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EFFECTS OF YTTRIUM, ALUMINUM AND CHROMIUM CONCENTRATIONS IN BOND COATINGS ON THE PERFORMANCE OF ZIRCONIA-YTTRIA THERMAL BARRIERS

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EFFECTS OF YTTRIUM, ALUMINUM AND CHROMIUM CONCENTRATIONS IN BOND COATINGS ON THE PERFORMANCE OF ZIRCONIA-YTTRIA THERMAL BARRIERS

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ABSTRACT

A cyclic furnace study was conducted on thermal barrier systems to evaluate the effects of yttrium, chromium, and aluminum in nickel-base alloy bond coatings and the effect of bond coating thickness on yttria-stabilized zirconia thermal barrier coating life. Without yttrium in the bond coatings, the zirconia coatings failed very rapidly. Increasing chromium and aluminum in the Ni-Cr-Al-Y bond coatings increased total coating life. This effect was not as great as that due to yttrium. Increased bond coat thickness was also found to increase life.

INTRODUCTION

Significant progress has been made in improving the performance and adherence of two-layer thermal barrier systems (TBS) on metallic substrates[1-4]. The reported Lewis Research Center data indicate that the performance of the NiCrAlY/ZrO_2-Y_2O_3 duplex system is best at certain specific NiCrAl-Y bond coating and ZrO_2-Y_2O_3 (TBC) compositions. One of the better systems, Ni-17.0 Cr-5.4Al-0.35Y/ZrO_2-7.9Y_2O_3*, has withstood 2000 1-hour cycles in a Mach 1.0 burner rig at a 1470°C surface temperature.

This study was conducted to examine the effects of yttrium, chromium, and aluminum in the bond coating and the effect of bond coating thickness on the life of ZrO_2-Y_2O_3. The evaluations were done in a cyclic furnace.

EXPERIMENTAL

The compositions of the bond coatings and ZrO_2-Y_2O_3 are given in tables I-V. Substrates were cast nickel-base alloys, B-1900+Hf and MAR-M-200+Hf. Flat specimens with all corners and edges rounded were used. The plasma spray depositions of the bond coatings and ZrO_2-Y_2O_3 was done in the same manner as described in references 1 and 4. Coating thicknesses reported in the tables are maximums. Bond coating thicknesses on the specimens used in the evaluation of the effect of bond coating thickness on life were measured with a micrometer. These measurements showed that thickness could vary by ± 0.004 cm.

Evaluations were done in a furnace cycled between either 990° and 280°C or 1095° and 280°C. The cycle consisted of a 6 minute heat-up, 60 minutes at

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* All compositions in weight percent.

temperature, and 60 minutes of cooling to about 280°C. Specimens were inspected every 12 cycles until failure, denoted by a visible crack, occurred in the TBC. Cyclic furnace tests appear to be reliable for comparison purposes. From prior investigations, it was found that the TBS having the longest life in the cyclic furnace tests also had the longest life in cyclic natural gas-oxygen torch rig tests as well as in cyclic Mach 1.0 burner rig tests[1,2,4].

RESULTS AND DISCUSSION

Effect of yttrium-free Ni-Cr, Ni-Al and NiCrAl bond coatings - The data in table I indicate that the use of an yttrium-free bond coating (8.9 micrometers rms) slightly improves the life of the yttria-stabilized zirconia TBC compared to the case with no bond coating, where cleaned substrate surfaces were relatively smooth (2.5 micrometers rms). If mechanical forces, due to interlocking, play the major role in determining TBS life, then the presence of a bond coating should result in a significant increase in life and the three bond coatings in table I should have similar lives. This is not the case. The greatest changes result from changes in bond coating composition. However, considerable roughness is required to achieve adherence of the oxide layer[5]. Thus, chemical-electrostatic bonding and mechanical forces responsible for adherence can act through a larger area. Failure of ZrO_2-Y_2O_3 applied directly on B-1900+Hf occurred by separation of the TBC from the substrate. Many small cracks in the ZrO_2-7.8Y_2O_3 and ZrO_2-11.5Y_2O_3 TBCs oriented either parallel or at acute angles to the substrate were observed (Fig. 1).

