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Progress in Protective Coatings for Aircraft Gas Turbines: A Review of NASA Sponsored Research

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ABSTRACT

The status of several recent NASA sponsored coatings technology programs are reviewed. These efforts were focused on problems associated with advanced aircraft gas turbines. In one program, metallic coatings for preventing titanium fires in compressors were identified. The other four efforts were focused on coatings for the turbine section. In one of the latter, ductile aluminide coatings for protecting internal turbine-blade cooling passage surfaces were identified. In a second, composition-modified external overlay MCrAlY coatings deposited by low-pressure plasma sprayings were found to be better in surface protection capability than vapor deposited MCrAlY coatings. The remaining two efforts focused on thermal barrier coatings (TBC). In one, computer-aided manufacturing technology was applied to the TBC coating of turbine airfoils. In the other, the design of a turbine airfoil was integrated with a TBC.

INTRODUCTION

In the past ten years, the NASA Lewis coatings programs stressed the improvement of aluminide and metal overlay coatings for aircraft gas turbines (References 1-14) and coated metallic and ceramic heat shield concepts

(References 15-24) for the space shuttle. Recently, our efforts have focused exclusively on advanced coating systems for aircraft gas turbines. The need for improved oxidation resistant coatings arises from the development of alloys with increased operating temperature/strength capability, but with poor environmental resistance. Very often these advanced alloys have mechanical or chemical properties which limit the use of conventional coatings; therefore, the alloy, the coating, and the turbine blade design are being addressed as an integral system.

With ever-increasing turbine temperature and pressures, protective coatings are not only required for external gas turbine airfoil surfaces but also for internal air-cooling passages. One recent NASA-sponsored program has addressed this internal coating need. In the past internal passage protection was obtained by a vapor deposited coating from a pack process. Coating composition was limited to that of a simple aluminide with accompanying low ductility.

The physical vapor deposited MCrAlY coatings were developed in the 1970's. Today, MCrAlY coatings needed to meet the protection requirements of advanced engine alloys are limited by compositional flexibility problems. In addition, high capital-cost equipment is required. These factors and the recent development of thermal barrier coatings (TBC) have resulted in our focusing the bulk of our effort on plasma sprayed coatings. Advances in plasma spray equipment and in computer-aided manufacturing are being exploited. The low-pressure plasma spray process has been used in one contract to expand the range of available metallic coating compositions and properties. In another contract effort, adaptive computerized plasma-spray coating equipment has been developed for the application of thermal barrier coatings. Adhering to the systems approach for advanced coatings, thermal barrier coating thickness contour can be designed and successfully manufactured with this equipment. This substrate/coating system philosophy was applied in another contract aimed at tailoring of a thermal barrier coating/gas turbine blade design.

In a departure from our past in-house and contractual dealing with the area of high-temperature surface protection efforts, a contract addressed the problem of titanium combustion in aircraft engine compressors. This effort was directed at prevention of sustained titanium combustion by means of protective coatings.

What follows are summaries of the results of five recently-completed contracts and a look at our future thrusts. The titanium combustion problem and the process development for internal coatings will be covered first followed by the MCrAlY and TBC coating studies and the automated plasma spray equipment development.

COATINGS FOR TITANIUM COMPRESSOR BLADES

Based on strength-to-density ratio up to 480°C (900°F), titanium offers a substantial weight reduction in gas turbine engine compressor components. However, there is one significant problem with titanium--combustion. When sufficient energy is supplied to titanium, it will spontaneously ignite (exothermic reaction) and continue to burn and melt until consumed or the metal temperature is reduced below the ignition temperature.

This problem has resulted in the removal of titanium alloys from selected regions in axial flow compressors—particularly to avoid potential of titanium-to-titanium rubs.

Two approaches to solve the problem of titanium fires in gas turbine compressors are abrasive blade tip treatments and coatings. The tip treatment approach is aimed at reducing the amount of energy transmitted to titanium blades during rubs with the case. With protective coatings, the surface melting and burn characteristics are modified so that ignition events do not result in sustained combustion. The abrasive blade tip treatment approach was sponsored by the Air Force, and the coating approach by NASA. In both cases the contractor was the Government Products Division of Pratt and Whitney Aircraft (PWA, Florida).

The objective of the titanium coating program was to develop, starting with the thirteen coatings shown in Table I, a coating system which could protect titanium under energy input conditions that ignite bare titanium. In addition, the coating must have no adverse effect on the titanium physical and mechanical properties, especially high cycle fatigue life. Using a laboratory laser screening test under the conditions shown in Table I, seven coatings provided ignition resistance at normal engine operating conditions and also under a more severe condition of increased temperature. However, ignition occurred in all seven of these coatings under temperature and pressure conditions beyond engine operating conditions. Examples of the burn response of the most fire-resistant coating, Pt/Cu/Ni, to a range of temperature/pressure/velocity parameters, are shown in figure 1.

Normally, coatings applied to titanium cause a loss in fatigue life. To further evaluate the seven best coatings, reverse bending fatigue tests were carried out. The results are shown in figure 2. The ion vapor deposited (IVD) aluminum and Pt/Cu/Ni coatings gave high-cycle fatigue lives equivalent to bare Ti-8Al-1Mo-1V.*

Concurrent with this program, an Air Force Wright Aeronautical Laboratory/Aeronautical Propulsion Laboratory (AFWAL/APL) contract with PWA, Florida examined the cascade combustion (molten metal ignition) of the IVD aluminum and electroplated Pt/Cu/Ni coatings developed under the NASA contract with PWA, Florida. The NASA sponsored effort examined the mechanical and physical properties of the two coatings on Ti-8Al-1Mo-1V and the AF alloy (Ti-3Al-6Cr-8V-4Mo-4Zr).

