

VACUUM PLASMA COATINGS FOR TURBINE BLADES

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Abstract

Recent occurrences of air foil cracks in flight engine turbine blades have re-emphasized the need for improved coatings, and work is being expedited to develop durable thermal barrier coatings and coating application processes. Significant progress has been realized in the turbine blade coating program with an attendant potential for improved SSME performance, improved safety, increased producibility, and reduced engine maintenance costs. Turbine blades, vacuum plasma spray coated with NiCrAlY, CoCrAlY or NiCrAlY/Cr₂O₃ under contract with Howmet Corp., were evaluated and rated superior to standard SSME coated blades. Ratings were based primarily on 25 thermal cycles in the MSFC Burner Rig Tester, cycling between 1700°F (gaseous H₂) and -423°F (liquid H₂). These tests showed no spalling on blades with improved vacuum plasma coatings, while standard blades spalled. Thermal barrier coatings of ZrO₂, while superior to standard coatings, lacked the overall performance desired. Fatigue and tensile specimens, machined from MAR-M-246(Hf) test bars identical to the blades were vacuum plasma spray coated, diffusion bond treated, and tested to qualify the vacuum plasma spray process for flight hardware testing and application. While NiCrAlY/Cr₂O₃ offers significant improvement over standard coatings in durability and thermal protection, studies continue with an objective to develop coatings offering even greater improvements.

Introduction

On April 12, 1981 the first Space Shuttle, Columbia, lifted off Kennedy Space Center Complex 39 with an

initial force of 375,000 lbs. The turbine blades in the High Pressure Fuel Turbopump of the SSME (Space Shuttle Main Engine) that supplies hydrogen to the combustion chamber were rotating at 34,700 rpm. Each turbine blade, about the size of a quarter (Figure 1), was developing roughly 600 Horse Power. Gaseous hydrogen flowing thru the turbopump heated the blades to approximately 1500^oF for 500 seconds of flight operation. The turbopump subsequently shutdown in a fuel rich environment, with the blades quenched in liquid hydrogen at -423^oF. This extreme and rapid thermal shock from 1500^oF to -423^oF, with the turbine blades under tremendous dynamic stress is a major contributor to blade cracking. This same thermal shock causes ceramic coatings once plasma sprayed on the blades as protective thermal barrier coatings to spall or flake off. The protective ZrO₂ (zirconia) thermal barrier coatings are no longer used on replacement blades because of the spalling problem.

The current overhaul cycle for the SSME fuel pump turbine blades is 3000 seconds (6 flights) with an ultimate goal of 27,500 sec (55 flights). Turbine blade cracks have been occurring within the existing 3000 second changeout period demonstrating the need for more durable protective thermal barrier coatings. Cracks have formed along the leading edges of the air foil of first stage fuel pump turbine blades and in the shank portion of the trailing edge adjacent to the platform of second stage fuel pump turbine blades. Blades are presently coated only with NiCrAlY bond coating which provides minimum thermal protection.

The goal of the program discussed herein is to develop a durable thermal barrier coating that will reduce the tendency toward crack formation and extend the effective performance life of the turbine blades. More durable coatings will allow the changeout cycle for the turbopump to be extended to 10 flights (5000 sec.), 15 flights (7500 sec), etc. until the goal of 55 flights (27,500 sec) is reached.

Baseline coatings for the SSME turbine blades were applied initially by plasma spray coating both NiCrAlY (Ni-16Cr-5.6Al-0.6Y) bond coating, and yttria stabilized zirconia ($ZrO_2 \cdot 12Y_2O_3$), thermal barrier ceramic coating, at atmospheric conditions. Even after the zirconia coating was deleted from the application procedure, the NiCrAlY coating, .007" thick, spalled during operation but to a lesser degree than before, as shown by the turbine wheel in Figure 2. A literature search^{2,3} indicated that a significant improvement in coating durability could be realized by applying the plasma coating in a vacuum. Vacuum plasma coatings offered the following advantages over atmospheric plasma sprayed coatings (Figures 3 & 4):

- (1). Exclusion of oxides
- (2). Denser, less porous coating
- (3). Reverse transfer arc cleaning
- (4). Mach 3 velocities
- (5). More uniform application (15" spray distance vs 3")
- (6). Improved coating thickness uniformity

