Replacement of Chromium Electroplating Using HVOF Thermal Spray Coatings

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Due to both environmental and life-cycle-cost issues, the Department of Defense has established a program to qualify HVOF thermal spray coatings as viable alternatives to hard chrome plating in aircraft maintenance. A Joint Test Protocol has been established to delineate the types of tests required to execute this qualification and successfully validate HVOF coatings for these types of operations. In this paper, the results of fatigue, corrosion, and abrasive wear tests for 83/17 WC/Co and Tribaloy 400 coatings deposited by HVOF are compared to those for hard chrome plating. For the fatigue studies, typical S/N curves were generated for the coatings deposited onto 4340 steel which showed that the HVOF coated specimens gave results equal to the uncoated steel whereas the hard-chrome-plated steel showed a substantial loss of properties. Corrosion studies were conducted using both the ASTM B117 and GM 9540 P/B protocols; in general, the hard-chrome plate performed better than the HVOF coatings on 7075 aluminum alloy substrates, but there was equivalent corrosion behavior on 4340 steel and PH13-8 Mo stainless steel substrates. In abrasive wear tests, the HVOF WC/Co coatings demonstrated lower wear rates than the hard-chrome whereas the T400 coatings demonstrated higher wear rates.

Introduction

Background

Hard chrome plating is a technique that has been in commercial production for over 50 years and which is a critical process associated with maintenance activities at all Department of Defense (DOD) depots and shipyards. In the aviation sector, it is used both for applying hard coatings to aircraft landing gear components and/or aircraft actuator parts, and for general re-build of worn or corroded components that have been removed from aircraft during overhaul.

Hard chrome plating utilizes chromium in the hexavalent state (hex-Cr), which is a known carcinogen. As a result, the Environmental Protection Agency has issued air emission standards for hex-Cr under the so-called MACT Standards, and the Occupational Health and Safety Administration (OSHA) has established permissible exposure limits (PEL) for hex-Cr in the workplace at a level of 100 micrograms/cubic meter. However, recent studies have indicated that there is a significantly increased cancer risk at this PEL and therefore there is consideration of reducing the PEL. In October 1997, Public Citizen and the Oil Chemical, and Atomic Workers (OCAW) Union filed suit to force OSHA to issue a proposed new hex-Cr PEL standard within a firm timetable. OSHA has indicated that existing data could support a reduction of the PEL from its current value to a new value in the range of 0.5 to 5.0 micrograms/cubic meter. In November 1997, OSHA indicated in the Federal Register that the proposed new standard would be issued in September 1998. According to an industry spokesman, a PEL of less than 10 micrograms/cubic meter would substantially increase the cost of chrome plating.

In 1995, a Navy/Industry task group under the coordination of the Naval Sea Systems Command conducted an assessment of the technical and economic impact of a reduction of the PEL to the lower 0.5 micrograms/cubic meter level. Their report concluded that the cost of compliance would be as much as $46 million per year in collection, treatment, and disposal costs, plus one time facilities costs of $22 million to upgrade exhaust and ventilation equipment, personal protective gear, and industrial waste treatment facilities.

Of particular additional interest to the DOD if the new hex-Cr PEL is implemented is that turnaround times for processing of components will be significantly increased, impacting mission readiness. There is a general consensus that if the lower value of the hex-Cr PEL is implemented, hard chrome plating will no longer be feasible at Defense Department depots.

Technology Assessment and Previous DOD Efforts

Under a study funded by the Defense Advanced Research Projects Agency, the Industrial Research Laboratory of Northwestern University evaluated current proposed alternatives to hard chrome plating. They first identified all of the requirements necessary to meet or exceed the performance standards of chromium and then assessed the ability of the alternatives to meet those standards, taking into account environmental issues as well. The assessment included alternative electroplated coatings as well as physical- and chemical-vapor-deposited coatings and thermal-spray coatings. Their conclusion was that thermal-spray coatings deposited by the high-velocity oxygen-fuel (HVOF) technique (so-called because of the use of oxygen and a fuel gas as the combustion propellant) were the best available alternatives to hard chrome plating. Although HVOF coatings must be deposited under line-of-sight conditions, they still have the capability of replacing up to 80% of all hard chrome coatings at DOD maintenance activities. Several different types of HVOF coating systems became commercially available in the late 1980’s, with further development throughout the l990’s.