In a cascade combustion test, a bare titanium specimen is placed upstream of a coated specimen. The bare specimen is laser ignited, and the molten titanium flows over the coated specimen causing it to ignite. The cordwise burn velocity (combustion rate) and burn severity were determined over the following parameter ranges:

Pressure	0.275-0.520 MPa (40-80 psia)
Temperature (gas)	315-440 $^{\circ}$C (660-875 $^{\circ}$F)
Air Velocity	183-305 m/sec. (600-1000 ft/sec.)
Coatings	IVD aluminum Pt/Cu/Ni
Coating Thickness	0.005, 0.008, 0.010 cm. (0.002, 0.003, and 0.004 in.)

Analysis of the data showed that the type of coating has no significant effect on cordwise burn velocity while increased coating thickness decreases it. Both pressure and air velocity have the greatest effect on cordwise burn velocity. Cordwise burn velocity increases with increasing pressure and temperature.

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* All compositions in weight percent.

In Table II is a summary of the tests used to determine what effect, if any, the Pt/Cu/Ni and IVD aluminum coatings had on several properties of Ti-8Al-1Mo-1V.

The conclusions from the program are that the Pt/Cu/Ni and IVD aluminum coatings provide potential systems to resist titanium ignition under certain high impact energy conditions.

As with all laboratory coating development programs, including three of the other programs described here, acceptance of a coating innovation or improvement requires engine verification. However, in this case, the risk in a ground-based engine test is high since titanium fires can destroy the engine. Therefore, engine verification of the potential of the abrasive blade tip treatments and the coatings to eliminate the titanium combustion problem can not be as readily confirmed as are other coating innovations. The report from this contract should be published during the second quarter of 1981, as NASA CR-165360.

INTERNAL COATING OF AIR-COOLED GAS TURBINE BLADES

Aircraft gas turbine engine performance has been improved by operating at higher temperatures and pressures. Air-cooling of first- and second-stage turbine blades and vanes were required to achieve the improved efficiency while keeping metal temperatures down to acceptable levels. With these higher operating temperatures and less resistant alloys, the external as well as the internal surfaces of blades and vanes need to be protected. Without internal coatings, internal passages with as much as ten percent of the cross-section consumed by hot corrosion have been seen in the field (Reference 25). The use of air-cooling in advanced airfoils also requires that both internal and external coatings be relatively ductile at low operating temperatures.

The objective of the internal coatings program with Solar was to develop coating compositions having a balance of environmental resistance and low temperature ductility. Coatings were applied to IN-792 + Hf using the dry powder pack method. The coating systems investigated were: Ni-19Al-1Cb, Ni-19Al-3Cb, Ni-12Al-20Cr and Ni-17Al-20Cr based on the results of a previous contract (Reference 25). These coatings were evaluated in a hot corrosion burner rig test at 900^{0}C, with a 4 ppm salt level in air. After 300 hours of hot corrosion exposure, the depth of hot corrosion penetration was least (19-32 μm) for the Ni-Cr-Cb systems while the Ni-Al-Cr systems showed deeper penetration (32-50 μm).

The results of a furnace oxidation test are shown in figure 3. The oxidation resistance of the coated specimens is significantly better than that for bare IN-792, with the 3Cb coating being the least oxidation-resistant coating. The data presented in Table III indicate that the Ni-Al-Cr and Ni-Al-Cb coatings have ductilities significantly better than aluminides. However, the high-cycle fatigue life of IN-792 with these coatings was only equivalent to that of the commercial RT-22 coating on IN-792.

The Ni-19Al-1Cb, Ni-19Al-3Cb and the Ni-12Al-20Cr coatings were applied to the internal surfaces of first-stage Mars Engine turbine blades. Metallgrapnic examination after a 500 hour cyclic endurance test showed that the Ni-19Al-1Cb coating provided the best protection. The Ni-12Al-20Cr coating was the least protective witn total coating consumption evident in areas of the blade where pack coating volume was insufficient to form a coating of the desired thickness.

In conclusion, a dry powder pack method for Ni-Al-Cb and Ni-Al-Cr alloyed aluminide coating systems has been demonstrated through laboratory tests and a ground-based engine test. Compared to the externally applied coating thicknesses, internally applied coating thicknesses were less by 10 to 20 percent because of the restricted pack volume that can be placed in the blade core. The Ni-19Al-1Cb system had superior oxidation and hot corrosion resistance compared to the other 3 systems examined. While the coating ductility was superior to that of simple aluminides, their effects on IN-792 properties (tensile, HCF, and stress rupture) were similar to that of aluminide coatings. The report from this contract should be published in the second quarter of 1981, as NASA CR-165337.

PLASMA SPRAYED COATINGS

The next two contracts were initiated as the result of NASA Lewis in-house coating efforts in the area of metal overlay and thermal barrier coatings (References 26-47). In the case of the overlay coatings (alloyed-aluminides generally called MCrAlY's), the electron beam-physical vapor deposition (EB-PVD) technique was used to apply MCrAlY overlay coatings on commercial aircraft gas turbine engine blades and vanes. Because EB-PVD is a vaporization process and the vapor pressures of the various elements (Ni, Co, Fe, Cr, Al, Y, Cb, Ta, Si, and others) are significantly different, it is difficult to add Si or one of the refractory elements to the MCrAlY metal pool stock and reproducibly obtain the coating composition desired and yet maintain an economic process.

