A SILICON AND HAFNIUM MODIFIED PLASMA SPRAYED MCrAlY COATING FOR SINGLE CRYSTAL SUPERALLOYS

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Summary

A highly oxidation and corrosion resistant silicon and hafnium modified NiCoCrAlY coating has been developed to protect the external surfaces of advanced single crystal turbine airfoils. This significant technical advance was made possible in part through the use of the low pressure chamber plasma spray process in fabricating this type of coating alloy which has been very difficult to deposit using conventional electron beam physical vapor deposition methods. The addition of silicon and hafnium to the NiCoCrAlY coating improved its surface oxide scale (primarily alumina) adherence and also increased its capability to reform alumina (once the oxide had spalled) during cyclic exposure. These improvements increased the durability of this new coating by at least two-fold vis-a-vis baseline NiCoCrAlY on single crystal PWA 1480 alloy samples in cyclic burner rig tests. Recently completed experimental JT9D endurance testing has confirmed the laboratory data and this coating has recently entered production for PW2037 commercial engine applications.

Introduction

Advanced gas turbine engines operate with very high combustor exit temperatures to achieve maximum engine performance and efficiency. These increasingly severe operating conditions have placed stringent demands on the materials utilized for turbine airfoils despite employment of sophisticated internal air cooling schemes. Use of the latest developments in heat resistant materials (e. g., directionally solidified, columnar grain and single crystal cast superalloys used for turbine airfoils by Pratt & Whitney) has provided airfoil mechanical properties to match these requirements. Therefore, modern turbine airfoils are frequently life limited by surface environmental resistance. The NiCoCrAlY overlay coating produced by electron-beam physical vapor deposition (EB-PVD), which has been utilized for several years in advanced transport aircraft engines such as the JT9D, is believed to be most durable coating available for high temperature use.(1,2) However, further improvements in oxidation protection were desirable to fully exploit the high temperature capability of single crystal superalloys. A coating development program was undertaken which culminated in the identification of a highly oxidation and corrosion resistant NiCoCrAlY+Si+Hf coating produced by the plasma spray process. This paper will describe the development and application of this advanced coating for use on single crystal turbine airfoils.

Background and Coating Development Philosophy

Prior to the present investigation, research studies(3,4,5) conducted at Pratt & Whitney had shown that further improvement in NiCoCrAlY durability could be obtained by modifying its composition for:

1. improved surface oxide (Al_2O_3) scale adherence and,
2. reduced oxide growth rate during high temperature cyclic exposure.

Unfortunately, many of the desired compositional modifications required the addition of elements (e. g., Ta, Hf, etc.) to NiCoCrAlY which have vapor pressures considerably lower than the basic NiCoCrAlY constituents. Process development work showed that it is not possible to consistently transfer low vapor pressure elements in the desired proportions to the depositing NiCoCrAlY coating by the EB-PVD process. In view of this limitation, aggressive development work was initiated to utilize plasma spraying as an alternate overlay coating process. Plasma spraying was considered attractive because it allows almost complete compositional flexibility for MCrAlY coatings, since any composition which can be fabricated into sprayable powder can be deposited.(5) Also, it has shown capability to maintain tighter compositional control than any other MCrAlY coating process.

It is well known that several plasma spray process variations can be used to produce MCrAlY overlay coatings. Among these three basic types are plasma spraying in:

1. air,
2. one atmosphere of an inert environment, and
3. a low pressure chamber.

Laboratory burner rig tests conducted on NiCoCrAlY coatings produced by these three generic plasma spray processes showed that the coating oxidation life was almost doubled by use of the advanced low pressure chamber plasma spray method compared to that observed with plasma spraying in air (Figure 1). However, the oxidation life of a NiCoCrAlY coating made by the best available process (low pressure chamber plasma spray) was still about 80-90 percent of that of comparable EB-PVD coatings on the Mar-M200+Hf superalloy(6). More severe spalling of the coating's protective alumina oxide scale was observed on the plasma spray coated samples during cyclic testing compared to that on the EB-PVD coated specimens (Figure 2). The lower oxidation life of the plasma sprayed coatings is believed to result, in part, from poorer oxide scale adhesion. Research indicated that the cause was due to ineffective utilization of the yttrium in the coating(6).