HVOF thermal spray systems are currently in use at some DOD depots and have been applied to selected chrome replacement applications, although until recently there was no comprehensive effort to replace hard-chrome with HVOF. As an example, in 1993, the Naval Aviation Depot in Jacksonville, Florida (NADEP-JAX) procured a Metco Diamond Jet HVOF system to facilitate replacement of chrome plating on J52 engine oil system components that had worn to the point that chrome plating was no longer a viable coating because of thickness and performance limitations. Twelve components were successfully demonstrated as candidates and full implementation of these was completed in 1994. Since then, additional components on the F404 and TF34 engines have been repaired using HVOF as a chrome plating replacement.

Current Efforts

A project entitled, “Tri-Service Dem/Val of Chromium Electroplating Replacements,” under the principal sponsorship of the DOD Environmental Security Technology Certification Program (ESTCP) is conducting studies to demonstrate and validate HVOF thermal spray coatings as an environmentally acceptable alternative to hard chrome plating. Participating in the project are the Jacksonville and Cherry Point Naval Aviation Depots, the Ogden and McClellan Air Logistics Centers, the Corpus Christi Army Depot, the Naval and Air Force Research Laboratories, Northwestern University, and commercial aircraft manufacturing and servicing companies. HVOF systems were already in existence at Jacksonville and Ogden and systems have been purchased and installed at Cherry Point and Corpus Christi.

The project team, designated the hard chrome alternatives team (HCAT), has developed a Joint Test Protocol (JTP) which involves extensive fatigue, wear, corrosion, and mechanical properties measurements on test coupons as well as limited component testing on HVOF-sprayed tungsten-carbide/cobalt and Tribaloy 400 (a cobalt-molybdenum-chromium alloy) coatings compared to hard chrome. Some of the components that will initially be evaluated in flight testing include landing gear axles and journals for the P-3 and F-18 E/F.

Under a separate ESTCP project, Coopers and Lybrand conducted a cost analysis related to the replacement of hard chrome with HVOF at NADEP-JAX. The analysis was based on the assumptions that 20,000 parts per year are chrome plated and 67 percent of the parts are suitable for HVOF coating. Their report concluded that, over a period of 15 years, Jacksonville could save $9.4 million by full implementation of HVOF to replace chrome, with a payback time on the capital investment of less than one year and with a reduction of the expected average part turnaround time by 40 percent. This analysis did not take into account the anticipated superior performance of the HVOF coatings, which would be expected to further reduce overall maintenance costs.

In parallel to the DOD effort, the commercial aircraft sector is aggressively pursuing the replacement of hard chrome with HVOF coatings. Lufthansa Airlines, in cooperation with Boeing, has implemented component testing on 737-300 nose-landing gear (NLG) main piston and axle journals and is reporting that the gear has undergone more than 2500 flight cycles with no degradation of the HVOF coatings, while showing better compatibility with the hydraulic seals than hard chrome. United, Delta, and Northwest Airlines as well as Boeing, Menasco, Aerospatial and Messier Dowty have agreed to have several additional NLG and main-landing-gear pistons and axle journals HVOF-coated for additional field testing.

The HCAT project is approximately 50% through its planned three-and-one-half year time period as of February 1998. It is the purpose of this report to present the results obtained to date on fatigue, corrosion, and mechanical properties testing on the HVOF WC/Co and Tribaloy 400 coatings compared to hard chrome. A significantly more detailed interim progress report will be issued by the Naval Research Laboratory in the near future.

Fatigue Studies

The fatigue test plan was formulated with several objectives in mind. The primary purpose for these coupon tests was to determine the effects of the coating processes on the substrate material, not to qualify coatings for specific applications. Second, the resultant data should be widely acceptable to the user community, and third, the data generated should be for coating application processes as simulative as possible of what would be utilized for actual components. In discussions with personnel from the aircraft maintenance depots and industry, it was decided that three substrate materials would be evaluated that would be representative of the different types of materials onto which hard chrome is currently being applied. These materials were 4340 steel, 2024 aluminum, and PH13-8Mo stainless steel. Results only on the 4340 steel are presented here.