Recent advances in air- (Reference 48) and low-pressure plasma spray equipment with the help of computerized control have made plasma spraying an attractive alternative to EB-PVD systems. Plasma spray equipment involves significantly lower capital investment, and it is easier to operate and to control the coating composition than with EB-PVD equipment. This becomes more pronounced as the coating compositions become more complex. In addition, the range of available coating compositions is virtually unlimited with the plasma spray process. However, up until recent contractual efforts, EB-PVD coatings have consistently outperformed plasma spray coatings of equivalent composition.

TAILORED PLASMA SPRAY MCrAlY COATINGS FOR GAS TURBINE APPLICATIONS

The purpose of the investigation, under a contract with the Commercial Products Division of Pratt and Whitney Aircraft (PWA, East Hartford), was to obtain equivalent or better plasma sprayed coating performance than current electron-beam physical vapor deposited MCrAlY coatings in both the high temperature oxidation and hot corrosion environments found in advanced aircraft gas turbines. Fifteen compositional/process variations of plasma sprayed MCrAlY coatings (NiCoCrAlY and CoCrAlY) were investigated. Table IV shows the processes and coating compositions used for the single crystal alloy 454 (Ni-10Cr-5Co-4W-12Ta-1 5Ti-5Al) in oxidation applications. With the same processes, a CoCrAlY coating (Co-22/29 Cr-10/12.5 Al-0.6 Y) plus 2.0 Si on B1900 + Hf was investigated for hot corrosion applications.

The microstructures of NiCoCrAlY coatings produced by different plasma spray methods (i.e.-air plasma sprayed, one-atmosphere argon chamber plasma sprayed (ACS) and low-pressure chamber plasma sprayed (LPCS)) are shown in figure 4. The LPCS NiCoCrAlY's are more dense and have less oxide present in the coating than the ACS and air-plasma sprayed NiCoCrAlY's. The effect of these differences on 1148°C (2100°F) burner rig oxidation life of Mar-M200 + Hf specimens is shown in figure 5.

The oxidation results of the best low-pressure chamber plasma spray (LPCS) MCrAlY + Si coating for each alloy are compared to electron-beam physical vapor deposited (EB-PVD) and LPCS MCrAlY coatings (without Si) in figures 6 and 7. The performance of both MCrAlY + Si coatings in these Mach 0.3 burner rig tests was superior to those of the EB-PVD and LCPS MCrAlY coatings without Si. In the case of NiCoCrAlY coatings, the silicon addition doubled the life of the coating; the CoCrAlY + Si coating in the oxidation test (1120°C) proved to be about fifty percent better than the coatings without Si.

In cyclic burner rig hot corrosion testing at 900°C (30 ppm sea salt; equivalent of 1.30 wt. percent sulfur in the fuel added via SO_2), all the MCrAlY coatings with and without additives (Si, Ta, and Hf) on both alloys provided satisfactory protection beyond 500 hours of exposure.

Superior fracture strain capability was shown by the LPCS MCrAlY coatings over similar EB-PVD compositions, figure 8. However, the addition of Si to the LPCS MCrAlY significantly lowered the fracture strain value. The percent fracture strain with Si is less than for EB-PVD coated alloys, but is more than sufficient for the intended application.

In summary, based on laboratory oxidation tests at 1120°C, the LPCS MCrAlY-plus-Si coatings on the single crystal alloy 454 and B1900 + Hf alloys are superior in performance to similar EB-PVD and LPCS MCrAlY coatings without

Si or with other elemental additions. Hot corrosion test results at 900°C, showed no significant difference in life between coating compositions or processes used. In the 315°C ductility test, the LPCS MCrAlY-plus-Si displayed greater ductility than aluminide coatings. Testing of these coated alloys in ground-based test engines will be used to confirm the laboratory results. The report (NASA CR-163234) from this contract was published in January 1981.

THERMAL BARRIER COATED TURBINE BLADE STUDY

Thermal barrier coatings on air-cooled blades can be used to extend the life or increase engine operating efficiency. The actual trade-offs are many and need to be identified with the total engine operation as well as the component involved. The most readily apparent trade-offs are lower component metal operating temperature with extended life, or reduced cooling air with increased engine efficiency while maintaining the same component operating temperature.

The approach taken in this program was to perform a parametric design study to identify the benefits and trade-off factors for a thermal barrier coating on CF6-50 second-stage turbine blades. This blade was selected because it is convection cooled whereas the first-stage blade is film-cooled and thus cannot be readily coated without extensive fixturing. Table V illustrates the data obtained from one such trade-off study where the rupture life and low cycle fatigue (LCF) life factors are compared for a number of cooling-air flow conditions when the maximum blade temperature is restricted to 980°C (1800°F). Using 100 percent cooling-air flow through a bare blade as the baseline factor of one, 0.025 cm of coating would increase the rupture life by a factor of 35 and the LCF life by a factor of 1.25. If there is a local spallation (down to the bond coating) with 100 percent air flow, there still would be a 24-fold increase in rupture life, while the LCF life would fall to 0.7 of the bare-blade baseline.

Of greatest significance is the case where cooling air flow is reduced by 50 percent while maintaining the baseline LCF life.

However, in this fully coated design the bond coat temperature is expected to limit coating life. Without the trailing edge of the blade coated, somewhat more than 65 percent of the cooling air would be needed to maintain a rupture and LCF life factor of one. This design has the aerodynamic advantage of no increase in blade trailing edge thickness. In another study, where a complete redesign of the blade for optimum benefits with a TBC coating was considered (integral design), the cooling-air could be reduced to around 55 percent of the baseline while maintaining the rupture and LCF life of a bare blade and not exceeding 980°C (1800°F) bond coat temperature. The above trade-off studies illustrate the need to examine all of the ramifications involved in applying thermal barrier coatings since their presence (or loss) can change the mechanical and/or physical characteristics of a component far more than any previously used coating system.

