

HOT CORROSION OF GAS TURBINE MATERIALS IN THE MARINE ENVIRONMENT

David A. Shifler
Carderock Division, Code 613
Naval Surface Warfare Center
9500 MacArthur Boulevard
West Bethesda, MD 20817-5700

Type I and II hot corrosion attack has been observed on certain marine gas turbine engines in the area of the first stage turbine hardware. In order to improve the service life of these engines, laboratory testing of the current, baseline coating and several candidate replacement coatings was initiated using a low-velocity, atmospheric-pressure burner-rig (LVBR). This paper examines the LVBR results of these high temperature coatings on Alloy M247 to determine the hot corrosion resistance relative to the baseline coating with the goal of replacing the current baseline coating better performing coating system.

Keywords: hot corrosion, aluminide coatings, overlay coatings, Alloy M247, sulfidation, MCrAlY coatings, marine gas turbine

INTRODUCTION

Marine gas turbine engines serve as primary and auxiliary power sources for several current classes of ships in the U.S. Navy. It is desired that marine gas turbine engines have a mean time between removal of 20,000 hours. While some engines have approached this goal, others have fallen significantly short. The main reason for this shortfall is hot corrosion (Type I and Type II) damage in the hot section turbine hardware due to intrusion of salts from the marine air and/or from sulfur in the gas turbine combustion fuels.

Ten blades removed from a marine gas turbine engine after operating for 4000 to 10000 hours were examined. Each of the blades displayed heavy deposits under the platform in the blade stem with some blades showing some form of corrosion. The blade substrate was analyzed and was found to conform to Alloy M247 chemical requirements. Metallographic examination showed that the coating thickness under the platform and in the curved area of transition between the platform to the blade stem was either very thin (up to 40 μm thick with one exception) or non-existent. The coating, if present, usually was porous or had entrained contamination under the platform due to lack of adequate spray deposition in these non-line-of-sight areas. MCrAlY coating thickness at other sites along the blade stem was 35 μm to 105 μm .

The area of transition between the platform and the blade stem also corresponded to heavy corrosion. The corrosion that was observed under the platform, in all cases, was caused by Type II, low-temperature hot corrosion which occurs in the temperature range of 1200-1350 $^{\circ}\text{F}$ (649-732 $^{\circ}\text{C}$). Corrosion penetrated the porous coating and caused undercutting of the coating along the coating/alloy substrate interface.

In addition to the presence of hot corrosion, cracking was observed to initiate at several hot corrosion sites. This was found to be advancing by varying degrees through the stem of several blades. The pitting caused by the Type II hot corrosion provided initiation sites for cracking to begin and reduced the overall undamaged cross-section at the stem, thus increasing the applied stress to the corroded area. The cracking initially advanced via corrosion fatigue, but later, in some blade cases, by high cycle fatigue. Some cracking proceeded through both blade stem walls, causing the blade to break off during service.

Low velocity, atmospheric-pressure burner-rig (LVBR) testing was engaged to evaluate replacement coatings and processes that could protect the 1st stage blade under the platform. The specific objectives of the LVBR testing performed were to: (1) evaluate alternative high temperature coating systems and processes on Alloy M247 for under the platform of the 1st stage blade of a marine gas turbine engine; (2) compare the performance of these alternative coating systems to the current, baseline 1st stage blade coating (Coating 71); (3) downselect the best performing coating systems (in terms of their LVBR hot corrosion and thermal cycling resistance).

EXPERIMENTAL PROCEDURE

Materials – Alloys and Coatings

The baseline coating and the alternative coatings were applied to Alloy M247 pin substrates. Table 1 lists the nominal chemical composition of cobalt-base Alloy M247.

**Table 1 - Nominal Composition of the 1st Row Blade Substrate Alloy M247
(compositions listed in weight percent)**

Alloy	C	Cr	Mo	Fe	Ti	Al	Co	Ni	W	Hf	Ta
Alloy M247	0.13-0.17	8-8.8	0.5-0.8	0.10	0.9-1.2	5.3-5.7	9-11	Bal. (~59.5)	10-10.5	1.2-1.6	2.9-3.3

Cylindrical Alloy M247 test pins 0.125-inch (0.318 cm) diameter x 2.5-inch (6.4 cm) long and domed on one end were vacuum cast and centerless ground to their final diameter dimension. The domed end minimized sharp angles that could cause geometry effects on the behavior of the high-temperature coatings during testing. These pins were coated with the baseline and candidate replacement coating systems.

The current, baseline 1st stage blade coating (Coating 71, argon-shielded plasma sprayed) and several alternative coatings are candidate coatings for the 1st row of blades within the high-pressure section of this marine gas turbine engine. Four coated cylindrical pin specimens for each Alloy M247/coating combination were tested under different conditions in the LVBR.

Figure 1 shows the general features of the different coatings prior to testing. The baseline blade coating (Coating 71) was applied by argon-shielded plasma spray. A two-step process involving argon-shielded plasma spray followed by an AEP (electrophoretic diffused platinum aluminide) topcoat formed the layered CoCrAlY. Coatings 150 and E2 were both applied by electroplating. However, Coating 150 is subsequently aluminized using chemical vapor deposition and various heat treatments, while Coating E2 is aluminized by pack cementation. Coating 24 is processed by a proprietary electrophoretic process and subsequent aluminizing process. Table 2 summarizes the coated pin LVBR test matrix.

