Ion Beam and Plasma Based Alternatives to Chrome Plating of Gas Turbine Engine Parts

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The Propulsion Environmental Working Group (PEWG) has supported several projects focusing on electrolytic hard chrome (EHC) plating replacement to refurbish worn or corroded parts. One project has targeted improving the engineering properties of original equipment manufacturer (OEM) components for enhanced service life such that refurbishment with chromium would not be required until later in the component life cycle. This paper will discuss the results of this task, which was conducted through the National Defense Center for Environmental Excellence (NDCEE), in which seven deposition/surface modification techniques were investigated that had shown the potential to provide the required improvements. All techniques were applied to IN718 and 4340 steel and tested for wear and corrosion performance, hardness, adhesion, and overall visual quality. The results of the laboratory screening tests will be presented, as well as future plans for this project.

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Introduction

Virtually every military gas turbine engine (GTE) system in service utilizes electrolytic hard chromium (EHC) plating in engine overhaul operations. The Navy, Army, and Air Force repair facilities use EHC in GTE maintenance operations to restore the dimensions of worn or corroded parts and to provide a wear and corrosion resistant surface. This process involves the use and release of hexavalent chromium, a known human carcinogen. During plating, acid mists, which contain hexavalent chromium, are released to the atmosphere. These mists pose a health risk to nearby workers. Therefore, the Occupational Safety and Health Administration (OSHA) has imposed a permissible exposure limit (PEL) on hexavalent chromium at 0.1 mg/m^3 and is considering reducing that PEL to 0.0005 mg/m^3. Chromium compounds are also targeted by the United States Environmental Protection Agency (EPA). The EPA is trying to implement a health standard in which guidelines on training and reporting will be required. Complying with these regulations has become more difficult, and the trend is expected to continue, thereby increasing the total operational costs of EHC plating.

In addition to environmental concerns with EHC, issues related to long-term maintainability and reliability of DoD systems must be considered. Reductions in funding for national defense has necessitated continued operation of aging propulsion systems in aircraft, ships, and certain military vehicles. Although EHC has been an accepted practice for GTE repair for many years, chromium is not necessarily the best material/process in terms of cost and mission effectiveness. The civil aircraft industry and the DoD have initiated a number of efforts to qualify thermal spray coatings, such as tungsten carbide, in aircraft and engine manufacture and rework. However, thermal spray processes are limited to line-of-sight applications (simple geometries) and can input a significant amount of heat into small components. It is estimated that these processes cannot accommodate 25-30 percent of the engine parts currently being refurbished. In addition, processes that are capable of providing surfaces that will perform better than conventional hard chromium are needed. Ideally, a repair process/material combination that only needs to be applied once during the life of the repaired part, complies with green engine initiative guidelines, and is environmentally friendly will be selected. Such a process also may be implemented at the original equipment manufacturer (OEM) level for initial improvements in service life, leading to reduced labor costs in the repair facilities.

The Propulsion Environmental Working Group (PEWG) and the National Defense Center for Environmental Excellence (NDCEE) operated by Concurrent Technologies Corporation (*CTC)* have collaborated on a project to identify, demonstrate, validate, optimize, and justify alternatives to hard chromium plating. The selected alternative must meet all military requirements. This paper discusses the current status of the project and results obtained to date.

Project Overview

The scope of this project is to demonstrate ion beam and plasma-based deposition and surface modification techniques, and justify them as environmentally benign processes that can reduce or eliminate EHC operations. The new process must meet or exceed performance and operational requirements of current processes. Information obtained in the execution of this project is transferable to DoD repair depots and OEMs. Successful completion of this project is expected to

- Reduce the use of hexavalent chromium, leading to reductions in environmental, health, and safety costs
- Reduce the operational costs and labor requirements as a result of eliminating hazardous materials and the associated compliance procedures/processes
- Reduce operator exposure to hexavalent chromium
- Reduce waste generation.

Phase I of this project is being completed in four tasks. The first task involved identifying classes of GTE components that are currently being EHC plated. Testing requirements, based on Federal Specification QQ-C-320B, were identified as well as other tests necessary to establish a technical performance baseline. These tests include adhesion, hardness, thickness, wear, corrosion, profilometry, and metallography. The NDCEE project team and representatives of the PEWG concurred that each test must be performed and the results compared to traditional EHC to determine whether the alternate process is capable of providing a surface of equal or better quality than the EHC coating.

