

HVOF Thermal Spray Coatings as an Alternative To Hard Chrome Plating on Military and Commercial Aircraft

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There are currently several ongoing projects designed to demonstrate and qualify HVOF thermal spray coatings as a functionally superior, cost-effective replacement for hard chrome plating in manufacturing and maintenance operations on military and commercial aircraft. Within the U.S. Defense Department, the Hard Chrome Alternatives Team (HCAT) is executing several projects to qualify HVOF coatings on landing gear, hydraulic actuators and propeller components. Joint Test Protocols are being prepared that include appropriate coupon tests combined with full-scale components rig and flight testing. The Canadian Government and Canadian landing gear manufacturers are partnering with the HCAT to execute a similar program. Several commercial aircraft manufacturers and airline companies are also conducting flight testing of selected aircraft components. This paper will describe these efforts and provide some results for initial testing.

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Introduction

Hard chrome plating is a technique that has been in commercial production for over 50 years and which is a critical process associated with manufacturing and maintenance activities for commercial and military aircraft. It is used by OEMs for applying hard, wear-resistant coatings to many types of aircraft components such as landing gear and hydraulic actuators, and it is used by repair depots 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 Safety and Health 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. Recently, several public interest groups and unions have filed suit to force OSHA to issue a proposed new hex-Cr PEL, but the courts have sided with OSHA, with the result that OSHA is now expected to issue a proposed new PEL in the Fall of 1999. Preliminary indications are that OSHA believes the new data supports a lowering of the PEL to a range of 0.5 to 5 micrograms/cubic meter. According to a spokesman from the surface finishing industry, a PEL of less than 10 micrograms/cubic meter would substantially increase the cost of chrome plating.

Beyond the concerns of aircraft manufacturers and repair facilities related to the cost of chrome plating are also concerns related to the in-service performance of chrome plating. In the past, chrome has been the best available coating to meet the industry and military requirements. However, because many aircraft are being flown considerably longer than originally anticipated and because of steadily decreasing funding of maintenance within the Defense Department, issues associated with life-cycle costs have increased in priority. Therefore, there is a strong incentive towards identifying new coating technologies that not only eliminate the environmental and health problems associated with

hard chrome plating but also demonstrate increased performance as compared to chrome. The technology that is most promising in terms of meeting these goals is HVOF thermal spraying.

HVOF Thermal Spraying

High-velocity oxygen-fuel (HVOF) thermal spraying was invented by James A. Browning in 1982. The first commercial systems were available by the late 1980's. The process uses an internal combustion (rocket) jet to generate supersonic gas velocities of approximately 1800 meters/second, generally in the range of Mach 4-5. Combustion fuels that are mixed with oxygen in the gun include propylene, acetylene, propane, hydrogen, and kerosene. When burned with pure oxygen, these fuels produce gas temperatures greater than 2700 degrees C.

Combustion ignition, gas control, and powder feed are fundamentally simple in HVOF spraying systems. Powder of the material to be deposited is fed into the HVOF gun, with feed rates automatically monitored. Powders deposited using HVOF include pure metals, metal alloys, cermets such as tungsten carbide/cobalt, and certain ceramics and polymers. Generally the stand-off distance between gun and the surface of the material being coated is usually between 15 and 30 cm. For most HVOF coatings, the porosity is less than 1%, the oxide content, even for fairly reactive metals, is less than 1%, and the bond strength usually exceeds 80 MPa (10,000 psi). The instantaneous deposition rate is approximately 50 micrometers (0.002") per minute although in normal operation the HVOF gun is mounted on a robot or other articulating arm and the component being coated is also manipulated (e.g., a cylinder will be rotated). It therefore generally takes less than 30 minutes to deposit a 100-micrometer-thick (0.004") coating onto a 0.5-meter-long, 0.1-meter-diameter cylinder. Figure 1 is a photograph of an HVOF coating being applied to a Boeing 737 nose landing gear cylinder. Note the air jets in the upper right hand corner of the picture which are used to maintain a low surface temperature of the component during processing. In general, with the use of air jets for cooling, materials such as aluminum can easily be coated.

