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Effects of Arc Current on the Life in Burner Rig Thermal Cycling of Plasma Sprayed $ZrO_2-Y_2O_3$

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EFFECTS OF ARC CURRENT ON THE LIFE IN BURNER RIG THERMAL CYCLING OF PLASMA SPRAYED ZrO_2-Y_2O_3

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ABSTRACT

An analysis of thermal cycle life data for four sets of eight thermal barrier coated specimens representing arc currents (plasma gun power) of 525, 600, 800, or 950 amps is presented. The ZrO_2-8Y_2O_3/NiCrAlY plasma spray coated René 41 rods were thermal cycled to 1040° C in a Mach 0.3-Jet A/air burner flame. The experimental results indicate the existance of a minimum or threshold power level below which coating life expectancy is less than 500 cycles. Above the threshold power level, coating life expectancy more than doubles and increases with arc current.

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INTRODUCTION

Ceramic coatings applied to the heated side of internally cooled hot-section components of gas turbine engines have the potential of increasing efficiency through the use of higher gas temperatures or less cooling air, or of extending component life by reducing metal temperatures (refs. 1 and 3). Previous research (ref. 3) has shown the life of the ceramic coatings to be quite limited under conditions of cycling heating in a 0.3 Mach burner. It was also shown by numerical calculations that compressive stresses occur in the coating when high heat transfer sources such as the 0.3 Mach flame first impact the coated object at ambient temperature. In a later study (ref. 4) it was shown that bond coat composition played an important role in determining coating life. The dominant effect on life is the number of thermal cycles even when the cycling frequency is varied. The time at temperature was of lesser importance.

The durability of the coating in thermal cycling and the ability of the coating to withstand the compressive stresses originating from initial heating may be influenced by the conditions of application of the plasma sprayed ZrO_2-Y_2O_3. This study was made to determine the effect on life in thermal cycling of varying the arc current of the plasma sprayed ZrO_2-Y_2O_3. The arc current could influence either the attachment of the ZrO_2-Y_2O_3 to the metal or the density of the plasma deposited ceramic. Other work (ref. 5) has shown that higher arc currents produce denser coating, reduced bond coat oxidation rates, and improved ceramic layer life in cyclic furnace tests. Changes in either density or attachment could also influence the life in the more severe burner rig cycling of the coating.

EXPERIMENTAL PROCEDURE

Materials and Coating Procedure

Solid René 41 rods 13 mm in diameter were coated with NiCrAlY bond coat and ZrO_2-Y_2O_3 ceramic by first grit blasting with Al_2O_3 and then plasma spraying in air using 3.5 vol% hydrogen gas in the plasma, with 0.013 mm Ni-18Cr-12Al-0.3Y bond coat. The specimens were then plasma sprayed with 0.038 mm of ZrO_2 prealloyed with 8 wt% Y_2O_3. Eight bars were plasma sprayed and tested at each arc current of 525, 600, 800, and 950 amps.

Apparatus and Test Procedure

The coated rods were evaluated by heating eight specimens in a rotating carousel with a 0.3 Mach burner flame (e.g., see ref. 4). The burner gas temperature was approximately 1450° C, and optical temperature measurements indicated that the steady state specimen temperature was 1014° C. The specimens were heated for 4 minutes followed by 3 minutes of forced air cooling. The burner was moved by a pneumatic cylinder to impinge on the specimens in less than 1 second. The condition of the ceramic coating was determined by visual inspection; spalling of the ceramic was used as an indication of coating as failure.* The fuel used was Jet A-1.

RESULTS AND DISCUSSION

Experimental Results

The cycle life of four sets of eight ceramic coated rods are shown in table I. The rod sets were prepared at arc currents of 525, 600, 800, and 950 amps and thermally cycled in the 0.3 Mach flame. The average life in cycles is shown in table I for coatings plasma sprayed at each arc current. The coatings prepared at 525 amps had only half of the life of coatings prepared at 600, 800, or 950 amps. Statistical methods were applied to each of these sets to determine significance. The standard deviation for each of the four sets varied somewhat about 350 cycles indicating variability in the process/procedures. It would appear that cycle life is enhanced by an increase in plasma spray arc current.

The entries of table I correlate with the samples in the photographs of figure 1. Each entry is representative of the carousel position in which samples in each group were run. The carousel held eight rods and as samples failed they were replaced with other coated rods, so that the carousel at any one time might contain rods prepared at several plasma arc currents.