Investigation of alternatives, the second task, began after identifying the requirements. Alternatives focused on dry processing methods, including physical vapor deposition, ion beam and laser technologies, and ion implantation. Performance criteria of the alternatives were evaluated during the selection process. PEWG preferences were solicited and incorporated into the identification of alternatives, where appropriate. Based on the findings, PEWG and the NDCEE project team members selected the most promising of the technologies. These technologies were further investigated in demonstration and validation activities.

The third task of the project involved demonstration of the alternative processes. Panels were treated using the selected technologies. Ion beam assisted deposition (IBAD) coatings were deposited using the ion beam system located in the NDCEE Demonstration Factory. Subcontractors performed the required services for the remaining alternatives, and some performed the work at no cost to this project. EHC coatings also were obtained and used as the baseline panels against which all other treatments will be compared.

Demonstration activities were designed according to a formal Demonstration Plan. This demonstration plan delineated: (1) the activities necessary to demonstrate each of the selected alternatives, and (2) the test methods and procedures used to evaluate the coatings and surface modifications. Test matrices were included to ensure sufficient data was collected to qualify or disqualify the alternatives.

The fourth task, which is occurring simultaneously with demonstration and testing, involves technology justification. The NDCEE project team members are using available EHC plating data to establish an economical and environmental baseline. The baseline information will include the following:

- Environmental, health, and safety (EHS) costs
- Labor costs associated with chromium rework operations
- Waste generation/disposal costs.

Tools, such as environmentally-based costing*, return on investment calculations, estimates of the potential reduction in the use and emission of hazardous materials, and estimates of product quality improvements will be used to obtain necessary cost justification data. This information will be captured in the Justification Report.

Upon completing the four tasks, the NDCEE project team expects to continue its efforts through follow-on work, which may include engine and rig testing and/or additional panel testing such as fatigue, fretting wear, carbon seal wear, or other specialty tests.

Work Completed

Requirements Analysis Task

To acquire all of the pertinent requirements, many discussions were held with members of the PEWG. Additionally, some requirements information was obtained from the Joint Test Protocol (JTP) entitled

*Environmental Cost Analysis Methodology (ECAM^{SM}), Concurrent Technologies Corporation, Johnstown, PA.

"Validation of Advanced Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Gas Turbine Engines." The information gathered through discussions with PEWG members and the JTP was assembled into a Requirements Report. This report contains information concerning the classes of parts in a GTE, the materials of fabrication, and the required performance characteristics for EHC plating.

Candidate GTE parts have been categorized into five families of components as follows:

- Shafts
- Hubs
- Gears
- Bearing housings
- Accessory gearbox components.

Although a variety of materials are used in the fabrication of GTEs, the most prevalent substrate materials are Inconel 718 (IN718) and 4340 steel. As a result, these materials were used to fabricate the test panels to be used for screening tests. Subsequent treatment and testing of the materials will determine the applicability of the technologies for components fabricated from these materials.

Identify Alternatives

Vendors were contacted to obtain information related to their respective processes. Vendor-supplied data for each of the alternative processes were organized into a Potential Alternatives Report (PAR) that provided a technical description of the process, material properties that can be obtained using the alternative, and advantages and limitations associated with each process. Where possible, performance comparisons to EHC plating were made. Eleven alternative processes were analyzed and seven were selected for demonstration. Based on the analysis results, the following technologies were selected for investigation.

- Ion beam assisted deposition (IBAD)
- Plasma Immersion Ion Processing (PIIP)
- Ion implantation
- Cathodic arc deposition
- Plasma assisted chemical vapor deposition (PACVD)
- Sputtering
- Surface modifications using lasers*

Technology Demonstration

After submission of the PAR and selection of the alternatives, the NDCEE project team contacted industrial vendors or research facilities, where appropriate, that perform the processes of interest to determine the specific, suitable treatment for obtaining the desired performance characteristics. The coatings included niobium nitride, chromium nitride, chromium oxycarbide, varieties of diamond-like carbon, and various metal-bearing carbon coatings. The implant species used for 4340 steel included chromium, titanium/nickel, and titanium. Tantalum, phosphorous, titanium/nickel, and aluminum were implanted into IN718. Sample surfaces were profiled before and after treatment to ascertain whether any treatment had a significant effect on surface roughness. Metallographic cross-sections were analyzed using scanning electron microscopy (SEM) to determine actual coating thickness. Adhesion, corrosion, nanohardness, and wear tests then were performed to evaluate the performance of the coatings. The following sections describe the details of testing.