Based on the literature search^{4,5,6,7} and telephone discussions with leaders⁸ in the plasma spray field, metal alloy bond coatings were narrowed to NiCrAlY, CoCrAlY and NiCoCrAlY while the thermal barrier ceramic coatings were narrowed to zirconia stabilized with, 8% and 12% yttria and to chromia. All known companies with vacuum plasma spraying capabilities were contacted, with competitive bid contracts let to Howmet Corporation, Whitehall, Michigan and Plasma Technics, Inc, Hollywood, Florida. Turbine blades of MAR-M-246(Hf) alloy (Ni-9Cr-10Co-2.5Mo-10W-1.5Ta-5.5Al-1.5Ti-0.15C-.015B-.055Zr-1.5Hf), rejected because of minor anomalies for use in space flight, but satisfactory for plasma coating development were obtained from Rocketdyne. Only blades vacuum plasma sprayed at Howmet are discussed in this study.

Vacuum Plasma Spray Process

The vacuum plasma spray facility and process used at Howmet have been fully described by Shankar, Koeing and Dardi². The pilot facility consists essentially of a 4-ft diameter vacuum chamber with a 120KW EPI-03 plasma head from Electro Plasma, Inc., Irvine, California. Minus 200/+325 or -400 mesh powder was supplied to the plasma head using Model 1250 Roto-feed powder hoppers from Plasmadyne, Inc., Santa Ana, California. An inert gas mixture of 80% argon, 20% helium was used as the plasma arc gas while pure argon was used as the powder carrier gas. Both plasma gun and workpiece motion were controlled by a computer. The chamber was maintained at 20-60 torr by regulating the vacuum for a given plasma spraying condition. The workpiece was preheated to 1500-1700^oF with the plasma gun power regulated between 80 and 90KW. Prior to coating, the turbine blades were electrically cleaned by negatively biasing the workpiece relative to the gun anode. Powder particles injected into the plasma arc stream were melted (or softened) and simultaneously accelerated toward the workpiece where they adhered on impact. Coating thickness was .006+.0015" for "M" CrAlY used alone or .003+.0015" with MCrAlY as a bond coating plus .004+.0015" of MCrAlY/Cr₂O₃ thermal barrier coating on top. All vacuum plasma applied MCrAlY and MCrAlY/Cr₂O₃ coatings were diffusion bond treated 4 hours in vacuum at 1975^oF to enhance the degree of bonding. The coated blades were surface finished to reduce drag. No further treatment was considered, such as hot isostatic pressing (HIP) or shot peening because of zero to minimal improvements from such work reported in the literature².

Coating Studies

Table I shows the results of the initial studies. Four MAR-M-246(Hf) HPFTP (High Pressure Fuel Turbopump) turbine blades were vacuum plasma sprayed for each condition with three blades each tested in the MSFC Burner Rig cyclic thermal tester (Figure 5). Each cycle duration was 15 seconds, cycling between the temperatures of gaseous hydrogen/steam

(1700°F) and liquid hydrogen (-423°F) simulating operation of the SSME. Actual chamber and blade temperatures were recorded at 1700°F and -350°F (Figure 6). The blades were tested 25 cycles and were examined after 5, 10 and 25 cycles.

With the exception of NiCoCrAlY, all other vacuum plasma sprayed MCrAlY coatings performed extremely well, showing no spalling after 25 cycles while the control, atmospheric plasma sprayed turbine blades, baseline for the SSME, spalled severely (Figure 7). NiCrAlY (Ni-16Cr-5.6Al-0.6Y) (Figure 8) vacuum plasma sprayed using -200/+325 mesh powder which is identical to the powder, atmospherically plasma sprayed on baseline SSME turbine blades, was rated best. Although statistically all samples were in the same population, -400 mesh CoCrAlY and -400 mesh NiCrAlY were rated 2nd & 3rd in that order. Plasma powder -200/+325 mesh is considered the limit in fineness that can be sprayed atmospherically, while the finer -400 mesh is considered optimum in producing a superior coating for vacuum plasma spraying. NiCoCrAlY, utilized as a powder for vacuum plasma spray coating jet aircraft turbine blades, cracked and spalled severely during the Burner Rig cyclic thermal testing.