Table 2 – Coatings Matrix Applied on Alloy M247 Test Pins for LVBR Evaluation

Coating Description	Nominal Composition (wt.%)	Target Coating Thickness (mils)	Process Comments
Layered MCrAlY	65 Co, 26Cr, 9Al, 0.3-0.5Y; 3-10 Pt, 20-25Al, 1-3%Si, 45-55Co	2-6	Argon-shielded plasma sprayed +electrophoretic application
Coating 150	20Pt, 20Al, ± 2%	2-2.5	Electroplate/CVD Al
Coating E2	30-35Pt, 25-30Al, 35-45Ni	3.0-3.5	Electroplate/Pack Al
Coating 24	20-25Pt, 20-25Al, 1-5Si, 45-59 Ni	2.5-3.0	Electrophoretic application +Al
Coating 71 CoCrAlY (current base)	65Co, 28Cr, 9Al, 0.3-0.5Y	2-6	Argon-shielded plasma sprayed

NOTE: 1 mil = 25.4 μm

Materials – Fuel

Coated alloys representative of current hot-section materials of the marine gas turbine engine were evaluated using a sulfur-doped NATO F-76 fuel. Di-tertiary butyl disulfide (C₈H₁₈S₂; M.W. 178.35) was added to modify the NATO F-76 fuel by increasing the sulfur concentration from 0.05% to 0.99 wt%, nearly the maximum prescribed sulfur level (1.0 wt.%) under MIL-F-16884J [1], since sulfur is a major reactant involved in the hot corrosion reaction of coatings and alloys [2-4].

Burner-Rig Test Procedures

A low-velocity, atmospheric pressure burner-rig (LVBR) was utilized to evaluate the hot corrosion resistance of candidate hot-section vane coating systems using sulfur-doped NATO F-76 (described earlier). Details of burner rig operation were described previously [5,6]. A schematic cross-sectional illustration of the burner rig is shown in Figure 2. The gases added to the fuel stream are thoroughly mixed by the swirling action of air entering through the tangential slots in the combustion tube. Downstream, the test pins are exposed to the products of combustion in a carousel rotating at 29 rpm to assure uniform temperature exposure of all test specimens. The air/fuel ratio during all LVBR tests was 30:1.

The LVBR tests for the alloy/coating combinations listed earlier in Table 2 were run either at 1650 °F (899 °C) or at 1300 °F (704 °C) since these are roughly the midpoint temperature ranges where Type I high-temperature hot corrosion (HTHC) and Type II low-temperature hot corrosion (LTHC) of materials are observed, respectively. Sea salt was injected into the burner-rig combustion zone at a rate of 10 ppm (in air) to duplicate the high-temperature reactions that occur in gas turbines in marine environments.

Thermal cycling of the test pins was performed during the LVBR test to simulate the off-and-on nature of gas turbine engine operation aboard ship. Stresses in the oxide scales induced by thermal cycling increase the possibility of spallation of some of the coating thereby increasing the tendency towards more severe high-temperature corrosion of the coating. The rig was allowed to operate continuously without cycling for a period of 48-72 hours each week, while during some days thermal cycling was done twice in a 9-hour period. When the specimen carousel was removed from the burner-rig, the specimens were allowed to cool to room temperature in ambient air. The specimens

were also visually examined to observe any signs of coating degradation during this time. Table 3 summarizes the LVBR conditions for each test; previously unexposed pins were placed in the carousel for each test run.

Table 3 – Summary of LVBR Exposure Conditions

LVBR Test Run	Test Duration	Temperature	Sea-Salt Concentration (in Air)	Thermal Cycles
20	1000 hours	1300 °F (704 °C)	10 ppm	40
21	1000 hours	1650 °F (899 °C)	10 ppm	40
22	1000 hours	1300 °F (704 °C)	10 ppm	40

Burner-Rig Test Specimen Evaluation Procedure

All pin specimens were sectioned and mounted for metallographic examination after completion of the LVBR test and initial pin evaluations. At least three cross-sections were cut from each test pin specimen. The three cross-sections were located along the exposed length of the test specimens at equivalent elevations among the pins designated as TOP, MIDDLE, and BOTTOM. Details of these pertinent measurements are found in other references [7-8].

RESULTS

Low Temperature Hot Corrosion Environment - 1300 °F (704 °C) LVBR Test Results

Pin Degradation during LVBR Exposure

Figure 3a shows the condition of coated pins in the LVBR carousel prior to exposure at 1300 °F (704 °C). Localized degradation of several coated pins observed as dark spots on the coatings was discovered after only 99 hours exposure. Surface deposits, though noticeable from the initial exposure times, were observed to substantially accumulate with continued exposure time. Sea salt deposition continued to become heavier, particularly along the top and middle elevations with increased LVBR exposure.

The LVBR test was completed after 1000 hours of exposure at 1300 °F (704 °C). Many of the pins showed significant level of coating distress with the exception of the pins coated with Coating 24, Coating 150, and the baseline Coating 71. Figure 3b shows the condition of the pins after 1000 hours of LTHC exposure.

Pin Measurements After 1000-hr LVBR Exposure at 1300 °F (704 °C)

LVBR pin measurement results after the 1000-hr LVBR test are summarized in Table 4. The average (of the four coating specimens 1, 8, 15, and 22) original coating thicknesses of the baseline coating (Coating 71) was 3.07 mils (78 µm). The average original coating thickness of Coating 24 was 3.23 mils (82 µm), and the layered MCrAlY coating system was 4.11 mils (104 µm) thick on average. The average coating thickness of Coating 150 was 2.96 mils (75 µm). The average original coating thickness of Coating 2E applied on Alloy M247 pins was 3.30 mils (84 µm).