*Laser Induced Surface Improvements (LISI^{SM}), Surface Treatment Technologies, Tullahoma, TN.

Profilometry

Surface roughness was measured before and after each coating/implant to provide an understanding of the surface created by the coating/implantation process. The profilometer was operated in accordance with the procedures listed in ANSI B 46.1, The American National Standard for Surface Texture. The measurements taken before each coating/implant were made on randomly selected panels. The average surface roughness was 8.7 rms for the IN718 panels and 8.6 rms for the 4340 steel panels. Measurements made on the undisturbed surfaces were performed at the NDCEE facilities in Johnstown, Pennsylvania. Profilometry also was used to measure the depth of the wear scars. However, measurements of the wear scars were performed using Army Research Laboratory (ARL) facilities.

Metallography

Coating thickness, fracture surface analyses, and coating composition was measured on all coated panels. To measure coating thickness, each coated panel was cross-sectioned and mounted to view and analyze the coating thickness using a scanning electron microscope (SEM). The analyses were performed in accordance with standard test method ASTM B 748, Standard Test Method for Measurement of Thickness of Metallic Coatings by Measurement of Cross Section with a Scanning Electron Microscope. The test was performed on various size panels at the NDCEE facilities in Johnstown, Pennsylvania.

Adhesion

The adhesion of the coating to the substrate was evaluated using a CSEM Micro Scratch Tester (MST). Scratch testing is considered a comparison test; i.e., the critical loads required for delamination depend not only on the mechanical strength of the coating/substrate, but also on the parameters of the test itself and the coating/substrate system. Adhesion of thin films deposited using ion beam and plasma-based methods depends on substrate cleaning prior to deposition, in-situ sputter cleaning, deposition conditions (presence of water vapor in the chamber), the stress of the coating, and the composition of the coating. Substrate hardness, coating thickness, and surface roughness also can have a large influence on the adhesion test [1]. Because the coatings tested varied greatly in thickness and hardness, the adhesion results are not being reported herein. The test was used only to provide a relative comparison of coatings and to provide data to assist in the interpretation of wear results.

Corrosion

A corrosion analysis was performed on all panels in accordance with ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus. The corrosion tests were performed on three 4” x 6” panels per coating/implant at the NDCEE facilities in Johnstown, Pennsylvania. Unscribed, coated panels were placed in the corrosion chamber at a 15° angle from the vertical. The panels were subjected to a corrosive environment created by a heated chamber and an atomized 5% sodium chloride solution was introduced into the sealed chamber. The corrosion rating was based on the percent of visible red rust using guidelines set forth in ASTM D1654. Table 1 shows the basis for the ratings used.

Table 1. Corrosion Rating	
Area Failed (%)	**Rating Number**
No Failure	10
0 to 1	9
2 to 3	8
4 to 6	7
7 to 10	6
11 to 20	5
21 to 30	4
31 to 40	3
41 to 55	2
56 to 75	1
Over 75	0

Nanohardness

The hardness of a film is affected by microstructure, composition (degree of covalent bonding), and intrinsic film stress. Although the wear properties of a material are not completely dependent upon the hardness of the material, the hardness can have a large influence on the wear properties, depending on the type of material against which it is worn. Nanohardness testing was performed on one 1”x1” panel per coating/implant at the NDCEE facilities in Johnstown, Pennsylvania to provide some insight into the wear properties of the films. Nine hardness measurements were performed on the top surface of each coating/implanted layer rather than the cross-section of the coating (as is often performed with thick coatings) due to the thin layer being measured. For very thin coatings (e.g., less 700 nm) and implanted layers, simple load-displacement tests at a fixed load of 1 mN were performed. For all other coatings, “continuous stiffness to constant depth” tests were performed. For these tests, the indentation depth ranged from 2000 nm for the very thick laser-deposited coating and the EHC baseline to 100 nm for coatings ranging in thickness from 1000 to 5000 nm. The different tests and displacement depths were used to reduce substrate influence in the hardness measurements.

