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ENVIRONMENTAL BEHAVIOR OF LOW THERMAL EXPANSION INCONEL® ALLOY 783

Eric A. Ott[1], Jon R. Groh[1], and Sarwan K. Mannan[2]
[1]GE Aircraft Engines, 1 Neumann Way, Cincinnati, Ohio 45215 USA
[2]Special Metals Corporation, 3200 Riverside Drive, Huntington, West Virginia 25705 USA

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Abstract

The chloride corrosion resistance of low thermal expansion INCONEL® alloy 783, was determined by 1,000 hour salt spray exposure tests. Selected samples were also intermittently exposed to 650˚C during salt spray testing. The objective of this investigation was to understand the corrosion resistance of 783 as compared to alloys 909, 718, and a martensitic stainless steel, M152, in marine environments. Testing was performed on as-machined, pre-oxidized, and chromide coated material conditions. Results indicate that alloy 783 provides chloride corrosion resistance similar to 718, a significant improvement over both alloy 909 and M152. In addition, the processing schedule of alloy 783 is more amenable to chromide coating. Performance of coated alloy 783 was also on par with that of coated alloy 718. Alloy behavior and preliminary assessment of scale constituents are presented for selected testing and base metal conditions.

Introduction

INCONEL® alloy 783 has been investigated for aero engine stator components requiring controlled thermal expansion and temperature capability to about 700°C. The use of low coefficient of thermal expansion (CTE) alloys is advantageous for clearance control structures in gas turbine engines, particularly in the high-pressure compressor stator. Production low CTE alloys include 903, 907, and 909 [1] as well as the more recently developed alloy 783[2]. Martensitic stainless steels, such as M152, also display favorable CTE characteristics and may be considered for such applications provided operating temperatures are less than about 480°C. Use of alloy 718 and other high temperature nickel-based alloys of higher CTE often require a trade-off of material versus engine performance.

Higher compressor pressure ratios of advanced military and commercial engines result in increased component operating temperatures in the aft portion of the compressor. Low CTE alloys in the 90X series have been limited to maximum operating temperatures of ~600°C as a result of metallurgical stability and environmental resistance. Even below 600°C, these alloys often require coatings to reduce environmental degradation. Use of diffusion coatings requires exposure at temperatures that compromise alloy 909 mechanical properties.

Special Metals Corporation developed the 783 alloy composition, Table I, to optimize the thermal expansion, strength, ductility, creep capability, notch resistance, oxidation and corrosion resistance, and resistance to stress accelerated grain boundary oxidation (SAGBO) [2]. Alloy 783 provides increased temperature capability and improved corrosion and oxidation resistance compared to previously developed alloys such as those in the 90X series.

Marine turbine engine applications, particularly on military aircraft, require resistance to chloride-assisted corrosion. The deposition of salt onto turbine components from the environment may occur through either intake air ingestion or atmospheric exposure while the engine is idle. Salt deposited while the engine is not operating can result in alloy degradation in some alloy systems. In addition, rapid heating during take-off and climb mission segments can result in significantly more additional cyclic degradation in the presence of salt. Alloys with insufficient corrosion resistance are often subjected to coating processes, such as pack chromiding, to impart improved chloride corrosion resistance.

Table I: Nominal composition of alloy 783 in weight percent

Ni	Fe	Co	Al	Nb	Ti	Cr
28.5	Bal.	34	5.4	3	0.1	3

Experimental Procedure

The resistance of alloy 783 to corrosion in the presence of a marine environment was investigated relative to traditional stator component alloys using selected bare and coated metal conditions. Testing was performed using laboratory exposure techniques including a 1,000 hour standard salt spray corrosion test as well as a modified salt spray method where test samples were subjected to an elevated temperature furnace exposure intermittently during the 1,000-hour salt spray exposure.

Test samples were prepared from wrought alloys 783, 909, 718, and a martensitic M152 alloy for salt spray testing. Two sample geometries - cylindrical and plate-type - were used during this assessment. Samples were machined from either bar, billet, or rolled ring material. A summary of sample geometries and salt spray corrosion testing conditions are given in Table II.

Cylindrical test specimens measuring 12.5 mm diameter x 50 mm long were cut from 783, 909, and 718 alloy 100 mm diameter bar or 17 mm diameter rolled rod used for capability testing. A series of specimens was fully heat-treated per specification and tested in the as-machined, bare metal condition. Two cylindrical alloy 783 samples (783C & 783D) were machined then fully heat-treated resulting in a thin heat treat scale. Samples were tested in this condition to assess the effects of pre-oxidization on salt spray corrosion resistance. A third series was processed to evaluate a chromide-coated condition.

In addition, plate-type specimens of dimensions 12.5mm x 76.mm x 3.2mm were excised from 783 and M152 rolled rings such that the long direction of the plate was in the tangential

INCONEL is a Trademark of the Special Metals Family of Companies orientation and the thickness direction was oriented parallel to the ring centerline. These specimens were tested in the as-machined and chromide coated surface conditions.

All alloys were heat treated prior to testing according to the specifications referenced in Table III. A representative ring rolled and heat-treated alloy 783 microstructure is provided for reference in Figure 1.

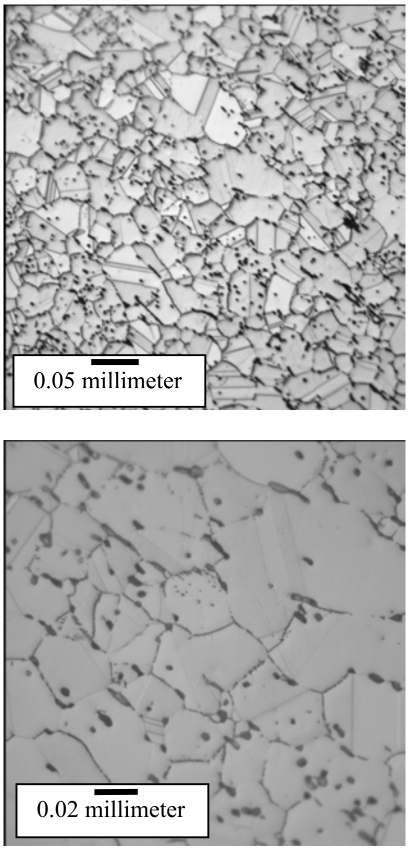


Figure 1 Representative microstructures of alloy 783 (AMS 5940) rolled ring material with an average grain size of ASTM 7,showing fine intragranular β-precipitates and grain boundary β phase decoration, characteristic of this alloy.