The 50/50 blend of Cr₂O₃ (Figure 9) with NiCrAlY or CoCrAlY, was applied because a good uniform coating could be produced with the existing plasma spray nozzle. All 50/50 Cr₂O₃/MCrAlY coatings were rated comparable to the 100% MCrAlY coatings in durability. A uniform spray could not be obtained with 50/50 blends of ZrO₂ and NiCrAlY, nor with 100% amounts of Cr₂O₃ or ZrO₂ at this time.

Blades were plasma coated with zirconia several months later using an automated atmospheric spray chamber specifically installed by Howmet to spray ceramic powders. Blades were first vacuum plasma sprayed with .003+.0015 NiCrAlY, then with .004+.0015 ZrO₂. Burner Rig thermal cyclic testing of the ZrO₂ coated blades showed erosion rather than spalling for the top rated blades. The

best thermal barrier coatings were rated 65-70 on a 100 equals perfect basis, being downgraded primarily because of erosion (Table 2). The erosion was attributed to a lower than desired ZrO_2 coating density. No statistical difference was found in the top three coatings (65, 66, 70 Rating) with results showing no difference between ZrO_2 stabilized with either 8% or 12% Y_2O_3 . The 7% Y_2O_3 stabilized zirconia was a Howmet proprietary coating and basically different from the 8% and 12% yttria stabilized coatings. Cracks appearing in the uncoated shank portion of the turbine blades were attributed to the diffusion bonding treatment. Therefore additional blades were coated with NiCrAlY bond coating, $ZrO_2 \cdot 12Y_2O_3$ thermal barrier coating, diffusion bond treated and then aged 24 hours at $1600^\circ F$ (Figure 10). Aging is a normal treatment in the manufacture of turbine blades. Although the zirconia coating rating improved from 65 to 75, cracks still persisted in the shanks following 25 Burner Rig cyclic thermal tests.

Physical Testing

Test bars were previously obtained that were produced from the same heat as the turbine blades being used in this development work. In the normal process of manufacturing turbine blades, the MAR-M-246(Hf) blades are first cast, solution treated 2 hours in vacuum at $2230^\circ F$, aged 24 hours at $1600^\circ F$, machined, inspected, and later plasma spray coated with -200/+325 mesh NiCrAlY. The test bars were subjected to the same processing conditions as the turbine blades thru the aging cycle, and were machined into tensile strength test specimens (2 each condition) and fatigue test specimens (4 each condition) as shown in Table 3. The test specimens were vacuum plasma coated with NiCrAlY bond coating, plasma coated with $ZrO_2 \cdot 12Y_2O_3$ thermal barrier coating and subsequently diffusion bond treated under identical conditions used for the turbine blades. Table 3 shows comparable tensile strengths for coated specimens non-treated and diffusion bond treated.

Fatigue specimens, diffusion bond treated 4 hours in vacuum at 1975°F and aged 24 hours at 1600°F, were in the same statistical population as the control, requiring 2.7 million cycles to break vs 2.9 million. The control was uncoated and untreated. Looking toward future blade coating studies, one set of fatigue specimens was solution treated 2 hours in vacuum at 2230°F, plasma sprayed first with NiCrAlY followed by $ZrO_2 \cdot 12Y_2O_3$ and then diffusion bond treated 4 hrs at 1975°F and aged 24 hrs at 1600°F. These four fatigue specimens broke in a close tolerance range and averaged 5.2 million cycles to failure vs. 2.9 million for the control. This work offers the potential of not only producing improved coatings for turbine blades but also reducing the tendency toward cracking on the exposed shank and fir tree areas of the blades.

Studies are continuing in the Metallic Materials Division of the Materials and Processes Laboratory, to investigate the following for each plasma blade coating and treatment condition listed in Tables 1 & 2: (1) Microstructural changes, (2) Bond Interface, (3) Coating Integrity, (4) Mechanical Properties and (5) Crack Initiation.

During this development period, work has been in progress to procure and install an automated 120 KW LPPS (Low Pressure Plasma Spray) unit from Electro-Plasma Inc. This unit, bought thru competitive procurement, was placed in service at MSFC in July 1984.

Currently planned studies involve utilizing our new LPPS (Low Pressure Plasma Spray) unit at MSFC and the plasma expertise in Industry to continue our development effort to produce a durable thermal barrier coating for the SSME (Space Shuttle Main Engine) fuel turbopump turbine blades. These studies will continue our work with 50/50 blends of Cr_2O_3 and NiCrAlY that have performed so satisfactorily in Burner Rig testing plus 50/50 blends of ZrO_2 and NiCrAlY and 90/10 blends of

Cr₂O₃ or ZrO₂ with NiCrAlY. Results of the metallurgical studies will be utilized in conjunction with refinements to blade heat treatments involving solutioning (2230^oF), diffusion bonding (1975^oF) and ageing (1600^oF).