Concurrent with the parametric design study, a coating development effort was performed to evaluate two plasma spray processes and the effects of coating thickness, bond and ceramic coating compositions, and substrate composition variables. Specimens were exposed to a series of one-hour furnace cycles from 140°C to 1100°C. The results for each of the variables investigated are illustrated in Figure 9. The study showed that magnesia-stabilized zirconia destabilized while yttria-stabilized materials exhibited no phase changes during the exposure. The ceramic thickness had no significant effect (< 5 percent) on life, while the bond coat deposition process di'. The low-pressure/high-velocity (LP/HV) processed bond coating gave about 25 percent longer life than the conventional air-processed bond coating. Bond coat and substrate composition were also significant variables. An increase in bond coat chromium content from 16 to 22 percent increased life about 20 percent. There was a 17 percent difference in coating life between the two substrate alloys (Rene 80 > Hastelloy-X).

The Ni-22Cr-10Al-1Y bond coating with the 8 Y_2O_3 - ZrO_2 ceramic system deposited by air and LP/HV processes were used to coat specimens for burner rig oxidation and hot corrosion tests, and based on the rig test results, the LP/HV process was used to coat second-stage blades for a CF6-50 engine test. The full-scale land-based CF6-50 engine test showed that thermal barrier coatings developed in this program can operate for at least 625 endurance cycles on the second stage blade. Further testing is in process. The contractor report should be published in the third quarter of 1981, as NASA CR-165351.

AUTOMATED PLASMA SPRAY PROCESS FEASIBILITY STUDY

The purpose of this contract with the Equipment Division of TRW was to conduct an automated plasma spray (APS) process feasibility study for the application of coating materials to turbine blades, specifically thermal barrier coatings at this time. The APS equipment developed integrates a multi-axis blade handling fixture, a non-coherent optical instrument for coating thickness measurement, plasma spray equipment operating in the ambient environment, and a microprocessor-based system controller. A schematic of the APS process is shown in Figure 10, and the actual equipment is shown in Figure 11. Figure 12 is a close-up showing the plasma gun and optical probe which move up and down along the vertical screw axes. The blade surface is always oriented perpendicular to both the optical probe during measurement and the plasma spray gun during spraying. Through deposition of a series of overlapping strips of spray, any coating contour thickness can be built up on the blade. Coating thickness is measured by manuevering the blade in front of the optical probe by means of the multi-axis blade handling fixture via the appropriate software program. With feedback from the optical probe measurement, the blade is repositioned if necessary, to complete the desired amount of coating buildup. Further details are given in reference 46.

In Figure 13, a comparison of APS optical probe and metallographic coating thickness measurements at various locations around a turbine blade airfoil is presented to illustrate the accuracy of the optical probe measurements. Table

VI shows a comparison of the coating uniformity and repeatability obtained on manual and APS sprayed blades. Production coated blades will require the uniformity and repeatability of an automated system.

The APS equipment developed is not a production prototype, but was built to prove the feasibility of an automated plasma spray process with feedback control to apply two-layer thermal barrier coatings and as a research and development apparatus to study plasma spray processing. Further improvements in APS durability are required for a production system.

CONCLUDING REMARKS

Our contractual coatings program efforts follow the directions pointed out by our in-house research and the future technology needs of the aerospace industry. Currently, there is a contract to improve the strain tolerance of thermal barrier coatings. NASA Lewis in-house efforts are continuing to better understand and improve thermal barrier coatings. We are presently studying the metallic coating instability problems associated with oxide dispersion strengthened alloys. In addition, we are addressing methods for overcoming the chemical/mechanical compatability problems anticipated for advanced superalloys and strategic materials conservation alloys. Finally, we are developing an improved coating-life prediction methodology.

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TABLE I. - LASER SCREENING TESTS OF TITANIUM FIRE PREVENTION COATINGS
(LASER ENERGY IGNITES BARE TITANIUM UNDER CONDITIONS SHOWN)

NOMINAL ENGINE CONDITIONS		ACCELERATED TESTS			
370° C/0.76 MPa/244 m/s		455° C/0.76 MPa/244 m/s		455° C/0.96 MPa/244 m/s	
COATING	% BURN	COATING	% BURN	COATING	% BURN
IVD Al	0	IVD Al	1	IVD Al	47.5
Pt - Cu - Ni	0	Pt - Cu - Ni	0	Pt - Cu - Ni	47.0
Cr - Mo - Cu - Ni	0	Cr - Mo - Cu - Ni	0	Cr - Mo - Cu - Ni	44.6
Cr - Mo - Ni	0	Cr - Mo - Ni	0	Cr - Mo - Ni	58.8
Cr - Mo - IVD Al	13	Cr - Mo - IVD Al	0	Cr - Mo - IVD Al	60.0
Cr - Mo - Al - Mn	0	Cr - Mo - Al - Mn	0	Cr - Mo - Al - Mn	64.7
Pt - IVD Al	0	Cr - TiC CERMET	1	Cr - TiC CERMET	100.0
Cr - TiC CERMET	0	Cr - Mo	37		
Al - Mn	0	Pt - IVD Al	38		
Cr - Mo	0	Al - Mn	55		
Pt - Al - Mn	56				
Cr	67				
Pt	100				

TABLE II. - SUMMARY OF TEST RESULTS FOR COATED
Ti-8Al-1Mo-1V ALLOY PROPERTIES

PROPERTY EVALUATED	Pt/Cu/Ni	IVD Al
COMBUSTION RESISTANCE	+	++
HCF	0	0
TENSILE	0	0
CREEP RUPTURE	0	0
HOT SALT S.C. RESISTANCE	0	0
STRESS RUPTURE	+	0
EROSION RESISTANCE	+	+
ADHESION	GOOD	GOOD
STATIC OXIDATION RESISTANCE	–	–
DIFFUSION	0	0
THERMAL SHOCK RESISTANCE	0	0
STRESS ANALYSIS	0	0

