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Effects of Plasma Spray Parameters on Two-Layer Thermal Barrier Coating System Life

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EFFECTS OF PLASMA SPRAY PARAMETERS ON TWO-LAYER THERMAL BARRIER COATING SYSTEM LIFE

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SUMMARY

A study was conducted to evaluate the effects of power level and arc gas composition used during plasma spraying on the life of two-layer thermal barrier systems (TBS). Experiments were done in a furnace which was cycled between 990° and 280° C or 1095° and 280° C. Ni-16.8Cr-5.8Al-0.31Y and Ni-16.3Cr-4.9Al-0.61Y bond coatings and ZrO_2-7.9Y_2O_3 and ZrO_2-11.8Y_2O_3 thermal barrier coatings (TBCs) applied on Mar-M200 + Hf specimens were investigated. The data show that increasing the current/voltage from 300 amperes -26 volts to 500 amperes -31 volts for the bond coating and from 500 amperes -31 volts to 700 amperes -35 volts for the TBC during plasma spraying in argon arc gas gives a significant improvement in coating life. The Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.9Y_2O_3 system plasma sprayed at the lowest power level withstood 89 1-hour cycles to 1095° C as compared to 213 1-hour cycles for the same system plasma sprayed at the highest power level. This improvement is believed to be due to an increase in bonding area between particles and a decrease in porosity in the bond coating and in the TBC. Increase of current-voltage during plasma spraying produced a TBS that exhibits a lower rate of oxidation weight gain.

The addition of up to 15 v/o hydrogen to argon arc gas during plasma spraying of the bond coating and up to 5 v/o of hydrogen during plasma spraying of the TBC adversely affected TBS life at constant power. The addition of hydrogen lowers the temperatures of the plasma and the powder particles being deposited. The effect is equivalent to a reduction in power. The rate of weight gain increases as the volume of hydrogen in the argon arc gas increases and TBS life decreases very rapidly. Increasing current during plasma spraying in argon-hydrogen arc gas improved TBS life.

INTRODUCTION

Prior research has demonstrated that a two-layer thermal barrier coating system (TBS), Ni-16Cr-6Al-0.6Y/ZrO_2-12Y_2O_3,* can withstand severe thermal cyclic conditions. For example, on flat solid specimens, this coating withstood 673 1-hour cycles between 975° and 280° C in a cyclic furnace (refs. 1 to 3). On air-cooled turbine blades, it withstood 3200 80-second cycles to 1280° C surface temperature and 246 1-hour cycles to 1410° C surface temperature in a Mach. 0.3 burner rig (refs. 1 to 3). This TBS also withstood 500 short cycles without failure in a 3 atmosphere research engine (ref. 4). However, under the more severe conditions of a JT9D gas turbine aircraft engine, coating failure occurred at the leading edge of the first stage blades in less than 38 hours (ref. 5).

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*Compositions throughout this report are expressed in weight per cent.

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Since that time, several studies were initiated to improve this TBS (refs. 6 and 7) and also to find new TBSs (ref. 8). Improvement of the NiCrAlY/ZrO_2-Y_2O_3 TBS was accomplished by reducing yttrium in the bond coat from 0.6 w/o to the 0.35 to 0.15 w/o range, and increasing chromium and aluminum concentrations in the bond coating. Additional improvements were realized by reducing yttria concentrations from 12 w/o to the 6 to 8 w/o range (refs. 6 and 7).

It was reported that the oxidation of the bond coating has a significant effect on the life of the TBS (ref. 7). This oxidation principally occurs along the boundaries of the plasma sprayed particles. Also, zirconia particle interfaces are the weak links in the oxide coating. The TBS tends to fail within the oxide coating near the bond coating-oxide coating interface (refs. 1, 2, 6 and 7).

The contact area and the adherence, between plasma sprayed particles in the bond coating and in zirconia and the adherence of the zirconia to the bond coating can be affected by plasma spray process parameters. For this reason, this study was undertaken to determine the effects of plasma spray parameters on the life of the two-layer thermal barrier system. The parameters investigated were the power levels and the amount of hydrogen added to the argon arc gas during plasma spray deposition of the bond coating and the zirconia coating. The effects of these parameters on TBS life were evaluted in a cyclic furnace, which was cycled between 990° and 280° C or 1095° and 280° C.

EXPERIMENTAL PROCEDURE

Materials

The compositions of the plasma spray powders of NiCrAlY bond coatings and yttria-stabilized zirconia (both -200 to +325 mesh) are reported in table I. The alloy used as a substrate in this study was the conventionally cast nickel-base superalloy MAR-M-200 + Hf (hafnium). The composition of this alloy is also reported in table I. Flat specimens, 2.5 by 2.5 by 0.5 cm, with all corners and edges rounded to about 0.28 cm radius were used.

Apparatus and Procedure

Plasma spray coating deposition. - Sample surfaces were grit blast cleaned with high purity alumina and within 10 minutes the NiCrAlY bond coating was applied with a plasma spray gun. The ZrO_2-Y_2O_3 coatings were applied with the same plasma spray gun within 25 minutes after completing application of the NiCrAlY bond coating. Bond coating thicknesses were maintained between 0.010 and 0.014 cm and zirconia thicknesses between 0.032 and 0.044 cm, as determined by vernier caliper measurements. The coating thicknesses for all specimens are given in the data tables.

The current and voltage levels used in the plasma spray applications of the powders are also given in the data tables. The plasma arc and powder feed gases were either pure argon or a mixture of argon and hydrogen. The concentrations of hydrogen in argon are given in the data tables.

Plasma spray deposition was done in an open air environment. The plasma-gun-to-specimen surface distance was maintained at about 13 to 15 cm. An attempt was made to maintain the plasma spray gun normal to the specimen surface being sprayed. However, this could not be maintained when the edges and corners were coated.

Cyclic furnace testing. - Coated specimens were heated in air to either 990° or 1095° C. The cycle in both cases consisted of a 6-minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C. The temperature in the furnace was measured with a platinum - platinum-13 percent rhodium thermocouple. The estimated accuracy of the temperature measurement was about ±10° at 1095° C.

After at least every 12 cycles the specimens were removed from the furnace at 350° to 400° C, cooled to room temperature, weighed, and inspected visually for the presence of an external crack in the oxide coating. Thus, specimens that withstood 1500 1-hour cycles were cooled to room temperature at least 125 times. Tests were continued until a visible external crack appeared in the oxide coating or until about 1500 cycles.

Coating density and porosity measurements. - The apparent densities of the bond coatings and the TBCs were determined from thin "foils". Thin bond coating and TBC foils were obtained by plasma spraying the bond coating or the TBC on a thin, clean stainless steel substrate. On cooling, the sprayed material broke away from the substrate. The bond coating foils were normally between 0.010 and 0.015 cm. thick, while the TBC foils were between 0.033 and 0.050 cm thick. Foils were about 3.0 cm wide and 3.5 cm long. The apparent densities of these foils were determined by two methods:

1. Each foil was weighed to the nearest milligram. The thickness of the foil specimen was measured with a pin micrometer. Normally, 32 measurements were taken at various locations on a foil. The area of the foil was measured with a planimeter and density was calculated from:

$$\rho = \frac{W}{t_{ave} A}$$

where ρ = density (gm/cm^3), W = weight (gm), t_{ave} = average thickness (cm), and A = area (cm^2).