The rods with failed coatings are shown in figures 1(a) to (d). There is no difference in the visual appearance of the failure of the ceramic coatings plasma sprayed at the various arc currents. Thus a more quantatitative examination was undertaken.

X-ray diffraction studies of selected sample specimens sprayed at 525 and 950 amps showed no apparent differences in phase composition either before or after the specimen was run in the Mach 0.3 burner. The predominant phase was tetragonal with lesser amounts of cubic and monoclinic zirconia.

Photomicrographs of specimens sprayed at 525, 600, 800, and 950 amps revealed little change in coating structure between 525 and 600 amps but lower porosity at 800 and 950 amps. These photographs also tended to show

*Inspection for spalling was made at approximately 150 cycle intervals.

some evidence of bond coat interface reheating, but it is rather weak. SEM photographs produced similar evidence with a more monotone decrease in porosity with increased arc current (figs. 2(a) to (d)). A more detailed SEM examination of the surface produced evidence of a development of a microcrack network with increasing arc current (figs. 3(a) to (d)).

Of several approaches to achieving improved durability in a plasma sprayed brittle ceramic material, two are: (1) presence of porosity; (2) presence of a microcrack network. Excessive porosity at 525 amps may lead to low cohesive strength and early failures (refs. 6,7). At 600 amps the presence of porosity and some microcracking may lead to a more optimum balance of strength and compliance. At 800 amps lower porosity may have resulted in a rigid more readily spalled coating even though some microcracks are present, while the higher density retards oxidation of the bond coat. A higher microcrack density appears in the more dense coating deposited at 950 amps, perhaps providing the enhanced durability observed.

In a more qualitative study of the plasma spray process, high speed motion pictures were used to determine the relative particle velocities and assess some surface characteristics such as 'spot-cooling'* and 'splat-impacts'**. Two camera speeds and two exposures were used. One camera speed was 10 000 pictures per second (pps), and the second at 5880 pps with exposures of 33.3 and 17 microseconds, respectively. At 10 000 pps, relative estimates of velocity, spot-cooling rates and splat-impact effects can be made. For better estimates, the exposure time was cut to 17 microseconds at 5880 pps using a frame splitter; however the pictures in a sense now represent time lapse exposures. Assigning a relative streak length of 1 at 525 amps, the relative particle velocities were found to be 1.2, 1, and 1.4 at 600, 800, and 950 amps, respectively. Studies of the surface characteristics (splat-impact and spot-cooling) indicated little difference for arc currents of 525 and 600 amps; however at 950 amps there appears to be a marked increase in 'splat-impacts' and 'spot-cooling' time.

A motion picture sequence (C305) illustrating some effects of plasma gun current on the formation of thermoprotective surface coatings is available on loan from the Lewis Research Center Photographic Branch.

SUMMARY OF RESULTS

An analysis of thermal cycle life data for four sets of eight thermal barrier coated specimens representing arc currents (plasma gun power) of 525, 600, 800, and 950 amps is presented. The ZrO_2-$8Y_2O_3$/NiCrAlY plasma spray coated René 41 rods were thermal cycled to 1040° C in a Mach 0.3-Jet A/air burner flame. To assess the effects of arc current on thermal cycle life, all specimens were subjected to the same coating and subsequent test procedures.

The experimental results indicate the existance of a minimum or threshold power level below which coating life expectancy is less than 650 cycles; above the threshold power level, coating life expectancy more than doubles and increases with arc current.

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*Spot-cooling refers to the time taken by a visible radiating particle to disappear from view.

**Splat-impact refers to the impact characteristics of a semi-molten droplet on a rough surface.

There were no apparent differences in the visual appearance of the failed specimen sets. In a more quantitative approach, X-ray diffraction studies of selected sample specimens sprayed at 525 and 950 amps showed no apparent differences in phase composition either before of after the specimen was run in the Mach 0.3 burner. Photomicrographs of unused specimens indicated a decrease in porosity and the development of a microcrack network with increased arc current, but did not fully clearify the life data of table I.

Motion picture studies of the plasma spray process did show significant changes in surface characteristics and particle velocity at 950 amps. A more exacting study of the surfaces, such as by surface thermography and plasma gun characteristics such as by laser-Doppler velocimetry, may provide further altrications to explain the life data.