At present there are no full-production HVOF systems in operation at aircraft manufacturers, commercial aircraft maintenance activities, or

Department of Defense (DOD) aircraft depots, that are being used to deposit coatings on a continuous basis onto components onto which hard chrome has been used in the past. There are some HVOF systems in operation at DOD aircraft depots that are being used for selected chrome replacement, however. As an example in 1993, the Naval Aviation Depot in Jacksonville, Florida, procured a Metco

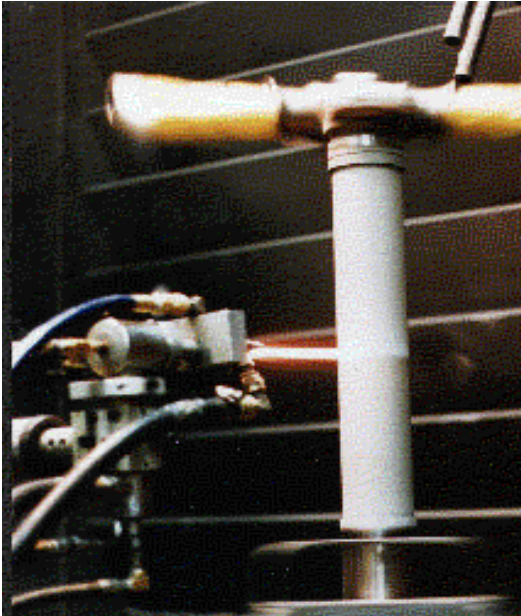


Figure 1. HVOF thermal spraying of WC/Co coating onto a nose landing gear cylinder from a Boeing 737. The cylinder is approximately 0.6 m long.

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 for HVOF in 1994. Since then, additional components on the F404 and TF34 engines have been repaired using HVOF.

Current Efforts in Defense Department

A project entitled, "Tri-Service Demonstration-Validation of Chromium Electroplating Replacements," under the principal sponsorship of the DOD Environmental Security Technology Certification Program (ESTCP), was initiated in 1996 to conduct studies to qualify and insert HVOF

technology into DOD aircraft maintenance depots. Among the original participants in the project were five demonstration sites: Cherry Point and Jacksonville Naval Aviation Depots, Ogden and Sacramento Air Logistics Centers, and Corpus Christi Army Depot. Other original participants included the Naval and Air Force Research Laboratories, Northwestern University, GE Aircraft Engines, and Metcut Research, Inc. The project team, designated the Hard Chrome Alternatives Team (HCAT), developed a generic test protocol and executed a significant amount of fatigue, corrosion, and wear testing on 4340 steel, 7075 aluminum alloy, and PH13-8Mo stainless steel substrate materials coated with either WC/Co (83%/17%) or Tribaloy 400 (a Co-Mo-Cr alloy) coatings deposited by HVOF.

More recently, the HCAT has formed a partnership with the DOD Joint Acquisition and Sustainment Pollution Prevention Activity (JASPPA), an organization chartered by the Joint Logistics Commanders that represents a merger of the previous Joint Group on Acquisition Pollution Prevention (JG-APP) and Joint Depot Environmental Panel (JDEP). Previously the JG-APP focused on inserting new non-polluting technologies in manufacturers of DOD weapons systems whereas the JDEP examined new technologies for DOD maintenance depots. The objective of the new organization is to identify projects that can drive down DOD total ownership costs, from production through sustainment to disposal. It is intended that JASPPA only initiate projects where the users, depots, program offices, and manufacturers all agree there will be cost benefits and agree to jointly fund efforts to reduce hazardous materials usage.