2. An immersion technique (ref. 9), which was slightly modified, was also used to determine the densities of the plasma sprayed bond and thermal barrier coatings. Each foil specimen was weighed dry. Then the specimen was coated with a cellulose sealer. The cellulose coated specimen was weighed when dry in order to determine the weight gain due to cellulose. The cellulose coated specimen was also weighed while immersed in water, and after immersion to check for imperfections in the seal. Using these three weights and making a correction for the cellulose, apparent density was calculated from:

$$\rho = \frac{W_D \times \rho_{H_2O}}{W_C - W_I}$$

where ρ = density (gm/cm^3), W_D = dry weight (gm), ρ_{H_2O} = density of water (gm/cm^3), W_C = corrected weight of wet cellulose coated specimen (gm), and W_I = corrected weight of cellulose coated specimen immersed in water (gm).

3. Porosity - Mean porosity in the bond coating or in zirconia was calculated from the measured density of the plasma spray coating and the theoretical density. The theoretical density of the bond coating was assumed to be about the same or very close to that of a cast Ni-16.0Cr-4.75Al-0.6Y specimen. The density of this material was found to be 7.733 gms/cm^3. The theoretical density of zirconia was assumed to be about 6.1 gm/cm^3. This value

was reported as a theoretical density for ZrO_2-10.6Y_2O_3 in reference 10. It was assumed that the theoretical density of ZrO_2-7.9Y_2O_3 would only be slightly different from the above value.

RESULTS AND DISCUSSION

Effects of Plasma Spray Power

Coating life. - To study the effect of plasma spray power level on TBS life, the following amperage/voltage levels were used during plasma spray depositions of : (1) the bond coating - 300/26, 350/27, 400/28, 450/29 and 500 amperes/31 volts, and (2) the zirconia coating - 500/31, 550/32, 600/33, 650/34, and 700 amperes/35 volts. The data in table II show that the power level used during plasma spray deposition significantly affects the life of the TBS. This is not apparent from the data in table II for the Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.9Y_2O_3 system at 990° C. This system withstood 1500 1-hour cycles without failure regardless of the power level used. However, the rest of the data in table II show that as the current was increased from 300 to 500 amperes for the bond coating and from 500 to 700 amperes for zirconia, TBS life increased significantly. Data for the NiCrAl-0.31Y/ZrO_2-7.9Y_2O_3 system at 1095°C are cross-plotted in figure 1. For this system, about a 75 percent improvement over the base line conditions (bond coating sprayed at 350 amperes, zirconia at 550 amperes) was realized by going to 500 amperes for bond coating deposition and 700 amperes for zirconia deposition. All previous investigations were done at the 350 amperes/550 amperes (refs. 1 to 4, 6 and 7).

Bond coating oxidation. - Increasing the power during plasma spray deposition of the bond and zirconia coatings resulted in a significant decrease in the rate of weight gain, and thus, the amount of bond coating oxidation. The data in figure 2 obtained at 990° C show that the weight gain increases about 18 percent for every 50 ampere decrease in the current during plasma spray deposition of the bond coating. Only about a 6 percent increase in the weight gain was observed for the same amperage decrease during deposition of zirconia. Thus, the bond coating applied at 400 amperes should be less oxidized than the bond coating applied at 300 amperes, after testing for 1500 1-hour cycles at 990° C. This is supported by metallographic data. The microstructure of the TBS in the photomicrograph in figure 3 is representative of the as-sprayed condition. No significant metallographic differences were observed as power levels for bond coating and zirconia application were varied. Comparison of the photomicrograph in figure 4(a) with that in figure 4(b) shows that after 1500 1-hour cycles at 990° C, the bond coating plasma sprayed at 300 amperes is oxidized to a greater extent than the bond coating sprayed at 400 amperes. The use of higher power also afforded better protection of the substrate.

The effect of power on coating oxidation is better illustrated by the 1095° C data in figure 5. These data show that a 50-ampere increase during plasma deposition of the bond coating increases the TBS life by about two times more than the same current increase during the deposition of zirconia. The TBS life increased about 100 percent when currents for the bond coating/zirconia were increased from 300/500 to 400/600, respectively, as compared to an increase of about 20 percent when currents were increased from 400/600 to 500 amperes/600 amperes, respectively. The effects of plasma spray power on coating life and the rates of coating oxidation are evident. The data in figure 5 suggest that whenever the weight gain for a Ni-16.8Cr-5.8Al-

0.31Y bond coating reaches between 6.2 and 6.9 mgs/cm^2, the TBS will fail regardless of the current used during plasma deposition. Thus, this bond coating, when applied at various power levels to similar thicknesses, should be oxidized to about the same degree at the time the zirconia coating fails. This is supported by metallographic data. Comparison of the photomicrographs in figure 6 shows that there are some differences between the oxidation behavior of the bond coatings, but the overall amount of oxidation is about the same in spite of the fact that the TBS plasma sprayed at 300/500 amperes (fig. 6(a)) lasted only half as long as the TBS sprayed at 400 amperes/600 amperes (fig. 6(b)). Also, the longer-lived system sprayed at the higher power levels again afforded better protection to the substrate.

Similar results to those in figures 2 to 6 were obtained for the NiCrAl-0.31Y/ZrO_2-11.8Y_2O_3 and Ni-16.8Cr-5.8Al-0.61Y/ZrO_2-11.8Y_2O_3 systems at 990° and 1095° C. However, the lives for the above systems were shorter than for the same bond coating with ZrO_2-7.8Y_2O_3.

Coating densities. - The beneficial effect of increased power level during plasma spray deposition of the bond coating and zirconia on bond coating oxidation resistance and TBS durability can be explained in terms of the plasma spray process and resultant coating structures. As the current during plasma spray deposition increases, the temperature of the plasma increases; therefore, the temperature of the spray powder particles also increases. Consequently, the sprayed particles applied at higher power level (thus higher temperature) within the coatings should be in more intimate contact. This should decrease the open and closed porosities, increase density, and affect the boundaries between the coating particles. This would affect the oxidation of the bond coating, since it was reported in reference 11 that the degradation of the bond coating occurs principally through the formation of oxides along plasma sprayed particle boundaries.

The metallographic examinations discussed earlier indicated no differences in structure in the as-sprayed condition, and subtle differences in oxidation behavior after test at 990° or 1095° C. However, the data in table II and figures 2 and 5 show that the power level used during plasma spraying of the bond coating and zirconia affect TBS life, with the power level used during plasma spraying of the bond coating having the greater effect. Because metallography was insensitive to the changes in coating structures resulting from variations in plasma spray power levels, densities of the bond coating and zirconia were determined by two gravimetric/volumetric procedures. The data in figure 7 show that the density of the bond coating increased about 3 percent when current was increased from 300 to 500 amperes during plasma spraying. This increase in density is equivalent to about a 45 percent reduction in mean porosity (fig. 8). The density of the zirconia increased about 5 percent when current was increased from 500 to 700 amperes. This 5 percent increase is equivalent to about 30 percent reduction in mean porosity.