Conclusion

A 50/50 blend of Cr₂O₃ and NiCrAlY plasma sprayed on SSME high pressure fuel turbopump turbine blades provided significant improvements in coating durability and thermal protection when tested in a simulated service environment. The success of these studies warrants their continuation and the expansion of testing to include qualification in flight configured turbines.

References

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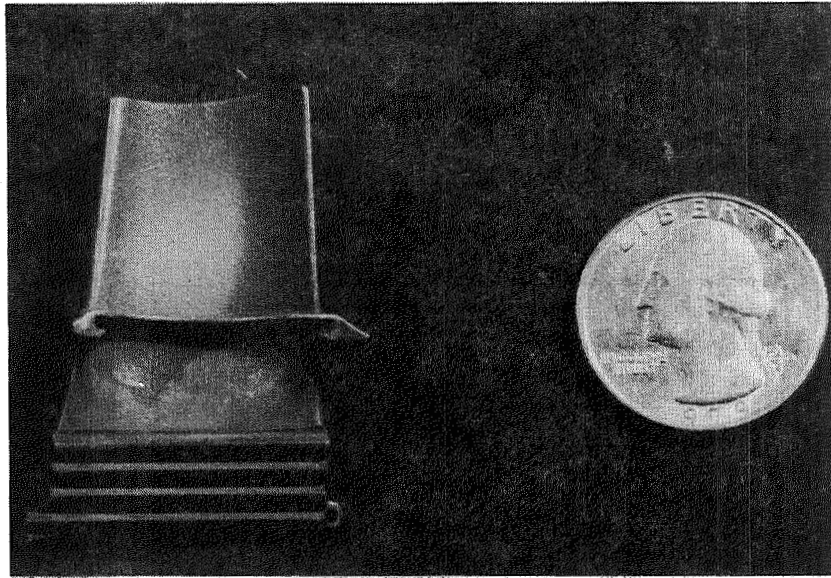


FIGURE 1. SSME FIRST STAGE HIGH PRESSURE FUEL TURBOPUMP TURBINE BLADE THAT DEVELOPS ROUGHLY 600 HP AT LIFTOFF, COMPARED TO A 25¢ PIECE.

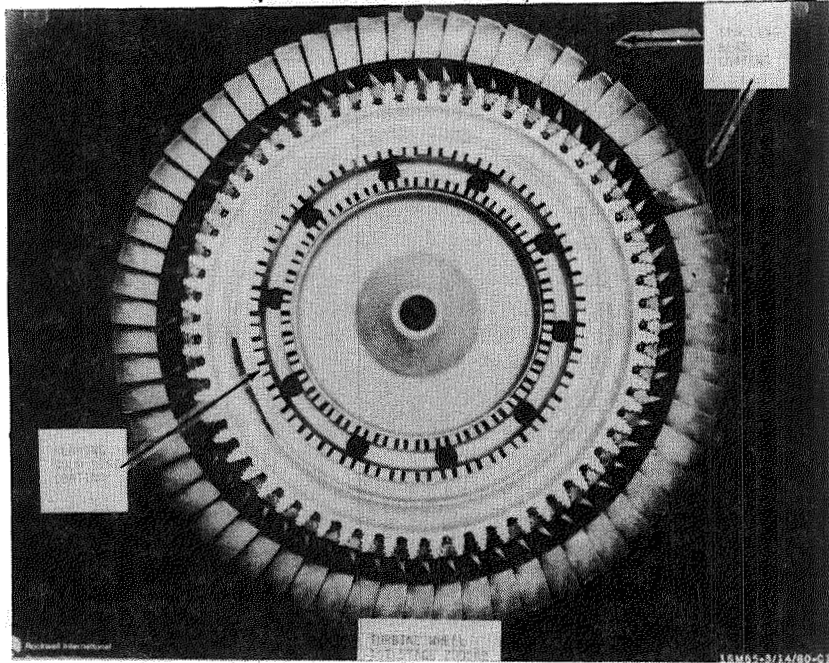


FIGURE 2. SSME FIRST STAGE HIGH PRESSURE FUEL TURBOPUMP TURBINE WHEEL SHOWING SPALLED TURBINE BLADES.