Effect of yttrium on NiCr and NiAl bond coatings - The data in tables II and III show that the addition of yttrium had a very signifiant beneficial effect on TBS life. Additions of 0.52Y improved life many times while 1.52Y additions were only slightly beneficial. Substitution of chromium for aluminum does not affect the life of TBCs as much as does the addition of yttrium.

Metallographic studies of failed ZrO_2-7.8Y_2O_3 coated specimens having yttrium-free bond coatings revealed failure at the substrate-bond coating interface and complete bond oxidation at 990°C. The Ni-19.8Cr-0.53Y bond coating after longer exposure at 990°C was less extensively oxidized. However, the Ni-19.8 Cr-0.53Y bond coating underwent more oxidation at 1095°C (Fig. 2a) than did the Ni-19.3Al-0.52Y bond coating (Fig. 2b). With yttrium in the bond coatings failure typically initiated through formation of cracks within the TBC near the bond coating, as shown in figure 2, and extension of these internal cracks to the surface. The oxide stringers formed within the as-deposited Ni-19.3 Al-0.52Y bond coating were identified to be principally aluminum oxides. These stringers grew during testing. Electron microprobe data also suggested that yttrium in the bond coating is diffusing toward the bond coating-TBC interface.

Effect of bond coating Cr and Al content - The data in table IV show that Cr and Al also have a significant effect on TBS life. At 990°C, all but the ZrO_2-17.4Y_2O_3 TBCs withstood 1500 1-hour cycles. At 1095°C, the best bond coating was Ni-25.7Cr-5.6Al-0.32Y, which when coupled with ZrO_2-7.8Y_2O_3 gave more than twice the life of a Ni-16.4Cr-5.1Al-0.15Y/ZrO_2-7.8Y_2O_3 system.

Figure 3 shows Ni-25.7Cr-5.6Al-0.32Y before testing. It is representative of other bond coatings sprayed in air in that it contains oxide particles and stringers at particle boundaries, is quite rough and convoluted, and is not of uniform thickness. Figure 4 shows the degree of oxidation of the bond coating in the Ni-25.7Cr-5.6Al-0.32Y/ZrO_2-7.8Y_2O_3 system after testing as 990° and 1095°C. Metallography indicated that oxidation resistance decreased from Ni-25.7Cr-5.6 Al-0.32Y, to Ni-19.9Cr-19.2Al-0.33Y, to Ni-16.6Cr-10.6Al-0.33Y as did the life of the TBS. Failure of the oxides with these bond coatings originated within the TBC near the bond coating-TBC interface.

Effect of bond coating thickness - The data in table V show that the thicker the bond coating, the longer the TBS life. Uniformity of bond coating thickness is probably also important because a thin spot could lead to a local, premature failure. The data indicate that manually applied bond coatings should be at least 0.015 to 0.020 cm thick. The bond coating thickness values reported in table V indicate the ranges measured with a micrometer before the oxide was applied. Thinner areas were observed by metallographic examinations. Photomicrographs of the NiCrAl-0.32Y/ZrO_2-7.8Y_2O_3 TBS showed that the 0.003 to 0.007 cm thick bond coating, which failed after 1419 1-hour cycles at 990°C, was nearly completely oxidized. Metallographic examinations of specimens tested at 990°C showed that as bond coating thickness increased, the thickness of the unoxidized bond coating next to the substrate also increased. Similar trends were noted after 1095°C tests.