There were three types of test specimens identified to be utilized in the fatigue testing. They included 0.63-cm (¼-inch) smooth round bar, 0.63-cm (¼-inch) hourglass bar, and 1.40-cm (0.55-inch) x 0.51-cm (0.20-inch) Kb bar specimens. For the smooth bar, the length of the area for which the 0.63-cm diameter was maintained was 1.9 cm. The largest group of testing was on the smooth bars since the were relatively inexpensive to fabricate. Hourglass bars were included because several of the industrial participants use that type and stated nothing else would be acceptable. The rectangular Kb bar was included because it allows the best simulation of coating application processing for flat surfaces and is more representative for large diameter parts than the 0.63-cm round bars. The diameter of the "necked-down" part of the bars was smaller than the HVOF gun plume so the coatings were always being deposited at low angles which raised the concern that the geometry might change the coating residual stresses for the fatigue specimens compared to those on actual components.

Both low-cycle-fatigue (LCF) and high-cycle-fatigue (HCF) tests were conducted and S/N curves generated over a wide range of maximum load conditions, thus being more useful to designers than doing selected individual loads. In the case of the smooth bars, uncoated specimens were tested as a baseline.

All fatigue specimens were fabricated by Metcut Research, Inc. following rigorous procedures. It was decided that a heat treat condition of 1.8-1.9 GPa (260-280 ksi) for the 4340 steel would be specified because it was typical of that used for landing gear parts done at Ogden ALC and would be more sensitive to fatigue effects than the lower strength 1.2 GPa (180 ksi) heat treat condition frequently used on hydraulic actuator parts at other DOD sites. Industrial representatives on the project team concurred that the 1.8-1.9 GPa heat-treated 4340 would be more sensitive than other steels such as 300M or 52100.

Surface preparation involved low-stress grinding followed by 600 grit alumina polishing which removed 25 micrometers minimum on all gage section surfaces. Specimens intended for HVOF coating were then grit blasted followed by shot peening, which was carried out in accordance with Mil-S-13165C on the gage sections which involved using S280 cast steel shot to an intensity of 8-10A. Specimens intended for chromium plating were prepared by lightly hand abrading the areas to be coated using a scotchbrite pad, followed by shot peening specified above.

The hard chrome and HVOF WC-17%Co were applied at Ogden ALC, with the latter deposited using a Tafa JP5000 gun and Stark Amperit 526.062 agglomerated/sintered powder. The HVOF Tribaloy 400 coatings were applied at Southwest Aeroservice using a Stellite JetKote II gun and Stellite JK554 atomized powder. In each case, the nominal coating thickness was 50 micrometers (0.002 inches)

Fatigue testing of the smooth bar and Kb bar specimens was conducted at Metcut Research Inc. and testing of the hourglass specimens was conducted at the Air Force Research Laboratory in Dayton, Ohio. The two test sources followed a set of documented test procedures to ensure there were no discrepancies. MTS Model 318 servo-hydraulic frames were used with test frame alignments conducted per ASTM E606 and 1012 and specimen alignments in the test frame per Metcut procedure 60.1.3. The LCF tests were conducted in axial strain control using a 2 hertz triangular waveform. The HCF tests were conducted in load control using a 60 hertz sinusoidal waveform. All testing of the 4340 specimens was conducted at room temperature since in-service applications seldom exceed 100^{o} C. All load calculations were based on the uncoated specimen dimensions and strain measurements were made as the average for the gage section with the extensometer attachments well beyond the coated area on both end of the gage section. The LCF tests were considered a runout at 500,000 cycles, and were switched to load control and 9 hertz for the duration of the test if failure did not occur in the first 24 hours (172,800 cycles). Strain control LCF tests were not run for the hourglass bar specimens, since that geometry is unsuitable for strain control. The HCF tests were considered a runout beyond 10,000,000 cycles. Table 1 indicates the number of specimens tested for each type of coating and geometry.