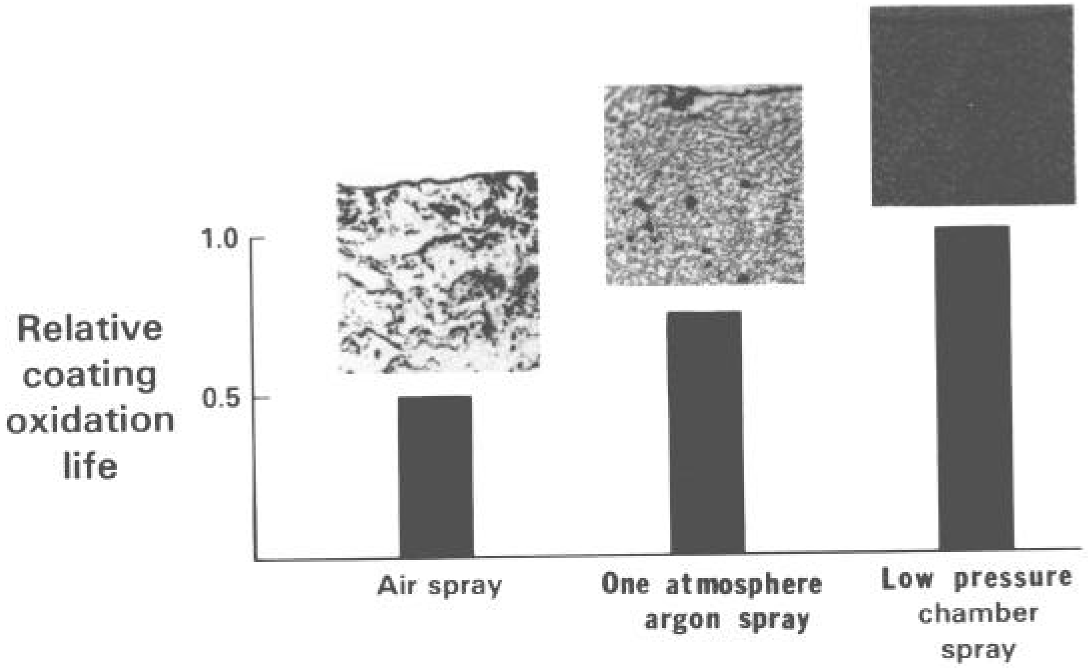

Figure 1 - Relative oxidation resistance of NiCoCrAlY coatings produced by the three plasma spray processes in 1149°C burner rig tests.

These and other coating and process development studies provided a plasma spray coating development approach to meet the program goal of a 2X durability improvement over the EB-PVD NiCoCrAlY. The approach contained the following guidelines.

- The basic NiCoCrAlY composition would be modified to contain: (1) increased levels of active elements such as yttrium and hafnium, etc., for improved oxide scale adherence; and (2) elements such as silicon and tantalum, etc., would be added for reduced oxide scale growth and improved hot corrosion resistance.
- The new coating composition and structure could not compromise (reduce) the excellent ductility and thermal fatigue resistance of the baseline EB-PVD NiCoCrAlY.
- Improved low pressure plasma spray process methods would be used to fabricate the highly alloyed coating materials with a dense and relatively contaminant (oxide) free structure.

The above guidelines were used to address the challenge of developing a coating having a high temperature durability greater than that of all existing coatings.