The relative magnitude of the improvement in TBS life and in the reduction of bond coating oxidation rate with increasing plasma spray power for both bond and zirconia applications correlate with the relative magnitudes of bond and zirconia porosity reduction with increasing power levels. Also, the fact that the oxidation is sensitive to the amount of porosity in zirconia indicates that a significant fraction of oxygen transport probably occurs through coating pores as opposed to ionic transport through the solid.

The effect of power level during plasma spraying on bond coating roughness was also investigated to determine if this might have an influence on the results observed. In reference 12, it was reported that the rougher the bond coating surface, the better the adherence between the bond coating and zirconia. At 300 amperes, the bond coating roughness was about 10.5 μm (415 μin.) rms, while at 400 amps and above, the bond coating roughness was about 9.7 μm (380 μin.) rms. This small decrease in bond coating roughness probably had little effect on the durability of the TBS life. However, any effect due to roughness was overwhelmed by the effects resulting from the higher densities of the bond and zirconia coatings achieved at higher power levels.

Effect Of Arc Gas Composition

Arc gas used during plasma spraying can affect the microstructure and thus the life of the thermal barrier system. Two gases were used, argon and argon-hydrogen mixtures. Argon was chosen because it is monatomic and inert. Monatomic gases have a linear increase in enthalpy with temperature increase, since no dissociation energy is involved (ref. 13). Hydrogen was chosen for its high enthalpy (ref. 14), and the more rapid quenching achieved with an argon-hydrogen jet (ref. 15) than with pure argon. It was also believed that addition of hydrogen to argon would reduce the oxidation of the bond coating during plasma spraying. Nitrogen was not evaluated for the simple reason that it can form nitrides during plasma spraying (ref. 16).

The data in table III show that the addition of hydrogen to the argon has an adverse effect upon the life of the thermal barrier system at constant power level. At both 990° and 1095° C, as the hydrogen content in the argon arc gas was increased to 15 v/o for the bond coating at the same current, and to 5 v/o for the TBC at the same current, the life of the TBS decreased very significantly. Increasing current for the bond coating from 350 to 400 amperes or for the TBC from 550 to 600 amperes increased the life of the TBS. Thus, it seems that the addition of hydrogen to the argon arc gas has the same effect as a decrease in power during plasma spraying when using pure argon arc gas. At constant power, the addition of hydrogen gas lowers the plasma temperature, and also the temperature of the plasma spray particles being deposited. This can be attributed to the energy absorbed in dissociating the hydrogen. Since an increase in power during plasma spraying in argon-hydrogen arc gas improves the life of the TBS, it might be possible to obtain the same or even longer lives than with pure argon arc gas at higher current-voltage values.

For a given power level, specimens coated using argon-hydrogen mixtures were subject to higher rates of oxidation in the cyclic furnace tests at 990° and 1095° C than specimens coated in argon alone (figs. 9 and 10). At 990° C, the rate of weight gain was about 100 percent greater for a TBS with a bond coating applied with 85 v/o argon - 15 v/o hydrogen and zirconia with 95 v/o argon -5 v/o hydrogen than for a TBS applied with only argon arc gas. At 990° C, most of the thermal barrier systems plasma sprayed in argon-hydrogen arc gas failed when the amount of oxidation weight gain was between 5.8 and 6.1 mgs/cm^2 (fig. 9). At 1095° C, the thermal barrier systems failed when the amount of oxidation weight gain was between 6.9 and 7.2 mgs/cm^2. Thus, the amount of weight gain for specimens at 990° C that failed is somewhat lower and at 1095° C is somewhat higher than the 6.2 to 6.9 mgs/cm^2 observed at 1095° C for the thermal barrier systems plasma sprayed at various power levels in pure argon arc gas (fig. 5). The photomicrographs in figure 11 are representative of coatings deposited in argon/hydrogen mixtures at failure. The comparison of the photomicrographs of the specimens tested at 990° C shows that the bond coating applied with the argon/hydrogen mixture, is more oxidized (fig. 11(a)) than the one applied in pure argon (fig. 4). The results from the 1095° C tests show that the bond coatings applied with the argon/hydrogen mixture were oxidized at failure to about the same degree as those applied in argon only.

Metallographic examination of many tested specimens plasma spray coated in argon/hydrogen arc gas showed that there is a build up of oxides at the substrate-bond coating interface. This is particularly true for the bond coating applied with the 85 v/o argon-15 v/o hydrogen mixture at low power levels (fig. 12). In addition, the zirconia coating had more cracks than zirconia applied in argon arc gas.

SUMMARY OF RESULTS

A study was conducted to evaluate the effects of the power level and the arc gas used during plasma spraying on the structure and life of two-layer thermal barrier systems. The results from the cyclic furnace testing between 990° - 280° C and 1095° - 280° C show that:

1. Life of the two-layer thermal barrier system increases by about 140 percent when the current-voltage for the bond coating is increased from 300 amperes - 26 volts to 500 amperes - 31 volts and for the thermal barrier coating it is increased from 500 amperes - 31 volts to 700 amperes - 35 volts with an argon arc gas. At 1095° C, the Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.9Y_2O_3 system plasma sprayed at 300 amperes-bond coating/500 amperes - oxide coating and 500 amperes-bond coating/700 amperes - oxide coating withstood 89 and 213 1-hour cycles, respectively.
2. As the power level during plasma spraying of the TBS increases, the densities of the bond and thermal barrier coatings increase and the porosity in the bond coat coating and TBC decrease significantly. Relative life improvements with increasing power level were of about the same magnitude as relative reductions in porosity.
3. The longest life was obtained for the coated specimens that had the lowest rate of weight gain. The rate of weight gain decreases as the power level increases and increases as the volume of hydrogen in argon arc gas increases.
4. Transport of oxygen through pores in the zirconia was significant compared to ionic transport since oxidation kinetics were sensitive to zirconia density.
5. Life of the thermal barrier system decreases very rapidly as the volume of hydrogen in argon arc gas increases. Addition of hydrogen is effectively equivalent to a reduction in the power level used during plasma spraying.
6. Life of the thermal barrier system in argon-hydrogen arc gas was found to improve as a result of increasing the power level used during plasma spraying.

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TABLE I. - TYPICAL COMPOSITIONS OF SPRAY POWDERS AND SUPERALLOY SUBSTRATE[a]

Element	Composition, wt %		
	NiCrAlY	ZrO_2-Y_2O_3	MAR-M-200 + Hf
Al	[b]4.9-5.8	0.009	5.21
B	<0.001	<.001	.017
C	.007	[c]ND	.15
Ca	ND	.068	ND
Co	.034	<.005	10.12
Cr	[b]16.3-16.8	ND	8.49
Cu	.014	ND	.045
Fe	.041	.040	.37
Hf	<.01	1.80	2.08
K	<.001	<.001	<.001
Li	<.001	<.001	<.001
Mg	<.001	.032	<.001
Mn	.011	<.001	.01
Mo	<.005	<.005	<.005
Na	<.001	<.001	<.001
Nb	.039	.005	1.22
Ni	Major	.029	Major
O_2	.020	ND	ND
P	.01	ND	ND
Pb	ND	ND	.005
S	.01	ND	.01
Si	.060	.060	.19
Sr	.01	<.01	ND
Ta	<.05	.02	.05
Ti	.012	.042	2.02
V	.031	<.001	<.001
W	<.01	<.005	11.72
Y	[b]0.31-0.61	[d]6.2-9.3	ND
Zn	.05	<.05	<.005
Zr	ND	Major	.08

[a] Impurity values reported in the table are the maximum values encountered.