For each of the coating systems tested, at least 2 of the 4 pins in the set failed, i.e. the coating was fully penetrated. Three coatings systems (Coating 24, Coating 150, and the baseline Coating 71), had

similar values of average coating loss on a radius, and maximum coating penetrations. When there were no coating failures, the average coating loss of Coating 150 was lowest (of the two unfailed pins) with 0.15 mil (4 μm), followed by Coating 24 (0.46 mil; 12 μm) and baseline Coating 71 (0.84 mil; 21 μm). Layered CoCrAlY, despite having an average thickness of 4.11 mils (104 μm), suffered from considerable average coating loss (1.85 mils; 47 μm) and experienced coating failures on 3 of the 4 pins. Coating failures occurred on all pins using Coating E2; the average coating losses were 2.22 mils (56.5 μm). The maximum coating penetrations of each pin as well as the average maximum coating penetration from each coating set of 4 are also tabulated in Table 4.

Table 4 – Corrosion Measurements of Blade Baseline and Alternative Coatings on Alloy M247 Test Pins, after 1000-hr LVBR Test at 1300 °F (704 °C)

Coating Designation	Pin I.D.	Original Coating Thickness (mils)	Average Remaining Coating (mils)	Average Coating Loss on a Radius (mils)	Maximum Coating Penetration on a Radius (mils)
Coating 71 CoCrAlY (current base)	1	2.98	2.13	0.86	2.58
	8	2.94	2.13	0.81	2.74
	15	3.21	1.96	1.25	5.65 into substrate
	22	3.15	1.80	1.35	15.35 into substrate
	Avg.	3.07		1.07	8.17 (into M247)
Coating 24	2	3.11	2.68	0.43	2.11
	9	3.41	2.07	1.34	5.55 into substrate
	16	3.25	2.00	1.25	6.35 into substrate
	23	3.14	2.65	0.49	1.34
	Avg.	3.23		0.88	5.50 (into M247)
Layered MCoCrAlY	3	4.19	2.55	1.64	3.69
	10	4.10	1.68	2.42	4.10 into substrate
	17	4.28	1.82	2.46	6.70 into substrate
	24	3.88	3.00	0.88	8.80 into substrate
	Avg.	4.11		1.85	8.89 (into M247)
Coating 150	4	3.11	2.32	0.79	4.60 into substrate
	11	2.94	2.35	0.59	3.95 into substrate
	18	2.92	2.74	0.18	2.45
	25	2.88	2.76	0.12	2.45
	Avg.	2.96		0.42	4.68 (into M247)
Coating E2	5	3.13	0.98	2.15	6.05 into substrate
	12	3.37	1.20	2.17	6.00 into substrate
	19	3.31	0.90	2.41	5.90 into substrate
	26	3.39	1.22	2.17	7.00 into substrate
	Avg.	3.30		2.22	9.54 (into M247)

* NOTE: Layered CoCrAlY and Coating 24 results are from LVBR Run 22, other coating system results are from LVBR Run 20

Though most of the coatings experienced little to moderate corrosion, a few sites were subjected to severe corrosion. The layered MCoCrAlY experienced considerable hot corrosion degradation of its coating. Figure 4a shows one site where the coating has been completely penetrated by the activity of Type II hot corrosion. Similar penetration of the Coating 24 (Figure 4b) and Coating 150 (Figure 4d) were also observed. Hot corrosion of the baseline coating (Coating 71) shown in Figure 4c tended to proceed near oxide stringers that were artifacts of the plasma spray process. Figure 4e displays one of the numerous sites of coating penetration on a LVBR test with Coating E2.

High Temperature Hot Corrosion Environment - 1650 °F (899 °C) LVBR Test Results

Pin Degradation during LVBR Exposure at 1650 °F (899 °C)

Figure 5a shows the test pins prior to exposure. Surface deposits began to form on the LVBR test pins almost immediately upon exposure at 1650 °F (899 °C). The deposition was particularly heavy about 1.5-inch (3.8-cm) from the top (approximately the bottom elevation for subsequent pin measurements). Figure 5b shows the degree of accumulation that occurred after 999 hours of exposure.

Pin Measurements After 1000-hr LVBR Exposure at 1650 °F (899 °C)

Pin measurement results after the 1000-hr LVBR test at 1650 °F (899 °C) are summarized in Table 5. Coating 71 had a value of 1.91 mils (48 µm) of average coating loss on a radius.

Table 5 – Corrosion Measurements of Blade Baseline and Alternative Coatings on Alloy M247 Test Pins, after 1000-hr LVBR Test at 1650 °F (899 °C)

Coating Designation	Pin I.D.	Original Coating Thickness (mils)	Average Remaining Coating (mils)	Average Coating Loss on a Radius (mils)	Maximum Coating Penetration on a Radius (mils)
Coating 71 CoCrAlY (current base)	1	3.21	1.34	1.87	0.55 into substrate
	8	3.13	1.81	1.32	2.63
	15	3.45	1.22	2.23	12.65 into substrate
	22	3.67	1.46	2.21	1.65 into substrate
	Avg.	3.37		1.91	6.95 (into M247)
Coating 150	3	2.97	1.65	1.32	1.85 into substrate
	10	3.03	2.08	0.95	2.28
	17	3.01	1.80	1.21	2.31
	24	2.90	1.92	0.98	2.25
	Avg.	2.98		1.12	2.92
Coating E2	4	3.09	0.00	3.09	60.29 into substrate
	11	3.45	0.88	2.57	54.13 into substrate
	18	3.09	0.00	3.09	45.96 into substrate
	25	3.37	0.83	2.54	50.44 into substrate
	Avg.	3.25		2.82	55.95 (into M247)
Layered MCoCrAlY	5	4.47	3.19	1.28	3.92
	12	4.90	2.94	1.94	4.85
	19	4.64	2.94	1.70	4.40 into substrate
	26	4.87	2.53	2.34	4.52
	Avg.	4.72		1.82	5.58 (into M247)
Coating 24	7	3.40	1.80	1.60	3.90 into substrate
	14	3.63	1.37	2.26	3.85 into substrate
	21	3.78	1.96	1.82	1.65 into substrate
	28	3.58	1.49	2.09	8.20 into substrate
	Avg.	3.60		1.94	8.00 (into M247)