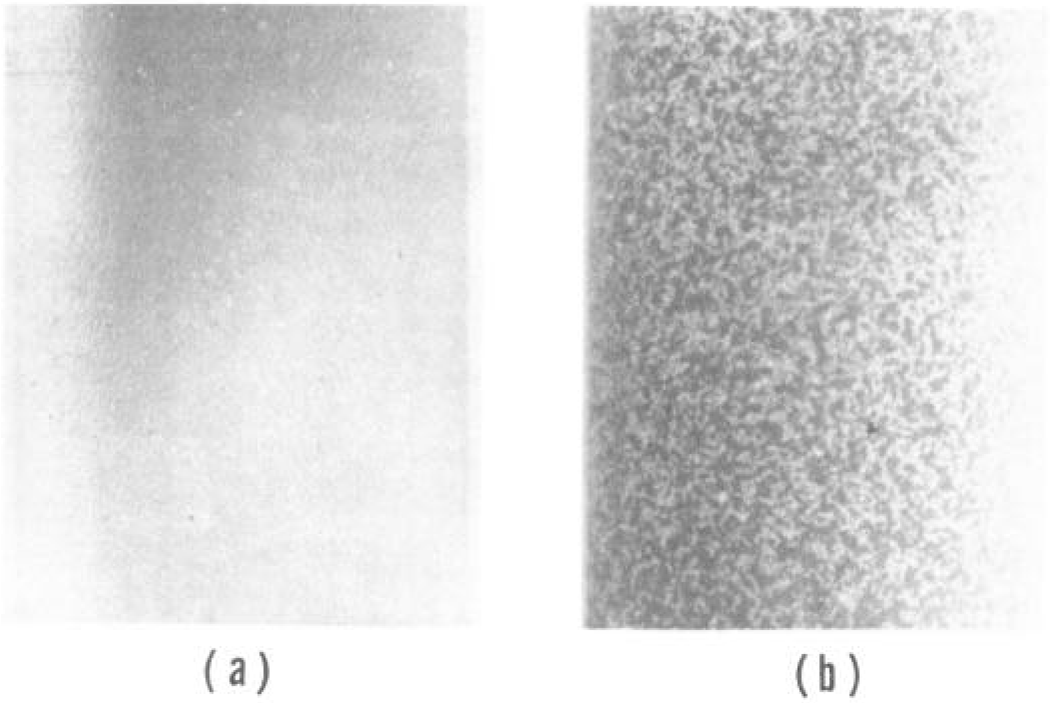

Figure 2 - Surface oxide scale appearance of NiCoCrAlY coatings produced by a) EB-PVD and b) low pressure chamber spray processes after 100 Hours of cyclic testing in a 1149°C burner rig test.

NiCoCrAlY+Si+Hf Coating Development

As mentioned before, one of the objectives of this program was to develop the new coating specifically for Pratt & Whitney's single crystal turbine airfoils. Therefore, all candidate coating systems were evaluated on single crystal PWA 1480 alloy samples. Also, all experimental compositions were based on the basic NiCoCrAlY chemistry (20 w/o Co, 18 w/o Cr, 12 w/o Al, 0.2 w/o Y, bal. Ni). The amount of yttrium in some experimental coatings was increased for improved oxide scale adherence. Silicon and hafnium were added individually, as well as in combination, to improve both oxide scale adherence and hot corrosion resistance. Also, combined addition of these two elements was expected to reduce the oxide scale growth rate. All candidate coating systems were produced by using the low pressure chamber plasma spray process parameters described previously(5). To improve coating density, surface smoothness, and interfacial bonding between the coating and the substrate alloy, all coated samples were glass bead peened at an intensity of 22N followed by heat treatment for four hours at 1029°C (1975°F) in hydrogen.

The relative durability of all experimental coatings was evaluated using cyclic oxidation burner rig tests (0.7 Mach gas velocity, one hour cycle) at 1149°C (2100°F). During this testing, the appearance of the surface oxide (as to its adherence, color and roughness) was carefully examined and documented for all coating systems. Figure 3 illustrates the progressive degradation behavior (surface oxide changes) of baseline EB-PVD

NiCoCrAlY, NiCoCrAlY with higher 'Y' (0.6 vs. 0.2 w/o), NiCoCrAlY+Si, NiCoCrAlY+Hf and NiCoCrAlY+Si+Hf as a function of exposure time. As can be seen from this figure, while individual silicon and hafnium additions and increased yttrium in NiCoCrAlY improve its high temperature durability, the best results are obtained when all of these three modifications are included together. It appears that the combination of yttrium, silicon and hafnium in the NiCoCrAlY+Si+Hf coating provides a synergistic improvement compared to that expected from additions of the individual effects of these elements. During cyclic testing, this coating exhibited excellent oxide scale adherence (less oxide scale spallation). In addition, the coating showed greater capability to reform alumina, once the oxide had spalled, suggesting that the activity of aluminum at a given aluminum concentration was significantly higher in this coating compared to that in other coatings. Based on these favorable results, NiCoCrAlY+Si+Hf was chosen for further optimization to define the optimum silicon and hafnium concentrations.