Table 1. Number of fatigue specimens tested for different coatings and geometries for 4340 steel

Coating	Smooth Bar		Hourgl. Bar		Kb rec bar	
	LCF	HCF	LCF	HCF	LCF	HCF
baseline	10	10	0	0	0	0
chrome	10	10	0	6	6	6
WC/Co	8	8	0	6	6	6
T400	8	8	0	6	6	6

Figure 1 shows the smooth round bar fatigue data for the uncoated 4340 specimens and the three coated 4340 specimens. The data for the hard-chrome-coated specimens indicated a substantial loss of fatigue strength. The uncoated specimens fell within the scatter for both of the HVOF coatings, indicating essentially no loss of fatigue strength. The Kb bar data also indicated the HVOF-coated specimens demonstrated higher fatigue strength than those that were chrome-coated. The results for the HVOF-coated hourglass specimens were similar to those for the other geometries, but the fatigue debit for the chrome-coated hourglass specimens was substantially greater than for the other geometries. The reason for this is not clear at present.

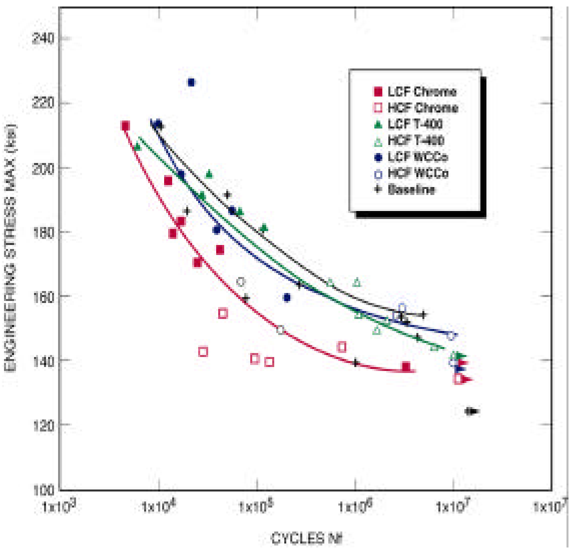

Figure 1. S/N data for smooth bar uncoated 4340 steel specimens and 4340 specimens coated with hard-chrome, HVOF WC/17%Co, and HVOF Tribaloy 400.

The tested smooth bar and Kb bar fatigue specimens were evaluated for failure locations. The hard chrome plate resulted in 18 failures under the coating and 2 failures outside the coating. The HVOF Tribaloy 400 gave exactly the opposite, 18 failures outside the coating and only 2 failures under the coating. The HVOF WC/Co had 10 failures each under the coating and outside the coating. The significance of failure location is that those failures outside the coated area are parent metal failures unaffected by the coating or coating process. Thus, one clearly concludes the hard chrome coating/process usually caused failures (and at reduced strengths) while the HVOF Tribaloy 400 coating/process had no effect. Also, the HVOF WC/Co coating/process probably had little effect since the 50% of failures within the coated area were at virtually the same fatigue strengths and lives as uncoated 4340 steel.

Corrosion Studies

Two types of corrosion tests were conducted on the coated specimens. The first was the ASTM B117 salt fog test and the second was the GM9540P/B cyclic corrosion test. Both of these tests were conducted in Q-Fog Model Cabinets in which the appropriate test protocol was stored in the controller memory. The specimens were all 7.6 x 10.2 x 0.48 cm thick (3" x 4" x 3/16" thick). The substrates consisted of 4340 steel, 7075 Al alloy, and PH13-8Mo stainless steel. Prior to coating, each sample was grit blasted to remove surface scale. The HVOF Tribaloy 400 coatings were applied by Southwest Aeroservice on all surfaces and edges of the specimens using the same parameters as for the fatigue specimens. The hard-chrome and HVOF WC/17%Co coatings were applied at NADEP JAX, with the WC/Co coatings applied using a Metco Diamond-Jet hybrid system. The 7075 Al specimens intended for chrome-plating first received a double-zincate process followed by a copper and nickel strike. This is a standard procedure for applying chrome-plate to any aluminum alloy substrates. Portions of these specimens were uncoated, requiring the application of an inert epoxy outside the coated areas to ensure no interaction between coated and uncoated surfaces. In all cases, the nominal thickness of the coating was 100 micrometers (0.004 inches).