The HCAT/JASPPA effort on hard chrome replacement using HVOF represents the first of these projects. Whereas HCAT had initially hoped for a complete across-the-board qualification of HVOF coatings on all types of aircraft components, it became apparent that this was not feasible and that, working with JASPPA, a more logical approach was to execute projects qualifying HVOF coatings on types of aircraft components. As a result, individual projects on landing gear, hydraulic actuators, propeller hubs, and rotary wing aircraft components (such as helicopter rotor heads) have been initiated. The landing gear effort is the most advanced, with a Joint Test Protocol (JTP) nearing completion. The JTP is a comprehensive document that describes in detail coupon, rig, and flight testing of specific types

of HVOF coatings. For the landing gear coupon testing, three types of base materials will be used, 4340, 300M, and Aermet 100 steels, and one type of HVOF coating will be evaluated, 83WC/17Co, in comparison to hard chrome. The JTP describes in detail how the substrate materials are prepared, how the coatings are deposited, and how the coatings are ground for testing. Extensive fatigue, corrosion, sliding wear, abrasive wear, and hydrogen embrittlement tests will be conducted. Rig tests are planned for the main landing gear of the F18-E/F fighter in which several support components that are currently chrome plated will have the WC/Co HVOF coatings applied to them. Finally, actual flight testing on a HVOF-coated main landing gear cylinder for the P3 aircraft will be conducted. Results of all of the testing will be provided to appropriate stakeholders in order to obtain approval to apply HVOF coatings in production to landing gear components.

Results of Previous Testing

As mentioned above, the HCAT had conducted a significant amount of testing on HVOF coatings on several different materials. Only a brief overview will be provided here, with considerably more detailed information presented in reference #1.

Fatigue Tests

Axial fatigue studies were conducted on 4340 steel, 7075 aluminum alloy, and PH13-8Mo stainless steel coupons which had been coated with hard chrome, 83WC/17Co, and Tribaloy 400 HVOF coatings. The specimen geometry was designated as “smooth-bar” in which the “necked-down” region was 0.63-cm-diameter over a length of 1.9 cm. Both low-cycle-fatigue (LCF) and high-cycle-fatigue (HCF) tests were conducted and S/N curves were generated over a wide range of maximum load conditions. Figure 2 shows the data for the uncoated 4340 specimens and the three coated 4340 specimens. The data for the hard-chrome-coated specimens indicates a substantial loss of fatigue strength. The data for the HVOF coatings fell within the statistical uncertainty of the uncoated specimens, indicating essentially no loss of fatigue strength. Subsequent to failure, the specimens were examined for failure location. The hard chrome plate indicated 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.

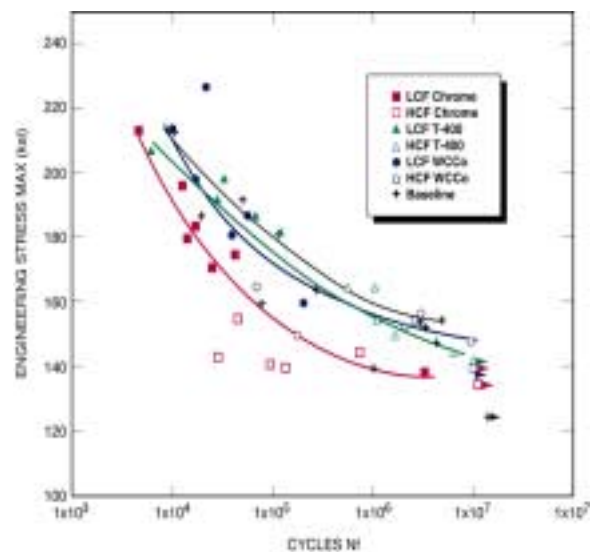


Figure 2. S/N data for smooth bar uncoated 4340 steel specimens and 4340 specimens coated with hard-chrome, HVOF WC/17%Co, and HVOF Tribaloy 400.

Corrosion Studies

Extensive corrosion tests of the same substrate materials and same coatings were conducted using the protocols of the ASTM B117 salt fog tests and GM9540P/B cyclic corrosion test. At least five specimens for each coating/substrate combination were evaluated. Photographs were taken prior to exposure to document the surface and the samples were visually examined at 125-hour intervals and given an appearance ranking, based on ASTM protocols. The rankings ranged from 10, representing a pristine surface, to 0, representing complete

corrosion of the surface. The total duration of the tests were 1000 hours.