The effect of bond coating thickness on life is even more strikingly shown by results obtained at 1095°C with 0.020 cm thick Ni-25.7Cr-5.6Al-0.32Y bond coatings coupled with 7.8Y_2O_3- and 6.1Y_2O_3-stabilized zirconia coatings. The former withstood 635 and 656 cycles and the latter withstood 668 and 681 1-hour cycles. This is about a 2.5-fold increase in life resulting from an increase in bond coating thickness from about 0.011 to about 0.020 cm. Bond coating thickness did not affect the failure mechanism.

SUMMARY OF RESULTS AND CONCLUSIONS

Bond coating resistance to oxidation has a significant effect on the adherence and life of the TBS. The presence of yttrium in the bond coating is very critical. Without it, the TBS fails rapidly at the substrate-bond coating interface. With yttrium, failure occurs within the oxide coating near the bond coating-oxide coating interface. Yttrium, aluminum, and/or chromium in the bond coating critically affect TBS life. The best bond coating was Ni-25.7Cr-5.6Al0.32Y which was about 2 times better than Ni-16.4Cr-5.1 Al-0.15Y. Coating life improvements of about 1.5 to 2.0 times were obtained with bond coatings exceeding 0.010-0.012 cm.

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TABLE I. - THE EFFECTS OF VARIOUS-YTTRIUM-FREE BOND COATINGS ON THE PERFORMANCE OF THE YTTRIA-STABILIZED ZIRCONIA THERMAL BARRIER COATINGS

[Cyclic furnace test results]

Bond coating		Thermal barrier coating		Average number of cycles to failure for two specimens
Composition, wt %	Thickness, cm	Composition, wt %	Thickness, cm	
990° - 280° C				
No bond coating	-----	ZrO_2-7.8Y_2O_3	0.055	85
Ni-19.8Al	0.009	-7.8Y_2O_3	.042	103
-20.2Cr	.010	-7.8Y_2O_3	.034	205
-16.2Cr-5.5Al	.011	-7.8Y_2O_3	.036	455
No bond coating	-----	ZrO_2-11.5Y_2O_3	.044	55
Ni-19.8Al	.010	-11.5Y_2O_3	.034	68
-20.2Cr	.011	-11.5Y_2O_3	.039	118
-16.2Cr-5.5Al	.011	-11.5Y_2O_3	.040	326

TABLE II. - EFFECT OF YTTRIUM CONCENTRATION IN Ni-Cr BOND COATINGS ON YTTRIA-STABILIZED ZIRCONIA THERMAL BARRIER COATING LIFE

[Cyclic furnace test results]

Bond coating		Thermal barrier coating		Average number of cycles to failure for two specimens
Composition, wt %	Thickness, cm	Composition, wt %	Thickness, cm	
990° - 280° C				
Ni-20.2Cr	0.010	ZrO_2-7.8Y_2O_3	0.034	205
-19.5Cr-1.53Y	.009	-7.8Y_2O_3	.042	300
-19.8Cr-0.53Y	.011	-7.8Y_2O_3	.040	[a]1550
Ni-20.2Cr	.011	ZrO_2-11.5Y_2O_3	.039	118
-19.5Cr-1.53Y	.011	-11.5Y_2O_3	.040	169
-19.8Cr-0.53Y	.012	-11.5Y_2O_3	.039	1537
Ni-20.2Cr	.010	ZrO_2-17.4Y_2O_3	.037	90
-19.5Cr-1.53Y	.009	-17.4Y_2O_3	.034	152
-19.8Cr-0.53Y	.013	-17.4Y_2O_3	.040	612
Ni-20.2Cr	.011	ZrO_2-24.4Y_2O_3	.042	75
-19.5Cr-1.53Y	.011	-24.4Y_2O_3	.046	93
-19.8Cr-0.53Y	.011	-24.4Y_2O_3	.039	354
1095° - 280° C				
Ni-20.2Cr	0.012	ZrO_2-7.8Y_2O_3	0.043	27
-19.5Cr-1.53Y	.010	-7.8Y_2O_3	.043	47
-19.8Cr-0.53Y	.010	-7.8Y_2O_3	.039	56
Ni-20.2Cr	.011	ZrO_2-11.5Y_2O_3	.043	13
-19.5Cr-1.53Y	.011	-11.5Y_2O_3	.039	24
-19.8Cr-0.53Y	.011	-11.5Y_2O_3	.044	46
Ni-20.2Cr	.012	ZrO_2-17.4Y_2O_3	.043	10
-19.5Cr-1.53Y	.009	-17.4Y_2O_3	.046	20

[a]No failure.

