NASA

Technical Memorandum 79273

AVRADCOM

Technical Report 79-47

N79-33325

(NASA-TM-79273) PLASMA-SPRAYED ZIRCONIA GAS PATH SEAL TECHNOLOGY: A STATE-OF-THE-ART REVIEW (NASA) 17 p HC A02/MF A01 CSCL 11A

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Prepared for the

Manufacturing Technology Advisory Review

sponsored by the Society of Manufacturing Engineers

Phoenix, Arizona, October 21-25, 1979

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ABSTRACT

The benefits to be derived from application of ceramic materials to high pressure turbine gas path seal components are described and the developmental backgrounds of various ceramic gas path seal approaches are reviewed. The most fully developed ceramic gas path seal approaches are identified as being those employing plasma-sprayed zirconium oxide as the ceramic material. Prevention of cracking and spalling of the zirconium oxide under cyclic thermal shock conditions imposed by the engine operating cycle is the most immediate problem to be solved before implementation can be undertaken. Three promising approaches to improving cyclic thermal shock resistance are described and comparative rig performance of each are reviewed. Some advanced concepts that show potential for further performance improvements are described.

INTRODUCTION

The efficiency and performance of a gas turbine engine is very sensitive to gas path seal clearances throughout the engine. In most cases, the single most significant gas path seal location is the high pressure turbine outer air seal, shown schematically in Fig. 1 (ref. 1). Studies have indicated that depending on the nature of the turbine design, from 1 to 3 percent turbine efficiency loss is suffered for each 1 percent increase in blade tip clearance to blade span ratio (ref. 2).

State-of-the-art turbine seal technology is based on the use of metallic seal material systems. These materials are prone to gradual clearance degradation due to erosive and corrosive mechanisms at turbine operating temperatures. Furthermore, they require significant amounts of cooling air to maintain them at allowable temperatures, and there are engine efficiency penalties associated with the expenditure of this cooling air.

Ceramic materials are an alternative to the currently used metallic systems, and hold promise for significantly higher allowable temperatures and improved chemical stability. In order to perform as effective high pressure turbine seal materials, though, the ceramic materials must afford some degree of abradability and erosion resistance, and have the ability to survive thermal stresses imposed by the engine operating cycle.

In many respects, the high pressure turbine seal is a logical choice of component for the introduction of ceramic materials. As a nonstructural stationary component, any unexpected deterioration of ceramic material properties or integrity need not lead to catastrophic engine failure. Perhaps the application of ceramic materials to the high pressure turbine seal location offers an opportunity to "walk before we run" in regard to eventual broader use of ceramic gas turbine engine components.

Various ceramic high pressure turbine seal systems have been explored. Systems based on hot pressed SiC and molded Si-SiC composites (ref. 3), and ceramic honeycomb structures (ref. 4) have been evaluated for use in 2500° F turbine applications. These approaches have the drawbacks of rather costly manufacturing procedures combined with difficulties in interfacing the ceramic parts with the metallic engine structure. A seal system employing sintered ZrO_2 with sintered, graded metal/ceramic intermediate layers applied to a cast metallic substrate (ref. 5) offered a method of getting around the interfacing problem, but manufacturing was still expensive and difficult to control. The greatest activity is presently concentrated on approaches incorporating plasma-sprayed yttria stabilized zirconium oxide (YSZ) with various intermediate layer schemes, applied to a structural metal support substrate (refs. 6 to 9), and these approaches are the subject of this paper. An example of such a turbine seal is shown in Fig. 2. The most significant concern, and the primary function of the intermediate layers, is to provide resistance to the cracking and spalling associated with exposure to the engine thermal environment.

The purpose of this paper is to describe some approaches to the successful application of plasma-sprayed YSZ materials to the high pressure turbine seal. Manufacturing methods used, rig performance data and some recent engine test experience are described.

THE PLASMA-SPRAY PROCESS

Before considering the performance of plasma-sprayed ceramic turbine seals, let's look at the plasma-spray process itself. All of the important elements of the plasma-spray process are summarized in Fig. 3(a). An arc discharged across a flowing stream of inert gas (typically a mixture of argon and H_2) generates an extremely hot plasma in which temperatures are estimated to be 10 000 to 20 000 K. The hot, expanding plasma accelerates to high velocities as it emerges from the gun opening. At some location, varying from one plasma-spray gun model to another, the material that comprises the coating is injected as a powder into the high temperature, high velocity plasma stream. In some plasma-spray guns, as shown in Fig. 3(a), powder may be introduced at more than one location. The particles are brought very quickly to a molten state, and impinge at high velocities onto the substrate to be coated.