Figure 3 shows the appearance rankings as a function of time for the 4340 steel substrates with the hard chrome and HVOF coatings subjected to the B117 test. Based on these rankings, the HVOF coatings demonstrated increased corrosion resistance over the chrome, but in fact it was discovered that there were blistered areas on the HVOF coatings which, when removed, showed that overall the extent of corrosion was the same for the HVOF coatings as for the hard chrome. Therefore, it was concluded that all coatings performed approximately equally in the B117 test.

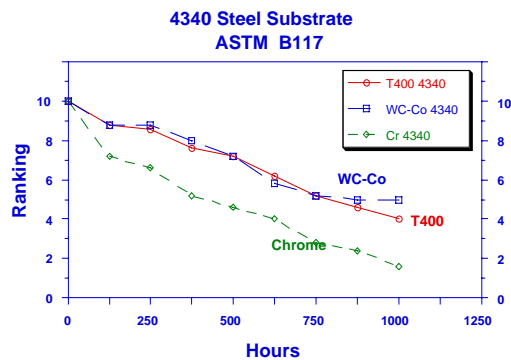


Figure 3. Appearance rankings for various coatings on 4340 steel specimens subjected to the B117 salt fog test

The GM cyclic corrosion test is generally less aggressive than the B117 test and this was found to be true for the hard chrome and HVOF coatings. Figure 4 shows the results of the GM testing of the coatings as a function of time, and again the performance of the three coatings was comparable.

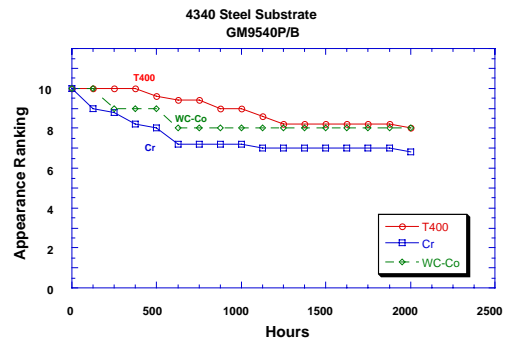


Figure 4. Appearance rankings for various coatings on 4340 steel specimens subjected to GM cyclic corrosion test.

Hydraulic Actuator Simulation Test

The aerospace industry has used chrome-plated hydraulic actuator rods for decades, and generally they have performed satisfactorily. However, for the reasons given in the Introduction, several types of coatings, including HVOF, are being investigated as an alternative to the chrome. Greene, Tweed & Co., in cooperation with the Air Force and HCAT, conducted tests on simulated actuator rods that received the following coatings:

1. Standard dense hard chrome
2. HVOF 88WC/12Co applied by Sulzer Metco
3. D-Gun 88WC/12Co applied by Praxair Surface Technologies
4. Takada Ni-W-SiC (48/48/4), an electrochemical process applied by Delta Pollution Control
5. Diamonex, an amorphous carbon coating applied by physical vapor deposition.

Two seal types were used as a reference for evaluation of the candidate rod coatings. The GTC Ener-Cap which is a capped “slipper” type seal and the GTC AGT ring (T-seal) which is an elastomeric type seal. These two seals represent the two broad categories of seal types used in general aircraft hydraulic systems. The laboratory evaluation was conducted by Greene, Tweed in order to assess the performance of individual rod and seal combinations. Each seal and rod was tested for 2 million cycles. The load and stroke “duty” profile was based on Air Force data² which simulated stroke amplitudes, frequencies and operating times for fighter type aircraft. Prior to and after each test, all seal, rod and