[b] Aluminum, chormium, and yttrium concentrations for two bond coatings used are given in tables presenting experimental data.

[c] ND, not determined.

[d] Yttria concentrations for two yttria-stabilized zirconias used are given in tables presenting experimental data.

TABLE II. - THE EFFECT OF THE PLASMA SPRAY POWER PARAMETERS ON THE LIFE OF THE THERMAL BARRIER SYSTEM AS DETERMINED BY CYCLIC FURNACE TESTING[a]

Bond coating				Thermal barrier coating				Average number of cycles to failure[d]
Composition, wt %	Thickness, cm[b]	Ampere	Volt	Composition, wt %	Thickness, cm[c]	Ampere	Volt	
990°-280° C								
Ni-16.8Cr-5.8Al-0.31Y	0.010	400	28	ZrO_2-7.9Y_2O_3	0.044	600	33	[e]1500
	.011	400	28		.036	550	32	
	.012	350	27		.042	600	33	
	.011	350	27		.036	550	32	
	.013	350	27		.033	500	31	
	.011	300	26		.035	550	32	
↓	.010	300	26	↓	.038	500	31	↓
Ni-16.8Cr-5.8Al-0.31Y	0.011	400	28	ZrO_2-11.8Y_2O_3	0.039	600	33	[e]1500
-.31Y	.012	400	28	-11.8Y_2O_3	.039	550	32	1356
-.31Y	.011	350	27	-11.8Y_2O_3	.042	600	33	1288
Ni-16.3Cr-4.9Al-0.61Y	0.012	400	28	ZrO_2-11.8Y_2O_3	0.039	550	32	1130
-.61Y	.010	350	27	-11.8Y_2O_3	.036	600	33	1165
-.61Y	.012	350	27	-11.8Y_2O_3	.040	550	32	755
1095°-280° C								
Ni-16.8Cr-5.8Al-0.31Y	0.013	500	31	ZrO_2-7.9Y_2O_3	0.040	700	35	213
	.012	450	29		.039	700	35	207
	.012	500	31		.039	650	34	201
	.012	500	31		.039	600	33	199
	.012	450	29		.039	650	34	193
	.011	400	28		.040	700	35	189
	.011	450	29		.038	650	34	188
	.011	400	28		.037	650	34	182
	.013	400	28		.038	600	33	177
	.011	400	28		.036	550	32	148
		350	27		.032	600	33	141
		350	27		.039	550	32	122
		350	27		.032	500	31	109
	↓	300	26		.036	550	32	99
↓	.013	300	26	↓	.033	500	31	89
Ni-16.3Cr-4.9Al-0.61Y	0.011	400	28	ZrO_2-11.8Y_2O_3	0.036	550	32	79
-.61Y	.011	350	27	-11.8Y_2O_3	.033	600	33	76
-.61Y	.011	350	27	-11.8Y_2O_3	.038	550	32	58

[a] MAR-M-200 alloy with about 2.1 wt % Hf was used as the substrate material; specimens were about 2.5 by 2.5 by 0.5 cm. A minimum of two specimens were run per each test.

[b] Bond coating on each specimen could vary by ±0.004 cm.

[c] Thermal barrier coating on each specimen could vary by ±0.006 cm.

[d] Cycle = 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C. Test stopped when a visible crack occurred in the thermal barrier coating.

[e] No failure.

TABLE III. - THE INFLUENCE OF THE ARC GAS AND THE CURRENT/VOLTAGE USED DURING PLASMA SPRAYING ON THE LIFE OF THE Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.9Y_2O_3 THERMAL BARRIER SYSTEM[a]

Bond coating					Thermal barrier coating					Average number of cycles to failure[d]
Thickness, cm[b]	Argon	Hydrogen	Ampere	Volt	Thickness, cm[c]	Argon	Hydrogen	Ampere	Volt	
990°-280° C										
0.011	100.0 v/o	0 v/o	350	27	0.036	100.0 v/o	0 v/o	550	32	[e]1504
.013	85.0	15.0	350	49	.032	100.0	0	550	32	[e]1568
.011	90.0	10.0	350	47	.032	97.5	2.5	550	39	1190
.015	85.0	15.0	350	49	.039	95.0	5.0	550	43	918
0.013	85.0	15.0	400	49	0.037	95.0	5.0	550	43	1530
1095°-280° C										
0.011	100.0 v/o	0 v/o	350	27	0.039	100.0 v/o	0 v/o	550	32	126
.011	85.0	15.0	350	49	.033	100.0	0	550	32	86
.009	90.0	10.0	350	47	.037	97.5	2.5	550	39	66
.013	85.0	15.0	350	49	.032	95.0	5.0	550	43	55
0.011	85.0	15.0	350	49	0.034	97.5	2.5	600	39	70
.013	85.0	15.0	350	49	.036	95.0	5.0	600	43	60

[a] MAR-M-200 alloy with about 2.1 wt % Hf was used as the substrate material; specimens were 2.5 by 2.5 by 0.5 cm. A minimum of two specimens were run per each test.

[b] Bond coating on each specimen could vary by ±0.004 cm.

[c] Thermal barrier coating on each specimen could vary by ±0.006 cm.

[d] Cycle consisted of 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C. Test stopped whenever a visible crack occurred in the thermal barrier oxide coating.

[e] No failure.

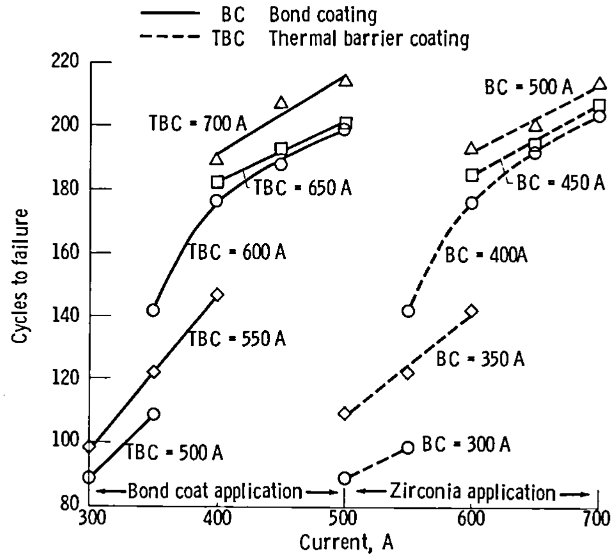
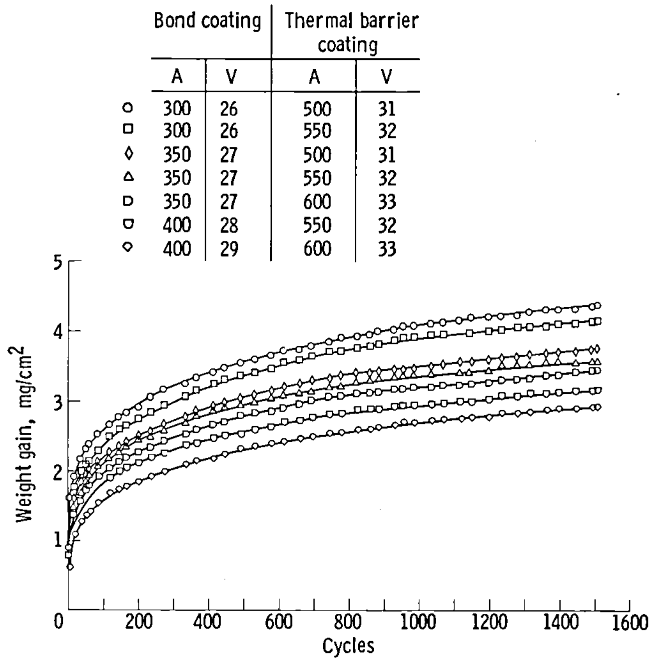