ACKNOWLEDGEMENTS

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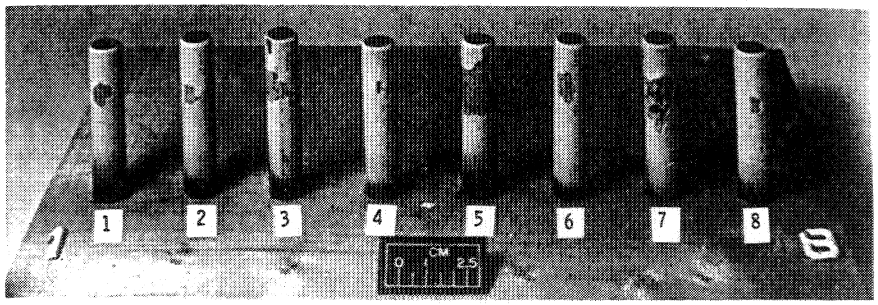
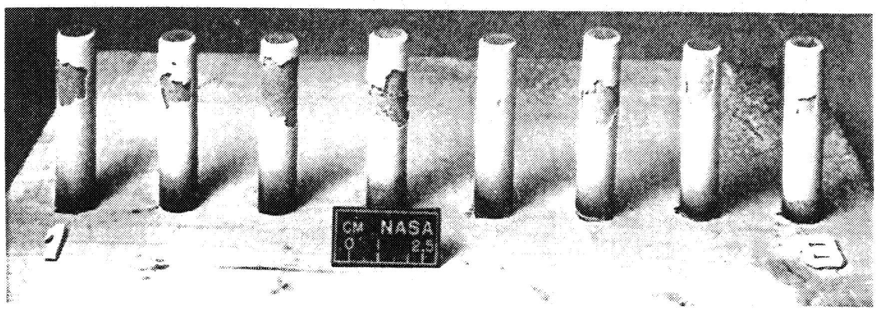
TABLE I. - LIFE IN THERMAL CYCLING OF COATINGS

Sample number	Plasma arc current, amps				
	525	600	800	950	
1	438	1730	1345	1716	
2	576	1730	1555	1716	
3	719	1730	1555	1801	
4	342	1922	1922	156*	
5	534	746	1006	2965	
6	1334	1598	1020	2157	
7	500	1955	653	3502	
8	904	1763	1298	1590	
Average	668	1648	1294	1950	
Standard deviation	323	382	397	692	(308)**

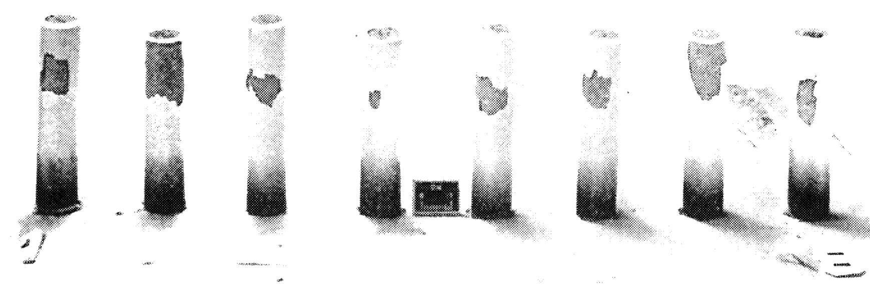
*Spall formed but did not enlarge over 2200 cycles.
**Without point 4.



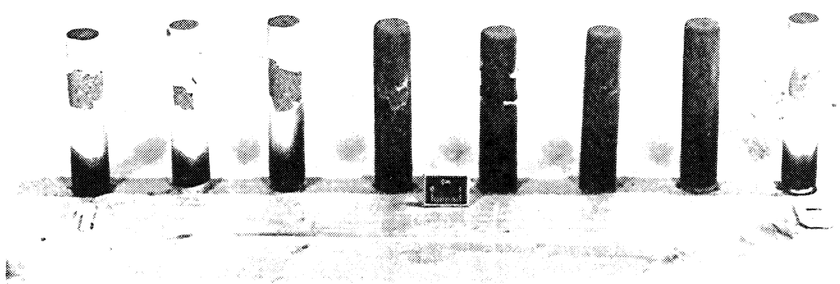
A. FAILED COATINGS PLASMA SPRAYED AT 525 AMPS.



B. FAILED COATINGS PLASMA SPRAYED AT 600 AMPS.



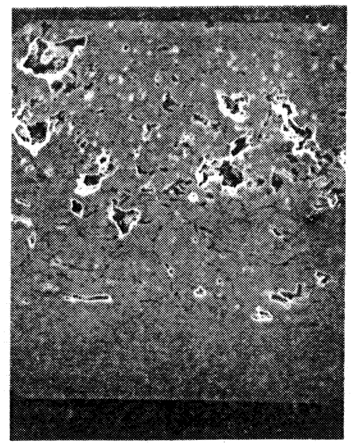
C. FAILED COATINGS PLASMA SPRAYED AT 800 AMPS.