A comprehensive list and description of the variables involved in the plasma-spray process may be found in Ref. 10. Substrate temperature and the distance between the plasma-spray gun and the substrate are among the significant controllable variables that affect the adherence of ceramic coatings to metal substrates (ref. 11). For plasma-sprayed ceramic coatings it was found that an optimum spray distance was about 75 mm, and adherence was observed to increase with increasing substrate temperatures, at least up to 600° C. Both of these observations are explained in terms of particulate melting and resolidification behavior. Also in Ref. 11, the effects of ceramic coating thickness and rate of deposition on residual stresses in the coating are recognized. In general it is recommended that thick coatings be applied in very thin successive applications with perhaps some cooling of the coating surface between gun passes.

In order to maintain optimum spray conditions on a manufacturing process basis, adaptive feedback control of the process is very desirable. Critical parameters such as substrate temperature, deposition rate, plasma power, and gun traverse rate could be held within specified tolerances, providing reliable, reproducible coatings. Promising advances in applying adaptive feedback control to the plasma-spray process have been demonstrated in an Air Force funded manufacturing technology program.

The high pressure turbine seal surface to be plasma-spray coated is geometrically simple, comprising an inner cylindrical surface. Individual seal segments may be loaded onto an appropriately sized carousel, the surface to be coated facing inward as shown in Fig. 3(b). The plasma-spray gun is traversed axially so that the entire seal surface of the segments is uniformly coated.

PERFORMANCE OF PLASMA-SPRAYED CERAMIC SEALS

The necessary performance features of a ceramic gas path seal system include abradability, erosion resistance, and resistance to the thermal environment. The latter includes thermal shock resistance, dimensional stability, and resistance to corrosion. Each of the performance features will be discussed in further detail.

Abradability

Abradability is a characteristic of the seal and blade tip material combination whereby, in the event of a rub interaction, wear occurs to the seal material rather than to the blade tips. Abradability is often expressed quantitatively as a "Volume Wear Ratio" (VWR), defined as the ratio of the volume of blade tip material worn to the volume of seal material removed.

The question naturally arises, "how can a hard, refractory ceramic material be abradable with respect to metallic blade tips?" In a plasma-sprayed structure there is always some degree of porosity. YSZ sprayed under conditions developed for thermal barrier coating applications has a porosity of about 15% as indicated in the micrographs of Fig. 4. Abradability tests conducted under a range of conditions are summarized in Fig. 5, from Ref. 6. Depending on rub parameters, rig tests indicate that a VWR as low as 0.3, comparable with the most abradable metallic systems at their operating temperatures may be achieved under some conditions. Metallographic sections through the rub groove (fig. 6) indicate that the rub was accommodated by a combination of removal of discrete sprayed particles and compaction of the rub surface.

Efforts to improve the abradability of ceramic seal systems have followed two lines of attack. In one, an abrasive material is bonded to the turbine blade tips turning the turbine stage into a sort of grinding wheel. The obvious problems, not yet completely overcome, are the need for a high temperature abrasive and a means of bonding that abrasive to the tip.

Another way of improving abaradability is to increase the porosity of the ceramic material. This may be done by co-spraying the ceramic with an easily volatilizable filler. Preliminary results of a program to develop a readily abradable ceramic in this manner have consistently shown VWR's much less than 0.1 under a broad range of rub conditions. Of course, this approach to increasing abradability succeeds at the cost of some loss in erosion resistance.

Erosion Resistance

Erosion resistance, like abradability, is an important characteristic from the standpoint of maintaning minimum cleaances over the blade tips. Erosion of turbine seal components arises from hot gas and particulate erosion, the particulates being both material ingested by the engine, and hard carbonaceous combustion product particles.

Results of hot particulate erosion rig tests of YSZ are shown in Fig. 7. The erosion rate of plasma-sprayed YSZ is almost an order of magnitude lower at a 15° impingement angle, believed to represent gas path seal conditions, than at a 90° impingement angle. Furthermore, consistent with classical erosion observations (ref. 12), the erosion rate of the ceramic seal material at shallow impingement angles is lower than that of currently used metallic systems.