Figure 1. - The effect of power used during plasma spraying of the Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.8Y_2O_3 thermal barrier system as determined in a cyclic furnace at 1095° C. (Cycle, 6 minute heat-up, 60 minutes at temperature, 60 minutes of cooling to about 280° C.)



	Bond coating		Thermal barrier coating	
	A	V	A	V
○	300	26	500	31
□	300	26	550	32
◊	350	27	500	31
△	350	27	550	32
◗	350	27	600	33
▽	400	28	550	32
◇	400	29	600	33

Figure 2. - The effect of power used during plasma spraying on the weight gain of Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.9Y_2O_3 thermal barrier system as determined in a cyclic furnace at 990° C. (Cycle, 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C.)

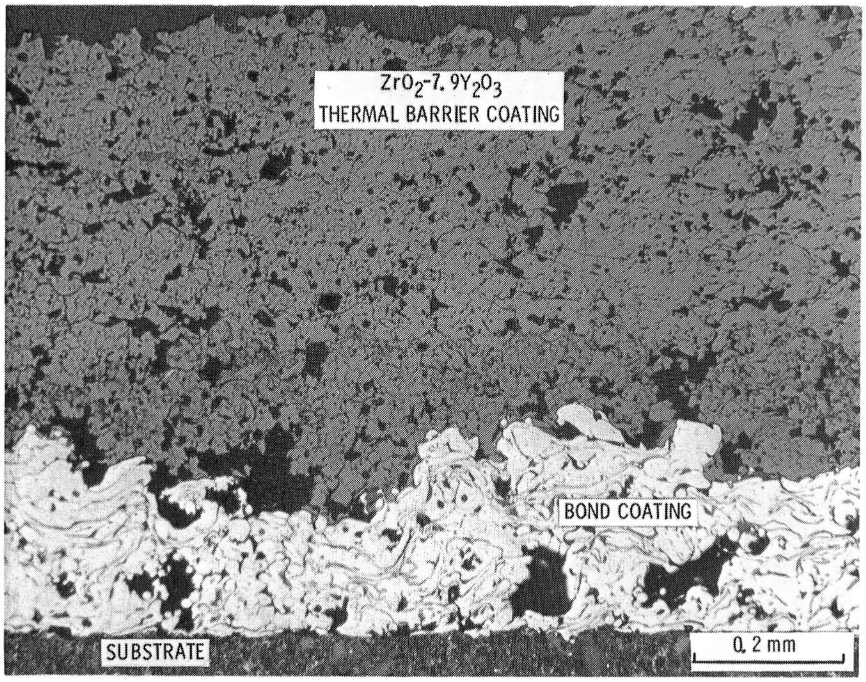


Figure 3. - Light optical photomicrograph of flat surface of MAR-M-200+Hf specimen coated with Ni-16.8Cr-5.8Al-0.31Y bond coating at 400 amperes and 28 volts and ZrO_2-7.9Y_2O_3 thermal barrier coating at 600 amperes and 33 volts.