WHERE: 0 - NO SIGNIFICANT INFLUENCE DUE TO COATING
– - COATING HAD DEGRADING EFFECT ON BASELINE
+ - COATING APPEARED TO PROVIDE IMPROVEMENT OVER BASELINE

TABLE III. - INTERNAL COATING STRAIN TOLERANCE TEST RESULTS

COATING	TEMPERATURE		STRAIN (%)	
	(°C)	(°F)	NO CRACKS OBSERVED	CRACKS OBSERVED
Ni-19Al-1Cb	27	80	1.0	1.7
Ni-19Al-1Cb	427	800	2.0	2.7
Ni-19Al-1Cb	538	1000	2.2	2.8
Ni-19Al-1Cb	538	1000	1.2	1.7
Ni-19Al-1Cb	649	1200	2.4	2.7
Ni-19Al-3Cb	427	800	2.6	3.1
Ni-19Al-3Cb	538	1000	1.2	1.7
Ni-17Al-20Cr	427	800	2.5	3.0
Ni-17Al-20Cr	538	1000	1.4	1.8
Ni-12Al-20Cr	427	800	2.5	2.9
Ni-12Al-20Cr	538	1000	1.5	1.9

NOTE: TWO STRAIN VALUES ARE LISTED, ONE FOR THE LAST STRAIN INCREMENT BEFORE CRACKING WAS DETECTED AND THE OTHER FOR WHEN CRACKS WERE ACTUALLY FOUND. TYPICAL ALUMINIDE COATING DUCTILITY AT 425° C IS 0.4%.

TABLE IV. - CANDIDATE COATINGS AND PROCESSES EVALUATED ON
THE SINGLE CRYSTAL ALLOY 454
(Ni-10Cr-5Co-4W-1.5Ti-12Ta-5Al)

Processes

- **Electron beam vapor deposition (baseline)**
- **Low pressure chamber plasma spray**
- **Atmospheric argon plasma spray**

Coatings

- **NiCoCrAlY + Hf (0.8 w/o Hf)**
- **NiCoCrAlY + Ta (8.0 w/o Ta)**
- **NiCoCrAlY + Si (1.2, 1.6, 2.1 w/o Si)**
- **NiCoCrAlY + Si + Ta (1.6Si-4.0Ta, 1.6Si-8.0Ta)**

TABLE V. - POTENTIAL EFFECT OF A THERMAL BARRIER COATING ON THE LIFE OF CF6-50 2HPT BLADE

CONFIGURATION	COOLING AIR %	CERAMIC THICKNESS, cm	RUPTURE LIFE FACTOR	LCF LIFE FACTOR
BARE BLADE	100%	0	1.0	1.0
*FULLY COATED	100%	0.025	35.0	1.25
*FULLY COATED	50%	0.025	9.7	1.0
FULLY COATED EXCEPT T.E.	65%	0.037	1.0	0.9
*WORST LOCAL SPALLATION	100%	0.025	24.0	0.7

*982° C BOND COAT LIMIT EXCEEDED AT TRAILING EDGE

$$\text{LIFE FACTOR} = \left\{\frac{\text{CALCULATED LIFE COATED}}{\text{CALCULATED LIFE UNCOATED}}\right\}$$

TABLE VI. COMPARISON OF COATING UNIFORMITY AND REPRODUCIBILITY FROM MANUALLY AND AUTOMATED PLASMA SPARAYED (APS) TURBINE BLADES

COATING	MANUAL	APS
UNIFORMITY	± 76 μm (3 mils)	± 38 μm (1.5 mils)
REPEATABILITY (10 BLADE AVERAGE)		
NiCrAlY BOND COATING	± 112 μm (4.4 mils)	± 68.1 μm (2.7 mils)
TOTAL COATING	± 190 μm (7.5 mils)	± 98.3 μm (3.9 mils)