Coating typical of that used for these alloy systems was performed on selected samples for corrosion testing. No attempt was made to tailor the coating process to base alloy characteristics. Chromide coating of alloys M152, 909, 718, and 783 was performed in the fully heat-treated condition using a production pack diffusion process. Coating conditions were used to achieve aim chromide coating thickness of ~0.0075 mm. Assessment of chromide coated 783 coupons confirmed that coating thickness was achieved with an average of 0.0074 mm based on 12 measurements of two coupons. Standard deviation of coating thickness was 0.0016 mm. A typical chromide coating on 783 is shown in Figure 2 prior to salt spray exposure testing. Chromide coating thickness of 909 treated in the same batch were significantly thicker than that of 783. Nickel plating was used during sample mounting to ensure adequate edge retention for coating assessment.

Table II: Test sample identification and test method.

Alloy/condition	Sample ID	Sample geometry	Test Method*
Alloy 718	718A&B	12.5mm dia. x 50.mm	A
Alloy 783	783A&B	"	A
Alloy 783 (preox.)	783C&D	"	A
Alloy 909	909A	"	A
Alloy 909 + chromide	909B	"	A
M152	M152-1	12.5mm x 76.mm x 3.2mm	A
Alloy 718	718-1B	"	A
Alloy 718 + chromide	718-4	"	A
Alloy 783 + chromide	783-3	"	A
Alloy 718 + chromide	718-2	"	B
Alloy 783 + chromide	783-2	"	B
M152	M152-2	"	B
Alloy 783	783-8	"	B
Alloy 718	718-3	"	B

* Total 1,009 hr. exposure time, A: ASTM B117-97, 35°C, 5% NaCl, B: ASTM B117-97, 35°C, 5% NaCl with 650°C/24hr. exposure 2 times per week.

Table III: Alloy specifications[3-6] used for heat-treatment

Alloy	Heat-treatment specification
783	AMS 5940
718	AMS 5663
909	AMS 5884
M152	GE specification (soln+temper), most similar to AMS5718

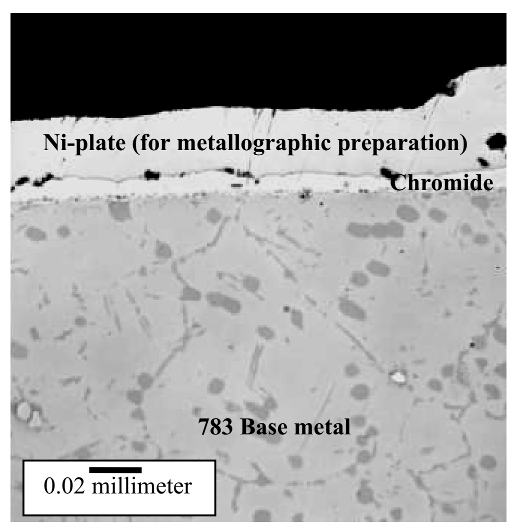


Figure 2: Typical microstructure of a chromide-coated base metal prior to corrosion test. Average thickness was 0.0074mm.

Salt spray corrosion testing was performed according to ASTM B117-97 for a total testing time of 1,009 hours (42 days). Test parameters included a salt spray cabinet temperature of 35°C and a NaCl concentration of 5%. Exposures were interrupted twice per week to enable visual observations and sample weight measurement. All samples were oriented at approximately 30 degrees from the horizontal during salt spray exposure. Samples were isolated from one another using a non-conductive tray and samples were not permitted to contact one another at any time during testing.

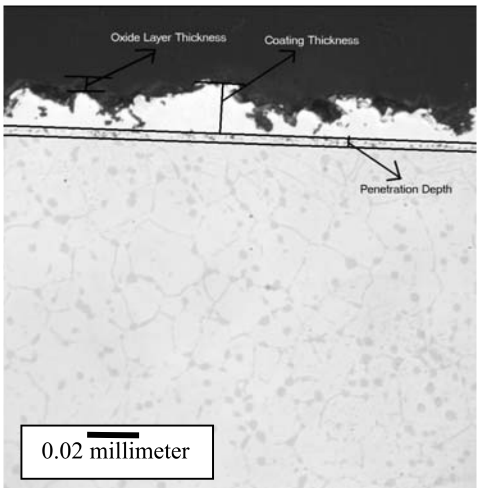


Figure 3 Measurement data used to assess the extent of corrosion susceptibility.

Salt spray testing involving an intermittent elevated temperature air exposure was also performed for selected material conditions. The total testing time was also 1,009 hours (42 days). Exposures involved salt spray testing as described above with an additional furnace exposure. The following schedule was used: ASTM B117-97 salt spray testing with removal 2 times per week for exposure at 650ºC in air for 24 hrs followed by air cooling. Sample orientation and visual examination was performed in the same way as described for the standard salt spray test samples above.

Examination of corrosion tested samples was performed after salt spray and cyclic salt spray tests. Regions of the most aggressive corrosion damage, as determined by visual assessment, were cross-sectioned for metallography. Samples were mechanically prepared following Ni-plate of the evaluation surface to improve edge retention during polish. Optical and scanning electron microscopy (SEM) techniques were performed in the as-polished condition to assess typical and maximum corrosive attack. A schematic of the measurement technique for this effort is detailed in Figure 3. Energy Dispersive Spectroscopy (EDS) was performed on selected features to gain a qualitative understanding of the main elemental constituents in the corrosion products.

Results

Standard Salt Spray Exposure Tests

Weight change measurements at selected intervals during the 1,009 hr. total exposure confirm that the martensitic stainless steel alloy, M152, develops a scale prone to spallation. Comparison of weight change data for each alloy is presented in Figure 4. Closer examination of weight change data for other alloys examined is given in Figure 5. Comparison of bare base metal behavior in Figure 5(a) indicates similar 783, 718, and 909 behaviors with regard to weight change with, perhaps, 718 being less subject to overall weight gain. The significant scatter in weight change data makes a more detailed assessment difficult. Similarly, the effect of 783 pre-oxidation prior to salt spray testing also is not clearly different from as-machined base metal samples as shown in Figure 5(b). The use of chromide coatings typically results in the lowest weight gains for 718, 783, and 909 as shown in Figure 5(c).