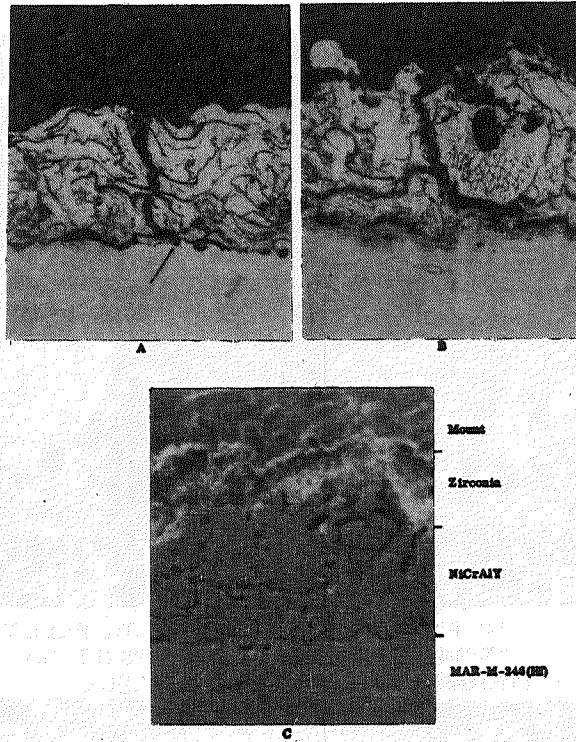


FIGURE 3. NiCrAlY AIRFOIL LEADING EDGE CRACKING ON BLADE 9Z13 FROM HPFTP 9005 (A&B) AND THIN LAYER OF ZIRCONIA ON NiCrAlY (C). MAG. 400X

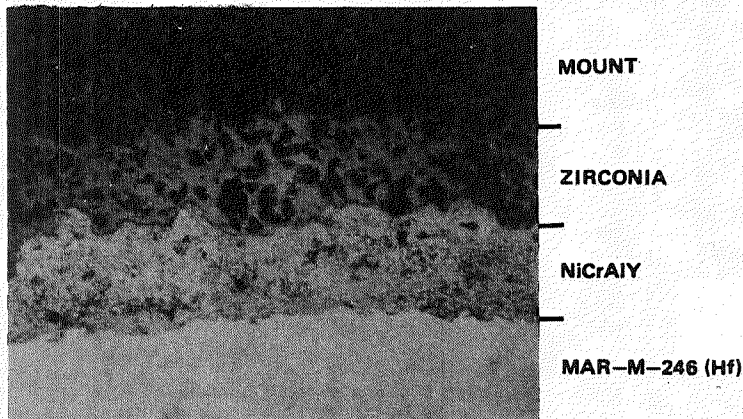


FIGURE 4. NiCrAlY AIRFOIL LEADING EDGE APPLIED BY LOW PRESSURE PLASMA FLAME SPRAY SHOWING IMPROVEMENTS: (1) NO CRACKS IN NiCrAlY BOND COATING. (2) NO OXIDE LAYERS IN NiCrAlY BOND COATING. MAG. 200X