TABLE III. - EFFECT OF YTTRIUM CONCENTRATION IN Ni-Al BOND COATINGS ON YTTRIA-STABILIZED ZIRCONIA THERMAL BARRIER COATING LIFE

[Cyclic furnace test results]

Bond coating		Thermal barrier coating		Average number of cycles to failure for two specimens
Composition, wt %	Thickness, cm	Composition, wt %	Thickness, cm	
990° - 280° C				
Ni-19.8Al	0.009	ZrO_2-7.8Y_2O_3	0.042	103
-19.4Al-1.60Y	.012	-7.8Y_2O_3	.041	233
-19.3Al-0.52Y	.010	-7.8Y_2O_3	.042	[a]1389
Ni-19.8Al	.010	ZrO_2-11.5Y_2O_3	.034	65
-19.4Al-1.60Y	.011	-11.5Y_2O_3	.040	150
-19.3Al-0.52Y	.012	-11.5Y_2O_3	.042	[a]1256
Ni-19.8Al	.010	ZrO_2-17.4Y_2O_3	.040	54
-19.4Al-1.60Y	.010	-17.4Y_2O_3	.050	85
-19.3Al-0.52Y	.011	-17.4Y_2O_3	.044	448
Ni-19.8Al	.010	ZrO_2-24.4Y_2O_3	.042	33
-19.4Al-1.60Y	.011	-24.4Y_2O_3	.043	59
-19.3Al-0.52Y	.011	-24.4Y_2O_3	.044	259
1095° - 280° C				
Ni-19.4Al-1.60Y	0.010	ZrO_2-7.8Y_2O_3	0.038	70
-19.3Al-0.52Y	.011	-7.8Y_2O_3	.038	198
Ni-19.4Al-1.60Y	.010	ZrO_2-11.5Y_2O_3	.040	35
-19.3Al-0.52Y	.011	-11.5Y_2O_3	.042	160
Ni-19.4Al-1.60Y	.012	ZrO_2-17.4Y_2O_3	.043	29
Ni-19.4Al-1.50Y	.010	ZrO_2-24.4Y_2O_3	.040	19

[a]No failure.

TABLE IV. - EFFECTS OF CHROMIUM AND ALUMINUM CONCENTRATIONS IN Ni-Cr-Al-Y BOND COATINGS ON YTTRIA-STABILIZED THERMAL BARRIER COATING LIFE

[Cyclic furnace test results]