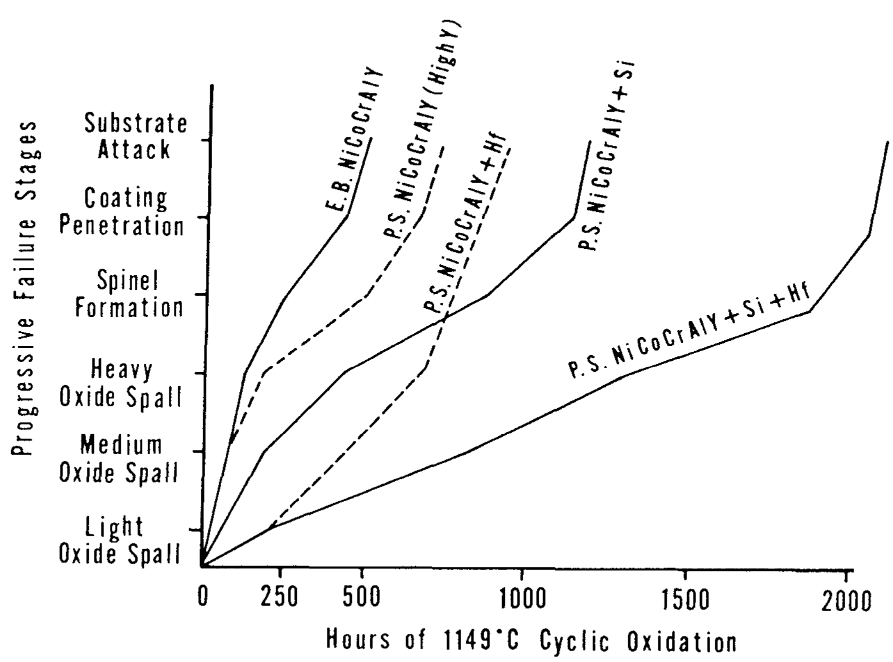

Figure 3 - Progressive degradation of electron beam vapor deposited (E.B.) and plasma sprayed (P.S.) coatings showing synergistic benefit of silicon and hafnium additions.

Additional cyclic burner rig tests were conducted on more than ten coating compositions having various hafnium and silicon amounts at peak temperatures of 1149°C (2100°F) and 1205°C (2200°F). The tests revealed that the ratio of hafnium to silicon was a critical variable. The data indicated that a hafnium-silicon ratio of 0.3 to 1.0 provided the best oxidation life for this coating system as illustrated in Figure 4. NiCoCrAlY+Si+Hf coatings having similar hafnium-silicon levels also exhibit excellent hot corrosion resistance. Based on these results, the composition of the optimized coating was selected and is identified Table I.

Table I. NiCoCrAlY+Si+Hf Coating Composition (Weight Percent)