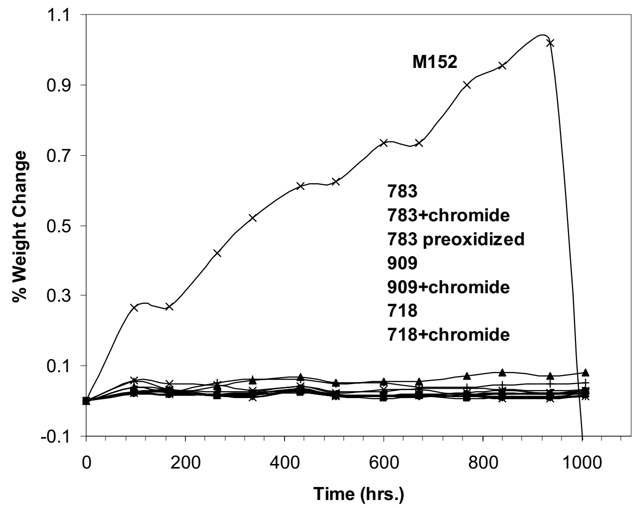


Figure 4 Weight change measurements determined during salt spray testing for 1,009 hours per ASTM B117-97 at 35°C and 5% NaCl.

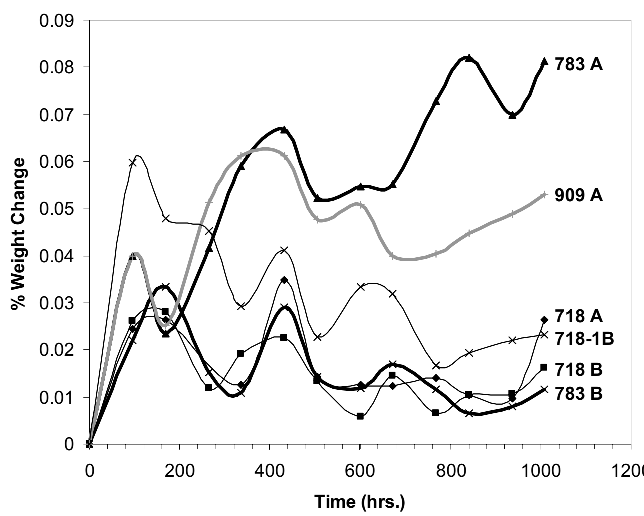


Figure 5a Weight change measurements determined during 1,009 hour salt spray testing showing comparisons of all austenitic bare base metal results.

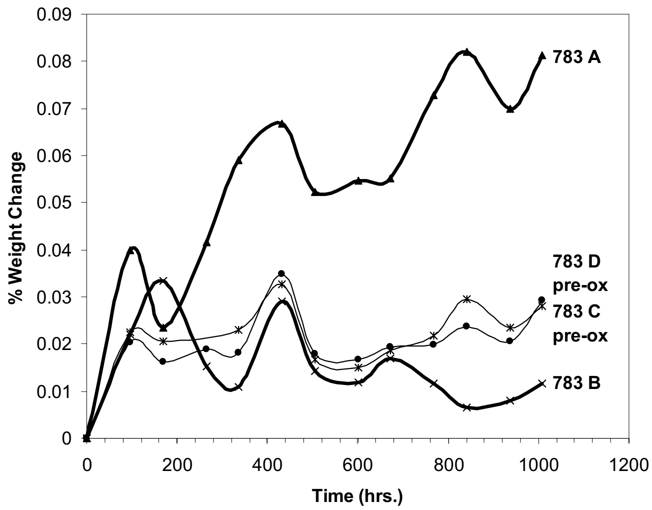
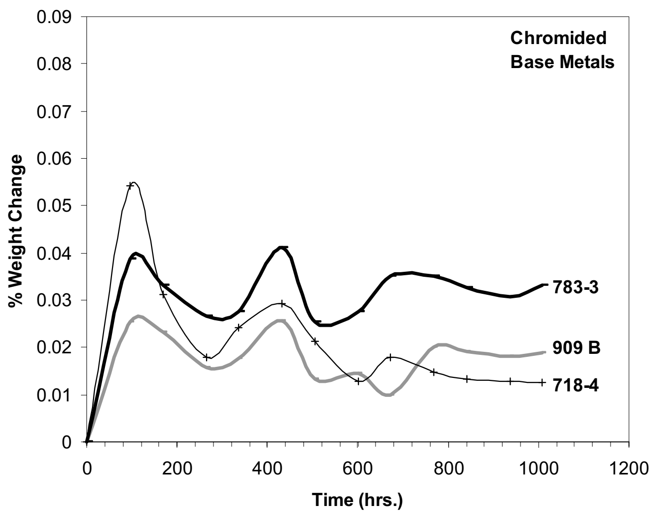


Figure 5b Weight change measurements determined during 1,009 hour salt spray testing showing comparisons of as-machined and pre-oxidized 783 samples.



(c)

Figure 5c Weight change measurements determined during 1,009 hour salt spray testing showing comparisons of chromide coated alloys.

The appearance of samples following testing (Figure 6) supports minimal weight changes recorded for all materials except bare M152 which exhibits extensive surface corrosion. The pre-oxidized 783 samples (783C&D) were essentially unchanged versus the pretest condition (not shown).

Measurements of the most affected region of each condition are indicated in Figure 7. Corrosion affected layers were a combination of surface scale and base metal penetration. Results show that, on average, the maximum affected regions are similar for alloys 783 and 718. Measurements for 909 were 2-3X this average while the M152 was nearly 50X. Note that sample 783A exhibited no measurable corrosion affected region. In all cases, chromide coating effectively prevented general chloride corrosion as indicated by the residual chromide coating thickness, and the lack of scale or internal corrosion products.

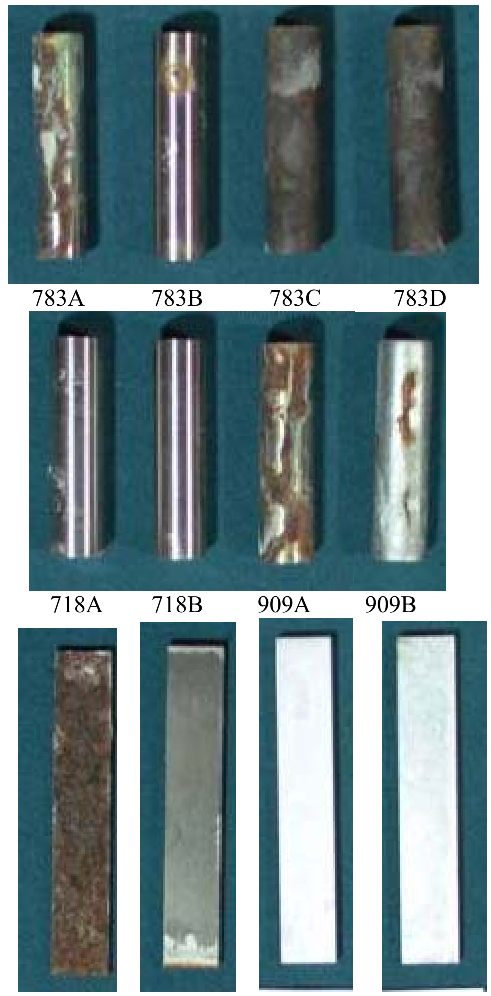


Figure 6 Macroscopic views of salt spray test specimens after 1,009 hours of exposure showing cylindrical specimens, and plate-type specimens.