Thermal Shock Resistance

Resistance to thermal shock damage is the most challenging requirement that must be met by plasma-sprayed YSZ turbine seals. It is nessary to accommodate the thermal expansion mismatch, as well as sinter shrinkage effects, between the ceramic material adjacent to the gas path and the metallic substrate throughout the entire spectrum of transient and steady engine operating conditions. Three methods of providing resistance to cracking and spalling under thermal shock conditions have been identified, two of which are represented schematically in Fig. 8.

One method, shown in Fig. 8(a), is to grade the thermal expansion properties in either a stepwise or a continuous manner by grading composition from fully metallic adjacent to the substrate to fully ceramic adjacent to the gas path. In principle, this method may be tailored so as to provide a nearly stress-free state at a selected operating condition. Engine tests have been successfully run on turbine seals prepared by this method, 20 hours of operation having been completed without distress to the ceramic. A shroud from this engine test is shown in Fig. 9. Realization of the full potential of the graded thermal expansion coefficient (graded α) method will require careful control of residual stresses in the as-fabricated seal. Residual stress control may be effected by pre-heating the substrate during psray deposition, post spray heat treatment, or imposition of mechanical stresses during spray deposition (ref. 13).

Another method, shown in Fig. 8(b), employs a low modulus cushion or strain isolator pad between the ceramic layer and the metal substrate. The strain isolator pad allows the ceramic layer to respond to its own temperature gradient independently of thermal strains and displacements in the metal substrate. Strain isolator pad materials that have been evaluated include low density sintered metals brazed to the substrate (refs. 7 and 8), and highly porous, thick, plasma-sprayed intermediate layers (ref. 14). Representative microstructures of materials comprising these layers are shown in Fig. 10. Thermal shock rig test results, summarized in Fig. 11, indicate that the thermal shock resistance of specimens incorporating low modulus strain isolator pads is superior to the thermal shock resistance of graded α specimens prepared without residual stress control. Engine tests conducted on various plasma-sprayed YSZ seal designs with strain isolator pads of a porous hot-pressed NiCrAlY material have shown promising results.

Yet another approach to providing thermal shock resistance has been identified, and it involves controlling the microstructure of the ceramic layer itself. It has been well documented that the existence of controlled porosity (size and distribution) or a fine, controlled network of microcracks in a ceramic structure can dramatically enhance the thermal shock resistance of the ceramic (refs. 15 and 16). Experimental results from simulated turbine seal specimens are consistent with this general observation (ref. 14). Specimens in which the YSZ layer porosity had been increased from its standard 15% to about 20% (fig. 12) by modifying the plasma-spray parameters, showed about twice the cyclic thermal shock life and a definite improvement in thermal stress rupture resistance compared to standard density specimens. Thermal stress analyses were conducted on the test specimen geometries evaluated. Taking into account a lower measured elastic modulus for the higher porosity ceramic layer, significantly lower thermal stresses are predicted for the specimen with the more porous ceramic layer, as may be seen in Fig. 13 (ref. 14). Hence, the experimental results are consistent with predicted thermal stresses as well as with microstructural thermal shock models. Incidentally, such thermal stress analyses have proved very helpful in preliminary screening of material property variations and experimental design ideas.

FURTHER DEVELOPMENTS

Rig tests have indicated various ways of further improving the performance of plasma-sprayed ceramic high pressure turbine seals. These improvements are of interest for applications in advanced gas turbine engines in which temperatures higher than those in current engines will be encountered.

Under conditions imposed by severe thermal shock testing on simulated turbine seal specimens, a failure mode often encountered involves delamination of the ceramic (YSZ) layer from the metallic bondcoat or first metal bearing layer immediately beneath the ceramic layer. By applying a sputter deposited YSZ "primer" directly onto the bondcoat of one particular seal design evaluated, cyclic thermal shock life wasincreased by a factor of about 3. The reason for this improvement is not entirely understood. One explanation is that the sputtered YSZ coating covers the metallic bondcoat more continuously than does the first layer of plasma-sprayed YSZ. Plasma-sprayed YSZ in turn, wets the sputtered YSZ more readily than it would wet the metallic bondcoat, thereby giving a stronger interfacial bond.