Co	Cr	Al	Y	Si	Hf	Ni
20	18	12.5	0.6	0.4	0.25	Balance

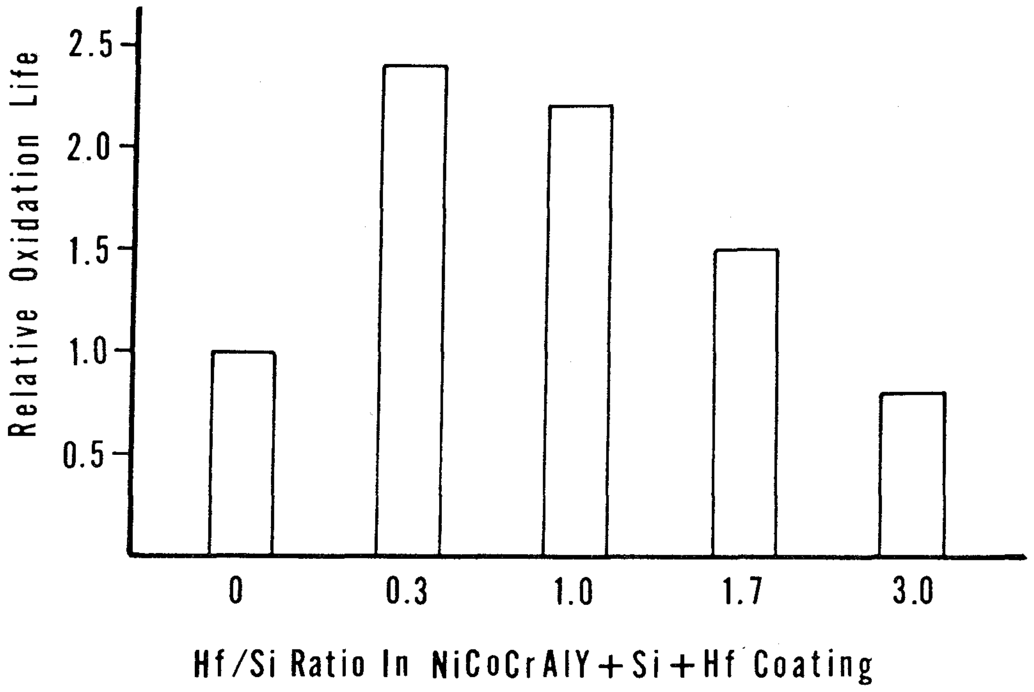

Figure 4 - Relative oxidation lives of various NiCoCrAlY+Si+Hf coatings on PWA 1480 in burner rig testing at 1149°C.

NiCoCrAlY+Si+Hf Properties

Several cyclic burner rig tests have been conducted to compare the oxidation resistance of the optimized NiCoCrAlY+Si+Hf coating with the baseline EB-PVD NiCoCrAlY on the single crystal alloy PWA 1480. Tests were conducted over a range of temperatures from 1010°C (1850°F) to 1205°C (2200°F). In all of these tests, the NiCoCrAlY+Si+Hf coating substantially outperformed the EB-PVD NiCoCrAlY specimens with improvements in oxidation life of 2.2X-3.4X observed. This is illustrated in Figure 5 where it can be seen that the cyclic oxidation resistance of the NiCoCrAlY+Si+Hf consistently exceeded the 2X goal at all temperatures. A two-fold improvement in high temperature durability corresponds to about a 40°C (75°F) metal temperature advantage. Based on this, the NiCoCrAlY+Si+Hf has a 44°C (82°F) to 68°C (127°F) temperature advantage over EB-PVD NiCoCrAlY, the most oxidation resistant production coating.

To evaluate the hot corrosion resistance of the subject coating, burner rig cyclic hot corrosion tests were conducted at 899°C (1650°F). To create a hot corrosive environment, a 35ppm sea salt solution and 1.3 w/o S (as SO_2) were added to the combustion medium. Similar to the cyclic oxidation tests, the exposure cycle here was also 55 minutes a peak temperature (899°C) followed by five minutes of forced air cooling. As can be seen in Figure 6, the NiCoCrAlY+Si+Hf coating exhibits superior hot corrosion resistance compared to that of the EB-PVD NiCoCrAlY. This improvement is believed to be associated with the presence of silicon in NiCoCrAlY+Si+Hf which is known to enhance hot corrosion resistance(7).