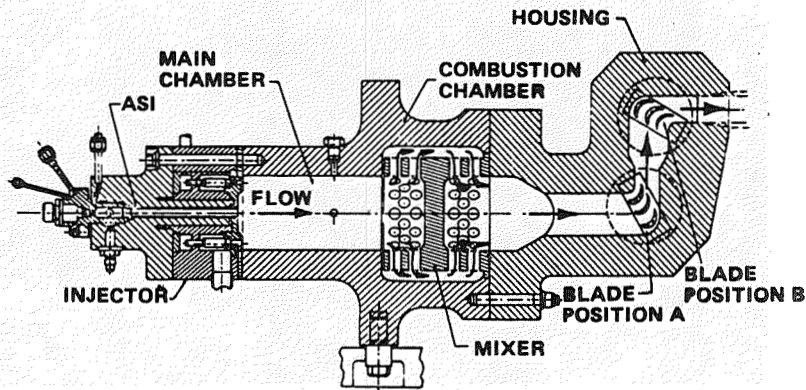


FIGURE 5. BURNER RIG THERMAL CYCLING TESTER

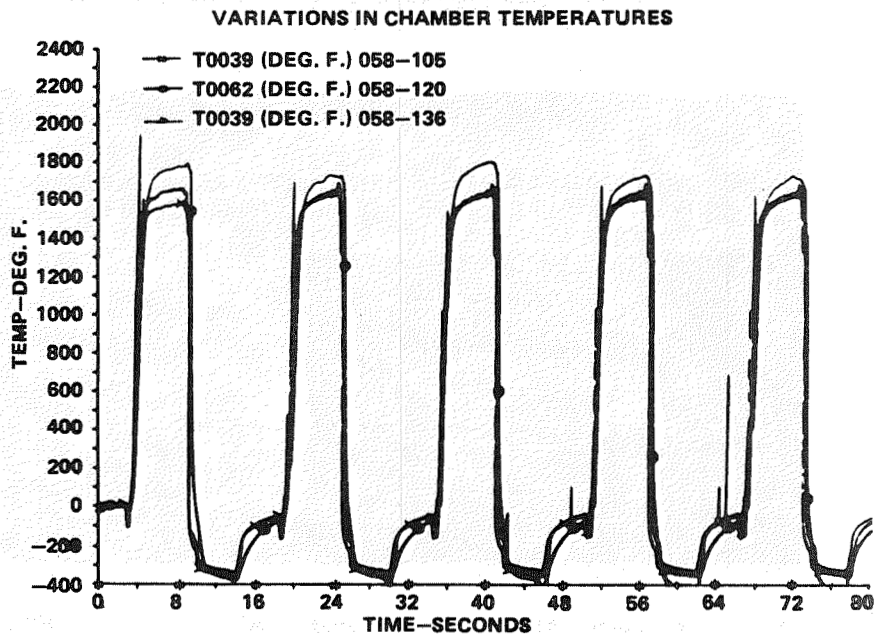


FIGURE 6. VARIATIONS IN BURNER RIG CHAMBER TEMPERATURE OVER FIVE 15 SECOND CYCLES BETWEEN 1700°F AND -350°F.

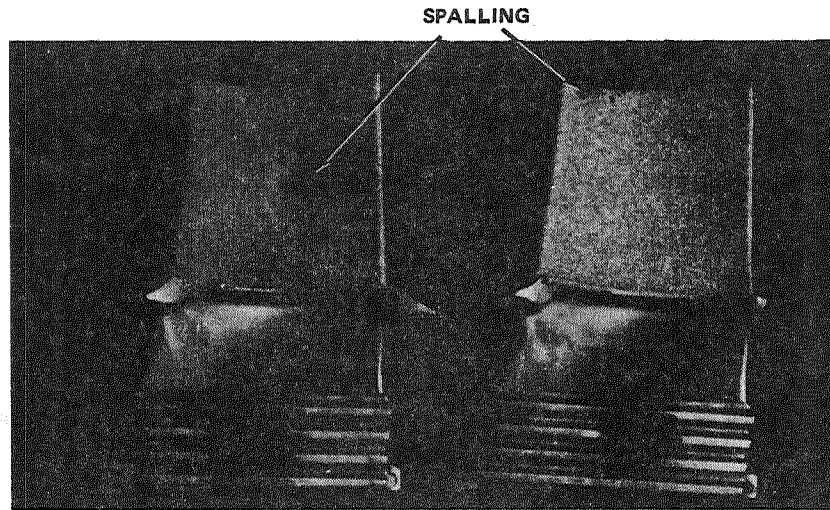


FIGURE 7. BASELINE SSME TURBINE BLADES, ATMOSPHERICALLY PLASMA SPRAY COATED WITH .007" -200/+325 MESH NiCrAlY AND TESTED 25 CYCLES IN MSFC BURNER RIG BETWEEN 1700°F AND -350°F.