ASTM B117 Salt Fog Tests

The solution used for this test was 5% sodium chloride and the pH was between 6.5 and 7.2. The temperature in the chamber was held at 35^o C. At least five specimens for each coating/substrate combination were evaluated. Photographs were taken prior to exposure to document the surface. The samples were visually examined at 125-hour intervals and given an appearance rating, based on a scale of 0-10, with 10 representing a pristine surface. Total test duration was 1000 hours. Photographs were taken after exposure to document the change in the surface and then the samples were cleaned with an abrasive pad to remove some of the corrosion product. Once the specimens were cleaned it was possible to identify surface defects such as blisters or pits. Removing the blisters and portion of the coating that were undercut by corrosion provided a better representation of the area that was affected by corrosion. A protection rating for the sample faces, i.e., how well the coating protected the substrate, was then determined. The ranking system used is described in ASTM B537-70. A protection rating for the sample edges was determined in a similar manner. The ASTM B537 protection rating system is presented in Table 2.

Table 2. ASTM B537 protection rating versus area of defect.

Area of Defect (in %)	Ranking
0	10
0 to 0.1	9
0.1 to 0.25	8
0.2 to 0.5	7
0.3 to 1.0	6
1.0 to 2.5	5
2.5 to 5.0	4
5 to 10	3
10 to 25	2
25 to 50	1
> 50	0

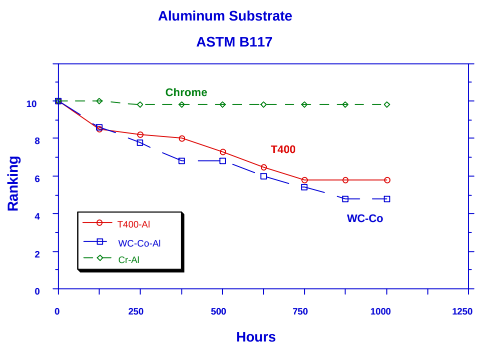

Figure 2. Appearance rankings for various coatings on the 7075 aluminum alloy specimens subjected to the B117 salt fog test

Appearance rankings that were determined at 125-hour intervals for the coatings on the aluminum alloy specimens are presented in figure 2. Following cleaning of the specimens it was possible to determine the protection rankings. Pitting had occurred on the face of 5 of the 6 samples with the T400 coating, but it was not extensive, with the number of pits ranging from 1 to 3. The pits were propagating into the bulk and there was no undercutting at the coating/metal interface. No pits or blisters were observed on the sample face coated with WC/Co. However, severe pitting was noted on the sample edges without any undercutting. The hard chrome performed extremely well, with an appearance and protection rating of 10 for the face and edges. It is believed that the double-zincate process and copper and nickel strike played a role in the high level of corrosion resistance of the hard-chrome on the aluminum alloy specimens. Table 3 presents the average appearance and protection rankings for the coatings on the 7075 Al specimens.

Table 3. Average appearance and protection rankings for hard-chrome and HVOF coatings on 7075 Al alloy specimens.

Coating	Appearance	Pro.Face	Pro.Edge
T400	5.8	9.0	3.0
WC/Co	4.8	10	10
Hard Cr	9.8	10	10

Appearance rankings for the coatings on the 4340 steel specimens are presented in figure 3. The appearance ranking for the hard chrome was the lowest because there were areas where the coating was missing. These bare areas were, for the most part, evident prior to sample cleaning. For the WC/Co and T400 coatings, there were blistered areas that were not evident before cleaning. Thus, these coatings appeared intact and received higher appearance ratings. After cleaning and removing the blisters, it could be seen that the area affected by corrosion was greatest for the samples with the T400 coating. Table 4 presents the average appearance and protection rankings for all of the coatings on the 4340.