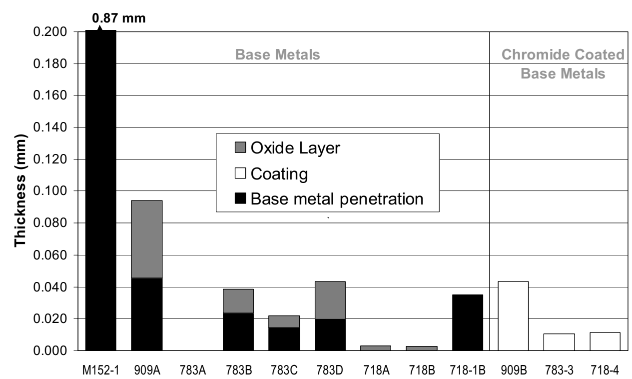
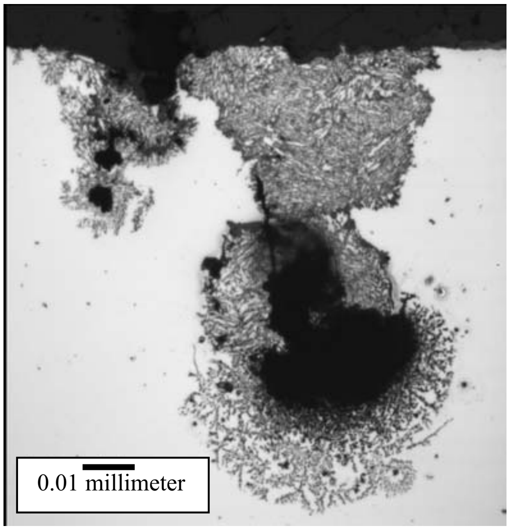
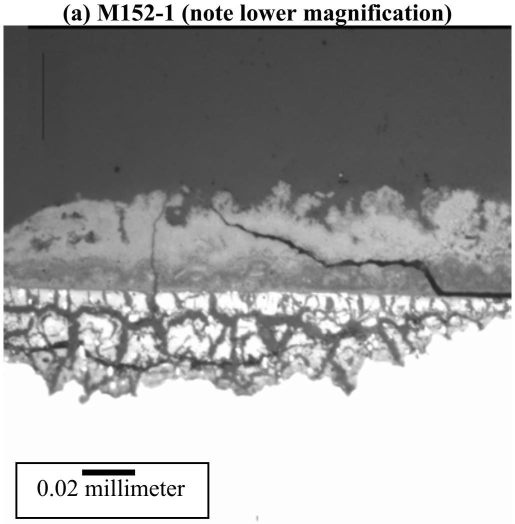


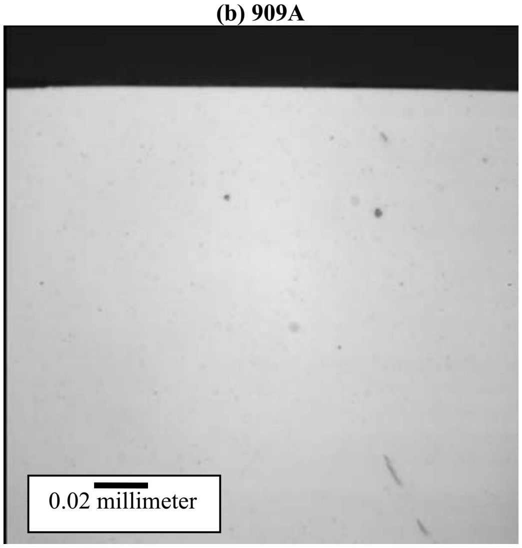
Figure 7 Measurements of metal affected by 1,009 hours of salt spray at 35°C in 5% NaCl. Trends indicate the resistance alloy 783 is far superior to other low CTE alloys and on par with alloy 718.



(a) M152-1 (note lower magnification)

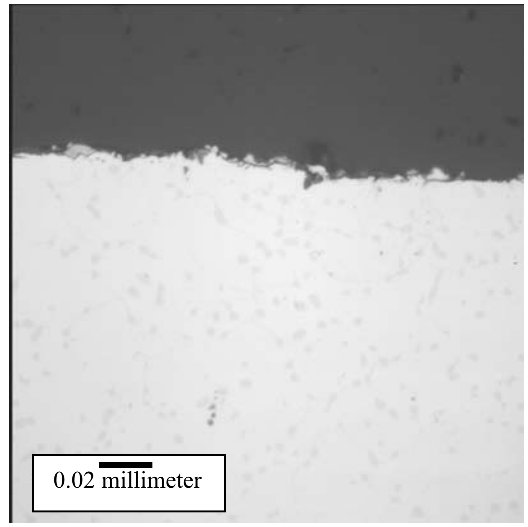


(b) 909A

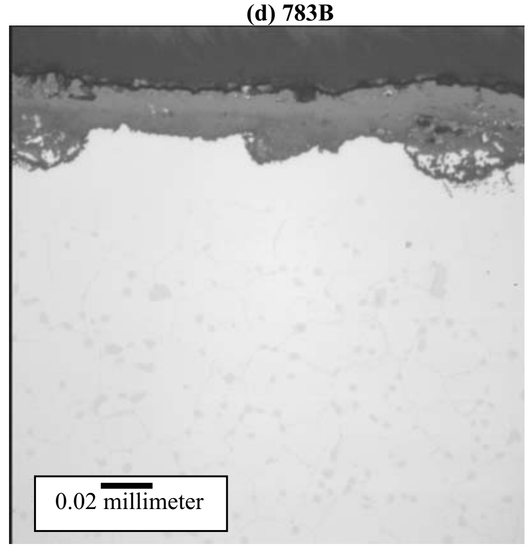


(c) 783A

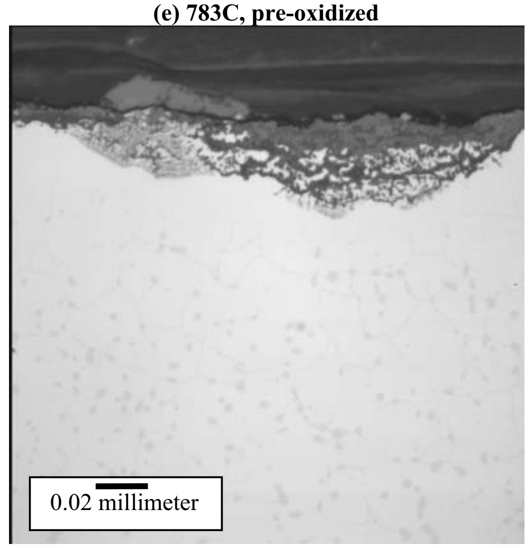
Figure 8 Optical micrographs of samples indicating corrosion is apparent in uncoated base materials tested for 1,009 hours of salt spray exposure at 35°C with 5% NaCl.