Wear

Sliding wear tests were performed on one 2” x 2” panel per coating/implant at ARL in Aberdeen, Maryland, by NDCEE and ARL personnel to assess the adhesive wear resistance of the treatments. The analysis was performed in accordance with ASTM G99, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. Selected panels were retested to ensure repeatability.

Table 2. Wear Test Pin Material, Loading, and Time			
Level	**Time (min)**	**Load (g)**	
		Al_2O_3	**440 C**
1	60	100	-
	30	-	100
2	30	150	125
3	15	300	175

Because the transfer of materials in adhesive wear depends on the nature of the materials in contact, the treatments were tested against spherical, ceramic and metallic pins of ½" in diameter. Others have noted that the transfer of material when similar metals are in sliding contact is 50 to 100 times greater than that of dissimilar metals [2]. Testing polymeric, ceramic, and metallic coatings against different materials was expected to show the differences in the type and severity of wear that may be detected for different combinations in service. Testing conducted with each pin was performed using three different loads, such that the combination of different loads and different materials produced different hertzian contact stresses in the coatings or surface modified layers. Table 2 identifies each test level, the corresponding load, pin material, and duration of testing. The criteria used to determine if the coating or surface modification should proceed to Level 2 testing was based on whether a measurable wear scar and/or debris were visible after testing. The criteria used in determining which coating or surface modification proceeded to Level 3 testing was based on 1) its performance on both the IN718 and 4340 steel panels at Level 2 testing and 2) the area of use in the engine, i.e. hot or cold part. In essence, materials that degrade at high temperatures, e.g., diamond-like carbon and metal-bearing carbon coatings, may have been tested on IN718, although it is not likely that these coatings would be used in the hot part of the engine. Therefore, these coatings may not be applied to IN718, if selected, unless a component is fabricated from IN718 and used in cooler areas of the engine.

Discussion of Results

Since a repair process/material combination that only needs to be applied once during the life of the repaired part was desired, PEWG and the NDCEE project team determined that hardness and wear performance would be the two primary performance criteria when selecting the alternatives. Therefore, vendors were asked to provide the best coating/implant and technology for super hard and super wear resistance for IN718 and 4340 steel. Tables 3 and 4 provide a summary of the hardness and wear data as well as, profilometry, thickness, and corrosion measurements performed on coatings and surface modifications applied to 4340 steel and IN718 substrates, respectively.

From the profilometry results it is clear that the coatings do not have a large impact on surface roughness. The range in surface roughness for unfinished coupons (i.e., those other than laser-treated or EHC-coated coupons), is likely due to replication of the underlying substrate material. However, it should be noted that the IN718 panels tend to be smoother than the coated 4340 panels. This is attributed to the surface finish of the substrate material prior to treatment. It was not expected that any ion beam treatment or PVD coating would provide any leveling of the surface. However, it was not known whether some PVD treatments might contribute to rougher surfaces due to the inclusion of macroparticles emanating from the deposition process. It is clear from the results that any inclusions that may exist do not have a profound effect on the ultimate surface finish. However, it should be noted that the laser-treated coating and the EHC-coated coating all required post-grinding operations. The laser-treated surface forms overlapping stripes that must be subsequently ground to achieve the desired surface finish. The post-ground surfaces of both the laser-treated panels and the EHC-coated panels were somewhat smoother than the other samples. Such smoothness could contribute to increased or decreased wear resistance (e.g., smoother surfaces can lead to increased adhesion between the metallic pin and the coating surface or can lead to decreased abrasive wear action due to reduced likelihood of removal of high asperities).

Coating thickness varied widely for all of the treatments tested, as is displayed in Tables 3 and 4. The coating thickness should be considered when evaluating adhesion and wear results; however, all hardness measurements accounted for coating thickness. The providers of the coatings were permitted to select the coating thickness that they thought would provide the greatest wear resistance. As a result, the thickness measurements are only to be used to understand the wear and corrosion results.