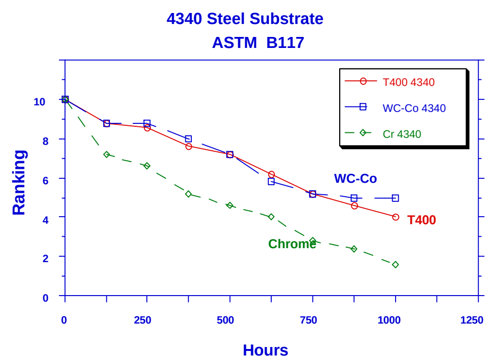

Figure 3. Appearance rankings for various coatings on 4340 steel specimens subjected to the B117 salt fog test

All sample faces coated with T400 on the 4340 steel showed a significant amount of blistering with from 10 to greater than 50% of the surface affected. The substrate was corroded beneath the blisters. For the sample edges, up to 50% were corroded, with a substantial amount of undercutting of the coating. The undercut area was greater for the T400 than for the hard chrome or WC/Co coatings.

The faces of all hard chrome samples showed a significant amount of blistering and exposed substrate. For the sample edges, 10 to 50% were corroded with a great deal of undercutting of the coating. The undercutting was less than for the T400 but more than for the WC/Co.

The faces of all the WC/Co coatings showed a similar amount of blistering to that for the hard chrome. The protection rankings for individual samples ranged from 2 to 5. Up to 25% of the edges were corroded with some undercutting observed, but less than for the other coatings.

Table 4. Average appearance and protection rankings for hard chrome and HVOF coatings on 4340 steel substrates.

Coating	Appearance	Pro.Face	Pro.Edge
T400	5.0	1.6	1.0
WC/Co	4.0	3.4	3.2
Hard Cr	1.6	3.2	2.0

The performance of all of the coatings on the PH13-8Mo stainless steel substrates was excellent, with the appearance rankings presented in figure 4.

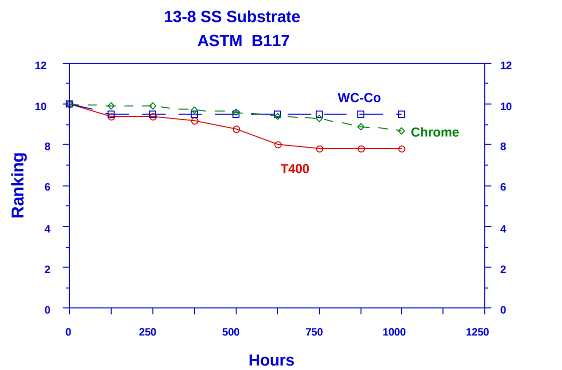

Figure 4. Appearance rankings for various coatings on the PH18-8Mo stainless steel specimens subjected to B117 salt fog test

The hard chrome and WC/Co coatings performed well as no pits were noted on the faces or edges. The WC/Co did darken with time and blemishes, i.e., small areas that were a slightly lighter color, were noted. The T400 coating face and edges had rust stains but defects were not visible to either the unaided eye or at a 7X magnification.

GM9540P/B Cyclic Corrosion Tests

In this test, the specimens are exposed to a variety of conditions, with the test protocol as follows:

Step 1	subcycle step 2-3 repeat 4 times	
Step 2	salt mist at 25 C	15 min
Step 3	dry-off at 25 C	75 min
Step 4	dry-off at 25 C	120 min
Step 5	RH 95-100% 49 C	8 hours
Step 6	dry-off at 60 C	7 hours
Step 7	dry-off at 25 C	1 hour
Step 8	Final step, go to step 1	

Note: RH = relative humidity

All of the specimens were visually examined at the same intervals as for the B117 test and the same specimen cleaning was performed. The total test duration was 2000 hours.

Figures 5, 6, and 7 present the appearance rankings for the three types of coatings on the 7075 Al alloy, 4340 steel, and PH13-8Mo stainless steel substrates.