Thermal fatigue cracks in many advanced cooled turbine blades and vanes initiate at the surface of the coated components. Therefore, the ductility of the coating becomes a very important design criteria since it is generally believed that a coating with higher ductility (other properties being equal) will resist crack initiation for a longer period of time (more cycles) than a relatively less ductile coating. To measure the ductility (the strain to the first observable crack in the coating) of the NiCoCrAlY+Si+Hf on the PWA 1480 alloy, interrupted tensile tests were conducted in the temperature range of room temperature to 538°C (1000°F). The procedure for this laboratory test is described elsewhere(8). Figure 7 provides the test results and compares the NiCoCrAlY+Si+Hf ductility data with that of the baseline EB-PVD NiCoCrAlY and a widely used diffusion aluminide coating (PWA 73). As can be seen from this figure, the fracture strain of NiCoCrAlY+Si+Hf was observed to be slightly superior to vapor deposited NiCoCrAlY, the most ductile coating currently in production for aircraft gas turbines. Both of these overlay coatings however, have outstanding ductilities compared to the diffusion aluminide coating because they have relatively lower amounts of the brittle beta (NiAl) phase in their structure. The slightly higher ductility of NiCoCrAlY+Si+Hf vis-a-vis EB-PVD NiCoCrAlY is associated with the use of the plasma spray process to produce the former coating. This process has been shown to produce coating structures which are less prone to cracking than structures of similar compositions produced by the EB-PVD process(5).

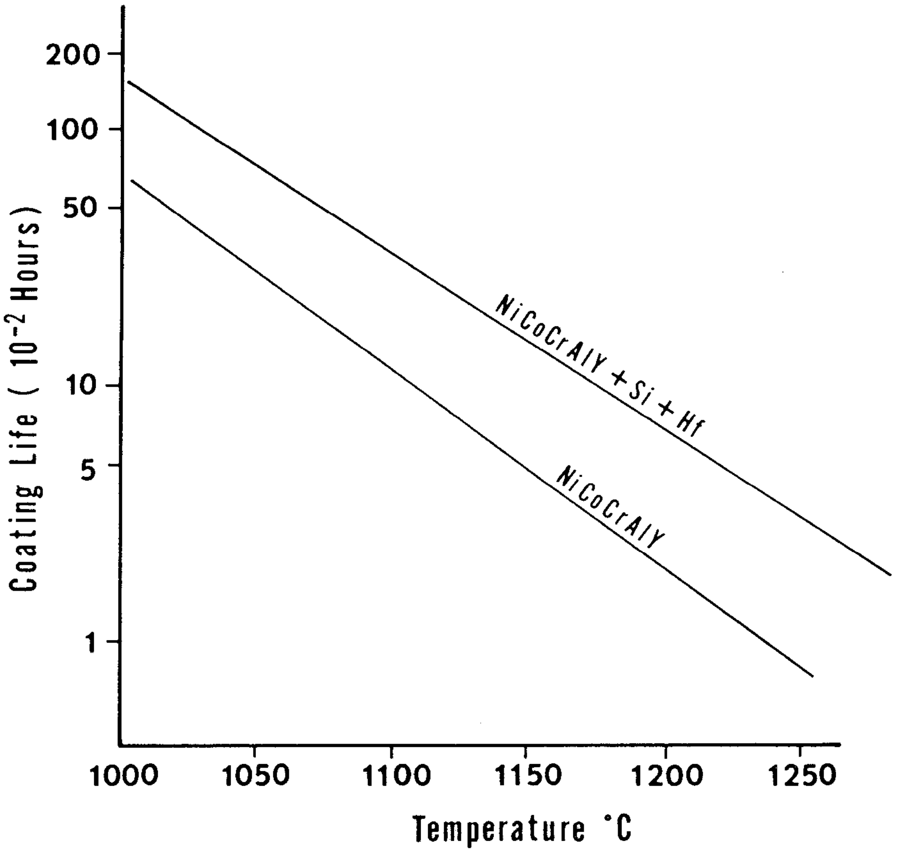

Figure 5 - Cyclic burner rig life of NiCoCrAlY+Si+Hf and EB-PVD NiCoCrAlY coatings on the single crystal PWA 1480 alloy.