Bond coating		Thermal barrier coating		Average number of cycles to failure for two specimens
Composition, wt %	Thickness, cm	Composition, wt %	Thickness, cm	
990° - 280° C				
Ni-25.7Cr-5.6Al-0.32Y	0.011	ZrO_2-7.8Y_2O_3	0.033	[a]1500
-16.4Cr-5.8Al-0.32Y	.009	-7.8Y_2O_3	.044	[a]1500
-19.8Cr-19.2Al-0.33Y	.011	-7.8Y_2O_3	.036	[a]1500
-16.6Cr-10.6Al-0.33Y	.013	-7.8Y_2O_3	.034	[a]1500
Ni-25.7Cr-5.6Al-0.32Y	.010	ZrO_2-11.8Y_2O_3	.032	[a]1500
-19.8Cr-19.2Al-0.33Y	.014	-11.8Y_2O_3	.033	[a]1500
-16.6Cr-10.6Al-0.33Y	.010	-11.8Y_2O_3	.039	[a]1500
Ni-25.7Cr-5.6Al-0.32Y	.011	ZrO_2-17.4Y_2O_3	.035	743
-16.6Cr-10.6Al-0.33Y	.009	-17.4Y_2O_3	.036	488
1095° - 280° C				
Ni-25.7Cr-5.6Al-0.32Y	0.011	ZrO_2-7.8Y_2O_3	0.033	246
-16.4Cr-5.8Al-0.32Y	.012	-7.8Y_2O_3	.036	114
-19.8Cr-19.2Al-0.33Y	.012	-7.8Y_2O_3	.032	208
-16.6Cr-10.6Al-0.33Y	.011	-7.8Y_2O_3	.031	152
Ni-25.7Cr-5.6Al-0.32Y	.011	ZrO_2-11.8Y_2O_3	.034	165
-19.8Cr-19.2Al-0.33Y	.010	-11.8Y_2O_3	.035	98
-16.6Cr-10.6Al-0.33Y	.011	-11.8Y_2O_3	.031	72
Ni-19.8Cr-19.2Al-0.33Y	.010	-17.4Y_2O_3	.039	23

[a]No failure.

TABLE V. - EFFECT OF BOND COATING THICKNESS ON YTTRIA-STABILIZED

ZIRCONIA THERMAL BARRIER COATING LIFE

[Cyclic furnace test results]

Bond coating		Thermal barrier coating		Average number of cycles to failure for two specimens
Composition, wt %	Thickness range, cm	Composition, wt %	Thickness, cm	
990° - 280° C				
Ni-16.4Cr-5.8Al-0.32Y	0.003-0.007	ZrO_2-7.8Y_2O_3	0.028	1419
-0.32Y	.005- .008	-7.8Y_2O_3	.028	1529
-0.32Y	.012- .018	-7.8Y_2O_3	.032	[a]1610
-0.32Y	.018- .026	-7.8Y_2O_3	.032	[a]1610
-0.32Y	.026- .032	-7.8Y_2O_3	.030	[a]1629
Ni-16.4Cr-5.8Al-0.32Y	.002- .007	ZrO_2-11.8Y_2O_3	.036	[illegible]
-0.32Y	.004- .010	-11.8Y_2O_3	.034	780
-0.32Y	.009- .015	-11.8Y_2O_3	.039	1294
-0.32Y	.018- .027	-11.8Y_2O_3	.038	1119
-0.32Y	.020- .027	-11.8Y_2O_3	.039	1132
Ni-16.8Cr-5.8Al-0.62Y	.005- .009	ZrO_2-7.8Y_2O_3	.036	676
-0.62Y	.007- .010	-7.8Y_2O_3	.040	726
-0.62Y	.014- .018	-7.8Y_2O_3	.042	877
1095° - 280° C				
Ni-16.4Cr-5.8Al-0.32Y	0.005-0.008	ZrO_2-7.8Y_2O_3	0.033	46
-0.32Y	.007- .010	-7.8Y_2O_3	.036	60
-0.32Y	.013- .019	-7.8Y_2O_3	.038	104
Ni-16.4Cr-5.8Al-0.32Y	.004- .007	ZrO_2-11.8Y_2O_3	.033	23
-0.32Y	.007- .010	-11.8Y_2O_3	.036	35
-0.32Y	.011- .016	-11.8Y_2O_3	.038	60

[a]No failure.