Laser surface fusion techniques have been used to improve the thermal shock resistance of plasma-sprayed YSZ turbine seals. A continuous laser beam is scanned over the entire plasma-sprayed ceramic surface, producing a thin molten film that is quickly quenched. The approximately two-fold improvement in cyclic thermal shock life resulting from this treatment is attributed to two effects. First, a network of fine microcracks is generated by the intense local thermal shock associated with the laser, as may be seen in Fig. 14. A second effect, made evident by the arrest of the microcracks before reaching the surface, is the presence of residual compressive surface stresses. These two effects would reduce the chance of formation of a deeply propagating crack growing through the ceramic layer.

Studies of plasma-sprayed ceramic materials other than the ZrO_2-12w/o Y_2O_3, primarily to serve as thermal barrier coatings, have identified an optimum Y_2O_3 concentration as being in the 6 to 8 weight percent range (ref. 17). Specimens containing 6 to 8 weight percent Y_2O_3 have demonstrated substantially improved resistance to spalling compared to other Y_2O_3 concentrations under severe thermal shock test conditions.

SUMMARY

The potential for ceramic turbine seal components based on plasma-sprayed zirconium oxide to survive and function efficiently in present day turbine environments has been demonstrated. Questions regarding long term dimensional stability and property retention at high temperatures are currently being addressed under NASA funded programs aimed toward improving the efficiency of commercial aircraft gas turbine engines. A TSFC reduction of between 1 and 2 percent is expected from the implementation of ceramic turbine seal technology in large commercial aircraft engines. Further benefits are expected in terms of reduced maintenance and overhaul costs.

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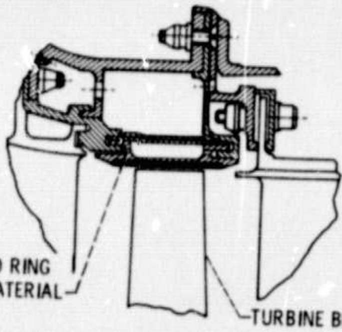

Figure 1. - High pressure turbine outer gas path seal arrangement.

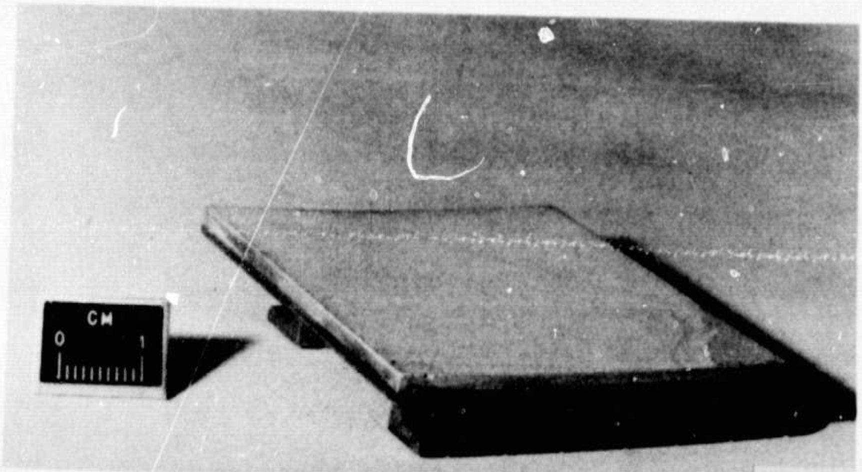

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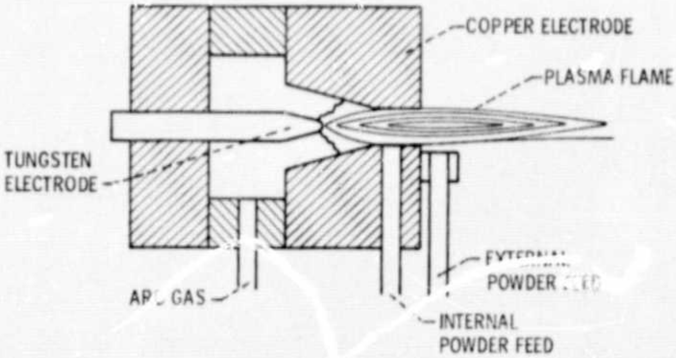
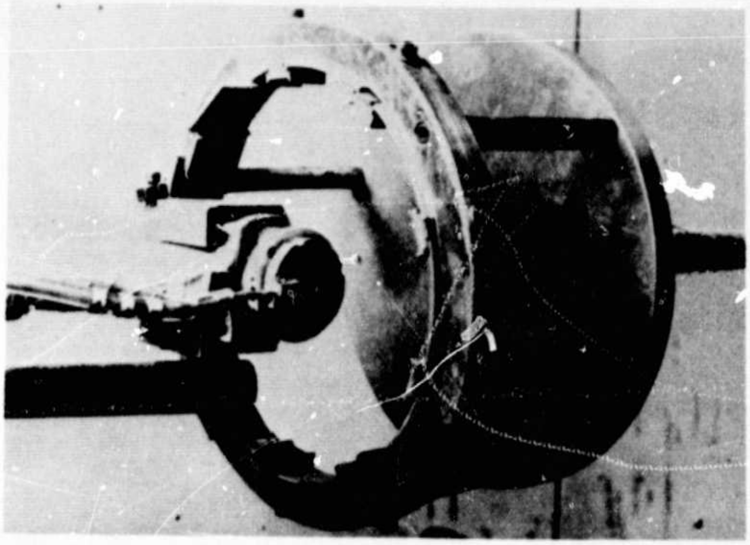
Figure 2. - Plasma-sprayed ceramic turbine seal shroud. Note intermediate layers and mounting rails.