Compared to the baseline coating, the average coating losses were less for Coating 150 (1.12 mils; 28.5 µm) and for the Layered MCoCrAlY coating (1.82 mils; 46 µm). Both Coating 150 and the Layered MCoCrAlY coating suffered from complete coating penetration on one pin out of the four pins tested.

Average coating losses on a radius for pins applied with Coating E2 and Coating 24 were greater than the average coating loss of the baseline coating. The average coating loss on a radius for Coating E2 was 2.82 mils (72 μm), while the average coating loss of Coating 24 was 1.94 mil (49 μm). The maximum coating penetrations of each pin as well as the average maximum coating penetration from each coating set of 4 are also tabulated in Table 5. The average maximum coating penetration of 6.95 mils (176.5 μm) for the baseline, Coating 71, coating system is a combination of the coating thickness and the average of further penetration into the substrate, if it occurred.

Figure 6 shows some conditions typical of the substrate coating systems tested for resistance to Type I hot corrosion. The baseline, Coating 71 displayed broad frontal attack in the coating as is typical of Type I hot corrosion (Figure 6a). Coating 150 experience some pitting type-attack, but the general advance of degradation was by broad phasal attack as shown in Figure 6b. Coating E2 suffered from extensive loss of coating and subsequent sulfidation corrosion of the remaining coating and Alloy M247 substrate (Figure 6c). Critical coating constituents were subjected to interdiffusion with the alloy substrate which caused changes in coating composition and subsequent attack of the altered coating. Figure 6d shows Type I hot corrosion attack of the altered coating. Coating 24, shown in Figure 6e displayed sulfidation and penetration of the protective coating into the alloy substrate and some incipient intergranular corrosion of the alloy.

DISCUSSION

The composition, the processing, and the test exposure conditions of the aluminide-coated and MCrAlY specimens in these tests can affect test results. Subsequent heat treatments help develop the proper mechanical properties and allow further coating diffusion. The principal protective oxide that causes improved oxidation and corrosion resistance of aluminide coatings is Al_2O_3 , although less protective oxides can form if other alloying elements are present in the substrate, either in solution or as precipitated phases [9]. Degradation of aluminide coatings can initiate by basic fluxing of Al_2O_3 , and later proceeds by both basic fluxing and sulfide oxidation [9]. The degradation of coatings usually requires a period of time for hot corrosion to initiate which is then followed by propagation. This usually requires a threshold concentration of salt deposited on the pin surface to start the corrosion processes.

One engine manufacturer has indicated that certain aluminide coatings perform well at temperatures in the Type I hot corrosion range (800-950 $^{\circ}\text{C}$) but have poor resistance to Type II hot corrosion [10]. Cracking of the aluminide coating may also occur if the service or test temperature is below the ductile-to-brittle transition temperature of the specific coating [11].

For MCrAlY coatings (where M = Ni, Co, or Fe) the literature indicates that chromium promotes alumina formation at lower aluminum concentrations than would otherwise form without the presence of chromium [12]. Aprigliano found that high concentrations of alumina and yttria formed on the outer layers of a CoCrAlY coating while chromium was the primary oxide along the inner layer of the protective coating [13]. Earlier work in U.S. Navy coating development programs evaluated hot corrosion performance of MCrAlY coatings. Both Aprigliano, [14] using electron beam physical vapor deposited (EB-PVD) high-chromium CoCrAlY coatings, and Clarke, [15] using both EB-PVD and plasma sprayed CoCrAlY coatings, found these metallic overlay coatings were resistant to Type II, low temperature hot corrosion. These results agreed with an earlier conclusion that chromia-forming coatings were more resistant to Type II hot corrosion than alumina-forming coatings [16].

The LVBR test results from the 1000-hr exposure at 1300 $^{\circ}\text{F}$ (704 $^{\circ}\text{C}$) are summarized in Figure 7. Absolute coating loss values provide a better comparison to the overall performance than the percentage loss. The LTHC ranking was based on resistance to Type II hot corrosion using both

average coating loss for a coating system set and the average maximum coating penetration for each set listed in Table 4 (in order of decreasing resistance to Type II hot corrosion) was: Coating 150, Coating 24, baseline Coating 71, Layered MCrAlY, and Coating E2.

In the LVBR high temperature hot corrosion environment (HTHC) at 1650 °F (899 °C), Coating 150 had the least average coating loss among the coatings reported here. The LVBR test results from the 1000-hr exposure at 1650 °F (899 °C) are summarized in Figure 8. The HTHC ranking of resistance to Type I hot corrosion on the basis of measurements for both average coating loss for each coating set and the average maximum coating penetration for each set listed earlier in Table 5 (in order of decreasing resistance to Type II hot corrosion) was: Coating 150, Layered MCrAlY, baseline Coating 71, Coating 24, and Coating E2.