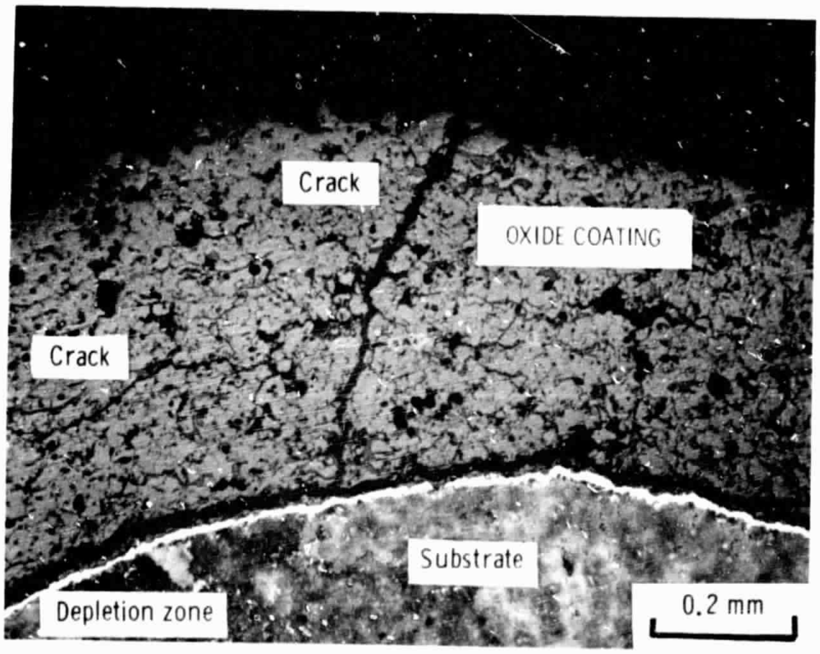

Figure 1. - Light optical photomicrograph of edge of B-1900 + Hf specimen coated with ZrO_2-7.8Y_2O_3 after testing for 85 cycles at 990° C.

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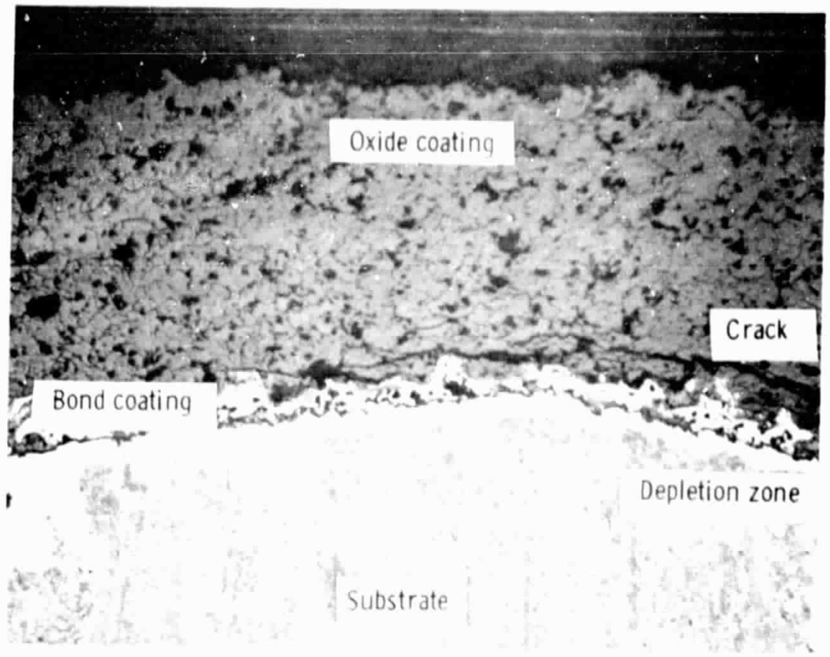