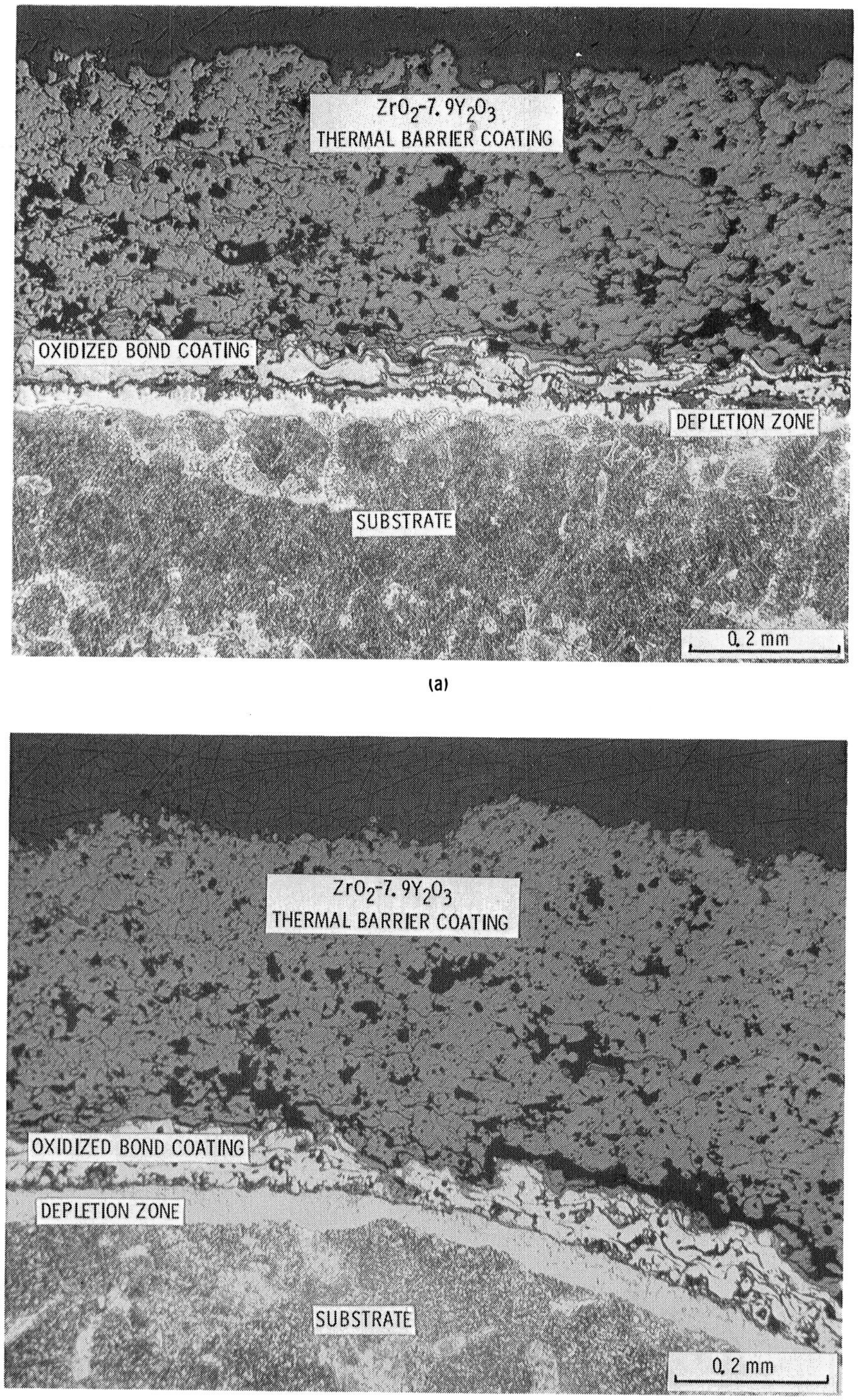


Figure 4. - Light optical photomicrograph of flat surface of MAR-M-200+Hf specimen coated with Ni-16.8Cr-5.8Al-0.31Y bond coating and ZrO_2-7.9Y_2O_3 thermal barrier coating after 1500 1-hour cycles at 990° C: (a) bond coating plasma sprayed at 300 amperes/26 volts and the oxide coating at 500 amperes/31 volts; (b) bond coating plasma sprayed at 400 amperes/28 volts and the oxide coating at 600 amperes/33 volts. (Cycle, 6 minutes heat up, 60 minutes at temperature, and 60 minutes cooling to about 280° C).

	Bond coating		Thermal barrier coating	
	A	V	A	V
○	300	26	500	31
□	300	26	550	32
◇	350	27	500	31
△	350	27	550	32
□	350	27	600	33
□	400	28	550	32
○	400	28	600	33
□	400	28	700	35
△	450	29	650	34
△	450	29	700	35
□	500	30	700	35

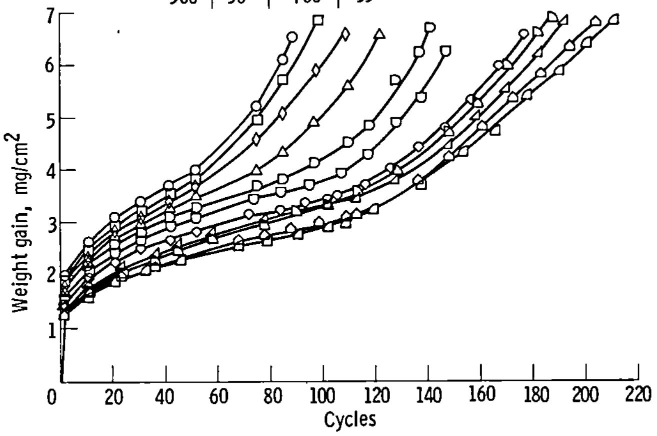


Figure 5. - The effect of power used during plasma spraying on the weight gain and the life of Ni-16.8Cr-5.8Al-0.31Y/ZrO$_2$-7.9Y$_2$O$_3$ thermal barrier system as determined in a cyclic furnace at 1095° C. (Cycle = 6 minute heat-up, 60 minutes at temperature, and 60 minutes cooling to about 280° C.)

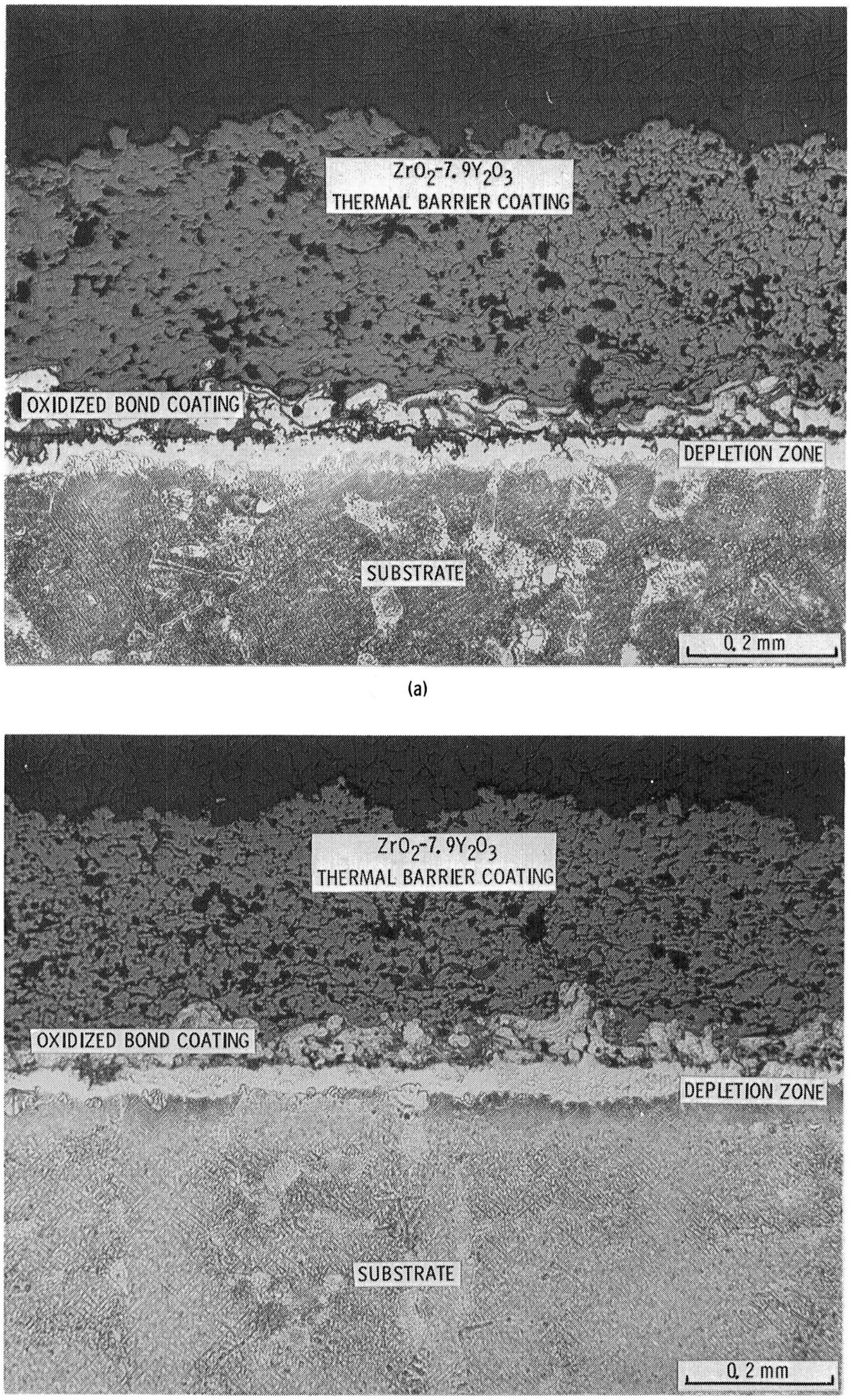


Figure 6. - Light optical photomicrograph of MAR-M-200+Hf specimens coated with Ni-16.8Cr-5.8Al-0.31Y bond coating and ZrO_2-7.9Y_2O_3 thermal barrier coating after testing at 1095° C: (a) bond coating plasma sprayed at 300 amperes/26 volts and the oxide coating at 500 amperes/31 volts after 115 1-hour cycles; (b) bond coating plasma sprayed at 400 amperes/28 volts and the oxide coating at 600 amperes/33 volts after 191 1-hour cycles. (Cycle, 6 minutes heat up, 60 minutes at temperature, and 60 minutes cooling to about 280° C).