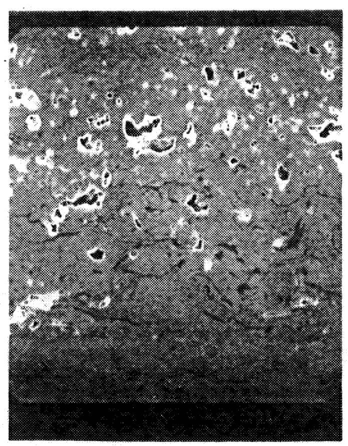
D. FAILED COATINGS PLASMA SPRAYED AT 950 AMPS.

FIGURE 1. EIGHT PLASMA SPRAYED SPECIMENS WHICH HAVE FAILED AFTER EXPOSURE TO A MACH 0.3 JET A/AIR BURNER. NUMBERS INDICATE CAROUSEL POSITION. SEE ALSO TABLE 1.

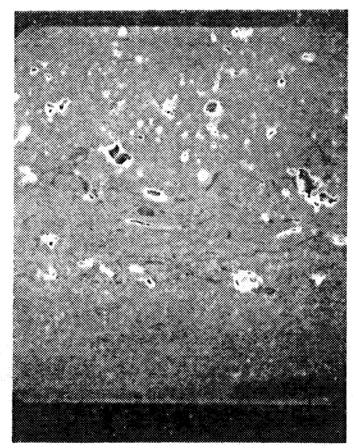
A. SUBSTRATE-BOND-CERAMIC PLASMA SPRAYED COATING AT 525 AMPS.



B. SUBSTRATE-BOND-CERAMIC PLASMA SPRAYED COATING AT 600 AMPS.

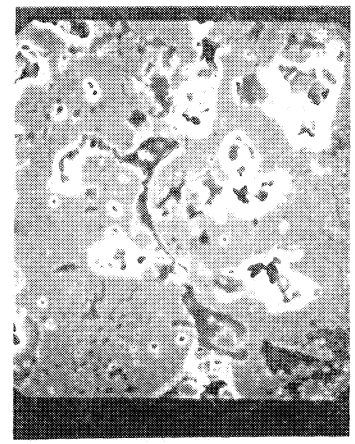


C. SUBSTRATE-BOND-CERAMIC PLASMA SPRAYED COATING AT 800 AMPS.



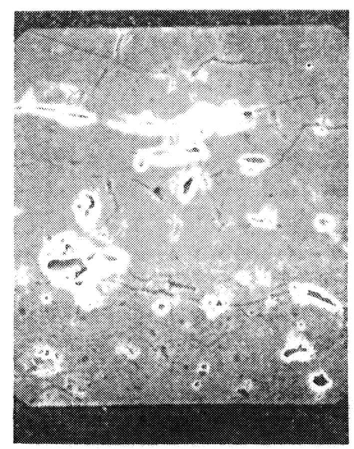
D. SUBSTRATE-BOND-CERAMIC PLASMA SPRAYED COATING AT 950 AMPS.

FIGURE 2. PHOTOMICROGRAPHS OF SAMPLE SPECIMENS PLASMA SPRAYED AT DIFFERENT ARC CURRENTS. MAGNIFICATION x 300.



A. CERAMIC POROSITY-MICROCRACK NETWORK AT 525 AMPS.

B. CERAMIC POROSITY-MICROCRACK NETWORK AT 600 AMPS.



C. CERAMIC POROSITY-MICROCRACK NETWORK AT 800 AMPS.

D. CERAMIC POROSITY-MICROCRACK NETWORK AT 950 AMPS.

FIGURE 3. PHOTOMICROGRAPHS OF SAMPLE SPECIMENS PLASMA SPRAYED AT DIFFERENT ARC CURRENTS. MAGNIFICATION x1000.

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An analysis of thermal cycle life data for four sets of eight thermal barrier coated specimens representing arc currents (plasma gun power) of 525, 600, 800, or 950 amps is presented. The ZrO_2-8Y_2O_3/NiCrAlY plasma spray coated René 41 rods were thermal cycled to 1040 °C in a Mach 0.3-Jet A/air burner flame. The experimental results indicate the existence of a minimum or threshold power level which coating life expectancy is less than 500 cycles. Above the threshold power level, coating life expectancy more than doubles and increases with arc current.

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