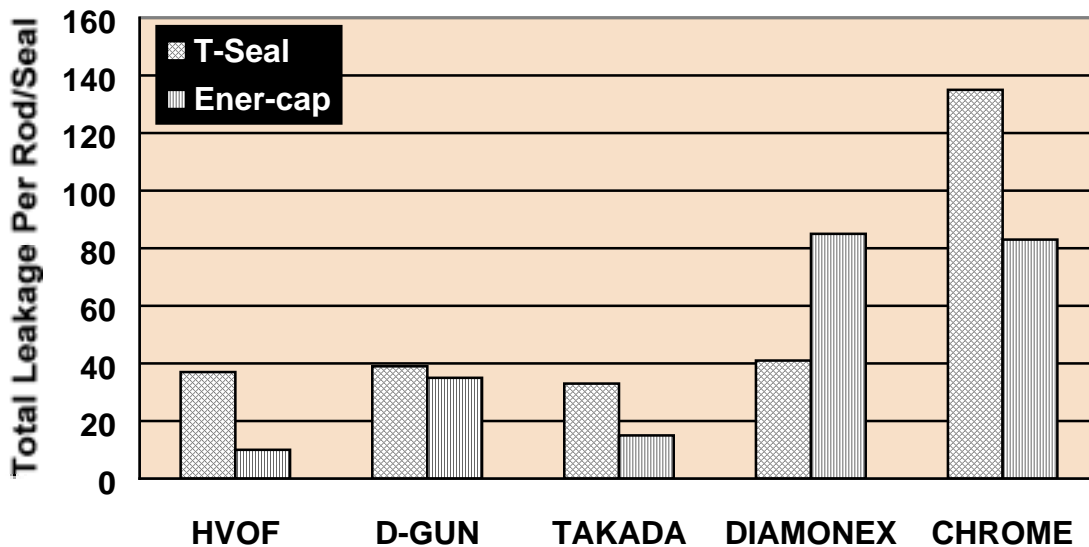
gland hardware critical dimensions were measured. Leakage of hydraulic fluid was measured after each phase of the testing. Figure 5 shows the total leakage for the 2 million cycles in grams. The leakage of all candidate rod coatings is substantially lower than that of the chrome. The seals were in excellent condition after the test with the HVOF, D-gun, and Diamonex coatings, with some seal degradation observed with the Takada and chrome. The HVOF and D-gun rod coatings were in excellent condition after the test, with the Diamonex showing very minor degradation followed by moderate degradation of the Takada rods and relatively higher degradation of the chrome rods.

These were only considered to be screening tests. The Air Force estimates that 10 million cycles would

hour time-between-overhaul test would require 30 million test cycles. Such tests are currently in progress, but it is apparent from the screening tests that the HVOF coatings should outperform hard chrome on hydraulic actuator rods.

Current Efforts in Commercial Aircraft Sector

There are a number of efforts within the commercial aircraft sector directed at replacing hard chrome with HVOF coatings on landing gear. Boeing Commercial Aircraft Group has been particularly aggressive in working with several different airlines on flight testing HVOF coatings on



be equivalent to 1000 flight hours. Therefore, a 3000

Figure 5. Leakage of hydraulic fluid, expressed in grams, for various coated rods against two seal types

different types of landing gear components. The strategy in these cases is to conduct the necessary flight testing to qualify the HVOF coatings on a component-by-component basis. Table 1 provides a summary of the flight tests that are currently in progress.

AL	Model	Part	Coating	DIS
DLH	737	NLG-IC	WC/Co	1-96
DAL	737	NLG-IC	WC/CoCr	12-97
BAB	757	NLG-IC	WC/CoCr	2-98
DAL	757	Axle	WC/CoCr	2-98
DAL	757	Axle	WC/CoCr	2-98
DAL	767	Axle	WC/CoCr	3-98
DAL	767	Axle	WC/CoCr	5-98

Table 1. Flight tests in progress to evaluate HVOF coatings as chrome replacement.

Legend: AL = airline

DIS = date in service
 DLH = Lufthansa
 NLG = nose landing gear
 IC = inner cylinder
 DAL = Delta Airlines
 BAB = British Airways

properties of the coatings. Copies of this specification can be obtained from SAE International at 724-776-4970.

Inspections have been conducted on most of these components with the result that the HVOF components have performed satisfactorily with no failures and no rejections.

The utilization of HVOF coatings in place of chrome is expected not only to increase performance of the component onto which the coating is applied, but also to reduce turnaround times associated with performing the total maintenance on the component. Sulzer Metco has done a study on personnel hours and total process hours associated with repairing a Boeing 737 nose landing gear inner cylinder piston. The results of that study are presented as figure 6, which indicate that the total labor hours can be reduced from 14.5 to 10.3 and, more significantly, the total process hours can be reduced from 53 to 10.3, principally because of the reduced coating time and the elimination of the post-coating bakeout cycle.