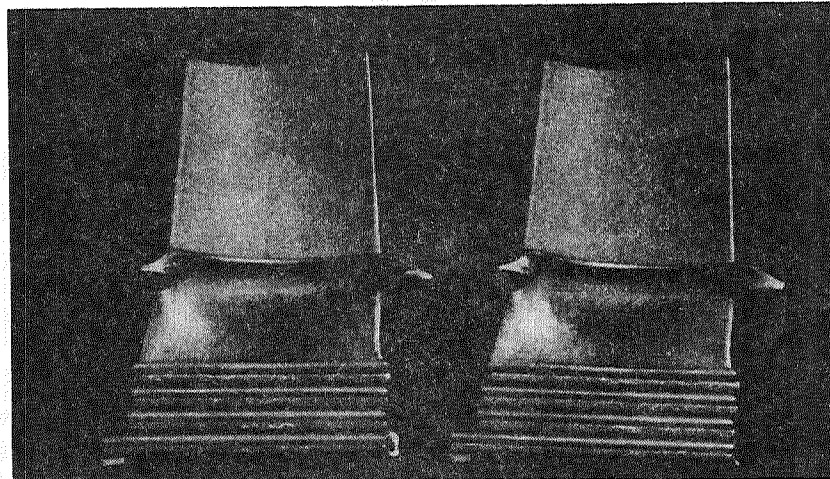


FIGURE 8. SSME TEST TURBINE BLADES VACUUM PLASMA SPRAY COATED WITH .006" -200/+325 MESH NiCrAlY AND TESTED 25 CYCLES IN MSFC BURNER RIG BETWEEN 1700°F AND -350°F.

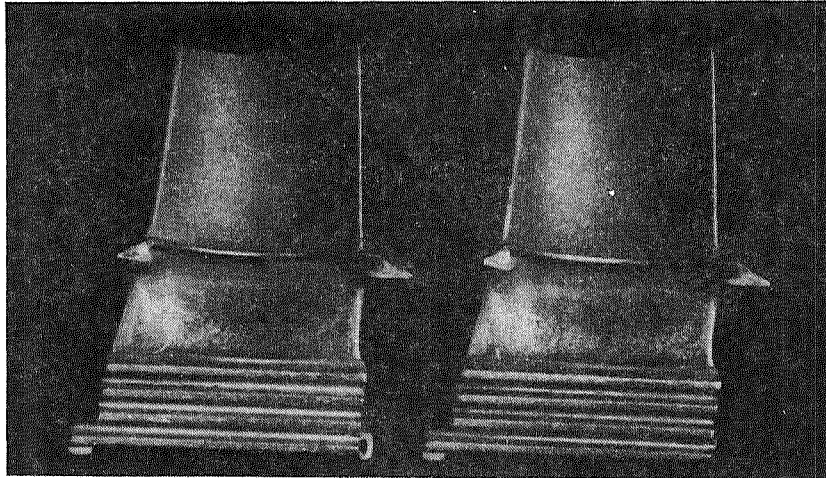


FIGURE 9. SSME TEST TURBINE BLADES VACUUM PLASMA SPRAY COATED WITH .003" -400 MESH NiCrAlY, AND .004" 50/50 NiCrAlY/Cr₂O₃ AND TESTED 25 CYCLES IN MSFC BURNER RIG BETWEEN 1700°F AND -350°F.

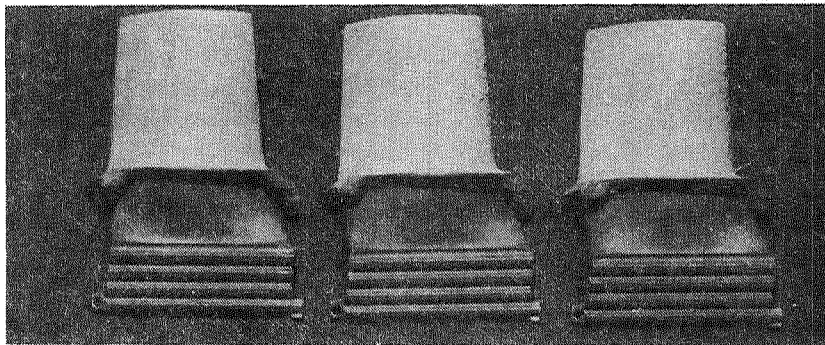


FIGURE 10. SSME TEST TURBINE BLADES VACUUM PLASMA SPRAY COATED WITH .003" -200/+325 MESH NiCrAlY AND ATMOSPHERICALLY SPRAYED WITH .004" -200/+325 MESH ZrO₂ AND TESTED 25 CYCLES IN MSFC BURNER RIG BETWEEN 1700°F AND -350°F.