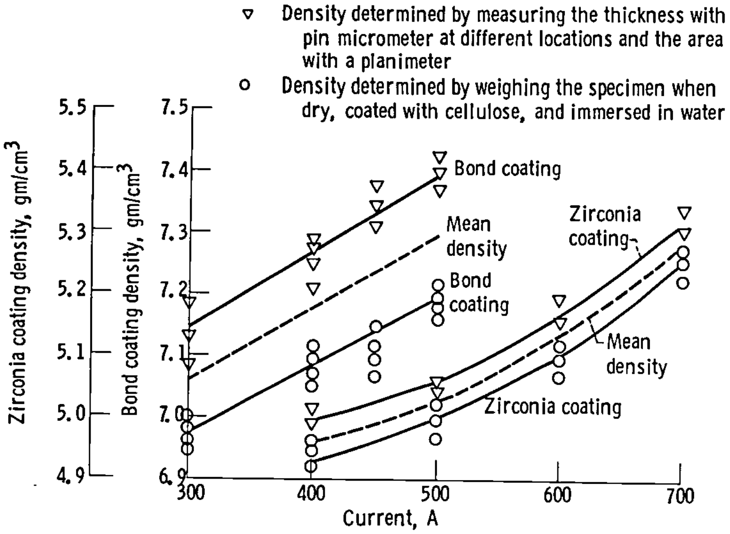


Figure 7. - The effects of currents used during plasma spraying of the bond coating and zirconia coating on the densities of these coatings.

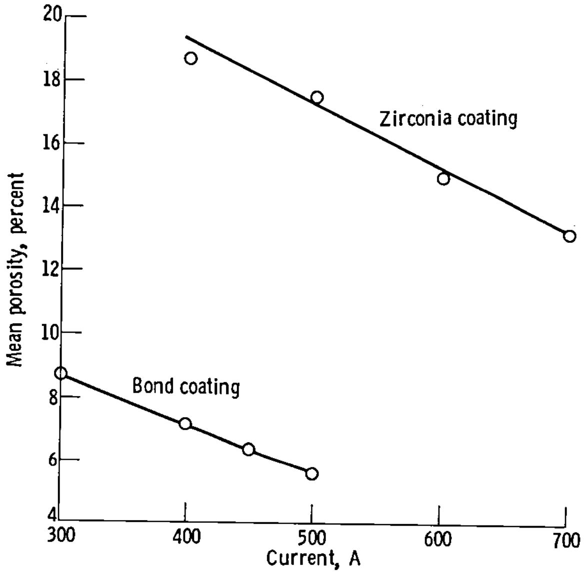


Figure 8. - The effects of currents used during plasma spraying of the bond and zirconia coatings on the mean porosities of these coatings.

	Bond coating				Thermal barrier coating			
	A	V	Arc gas, vol.%		A	V	Arc gas, vol.%	
			Argon	Hydrogen			Argon	Hydrogen
○	350	49	85	15	550	43	95.0	5.0
□	350	47	90	10	550	39	97.5	2.5
◊	400	49	85	15	550	43	95.0	5.0
△	350	49	85	15	550	32	100.0	0.0
◗	350	27	100	0	550	32	100.0	0.0

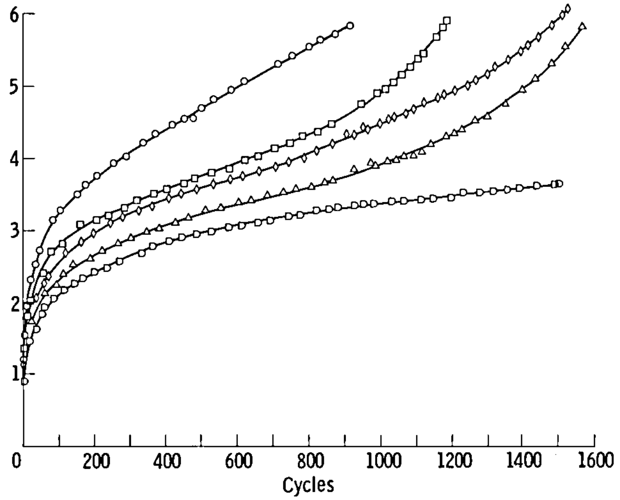


Figure 9. - The effect of arc gas composition and the current/voltage used used during plasma spraying on the weight gain and the life of Ni-1.6.8 Cr-5.8Al-0.31Y/ZrO_2-7.8Y_2O_3 system as determined by cyclic furnace testing at 990° C. (Cycle - 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C.)

	Bond coating				Thermal barrier coating			
	A	V	Arc gas, vol.%		A	V	Arc gas, vol.%	
			Argon	Hydrogen			Argon	Hydrogen
○	350	49	85	15	550	43	95.0	5.0
□	350	49	85	15	550	39	97.5	2.5
◊	350	49	85	15	600	43	95.0	5.0
△	350	47	90	10	550	39	97.5	2.5
◗	350	49	85	15	600	39	97.5	2.5
◡	350	49	85	15	550	32	100.0	0.0
◇	350	27	100	0	550	32	100.0	0.0