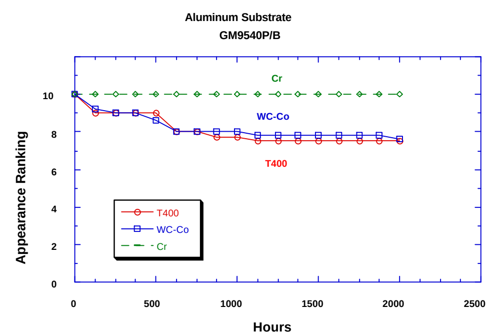

Figure 5. Appearance rankings for coatings on 7075 Al alloy substrates subjected to GM cyclic test.

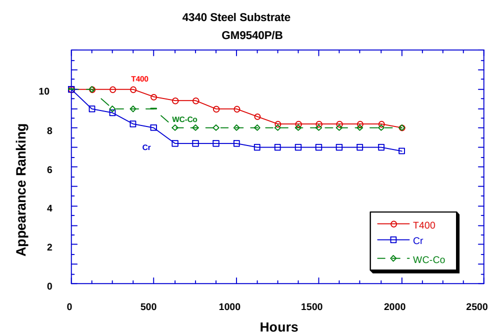

Figure 6. Appearance rankings for coatings on 4340 steel substrates subjected to GM cyclic test.

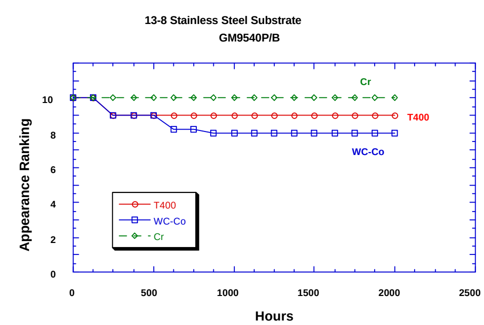

Figure 7. Appearance rankings for coatings on PH13-8Mo stainless steel substrates subjected to GM cyclic test

On the aluminum alloy substrates, pitting had occurred on the face of two of the five samples with the T400 coating. The pits were propagating into the bulk and there was no undercutting at the coating/metal interface. There was a significant amount of pitting on the edge of the samples.

No pits or blisters were observed on the face of the samples with the WC/Co coating. The overall coating surface was darker after exposure, but this phenomenon was also observed for those WC/Co coatings that were simply exposed to ambient atmosphere conditions near the test cabinets. Severe pitting was noted on the sample edges, but there was no undercutting of the coating next to the pits.

The hard chrome on the aluminum alloy performed very well as with the B117 test, presumably due to the double-zincate process and copper and nickel strike. On the face and edges, all samples appeared pristine after the exposure.

For the T400 coatings on the 4340 substrates, four out of the five samples showed no indication of pits or blistering, with only one pit on the fifth sample. However, there was extensive pitting observed on the edges, with no undercutting of the coating.

For the WC/Co coatings on the 4340 substrates, no evidence of corrosion could be seen on any of the faces of the five samples. There was also virtually no corrosion on the edges, with only a few pits observed.

Four of the five faces of the hard chrome coatings appeared to be unattacked, with only a rust-stained area on the fifth sample. There was significant pitting observed at the edges, however.

Finally, similar to the B117 test, all of the coatings on the PH13-8Mo stainless steel substrates performed very well, both on the faces and edges. Tables 5, 6, and 7 summarize all of the average appearance and protection rankings for the coatings subjected to the GM cyclic corrosion test.

Table 5. Average appearance and protection rankings for hard chrome and HVOF coatings on 7075 Al alloy substrates subjected to GM cyclic test.

Coating	Appearance	Pro.Face	Pro.Edge
T400	7.5	9.2	1.8
WC/Co	7.6	10	1.6
Hard Cr	10	10	10

Table 6. Average appearance and protection rankings for hard chrome and HVOF coatings on 4340 steel substrates subjected to GM cyclic test.

Coating	Appearance	Pro.Face	Pro.Edge
T400	8.0	9.6	2.4
WC/Co	8.0	10	8.8
Hard Cr	6.8	9.8	1.0

Table 7. Average appearance and protection rankings for hard chrome and HVOF coatings on PH13-8Mo stainless steel substrates subjected to GM cyclic test.