As expected, no thin coating or implant provided a significant level of corrosion protection to the 4340 steel substrates. Coating porosity in thin films typically leads to a reduced level of corrosion protection. The use of implanted species, likewise, does not provide adequate protection. Chromium coatings are not very corrosion resistant, but still provide significantly more protection than thin films or implanted surfaces in severely corrosive environments. It is interesting that the thick, laser-treated surface provided no improved corrosion protection over the thin films. Because IN718 is inherently corrosion-resistant, all of the thin films performed well. However, the presence of the EHC-coating caused black corrosion products to form on the surface of the exposed specimen. Several other samples treated with thin films displayed similar corrosion products, although in reduced frequency, leading to ratings less than 10.

Table 3.
Test Results on 4340

	Technology	Coating/ Implants	Hardness (HV_{100})	Volume of Worn Material (E-06cm^3)						Corrosion Rating	Profilometry - after processing (rms)	Thickness (mm)
				Al_2O_3			440C					
				Level 1	Level 2	Level 3	Level 1	Level 2	Level 3			
	EHC	Cr (+6)	1208	29.57	32.35	0.17	0.02	debris	38.08	5	1.53*	124 ± 2.0
Coatings	Cathodic Arc	CrN - Vendor B	2081	none	none		debris			0	10.50	1.4 ± 0.1
		CrN - Vendor A	341	none	none		debris			0	8.14	3.0 ± 0.1
	IBAD	CrN	1337	none	none	none	none	none	none	0	10.04	2.5 ± 0.1
		NbN	1567	none	none		none	none		0	8.54	1.5 ± 0.1
	Sputtering	Metal Bearing Carbon 1	967	none	none		none	none		0	11.02	2.3 ± 0.1
		Metal Bearing Carbon 2	1151	none	none		none	none		0	11.54	2.5 ± 0.1
		CrN	1134	none	1.29		none	none		0	9.45	2.0 ± 0.1
		Cr+W-C:H	775	none	none	0.52	none	none	none	0	9.32	2.6 ± 0.1
		CrN/NbN (super lattice)	2383	1.64			debris			0	11.81	3.8 ± 0.1
	PIIP	DLC	1147	none	none	0.99	none	none	none	1	9.92	5.0 ± 0.1
		CrC_XO_Y	622	none	4.45		none	debris		0	9.32	0.2 ± 0.1
	PACVD	DLC	1666	none	none	none	none	none	none	0	8.80	0.5 ± 0.1
	LISI	Cr/Cr Diboride	637	0.31			none	debris		0	2.10*	162 ± 2.0
Implants	Ion Implantation	Cr - Vendor C	1003	2.95			1.25			0	9.71	NA
		Cr - Vendor D	1060	1.69			debris			0	9.32	NA
		Ti	961	1.18		none	none	none	none	0	6.83	NA
		Ti/Ni	187	13.31			none	3.75		0	8.92	NA

*After grinding and/or polishing

Table 4.
Test Results on IN718 - Coatings

	Technology	Coating	Hardness (HV_{100})	Volume of Worn Material (E-06cm^3)						Corrosion Rating	Profilometry -after processing (rms)	Thickness (mm)
				Al_2O_3			440C					
				Level 1	Level 2	Level 3	Level 1	Level 2	Level 3			
	EHC	Cr (+6)	1269	1.79	none	none	debris	none	0.23	7.7	2.58*	150 ± 4.0
Coatings	Cathodic Arc	CrN - Vendor B	2533	none	debris		none			9.7	7.09	2.4 ± 0.1
		CrN - Vendor A	1693	0.21			none			10	7.09	2.5 ± 0.1
	IBAD	CrN	1506	none	none	none	none	debris	debris	10	5.98	2.4 ± 0.1
		NbN	1477	none	debris	debris	none	none	debris	9.7	4.46	1.5 ± 0.1
	Sputtering	Metal Bearing Carbon 1	1032	none	debris		none	0.74		9.5	4.07	2.7 ± 0.1
		Metal Bearing Carbon 2	1038	none	none		none	0.48		10	6.82	2.6 ± 0.1
		CrN	1150	none	none	none	debris		debris	10	4.86	2.2 ± 0.2
		Cr+W-C:H	561	none	none		none	none		9.7	5.51	2.6 ± 0.1
		CrN/NbN (super lattice)	NA	none	4.03		none			NA	6.04	3.6 ± 0.1
	PIIP	DLC	1112	NA	debris	none	NA	none	none	NA	NA	5.2 ± 1.0
		CrC_XO_Y	392	11.31			10.96			10	3.68	Not found
	PACVD	DLC	1927	NA	none		NA	none		10	NA	0.7 ± 0.1
	LISI	Cr/Cr Diboride	476	12.87			4.61			10	3.41*	NA
Implants	Ion Implantation	Al	573	0.27			8.06			10	5.51	NA
		P	793	0.82			5.83			10	5.38	NA
		Cr	539	6.6			9.15			10	4.33	NA
		Ta	747	7.41			6.53			10	3.94	NA
		Ti/Ni	774	7.22			10.74			9.7	4.20	NA