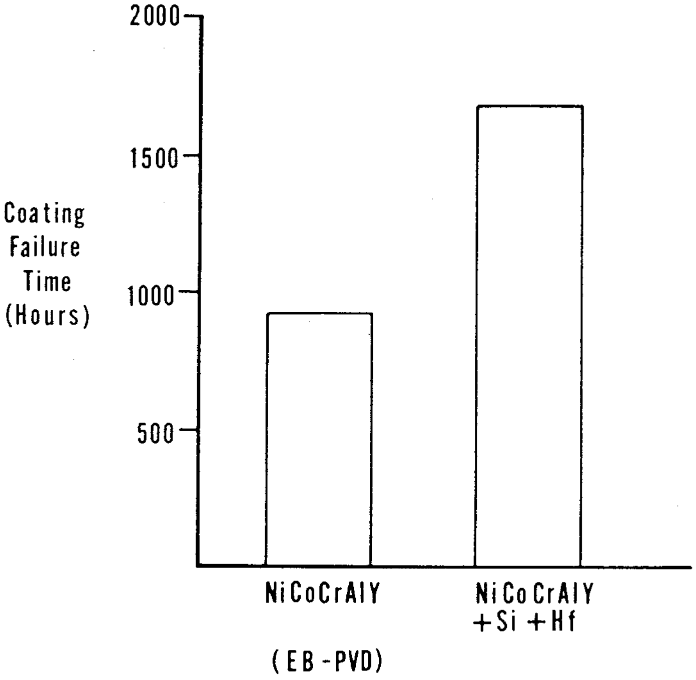

Figure 6 - Burner rig hot corrosion resistance of NiCoCrAlY+Si+Hf and EB-PVD NiCoCrAlY on the PWA 1480 alloy at 899°C (1650°F).

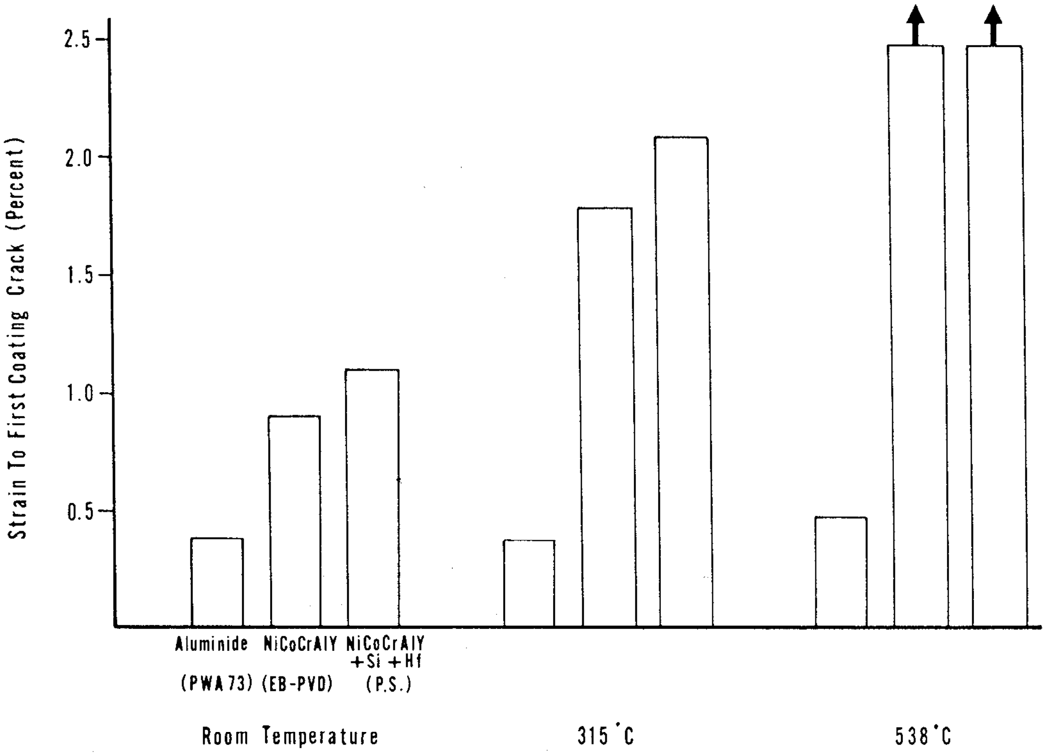

Figure 7 - Ductility of NiCoCrAlY+Si+Hf EB-PVD NiCoCrAlY and an aluminide (PWA 73) coating on the single crystal PWA 1480 alloy.