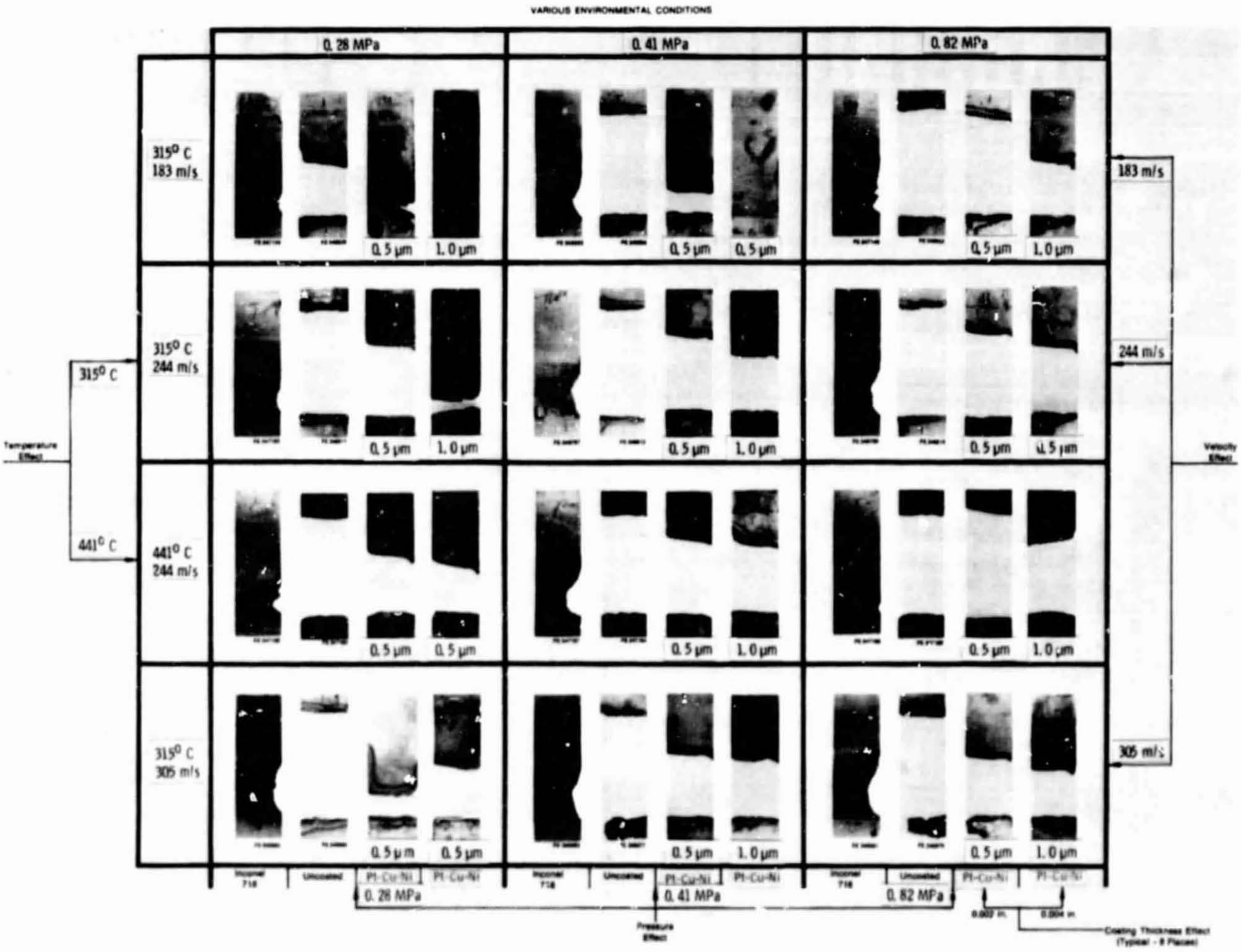

Figure 1. - Pt-Cu-Ni coated specimens after combustion screening tests.

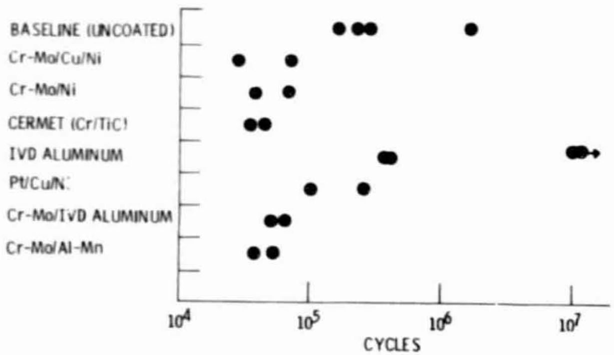

Figure 2. - Reverse bending fatigue results of coated Ti 8Al-1Mo-1V. (R = -1, alternating stress = + 0.38 GP temperature = 26° C.)

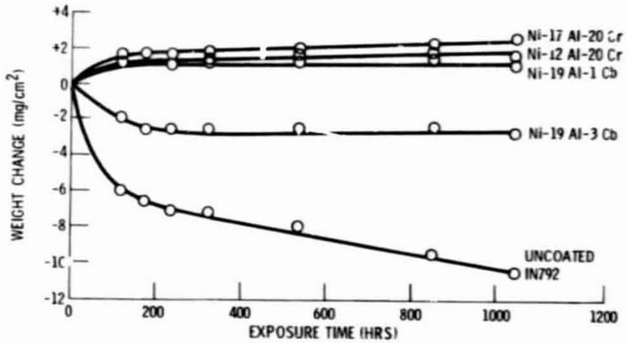

Figure 3. - Furnace oxidation weight change rate for potential internal coatings. (Static air at 1050° C (1920° F)).

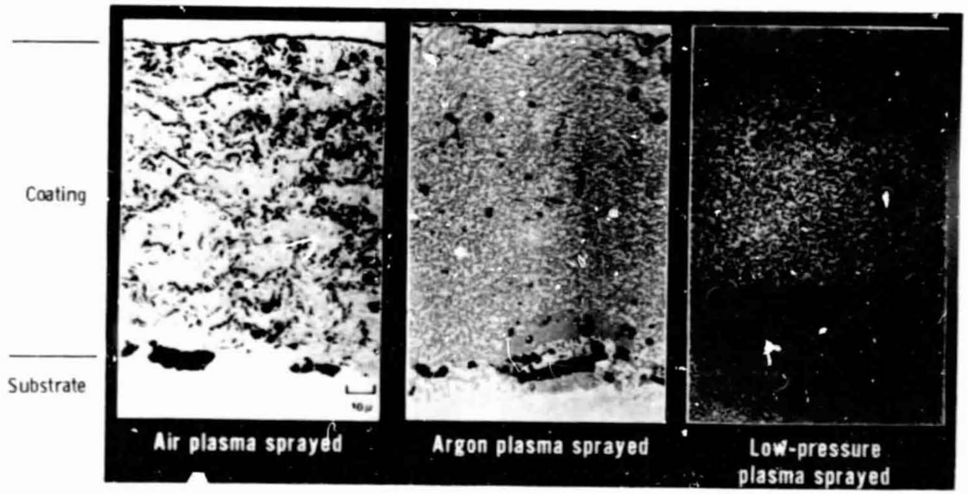

Figure 4. - Microstructures of plasma sprayed NiCoCrAlY coatings.