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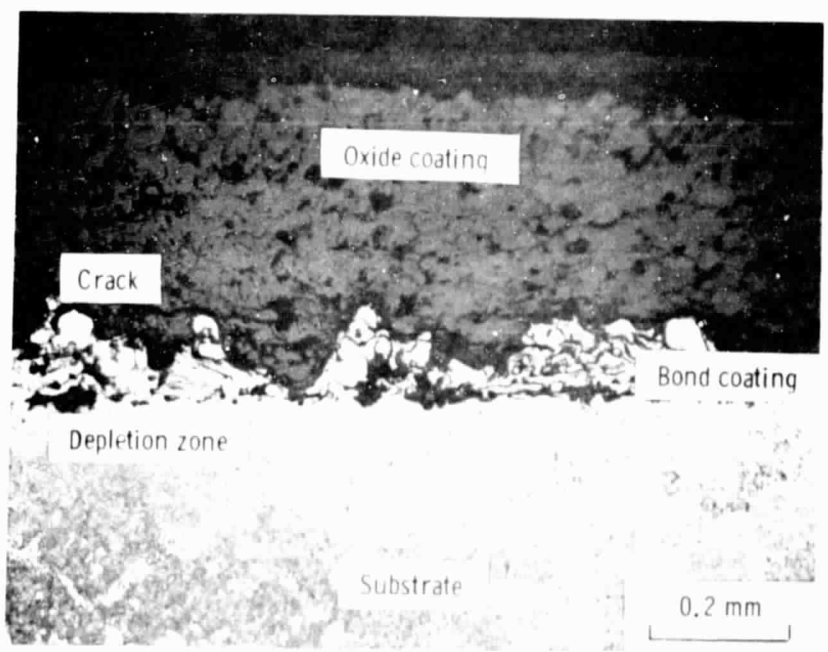

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Figure 2. - Light optical photomicrograph of: (a) the edge surface of MAR-M-200 + Hf specimen coated with Ni-19.8Cr-0.53Y and ZrO_2-7.8Y_2O_3 after 56 1-hour cycles at 1095° C, and (b) the flat surface of MAR-M-200 + Hf specimen coated with Ni-19.3Al-0.52Y and ZrO_2-7.8Y_2O_3 after 198 1-hour cycles at 1095° C.

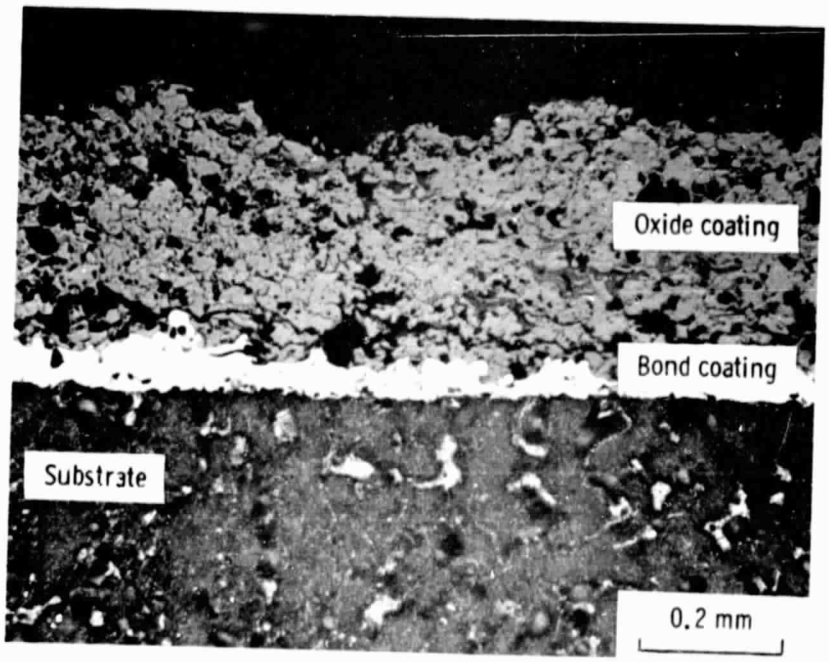

Figure 3. - Light optical photomicrograph of flat surface of B-1900 + Hf specimen coated with Ni-25.7Cr-5.6Al-0.32Y and ZrO_2-7.8Y_2O_3 after plasma spraying with no cyclic testing.