(a) SCHEMATIC OF PLASMA-SPRAY GUN.



(b) SPRAY CAROUSEL FIXTURE.

Figure 3. - Typical plasma-spray equipment and fixturing.

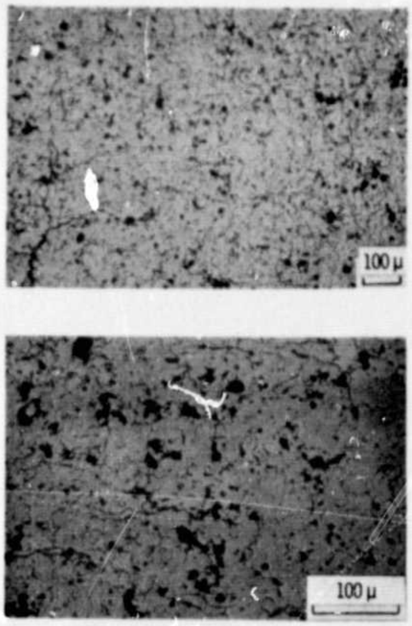


Figure 4. - Microstructure of plasma-sprayed yttria stabilized zirconia.

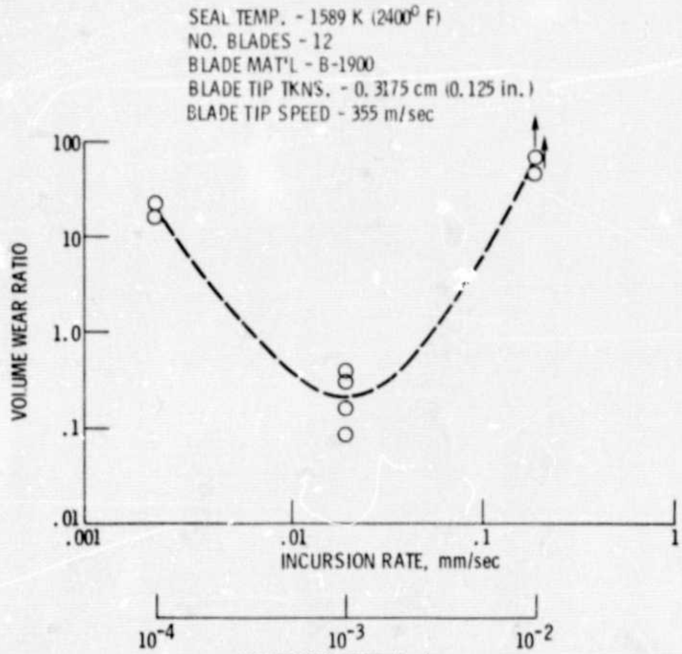


Figure 5. - Abradability of plasma-sprayed yttria stabilized zirconia as a function of incursion rate.