Since the hot section of marine gas turbine engines operate at temperatures where either Type I hot corrosion or Type II hot corrosion occur, the coating recommendation must consider the overall coating ranking based on LVBR testing in both hot corrosion environments. The overall ranking will lead to coatings that would provide the chances of the best overall service in the shipboard environment where both types of hot corrosion may occur.

The overall coating ranking based on their LVBR test performance in both Type I and Type II hot corrosion environments (in order of decreasing resistance to hot corrosion) was: Coating 150, Layered MCrAlY, baseline Coating 71, Coating 24, and Coating E2.

CONCLUSIONS

The low velocity, atmospheric pressure burner rig (LVBR) was used to evaluate the current baseline coating for the 1st stage vane of a marine gas turbine engine in both low temperature and high temperature hot corrosion environments.

Several alternative coatings were LVBR tested and their performance compared to the baseline coating.

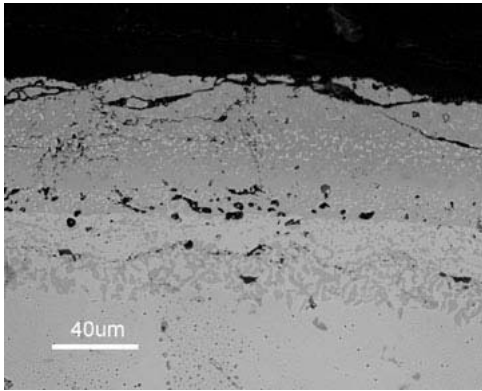
The use of these LVBR tests provided a low-cost alternative (compared to a full engine test) and a relatively rapid determination of the relative performance of the coatings tested.

The overall ranking for the coatings based on the LVBR test results at both 1300 °F (704 °C) and 1650 °F (899 °C), (in the order of decreasing resistance to both types of hot corrosion) is: Coating 150, Layered MCrAlY, baseline Coating 71, Coating 24, and Coating E2

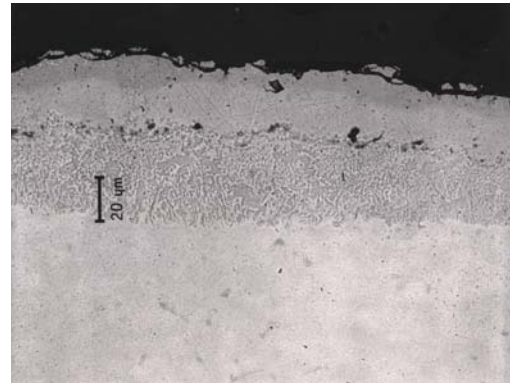
RERERENCES

- 1 – MIL-F-16884J, “Military Specification Fuel, Naval Distillate (NATO F-76)”, (31 May 1995).
- 2 – S. Mrowec, “The Problem of Sulfur in High-Temperature Corrosion”, *Oxidation of Metals*, v. 44, 177 (1995).
- 3 - J.A. Goebel, F.S. Pettit, G.W. Goward, "Mechanisms for the Hot Corrosion of Nickel-Base Alloys", *Metallurgical Transactions*, v. 4, 261 (1973).
- 4 - R.A. Rapp, Y.S. Zhang, "Hot Corrosion of Materials: Fundamental Studies", *JOM*, v. 46, No. 12, 47 (Dec. 1994).
- 5 - H. von E. Doering, P.A. Bergman, "Construction and Operation of a Hot-Corrosion Test Facility", *Materials Research and Standards*, v. 9, No. 9, 35 (1969).

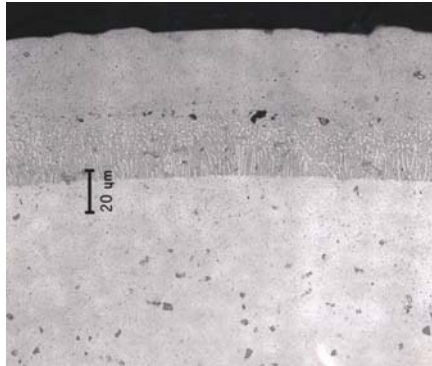
- 6 – G.C. Booth, R. L. Clarke, “Evaluation of Corrosion Resistance of Coated Superalloys in Rig Tests”, *Materials Science and Technology*, v. 2, 272 (1986).
- 7- D.A. Shifler, “Evaluating the Hot Corrosion Resistance of High Temperature Coatings”, **CORROSION/2003**, paper 353, Houston, TX (2003).
- 8 – D.A. Shifler, “High Temperature Gaseous Corrosion Testing”, Vol. 13A: Corrosion Principles, ASM Handbook, ASM International, Materials Park, OH, (2003).
- 9 - G.W. Goward, "Protective Coatings for High Temperature Alloys: State of Technology" in Proceedings of the Symposium on 'Properties of High Temperature Alloys', Z.A. Foroulis, F.S. Pettit, eds, PV 77-1, The Electrochemical Society, Pennington, NJ, 806 (1976).
- 10 - P. Carter, "The Correlation of HP Turbine Blade Corrosion Attack in Dissimilar Marine Gas Turbines", in Proceedings of the 4th US/UK Conference on ' Gas Turbine Materials in a Marine Environment', v. 1, Annapolis, MD, 1 (1979).
- 11 - S.M. Saad, J.R. Nicholls, P. Hancock, "The Influence of Pack Aluminized Coatings on Creep Behavior of Nimonic 105", in High Temperature Corrosion, NACE-6, R.A. Rapp, ed., NACE International, Houston, TX, 568 (1983).
- 12 - G.W. Goward, “Materials and Coating for Gas Turbine Hot-Section Components”, Proceedings: Gas Turbine Materials Conference, Naval Ship Engineering Center/Naval Air Systems Command, Hyattsville, MD (October 1972).
- 13 - L.F. Aprigliano, “Protective Oxides Formed on CoCrAlY Coatings”, DTNSRDC/SME-86/52, (August, 1986).
- 14 - L.F. Aprigliano, "Low- and High-Temperature (1300 and 1650 °F) Burner Rig Tests of MCrAlY Composition Variations", in Proceedings of the 4th US/UK Conference on ' Gas Turbine Materials in a Marine Environment', Annapolis, MD, 151 (1979).
- 15 - R.L. Clarke, "Low- and High-Temperature (704 and 899 °C) Burner Rig Evaluations of Advanced MCrAlY Coating Systems", in Proceedings of the 4th US/UK Conference on ' Gas Turbine Materials in a Marine Environment', Annapolis, MD, 189 (1979).
- 16 - A.F. Taylor, B.A. Wareham, C.G. Booth, J.F.G. Conde, "Low and High Pressure Rig Evaluation of Materials and Coatings" in Proceedings of 3rd US/UK Navy Conference on ' Gas Turbine Materials in a Marine Environment', Bath, Session III, paper 3 (1976).