*after grinding and/or polishing

In terms of coating hardness, the metal-bearing carbon coatings, CrO_xC_y, one variety of DLC, one variety of CrN, the laser-treatment, and some of the implanted materials displayed hardness values lower than that of EHC. It should be noted that the implanted specimens and extremely thin coatings (CrO_xC_y) were measured using a different mode to reduce the influence of the substrate on the hardness results, but the test is still difficult to perform. These specimens might produce different hardness values if performed using another mode of operation. Nevertheless, the mode was selected after consultation with an expert in hardness testing. Other coatings, often of the same variety (e.g., CrN and DLC produced by other means), displayed hardness values significantly higher than EHC. The differences in hardness within the same coating variety may be attributed to differences in coating stoichiometry, stress, and/or composition.

In terms of wear resistance, the information presented in Tables 3 and 4 must be clarified. Some coatings shown in Table 3 indicate that no wear or debris was measured, yet the sample was not subjected to Level 3 testing. Due to the large matrix of testing that was performed, the team determined that the coatings on 4340 substrates would not be further tested if the coating displayed adhesive wear on IN718 substrates or displayed notable wear scars when mated against aluminum oxide pins. As a result, some coatings (i.e., metal-bearing carbon coatings, the sputtered CrN, the cathodic arc CrN coatings produced by vendors A and B, and the NbN coatings) were not tested at the highest loads. The Cr+W-C:H and metal-bearing carbon (2) coatings on IN718 was not tested at Level 3 because the coatings are known to degrade at temperatures experienced in hot sections of the engine where IN718 is used.

From the tables, it can be seen that the coatings of the highest hardness did not display the greatest wear resistance against either material (e.g., aluminum oxide or stainless steel). Many have noted that stress often contributes greatly to elevated hardness readings, particularly in thin films. Although film stress was not measured in this project, it is thought that some films displaying high hardness, were, likewise, highly stressed. Upon subjecting the films to higher contact stress, a loss in cohesion or adhesion was experienced. Other specimens displayed severe adhesive welding of the 440C pin to the coating and/or removal of the coating and redeposition elsewhere in the scar area. In both instances, the adhesive wear is indicated in the table as having debris accumulated in the wear scar area. The coatings that displayed the greatest potential for use in the hot areas of the engine included CrN coatings produced by IBAD and sputtering. CrN produced by IBAD, a Ti implant, and DLC produced by PACVD showed the most promise for use in cooler sections of the engine (i.e., on 4340 substrates). DLC produced by PIIP and the metal bearing carbon coatings also are being recommended for consideration in follow-on projects.

Summary

Identification of families of components and processing requirements were crucial in establishing a baseline against which the alternative technologies could be compared. The technologies being examined in this project are technologies that are capable of offering next generation coatings. These next generation coatings and surface modifications are being sought to reduce the use of chromium through life extension at the OEM level. It also is believed that slight wear of the next generation coating, that affecting a shallow layer of only a few micrometers deep, may be repaired at the depot level using that same coating. Throughout testing, it was found that most of the coatings and surface modifications performed better than EHC in terms of wear resistance. Although this was a primary criterion of the project, the team will have to review methods by which greater corrosion protection may be imparted to steel substrates. In follow-on projects, the team also will focus on situational wear tests that better approximate the service conditions experienced.

References

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