(d) 783B

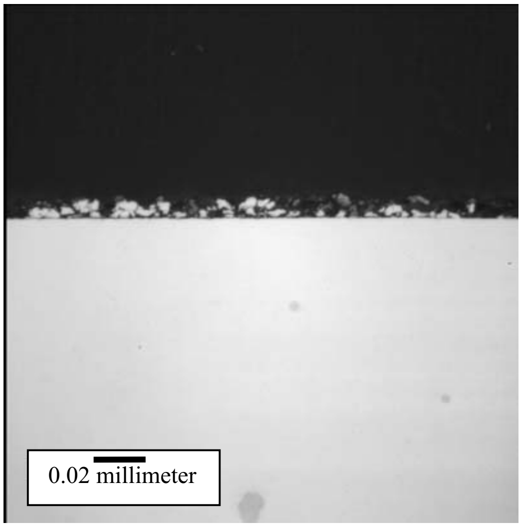


(e) 783C, pre-oxidized

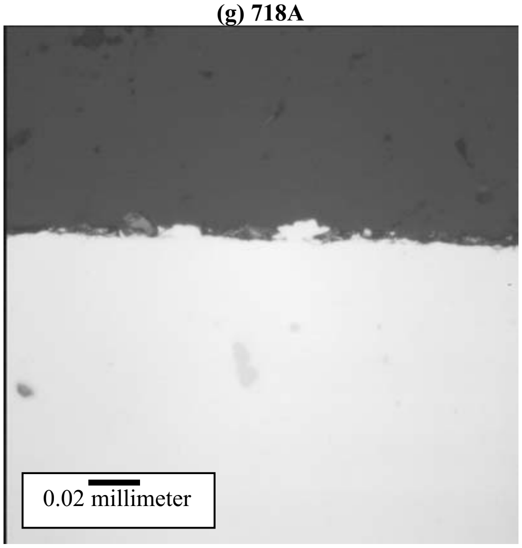


(f) 783 D, pre-oxidized

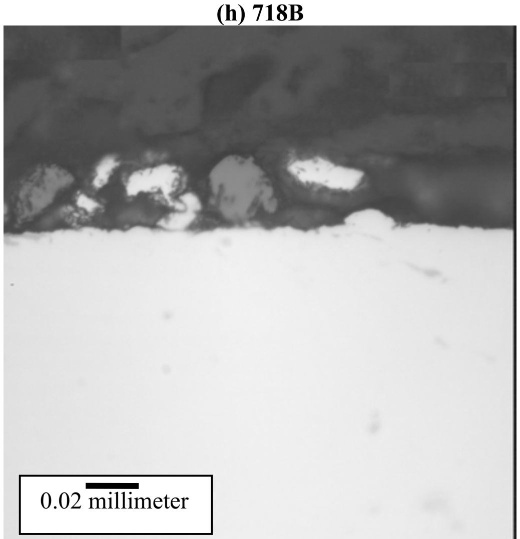
Figure 8 (cont.) Optical micrographs of samples indicating corrosion is apparent in uncoated base materials tested for 1,009 hours of salt spray exposure at 35°C with 5% NaCl.



(g) 718A

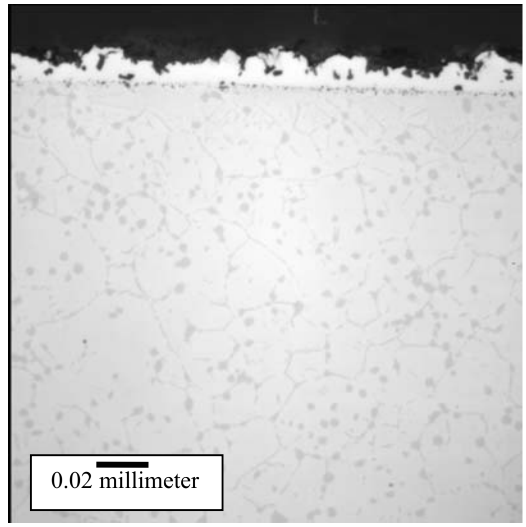


(h) 718B

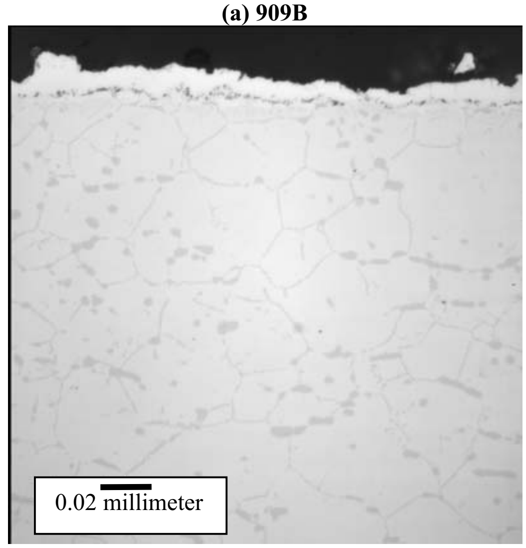


(i) 718-1B

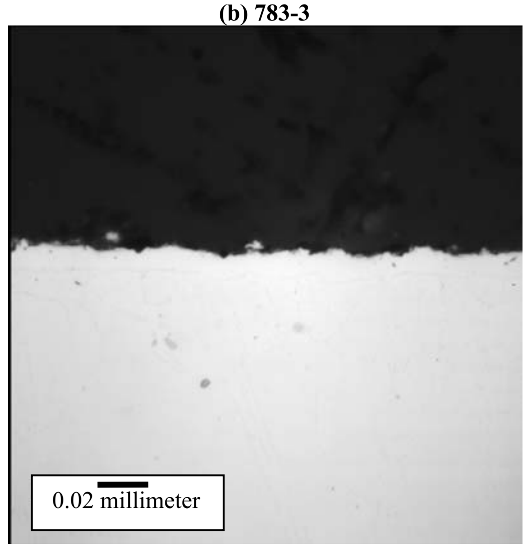
Figure 8 (cont.) Optical micrographs of samples indicating corrosion is apparent in uncoated base materials tested for 1,009 hours of salt spray exposure at 35°C with 5% NaCl.