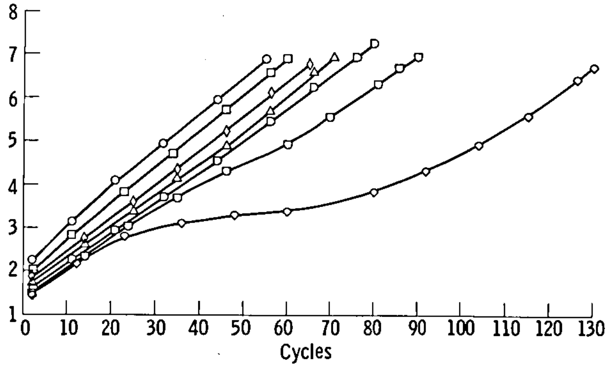
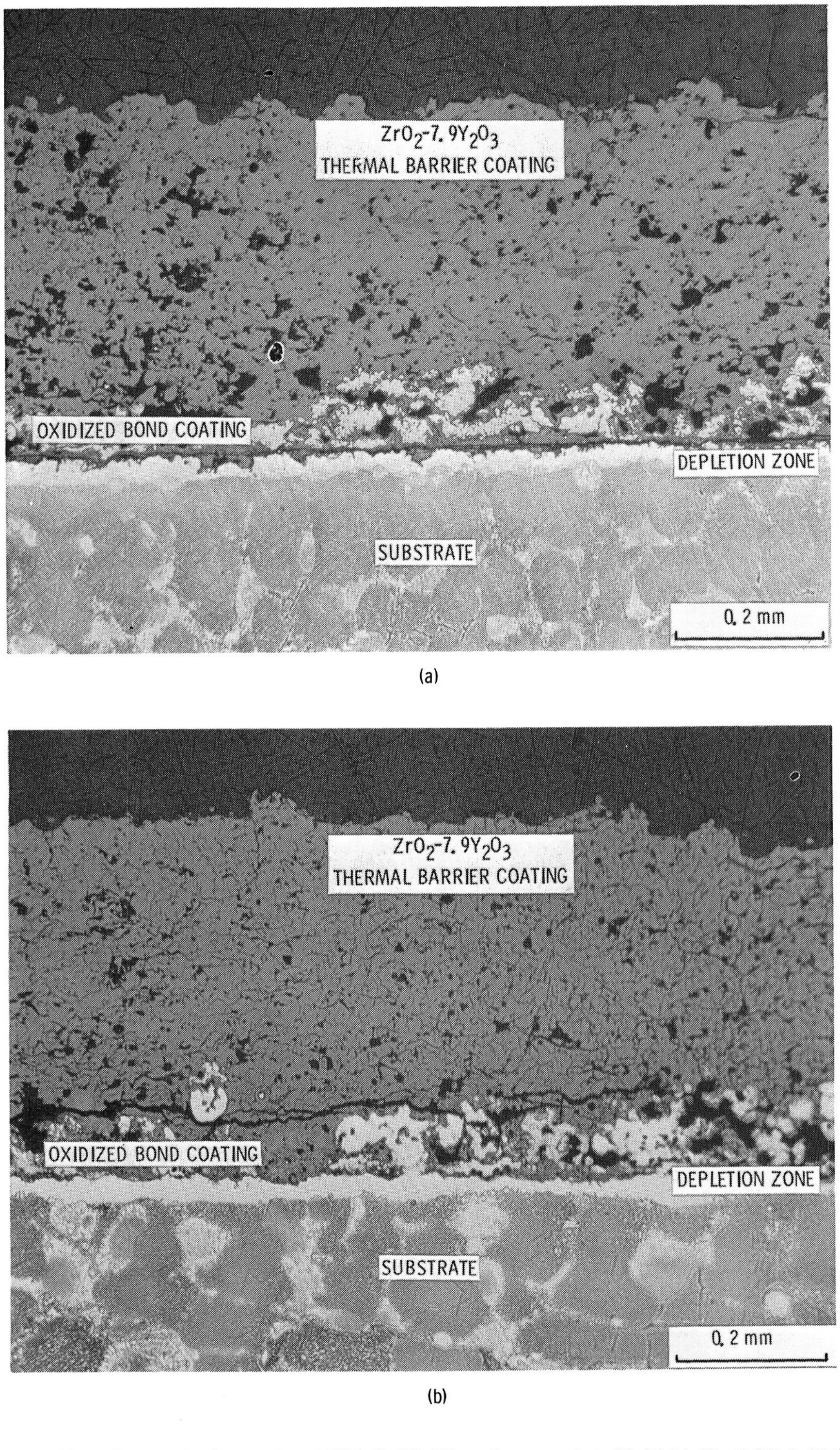


Figure 10. - The effect of arc gas composition and the current/voltage used during plasma spraying on the weight gain and the life of Ni-16.8Cr-5.8Al-0.31Y/ZrO_2-7.8Y_2O_3 system as determined by cyclic furnace testing at 1095° C. (Cycle - 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C.)



(a)

(b)

Figure 11. - Light photomicrographs of MAR-M-200+Hf specimens coated with Ni-16.8Cr-5.8Al-0.31Y/ ZrO_2-7.9Y_2O_3 system tested in cyclic furnace; (a) bond coating/zirconia plasma sprayed in argon-15v/o hydrogen/argon at 350 amperes/550 amperes - after 1568 1-hour cycles and no failure at 990° C; (b) bond coating/zirconia plasma sprayed in argon-15v/o hydrogen/argon-2.5v/o hydrogen at 350 amperes/600 amperes - after 70 1-hour cycles and failure at 1095° C. (Cycle = 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C).

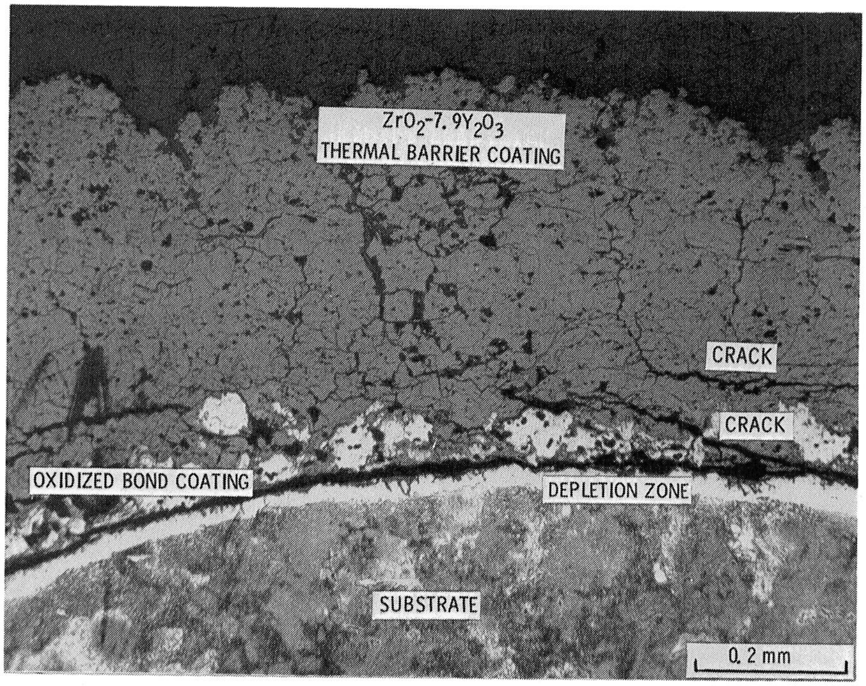


Figure 12. - Light photomicrograph of MAR-M-200+Hf specimen coated with Ni-16.8Cr-5.8Al-0.31Y bond coating applied in argon-15v/o hydrogen at 300 amperes and zirconia coating applied in argon-5v/o hydrogen at 500 amperes and after 41 1-hour cycles at 1095° C and failure. (Cycle = 6 minute heat-up, 60 minutes at temperature, and 60 minutes of cooling to about 280° C).

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15. Supplementary Notes

16. Abstract

The power level and the type of arc gas used during plasma spraying of a two-layer thermal barrier system (TBS) were found to affect the life of the system. Life at 1095° C in a cyclic furnace test was improved by about 140 percent by increasing the power during plasma spray applications of the bond and thermal barrier coatings. This improvement is due to increases in the densities of the bond and thermal barrier coatings by 3 and 5 percent, respectively. These increases in densities are equivalent to about 45 and 30 percent reduction in mean porosities, respectively. The addition of hydrogen to the argon arc gas had the same effect as the reduction in power level and caused a reduction in TBS life.

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