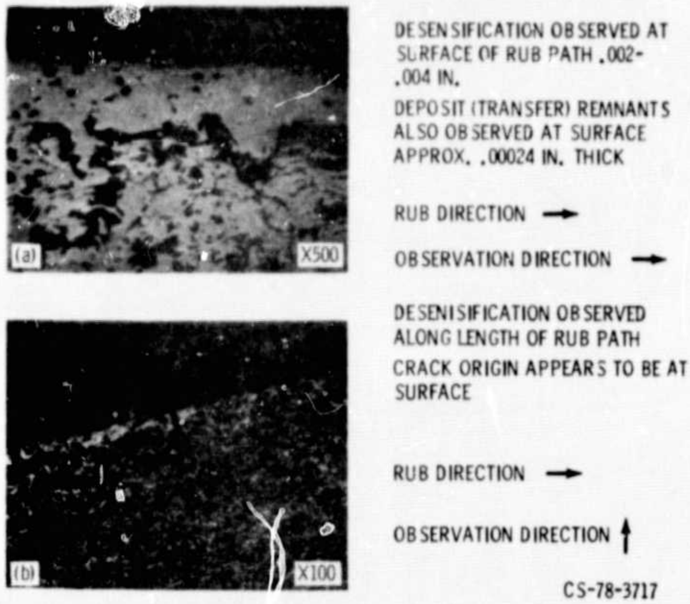


Figure 6. - Metal tra·sfer and seal densification in rub path.

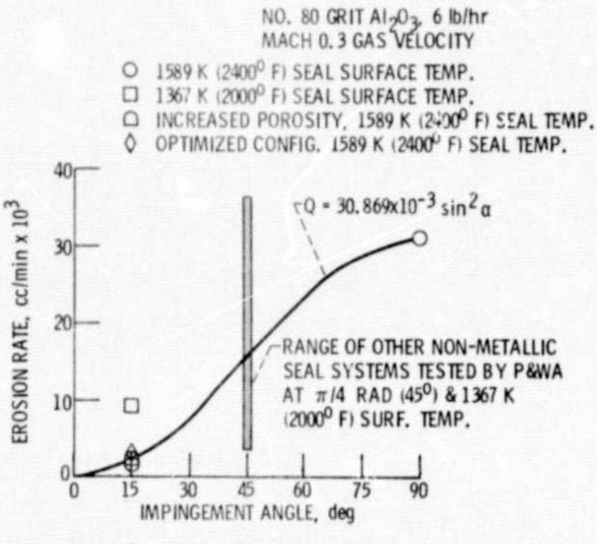
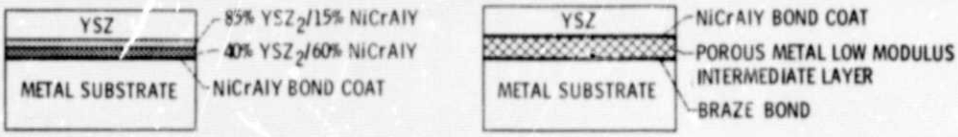


Figure 7. - Erosion test data correlation, plasma sprayed yttria stabilized zirconium oxide.



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

(b) Sintered-metal, low-modulus intermediate pad concept.

Figure 8. - Schematic representation of the two turbine seal concepts evaluated. (Compositions are in weight percent.)

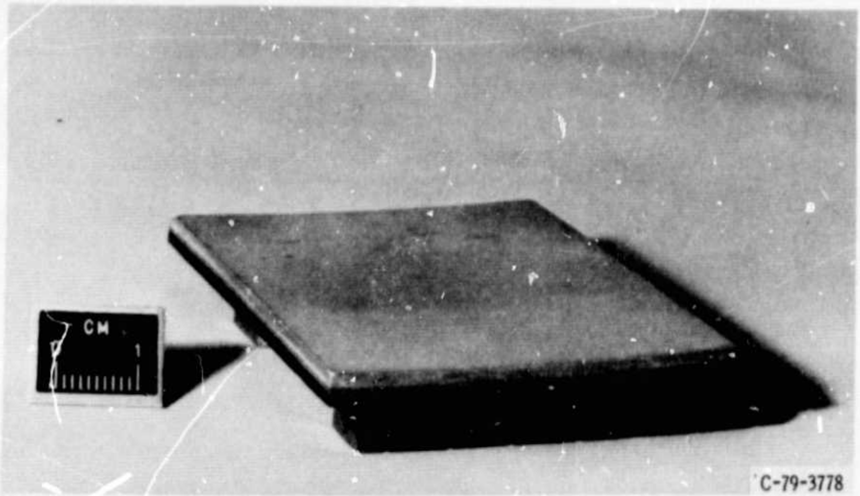


Figure 9. - Plasma-sprayed ceramic turbine seal shroud after approximately 20 hours of engine testing.

