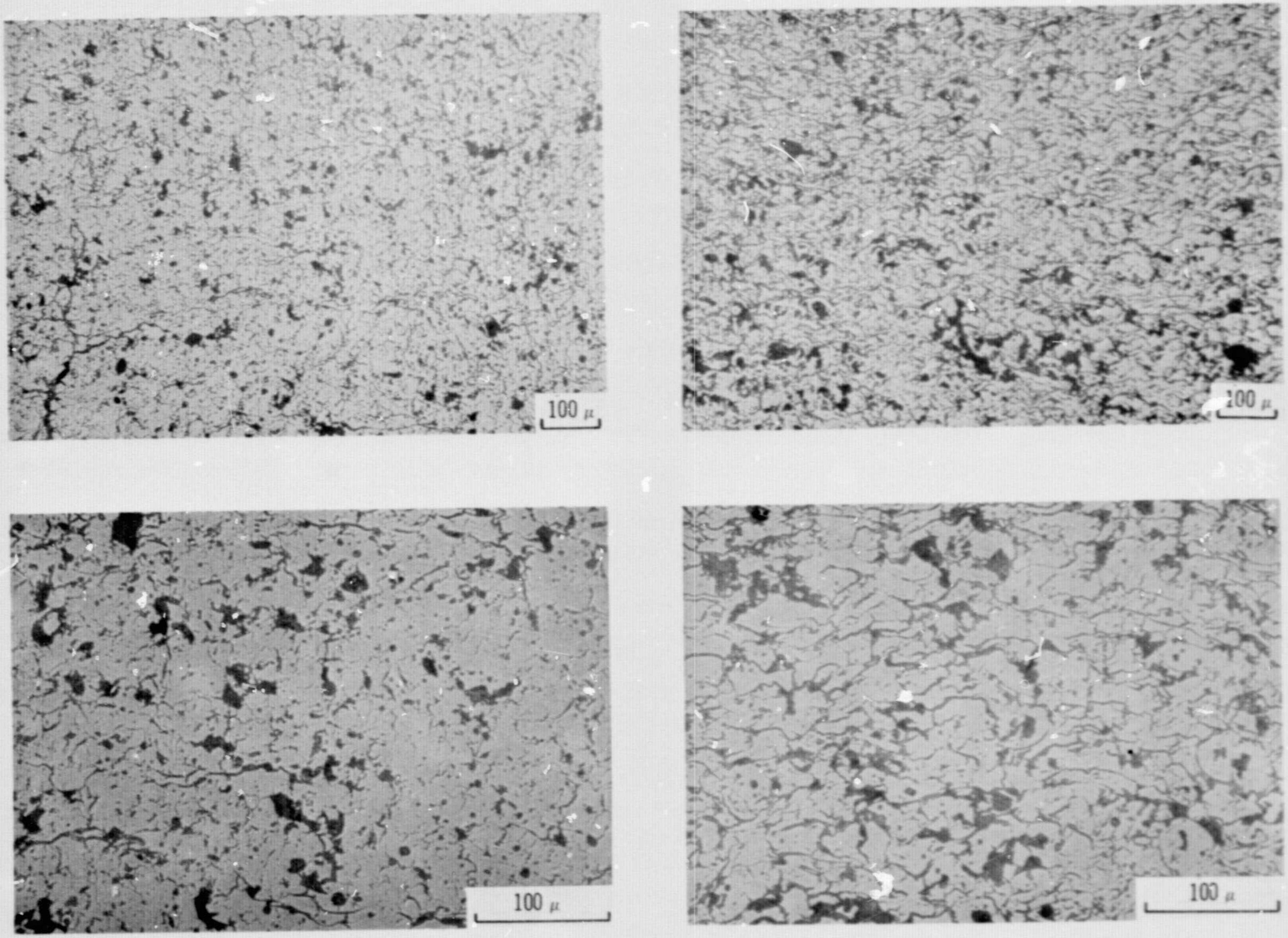


Figure 4. - Number of thermal shock cycles required to cause spallation of material for several turbine seal concepts evaluated.



(a) Standard spray conditions.

(b) Reduced intensity spray conditions.

Figure 5. - Microstructure of yttrio stabilized zirconium oxide prepared under standard (a), and reduced intensity (b) plasma-spray conditions.