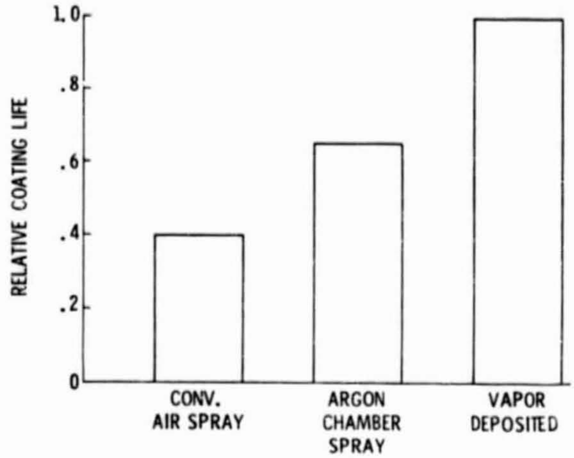

Figure 5. - Previous experience. 1148° C Mach 0.3 burner rig oxidation life of NiCoCrAlY coatings on Mar-M200 + Hf.

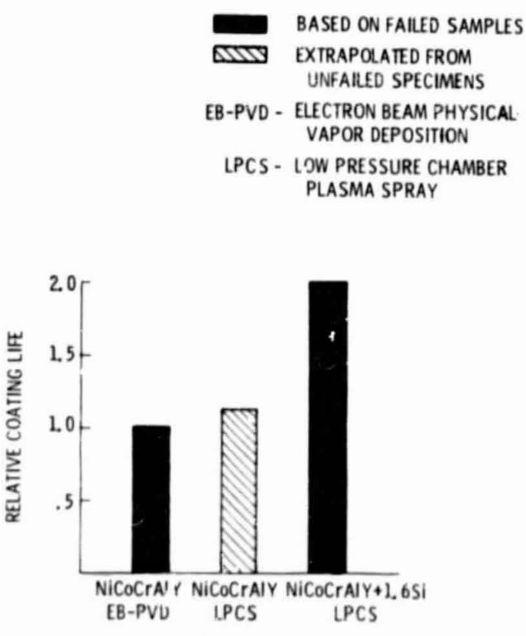

Figure 6. - 1120° C (2050° F) Burner rig life of NiCoCrAlY based coatings on a single crystal alloy 454.

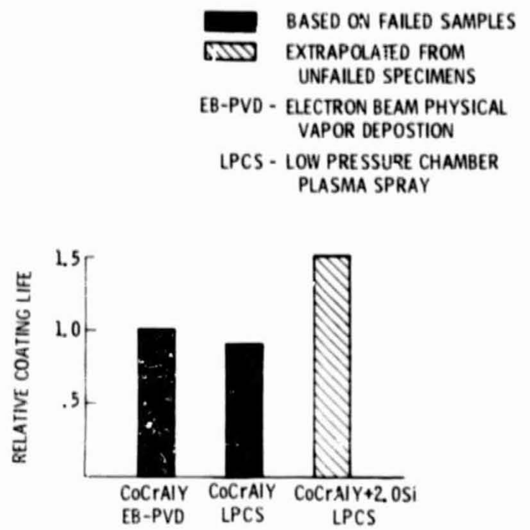

Figure 7. - 1120° C (2050° F) Burner rig life of CoCrAlY based coatings on B1900 + Hf alloy.

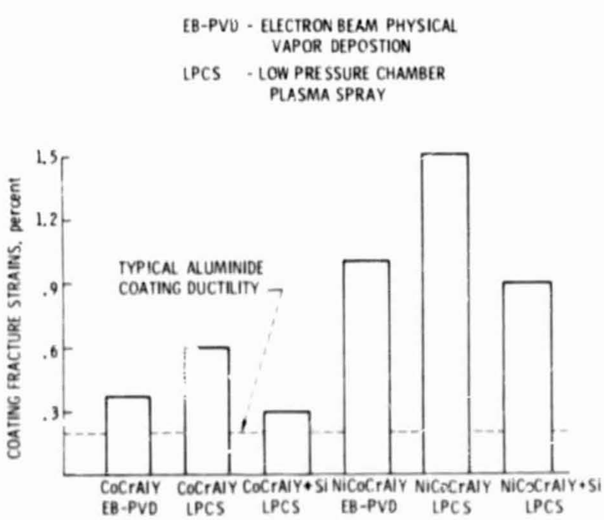

Figure 8. - 315° C (600° F) coating tensile ductility test results on coated B 1900 + Hf alloy.

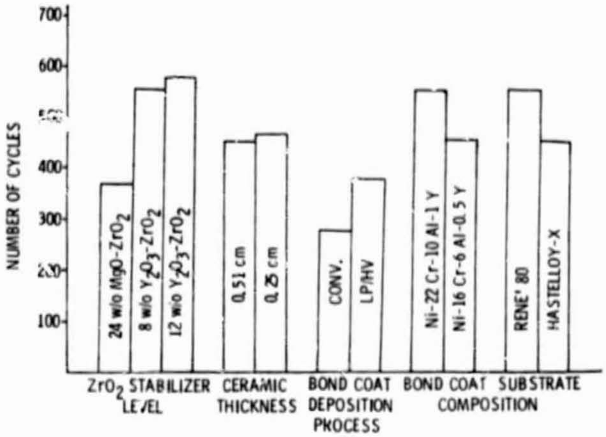

Figure 9. - Average lifetimes of TBC variations (static furnace exposure).