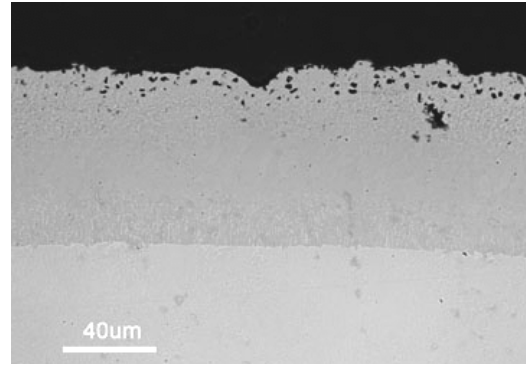
(a) 500X



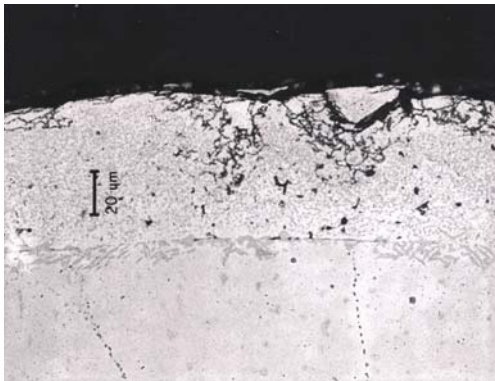
(b) 500X



(c) 500X



(d) 500X



(e) 500X

Figure 1 – Untested coated pin specimens, 500X. Shown are (a) Layered MCrAlY, (b) Coating 24, (c) Coating 150, (d) Coating 2E, and (e) baseline Coating 71.

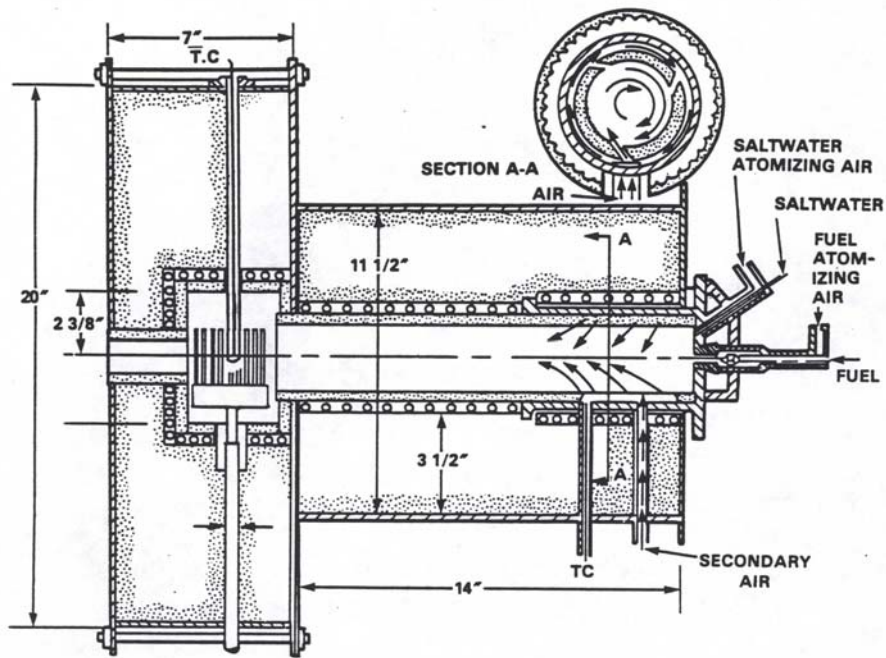


Figure 2 - Cross-sectional view of low-velocity, atmospheric pressure burner rig.