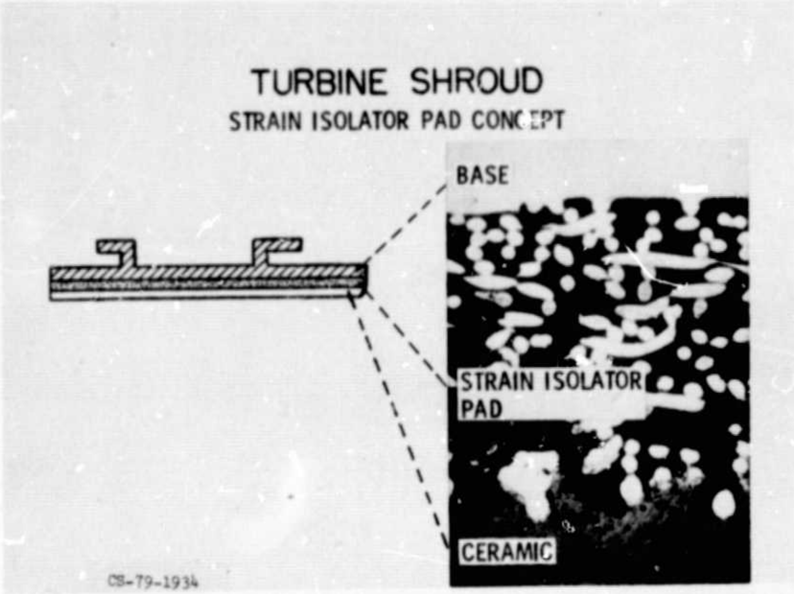


Figure 10. - Low modulus pad microstructure.