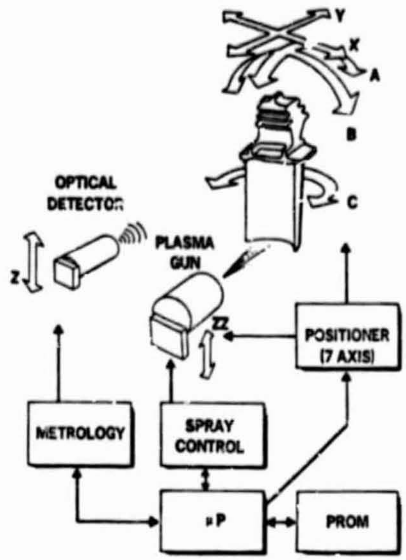

Figure 10. - Automated plasma spray process.

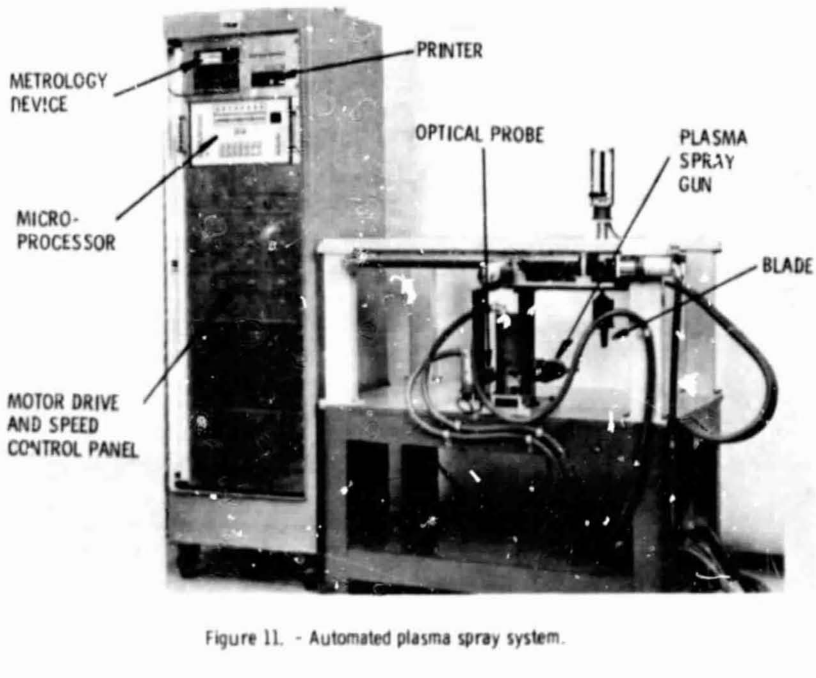

Figure 11. - Automated plasma spray system.

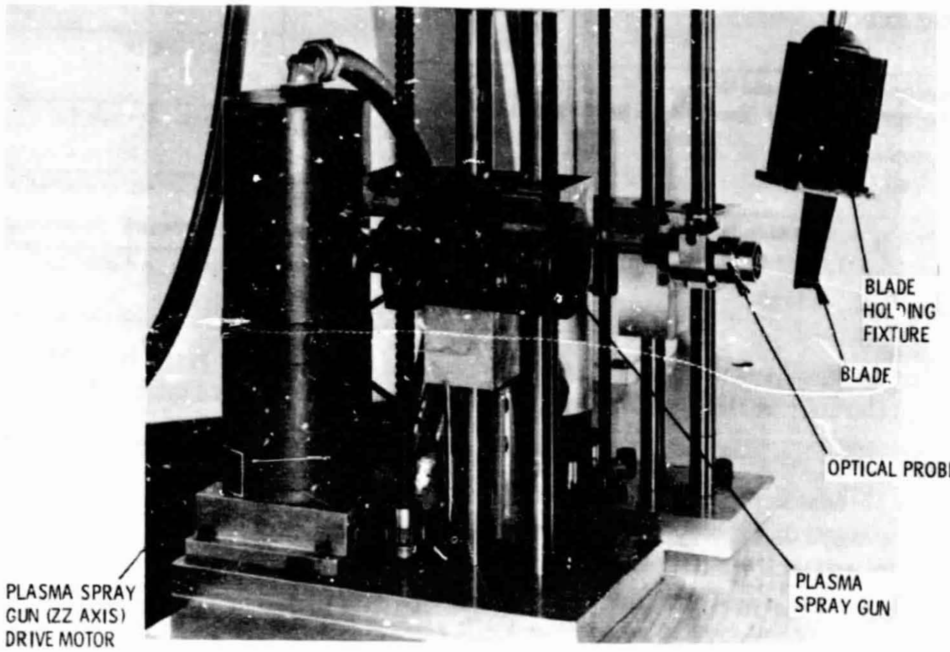

Figure 12. - Closeup of the automated plasma spray system during gage point measurement.

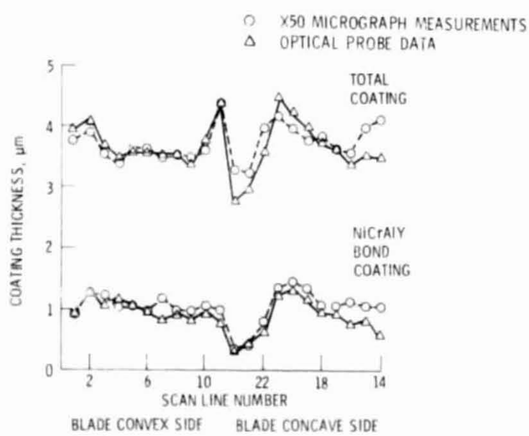

Figure 13. - Comparison of coating thickness measurements by APS optical probe and metallography.