Another aspect to the qualification of HVOF coatings on commercial aircraft landing gear has been the issuance of an Aerospace Material Specification related to application of HVOF thermal spray coatings. AMS 2447A was issued in July 1998 and provided engineering requirements for applying the HVOF coatings, including specifications for the

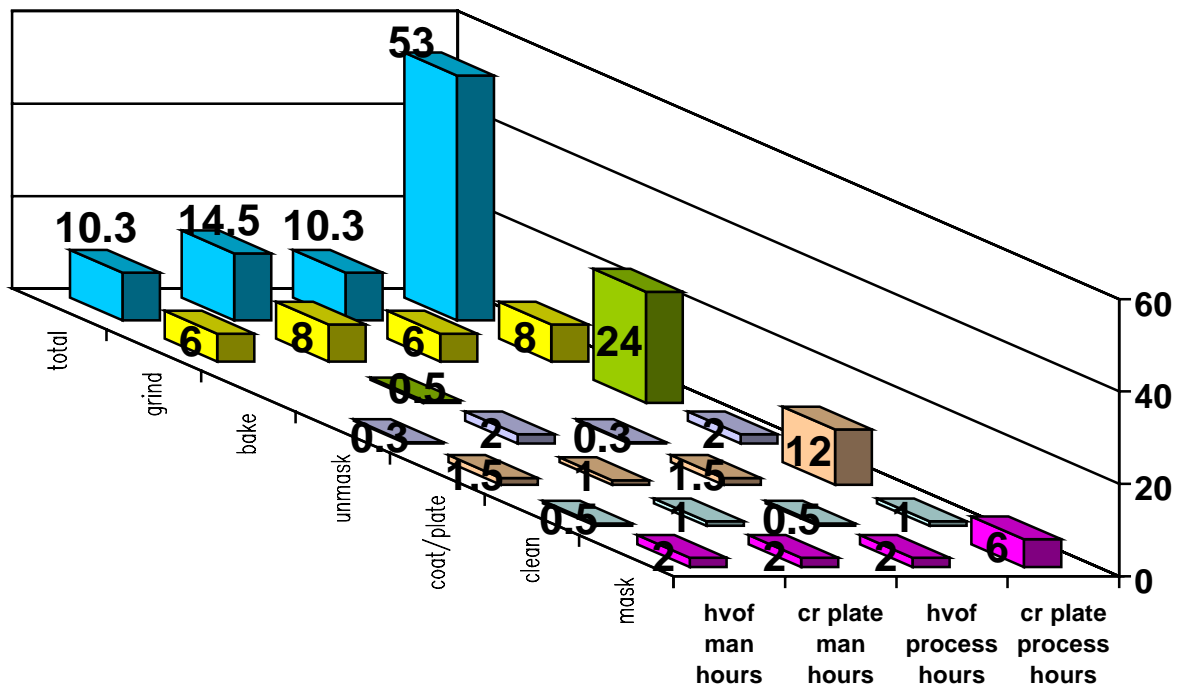


Figure 6. Personnel and process hours associated with repairing a Boeing 737 nose landing gear inner cylinder piston using chrome plating and HVOF thermal spray coatings.

Therefore, it is apparent that application of HVOF coatings can reduce maintenance time and thereby reduce overall maintenance costs which also will lead to a reduced requirement for maintaining a spare parts inventory.

Summary

There are currently ongoing programs both in the Department of Defense and in the commercial aircraft sector to qualify HVOF thermal spray coatings as a viable replacement for hard chrome plating. Results have generally shown that the performance of the HVOF coatings should exceed that of hard chrome, that the HVOF coating process does not produce any hazardous waste, and that turnaround times for maintenance should be substantially reduced. A final determination of the efficacy of HVOF coatings will have to await specific qualification in production and long-term usage data.

References

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