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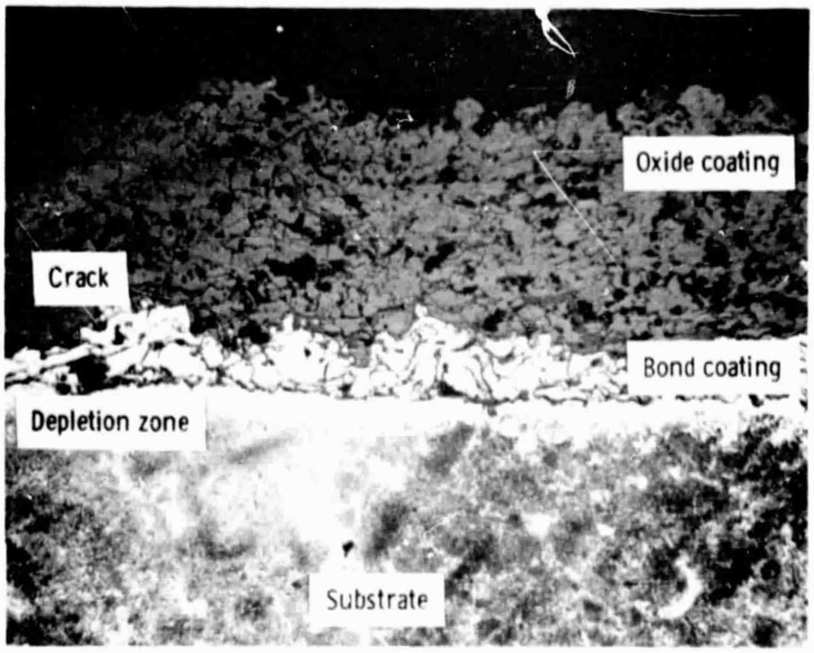

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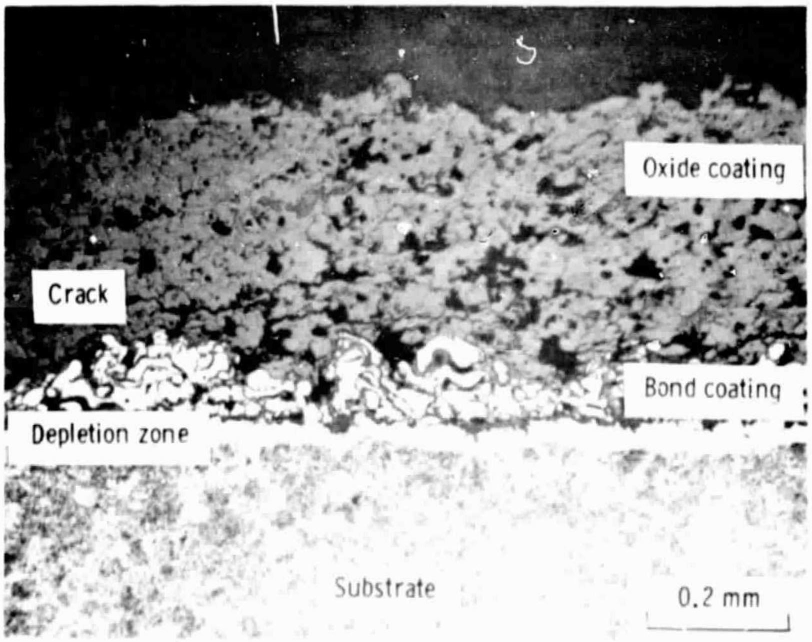

(b)

Figure 4. - Light optical photomicrograph of B-1900 + Hf specimen coated with Ni-25.7Cr-5.6Al-0.32Y and ZrO_2-7.8Y_2O_3: (a) flat surface of specimen after 1500 1-hour cycles and no failure at 990° C, and (b) flat surface of specimen after 249 1-hour cycles and failure at 1095° C.