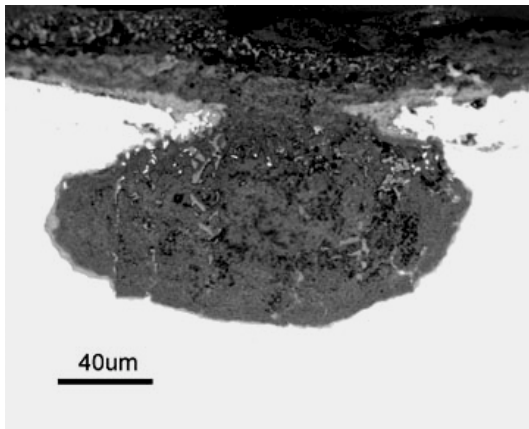


(a)

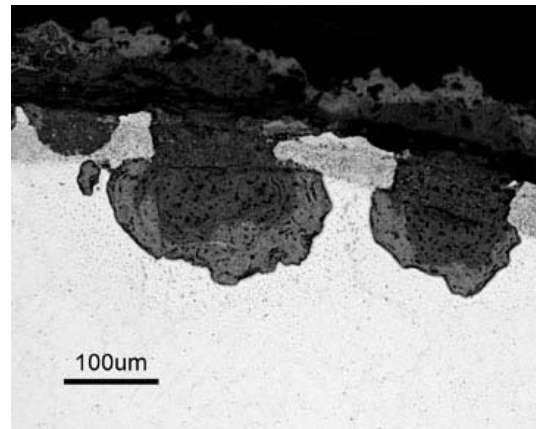


(b)

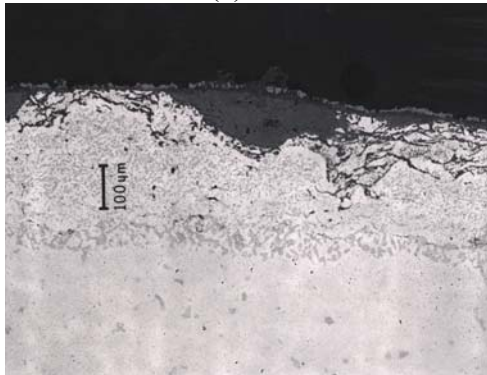
Figure 3 – (a) shows the appearance of the LVBR test pins in carousel prior to LVBR exposure while (b) illustrates the pin conditions after 1000 hours LVBR Exposure at 1300 °F (704 °C) for pins 26-6. Coatings of pins 1 (the baseline) and 4 (Coating 150) are virtually unaffected while pins 2,3 5, and 6 show significant degradation.



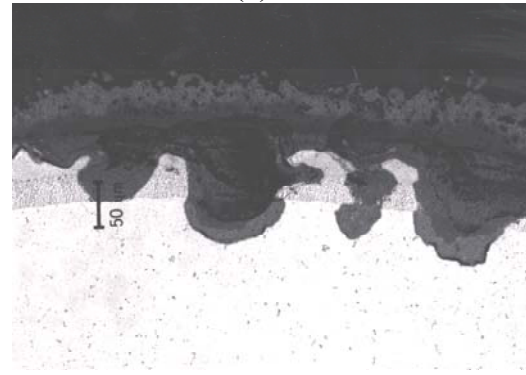
(a) 500X



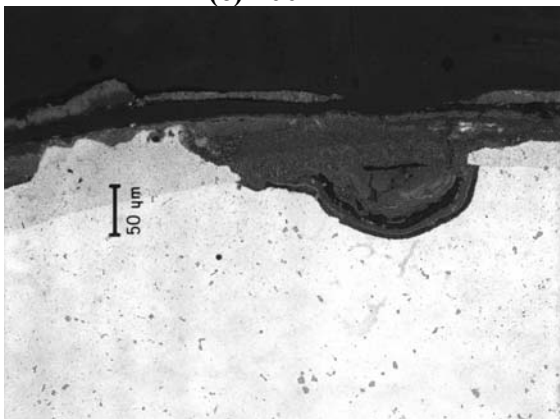
(b) 200X



(c) 100X



(d) 200X



(e) 200X

Figure 4 – Coating after 1000-hr LVBR test at 1300 °F (704 °C). In (a) Layered MCrAlY Type II hot corrosion found along coating surface. In (b) localized, pitting-type penetration of Coating 24 is observed. Figure (c) shows the baseline coating loss has occurred near some oxide stringers, while Figure (d) displays the Type II hot corrosion of Coating 150. Figure (e) displays the complete coating penetration for a test pin with Coating E2.



(a)

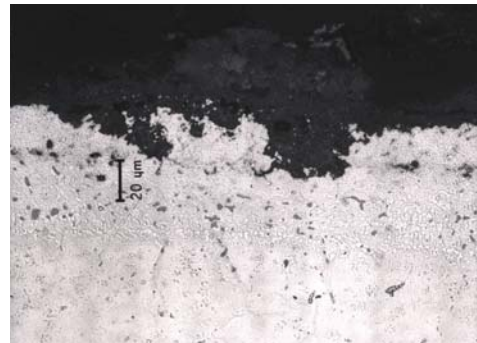


(b)

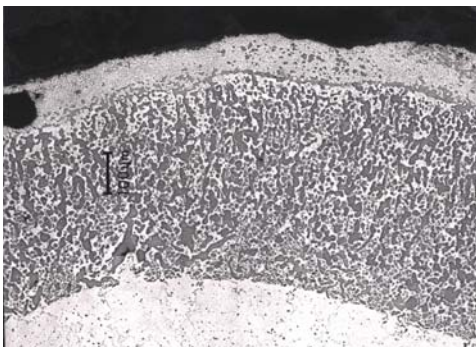
Figure 5 – (a) shows the LVBR pins prior to exposure at 1650 °F (899 °C). Salt deposition accumulated on the pin surfaces during the LVBR exposure. (b) shows the degree of accumulation after 999 hours. The bottom elevation has particularly heavy deposition.