(a) 909B

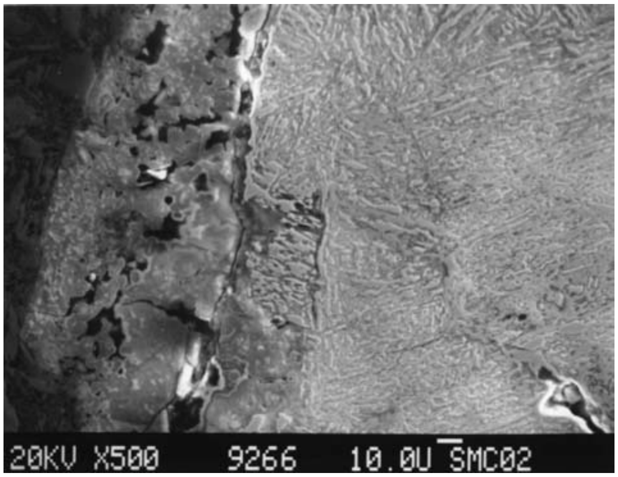


(b) 783-3

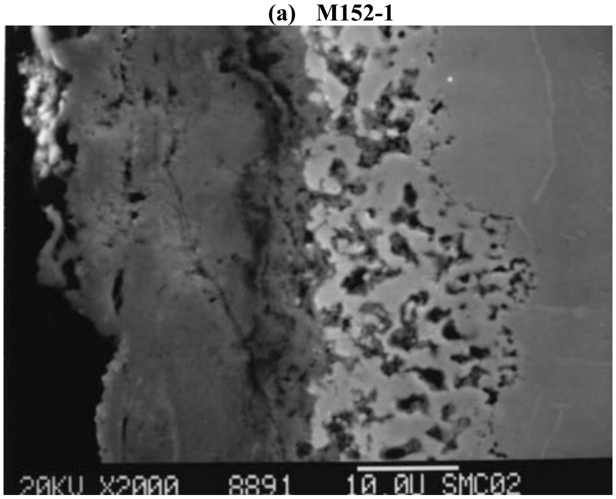


(c) 718-4

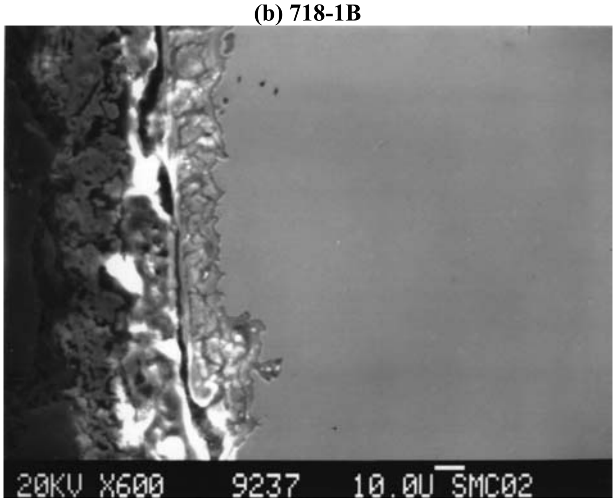
Figure 9 Optical micrographs of chromide coating effectively protecting base metals from the effects of 1,009 hours of salt spray exposure at 35°C in 5% NaCl.



(a) M152-1

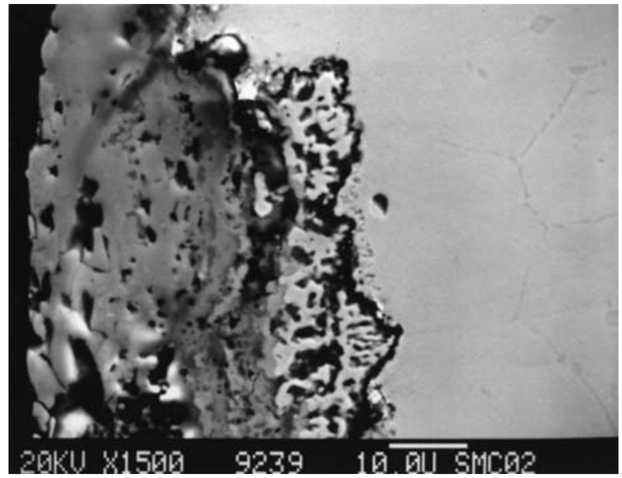


(b) 718-1B

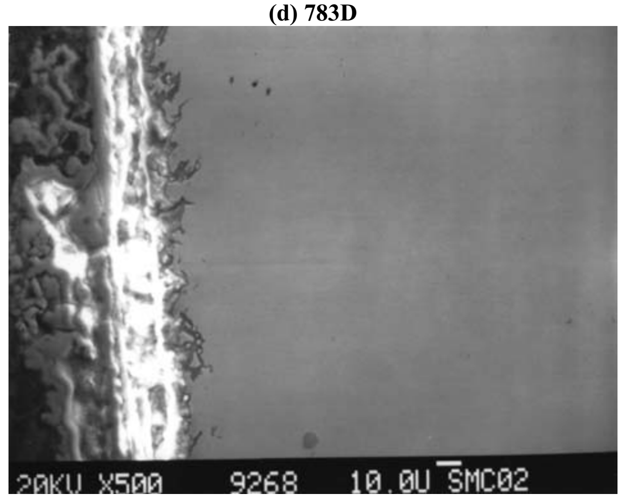


(c) 783A

Figure 10 SEM micrographs of test sample cross sections after salt spray corrosion testing for 1,009 hrs



(d) 783D



(e) 909A

Figure 10 (cont.) SEM micrographs of test sample cross sections after salt spray corrosion testing for 1,009 hrs

Post-test cross-sections (Figures 8 and 9) show regions of most significant corrosive attack for each sample. Cross sections confirm that alloys 783 and 718 are superior to alloy 909 and M152 in their resistance to chloride corrosion under these conditions. Pre-oxidized 783 samples clearly show a moderately thick oxide scale.

SEM and EDS analysis of selected samples was performed to better understand the identity of corrosion products and surface scales in these alloy systems (Figure 10). M152 is significantly affected by salt spray exposure with the formation of a thick, spallation-prone Fe-Cr-Cl scale identified by EDS. Alloy 718 shows a Cr-rich inner scale and a Ni-Cr-Fe outer scale. Alloy 783 forms a 3-layer scale comprised of an outer scale constituting primarily Fe with evidence of Cl, an intermediate scale of primarily Fe while the interior base metal penetration is a Ni-Fe-Co composition with some evidence of Cl. Pre-oxidized Alloy 783 samples maintained their original two-layer heat treatment scale throughout the exposure process with the outer scale being primarily Fe and the inner scale primarily composed of Ni with some Fe and Co present. EDS analysis of alloy 909 also indicates that an outer Fe-rich scale is present along with an inner scale constituting primarily Ni and Fe.