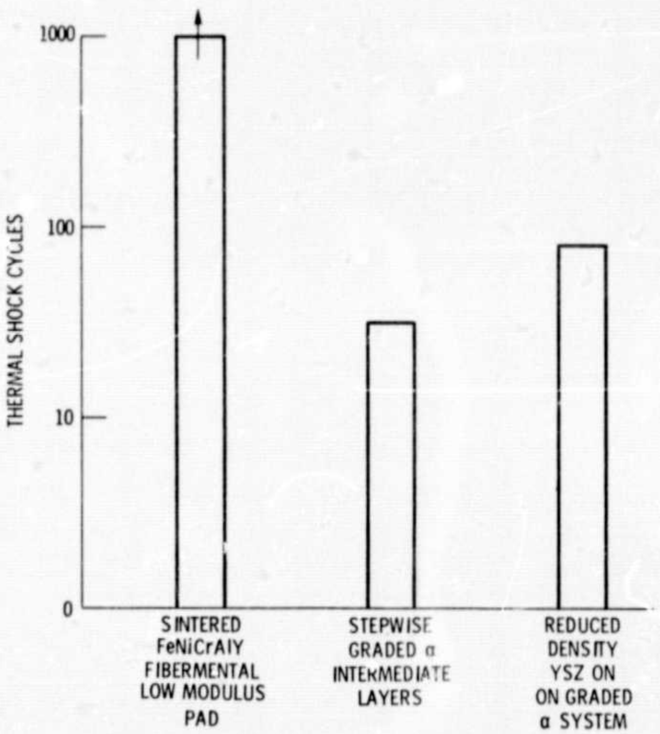
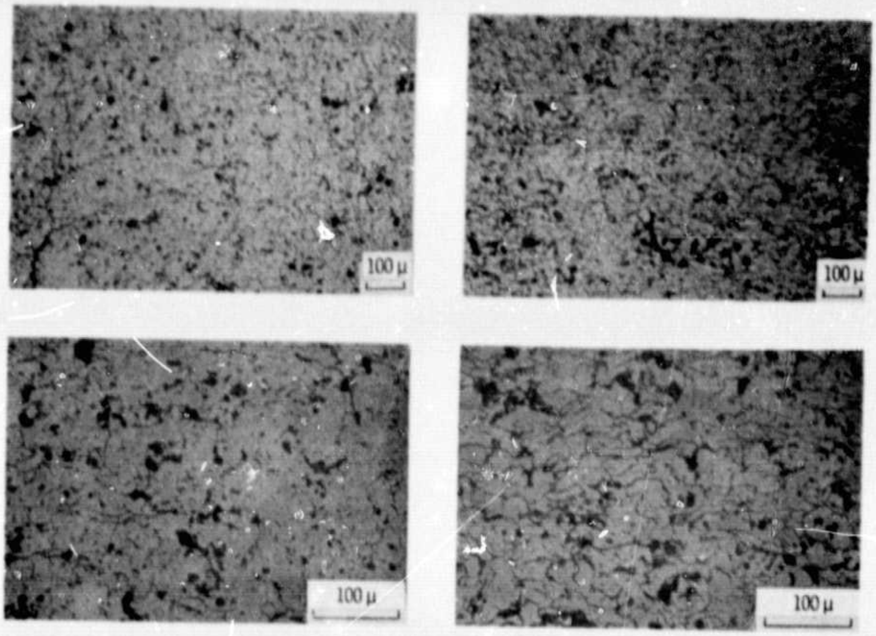
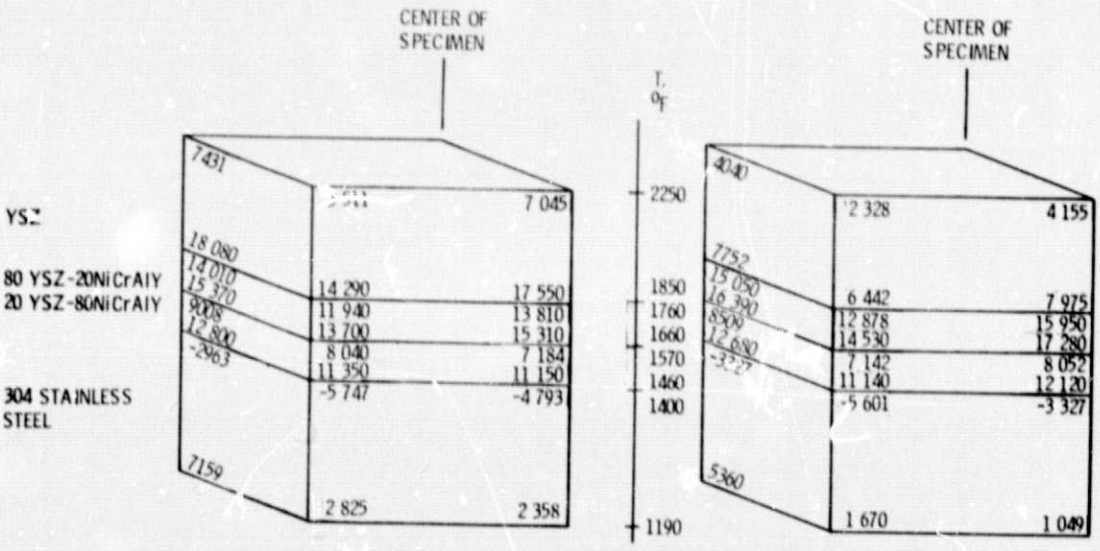


Figure 11. - Cyclic thermal shock test results indicating the number of thermal shock cycles required to cause the first incidence of ceramic spalling.



(a) STANDARD SPRAY CONDITIONS. (b) REDUCED INTENSITY SPRAY CONDITIONS.

Figure 12. - Microstructure of yttrio stabilized Zirconium oxide prepared under standard (a), and reduced intensity (b) plasma-spray conditions.



(a) E = 6. x10⁶ psi. (b) 2.08x10⁶ psi.

Figure 13. - Effect of Modulus of elasticity (E) on thermal stress distribution through specimen at 209 seconds into the thermal cycle. Temperature distribution is also represented. Quarter symmetry element of full specimen is shown. For purpose of analysis, properties of 80 YSZ/20 NiCrAlY and 20 YSZ/80 NiCrAlY layers are those measured for 85 YSZ/15 CoCrAlY and 40 YSZ/60 CoCrAlY layers reported in reference 15.

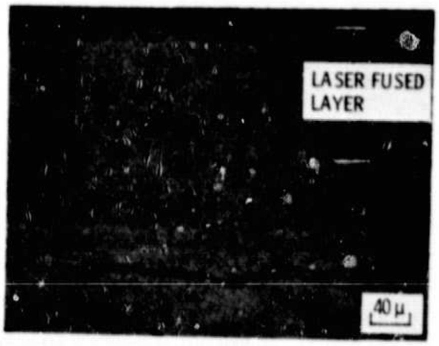


Figure 14. - Metallographic section showing the laser fused surface , layer on plasma sprayed YSZ after 1000 thermal shock cycles.