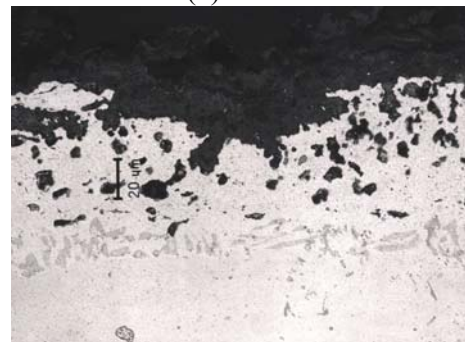
(a) 200X



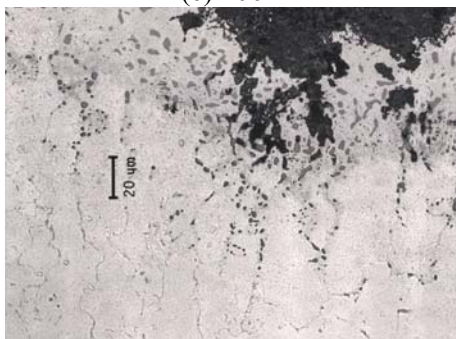
(b) 500X



(c) 100X



(d) 500X



(e) 500X

Figure 6 Photomicrographs of coated pin samples after 1000-hr LVBR test at 1650 °F (899 °C). (a) baseline CoCrAlY, (b) Coating 150, (c) Coating E2, (d) Layered CoCrAlY, and (e) Coating 24.

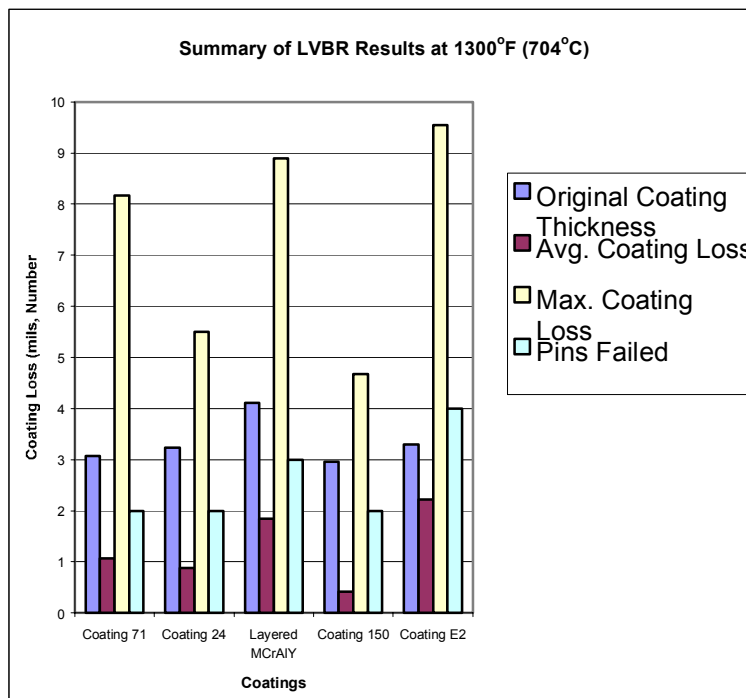


Figure 7 – Summary of LVBR test results on coatings performance (starting original thickness, average coating loss on a radius, and maximum penetration) in the low temperature hot corrosion regime (LTHC) at 1300 °F (704 °C).

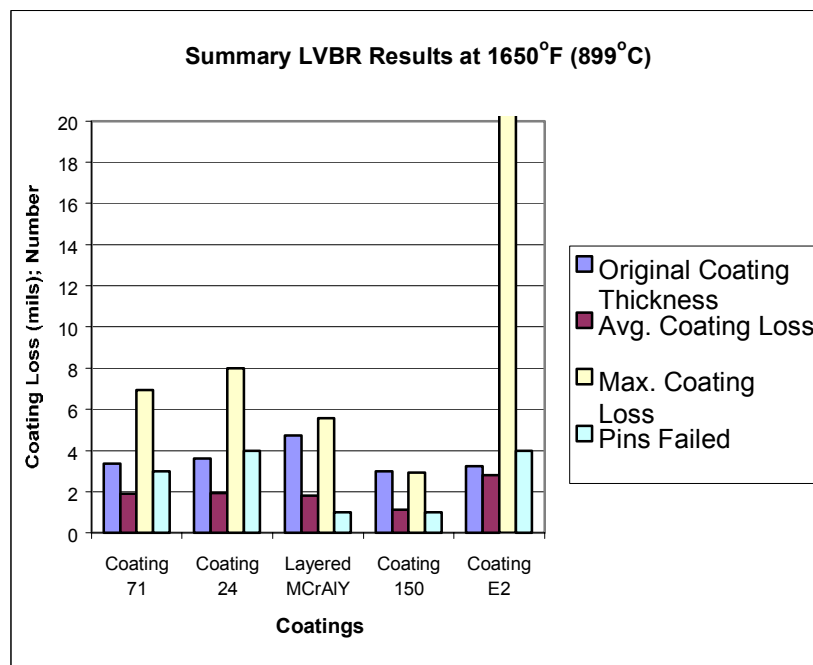


Figure 8 – Summary of LVBR coatings performance test results (original thickness, average coating loss on a radius, and maximum penetration) in the high temperature hot corrosion regime (HTHC) at 1650 °F (899 °C).