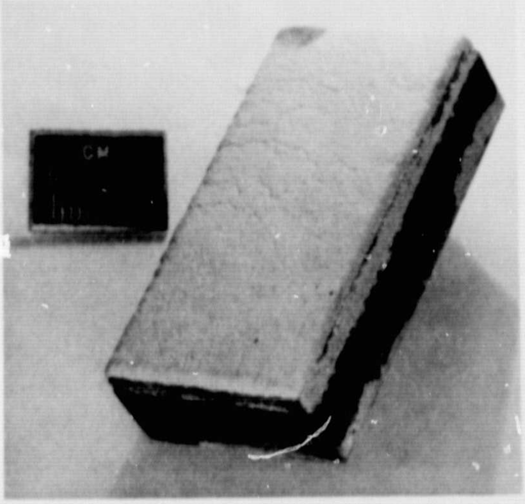


Figure 6. - Ceramic turbine seal system with porous sintered NiCrAlY intermediate layer after 180 thermal shock cycles.

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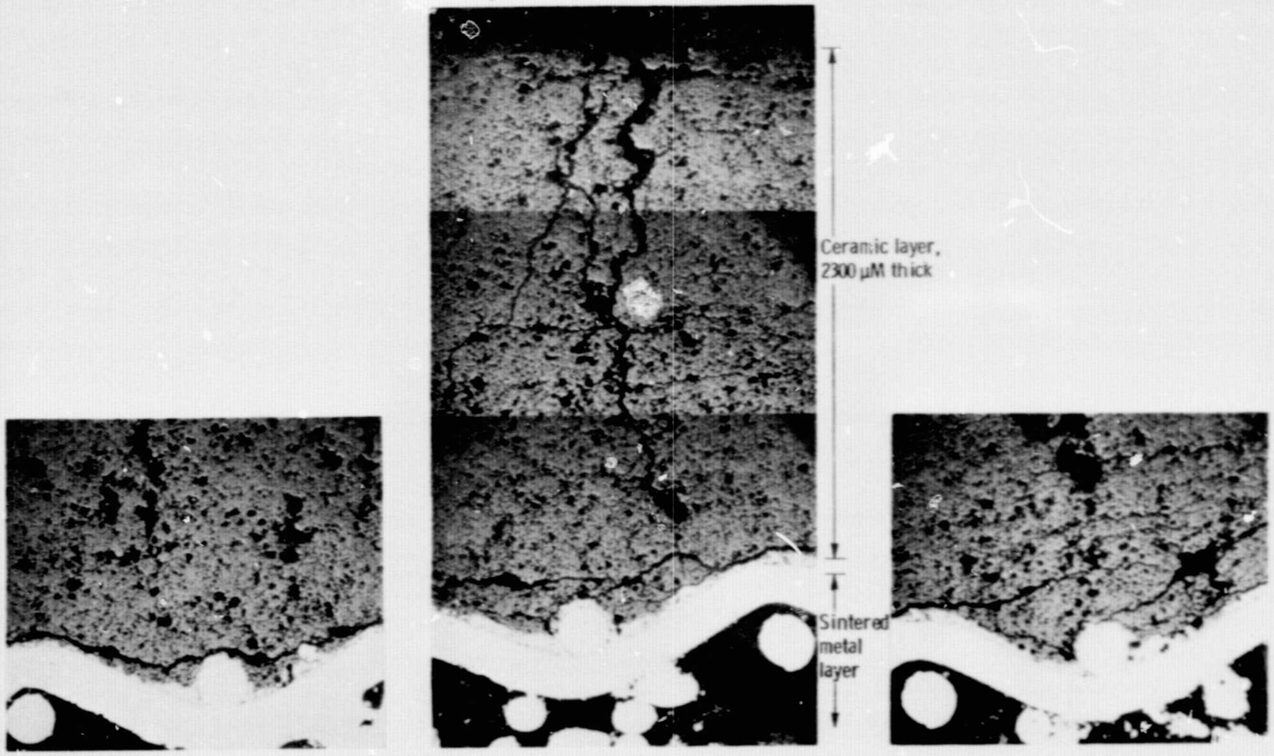

(a) Ceramic/sintered metal interface, about 2 mm from edge of specimen.

(b) Section through entire ceramic layer, about 4 mm from edge of specimen.

(c) Ceramic/sintered metal interface, about 6 mm from edge of specimen.

Figure 7. - Section view of specimen with sintered NiCrAlY fibermetal intermediate layer, after being subjected to 160 thermal shock cycles.