TABLE 1
 PLASMA COATED TURBINE BLADES
 BURNER RIG CYCLIC THERMAL TESTING
 25 CYCLES (1700°F TO -350°F)

<u>VACUUM SPRAY POWER MESH</u>	<u>BOND COATING*</u>	<u>THERMAL BARRIER COATING (4 MIL)</u>	<u>RATING** 100=PERFECT</u>	<u>COMMENTS</u>
-200/+325	NiCrAlY	-	95	NO SPALLING
-400	CoCrAlY	-	94	NO SPALLING
-400	NiCrAlY	-	93	NO SPALLING
-200/+325	NiCrAlY	Cr ₂ O ₃ .50 NiCrAlY	94	NO SPALLING
-400	CoCrAlY	Cr ₂ O ₃ .50 CoCrAlY	94	NO SPALLING
-400	NiCrAlY	Cr ₂ O ₃ .50 NiCrAlY	93	NO SPALLING
-200/+325	NiCoCrAlY	-	25	SPALLING
<u>ATMOSPHERIC SPRAY SSME BASELINE</u>				
-200/+325	NiCrAlY	-	35	SPALLING

* BOND COATING ONLY : 6 MIL THICKNESS
 BOND COATING BEFORE ADDING THERMAL BARRIER COATING: 3 MIL THICKNESS

** 3 BLADES EACH SAMPLE

TABLE 2
 PLASMA COATED TURBINE BLADES
 BURNER RIG CYCLIC THERMAL TESTING
 25 CYCLES (1700°F TO -350°F)

VACUUM SPRAY MESH	BOND COATING (3 MIL)	THERMAL BARRIER COATING (4 MIL)	DIFFUSION BOND 4 HRS VAC	RATING † 100=PERFECT
-200/+325	NiCrAlY	ZrO ₂ . 12Y ₂ O ₃	1975°F**	75
-200/+325	NiCrAlY	ZrO ₂ . 8Y ₂ O ₃	1975°F	66
-200/+325	NiCrAlY	ZrO ₂ . 12Y ₂ O ₃	1975°F	65
-200/+325	NiCrAlY	ZrO ₂ . 7Y ₂ O ₃ *	1975°F	70
-400	NiCrAlY	ZrO ₂ . 8Y ₂ O ₃	1975°F	51
-400	NiCrAl*	ZrO ₂ . 7Y ₂ O ₃ *	1975°F	31
-400	CoCrAl*	ZrO ₂ . 7Y ₂ O ₃ *	1975°F	21

* PROPRIETARY COATINGS

** AGED 24 HRS @ 1600°F AFTER DIFFUSION BOND TREATMENT

+ 3 BLADES EACH SAMPLE

TABLE 3
PLASMA COATED TEST SPECIMENS
TESTED AT 1500°F

VACUUM SPRAY MESH	BOND COATING	THERMAL BARRIER COATING	DIFFUSION BOND 4 HRS @ °F	AGEING 24 HRS	TENSILE [†] STREN. (LB/IN. ²)
-200/+325	NiCrAlY	ZrO ₂ .12Y ₂ O ₃	—	—	147,000
-200/+325	NiCrAlY	ZrO ₂ .12Y ₂ O ₃	1975°F	1600°F	154,000
					FATIGUE LIFE [†] (CYCLES)
-200/+325	NiCrAlY	ZrO ₂ .12Y ₂ O ₃	1975°F	1600°F	2.7 x 10 ⁶
-200/+325	NiCrAlY	ZrO ₂ .12Y ₂ O ₃	1975°F	1600°F	5.2 x 10 ^{6*}
-400	CoCrAl**	ZrO ₂ .7Y ₂ O ₃ **	1975°F	1600°F	2.9 x 10 ⁶
NO COATING	CONTROL	—	—	—	2.9 x 10 ⁶

* THESE TEST SPECIMENS DIFFER FROM THE OTHERS IN THAT AFTER MACHINING FROM TEST BARS, THEY WERE SOLUTION TREATED AT 2230°F FOR 2 HRS IN VACUUM BEFORE PLASMA SPRAYING WITH NiCrAlY FOLLOWED BY ZrO₂.12Y₂O₃. ALL PLASMA COATED FATIGUE SPECIMENS WERE SUBSEQUENTLY DIFFUSION BOND TREATED 4 HRS AT 1975°F IN VACUUM AND AND AGED 24 HRS AT 1600°F IN AIR.

** HOWMET PROPRIETARY COATINGS

† 2 TEST SPECIMENS EACH TENSILE TEST

† 4 TEST SPECIMENS EACH FATIGUE TEST