Coating	Appearance	Pro.Face	Pro.Edge
T400	9.0	9.6	9.8
WC/Co	8.0	10	10
Hard Cr	10	10	10

It is apparent from both the B117 and GM cyclic corrosion tests that there are substrate effects associated with the performance of the coatings. Since the coatings were reasonably thick (100 micrometers) with an expectation of high density, then it would not be expected that there would be any through-thickness defects. Additional analyses will have to be performed to determine the reason for the substrate effects.

Hardness and Abrasive Wear Tests

To obtain accurate values of hardness for each of the coatings, cross-sections were obtained for several coatings on different substrates and a Fischerscope H100 continuous-indentation microhardness testing system with a Vickers indenter was used. The cross-sections were first ground using sandpaper of progressively smaller grit sizes down to 1500 which was then followed by polishing using 1 micrometer diamond paste. Ten indents were then made on each coating approximately halfway between the surface and substrate. The hardness H, modulus of elasticity E, and maximum indentation depth D were recorded and averaged for each coating. Table 8 presents the results of these measurements for the coatings on the 4340 steel substrates.

Table 8. Hardness, elastic modulus, and maximum indentation depth data for three coatings on 4340 steel.

Coating	H (GPa)	E (GPa)	D(micrometers)
T400	5.7	130	2.8
WC/Co	12.8	272	1.8
Hard Cr	10.1	201	2.1

A CSEM Calowear tester was used to perform abrasive wear resistance testing. The test consisted of sliding a 2.5-cm-diameter hardened steel ball against the coating with a normal force of between 0.25 and 0.35 N as measured by a sensitive load cell. For most measurements, the normal force was 0.27 N. Then an abrasive slurry containing 4-micrometer-diameter silicon carbide particles in distilled water was drip fed onto the steel ball. Wear craters were generated in the coatings, and the volume of each crater was measured as a function of the number of revolutions of the steel ball, with the total number of revolutions extending to 50,000. An average wear coefficient K was calculated for each coating/substrate combination, with K expressed as the volume removed per unit load and unit sliding distance.

Table 9. Average wear coefficients, K, expressed in units of 10^{-4} mm^3/N-m, for the various coating/substrate combinations.

Sample	# of tests	K
Cr-plate on 7075 Al	4	9.3
Cr-plate on 4340	5	9.9
Cr-plate on PH13-8	4	9.7
WC/Co on 7075 Al	5	6.7
WC/Co on 4340	5	5.7
WC/Co on PH13-8	5	6.4
T400 on 7075 Al	5	13.3
T400 on 4340	5	15.6
T400 on PH13-8	5	18.1

Table 9 summarizes the results of the abrasive wear tests, showing that the wear rates were lowest for the WC/Co coatings, followed by the hard-chrome and the Tribaloy 400, with the results independent of substrate. By comparing the values for the hardness, H, of the coatings with values for the wear coefficients, it can be noted that the abrasive wear resistance, which can be expressed as 1/K, increases in proportion to H, as expected.

Summary

A detailed Joint Test Protocol has been established to qualify HVOF thermal spray coatings as a viable alternative to hard chrome plating in aircraft maintenance and manufacturing operations. Initial testing has demonstrated that in fatigue testing, hard chrome plating causes a significant loss of properties whereas there is virtually no effect associated with HVOF deposition of WC/Co and Tribaloy 400 coatings. In corrosion testing, the HVOF coatings did not perform as well as the hard chrome on aluminum alloys, but this was believed to be due to the use of an under-coating for the hard chrome. Essentially equivalent corrosion resistance was observed for the HVOF coatings and hard chrome plate on 4340 and PH13-8Mo steel substrates, although there was a substrate effect that must be further investigated. Microhardness values were as expected, with the WC/Co HVOF coatings demonstrating the lowest abrasive wear rates.

Future studies will include the bench testing of actual coated components and flight testing of coated components to document real-life performance. Based on the results to date, there appears to be a high probability that HVOF thermal spray coatings will prove to be an environmentally-friendly, higher-performance alternative to hard chrome plating.

Acknowledgment

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