Salt Spray Testing Combined with 650°C Thermal Exposure

Results of NaCl salt spray exposure combined with intermittent 650°C thermal exposure suggest that 783 and 718 behave similarly as evidenced by weight change as a function of exposure time (Figure 11). M152 testing was also performed, although this alloy is typically limited to maximum use temperatures of ~480°C. The dramatic weight loss exhibited by M152 is indicative of significant spallation.

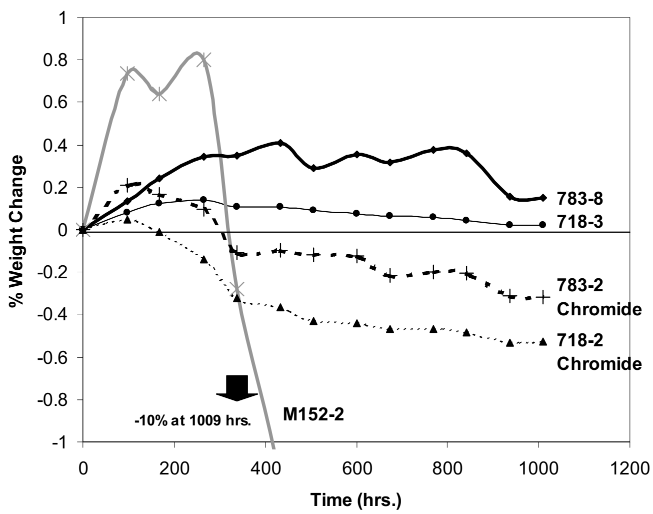


Figure 11 Weight change measurements on base metals and chromide-coated samples determined during salt spray testing for 1,009 hrs. per ASTM B117-97 at 35°C and 5% NaCl with a super-imposed 2 hour, 650°C air exposure twice per week.

M152-2 718-3 783-8 783-2 718-2

Figure 12 Macroscopic views of salt spray test specimens after 1,009 hrs. of exposure with intermittent 650°C thermal cycles.

Macrophotos after salt spray and exposure testing are given in Figure 12. All samples exhibit a uniform oxide scale as a result of testing. Affected metal measurements through the most affected region of each sample are shown in Figure 13 with corresponding micrographs in Figure 14. Chromide-coated alloy 783 again performs similar to coated 718. For the as-machined condition, alloy 783 resistance is reduced versus 718, but is still clearly improved over M152 when spallation, as evidenced by significant weight loss, is considered.

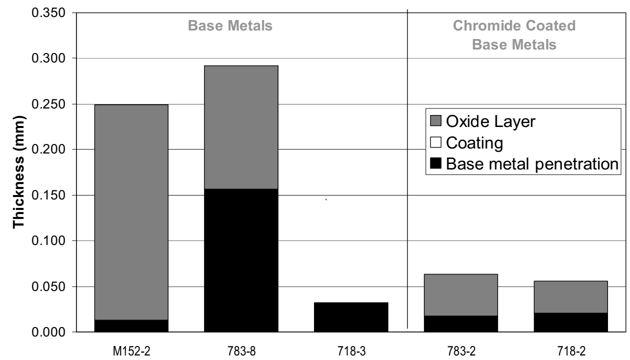
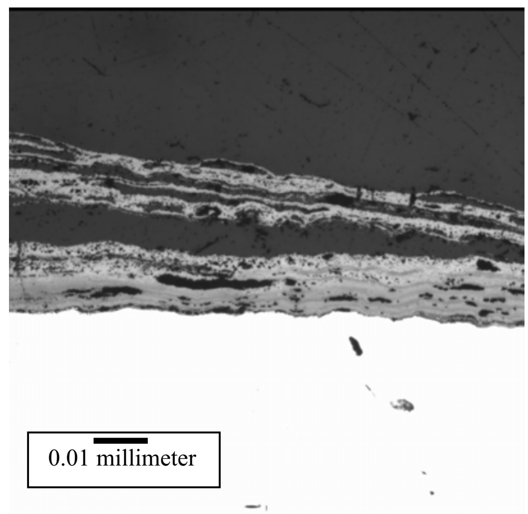
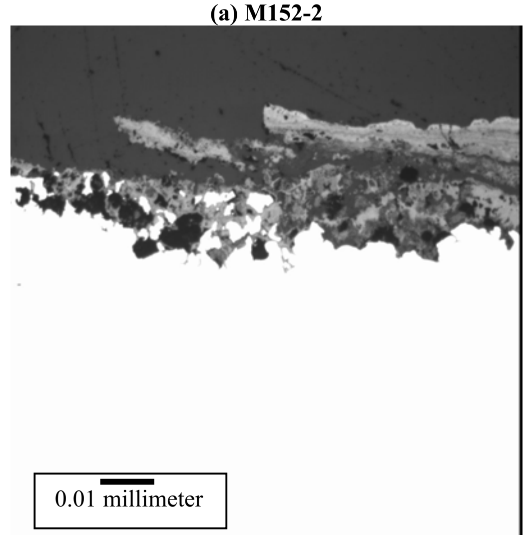


Figure 13 Extent of corrosive attack after 1,009 hours of salt spray exposure and 650°C thermal exposure.