Engine Testing of NiCoCrAlY+Si+Hf and Its Applications

To verify the excellent durability of the plasma sprayed NiCoCrAlY+Si+Hf coating as measured by the laboratory testing, several experimental engine tests have been conducted. For example, first stage turbine blades were coated with this coating and engine tested for 375 hours/2500 cycles in an accelerated high temperature JT9D engine test. As illustrated in Figure 8, the baseline EB-PVD NiCoCrAlY coating on the PWA 1480 alloy blades had failed at this interval while the NiCoCrAlY+Si+Hf coated components exhibited little visible degradation. Similar results have been obtained in other tests and to date NiCoCrAlY+Si+Hf coated high pressure turbine airfoils have accumulated approximately 54,000 endurance cycles in JT9D and PW2037 experimental engines.

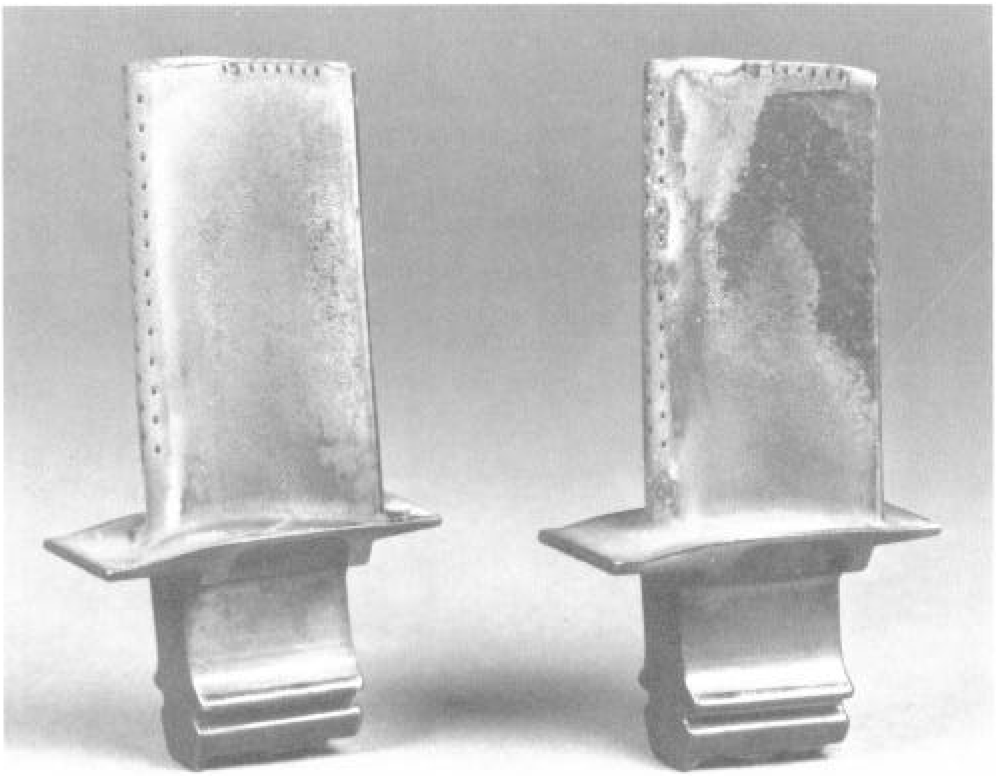

Figure 8 - PWA 1480 single crystal first stage turbine blades showing superior coating durability of the plasma sprayed NiCoCrAlY+Si+Hf coating (left) vs. the failed EB-PVD NiCoCrAlY coating (right) after 2500 endurance cycles in an accelerated JT9D engine test.

On the basis of these documented durability advantages and the developed low pressure plasma spray coating procedures, the NiCoCrAlY+Si+Hf has been chosen as the coating for the first stage turbine vanes and blades and the second stage turbine vanes in the PW2037 engine that will power the Boeing 757. Engine certification of this coating has been completed. This coating has also been selected as the coating for all high pressure turbine airfoils in the fuel efficient PW4000 engine currently under development. In addition, NiCoCrAlY+Si+Hf is presently undergoing field evaluation as a potential low cost replacement for EB-PVD NiCoCrAlY in all JT9D engines.

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