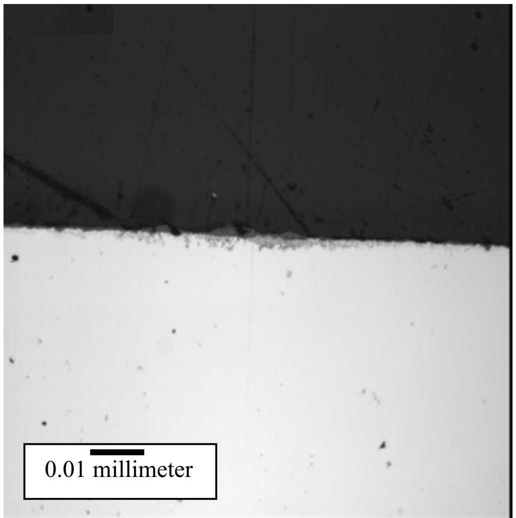


(a) M152-2

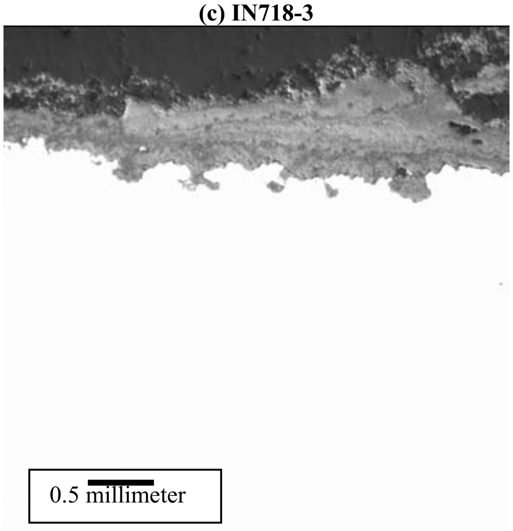


(b) IN783-8

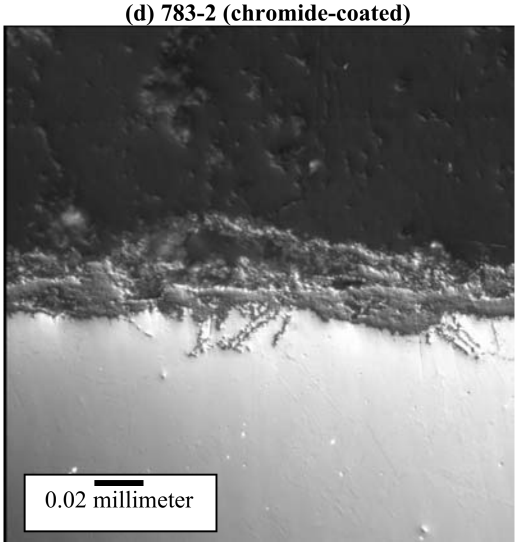
Figure 14 Micrographs of bare base metals and chromide-coated materials subjected to salt spray exposure and 650°C furnace cycles.



(c) IN718-3



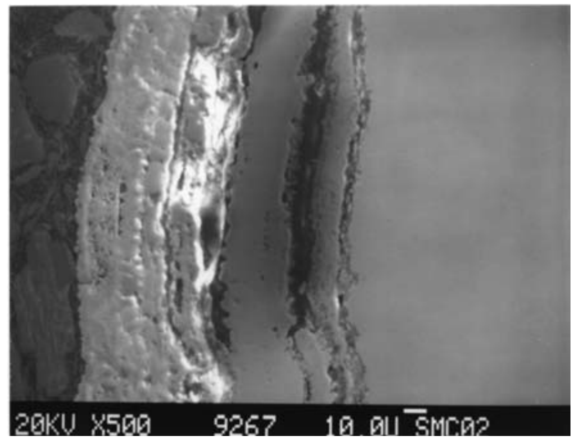
(d) 783-2 (chromide-coated)



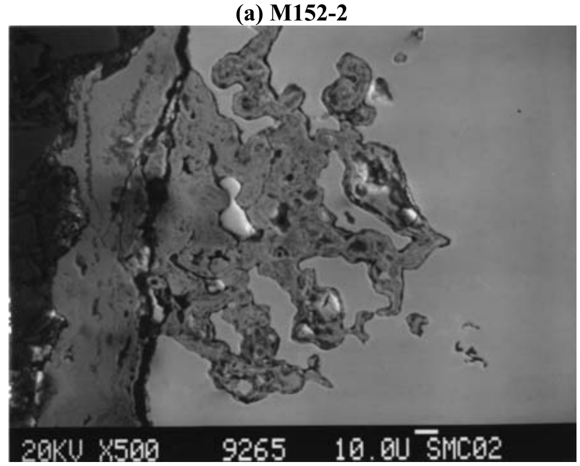
(e) 718-2 (chromide-coated)

Figure 14. (cont.) Micrographs of bare base metals and chromide-coated materials subjected to salt spray exposure and 650°C furnace cycles.

SEM micrographs of M152 and 783 are presented in Figure 15. SEM EDS of the M152 and 783 bare base metal suggest that the M152 alloy behavior is transformed from a single to multi-layer scale consisting of Fe and Cr. For alloy 783, the innermost layer is comprised primarily of Cr, Fe, Co, and Al while the outer scale is predominantly Co with a lesser amount of Fe, Ni, and Cr. Some scale composition and structure differences are apparent between salt spray and the corresponding tests with intermittent high temperature thermal exposure.



(a) M152-2



(b) 783-8

Figure 15: Cross sections after salt spray corrosion testing with intermittent 650°C thermal exposure.

Discussion

Alloy 783 low thermal expansion alloy, developed by Special Metals Corporation, exhibits a significant improvement in chloride corrosion resistance relative to other low CTE alloys. The observed similarity to alloy 718 salt corrosion resistance is especially significant considering its relatively low Cr content. This may be related to the high Co-content and volume fraction of NiAl-type beta phase precipitated in alloy 783 as a result of a high Al content.

Under standard salt spray conditions, alloy 783 is more resistant than M152 and 909 materials and similar to alloy 718. Under the more aggressive salt spray plus intermittent 650°C thermal exposures, chromide coated alloy 783 displays a similar degree of corrosion resistance as chromide coated alloy 718. Additional coating optimization studies would be beneficial in order to better utilize alloy capability under such extreme test conditions.

The salt spray corrosion resistance of alloy 783 was also reported by Heck, et al. [7] and results indicated similar trends in bare base metal salt spray corrosion resistance between 783, 909, and 718 as are reported in this study. The cyclic oxidation resistance of bare alloy 783 at 704°C was also reported [7] to be similar to that of bare alloy 718. The aggressive salt spray exposure combined with cyclic exposure conditions investigated in this study suggest that, although the oxidation resistance may be similar to that of 718, the presence of salt on the sample surface during the high temperature air exposure results in environmental degradation differences between 783 and 718.

Conclusions

The following conclusions were made based on the work performed in this study:

- Alloy 783 provides similar salt spray corrosion resistance during long duration testing at 35°C compared to alloy 718.
- Alloy 783 provides an improvement in salt corrosion resistance versus 909 and far better resistance versus martensitic stainless steel M152.
- The presence of a pre-oxidized scale prior to salt spray testing at 35°C did not significantly impact the corrosion resistance of alloy 783.
- The application of chromide coating to 783 imparts similar chloride corrosion resistance as 718 and M152 when provided a similar coating.
- During a combination salt spray exposure and a 650°C air exposure cycles, alloy 783 performed similarly to 718 when both materials were coated with a chromide coating. In the absence of a chromide coating, 783 performance is inferior to that of 718.

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