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Status of HCAT/JG-PP Program on Replacement of Hard Chrome Plating With HVOF Thermal Spray Coatings on Landing Gear

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The Department of Defense tri-service/industry Hard Chrome Alternatives Team (HCAT) and Joint Group on Pollution Prevention (JGPP) are collaborating on executing a program to qualify HVOF thermal spray coatings as a replacement for hard chrome plating in the manufacturing and repair of aircraft landing gear. The Canadian Department of National Defence and Industry Canada are also partners in this effort. A joint test protocol (JTP) has been prepared and approved by the stakeholder organizations, including OEMs and government organizations. Included in the JTP are material tests such as fatigue, wear, corrosion, hydrogen embrittlement and impact, and operational tests on actual components. Results will be presented for a substantial amount of the material testing as well as the results of a rig test on the Navy F/A-18 E/F main landing gear containing several HVOF-coated components and the status of flight testing on Navy P3 and E-6A aircraft containing HVOF-coated landing gear components.

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Introduction

Functional hard chrome plating is a critical process associated with manufacturing and maintenance operations on aircraft, vehicles, and ships, both in the civilian and military sectors. Since chromium is on the Environmental Protection Agency list of 17 toxic materials, fairly stringent air and wastewater emission limits have been established by the EPA. Also, hard chrome plating utilizes chromium in the hexavalent state (hex-Cr), which is a known carcinogen. As a result, the Occupational Safety and Health Administration (OSHA) has established permissible exposure limits (PEL) for hex-Cr in the workplace at a level of 0.1 mg/m^3. However, recent studies have indicated that the cancer risk is significantly increased at this level, so it is anticipated that OSHA will issue a new hex-Cr PEL that is substantially less than the current value. This would unquestionably increase the cost of plating operations that may be prohibitive in certain activities.

Compliance with increasingly stringent regulations under the broad category of environment, safety and occupational health (ESOH) is leading many organizations to investigate alternative coating processes. However, it is also found that in many instances the in-service performance of hard chrome plating is not satisfactory, so some organizations have investigated and qualified alternative processes solely on the basis of performance, but these have generally been on a piecemeal basis instead of an across-the-board qualification. As a result of these types of studies, it is apparent that as opposed to many ESOH-driven projects that seek an alternative process/material that is the "next-best thing" to the presently used process, for chrome plating replacement, it is possible to identify alternative processes that not only address ESOH issues but also improve performance. Improved performance is then translated into reduce life-cycle costs of the affected system.

In terms of identifying those technologies that are viable candidates for replacing hard chrome plating, it is essential to understand the current uses for chrome. Looking specifically at the aircraft industry, chrome plating is used in several different ways:

- As a wear-resistant coating, typically applied by OEMs to thicknesses ranging from 25 to 100 µm (0.001" to 0.004"), mostly for external wear areas
- As a rebuild coating, up to 0.5 mm (0.020") thick, to bring worn and/or machined components back to their specified dimensions
- As a light abrasion/corrosion barrier for many internal areas (designated as thin dense chrome or flash chrome), typically 5-10 µm thick.

The largest uses of hard chrome in the aerospace industry are:

- Landing gear (gas-over-fluid hydraulics) – inner cylinders, axles, and pins
- Hydraulic actuator rods
- Journals and shafts in engines
- Lugs and other wear surfaces
- Internal diameters (ID's) of hydraulic and landing gear outer cylinders (frequently thin dense chrome)

Due to the types of components and applications for which hard chrome is currently used in the aircraft industry, there are many types of coating technologies that would not be viable alternatives even though they can produce coatings with superior properties. These include chemical vapor deposition and the vacuum-based coating technologies such as ion plating, sputtering, and cathodic arc deposition. The types of coatings that are most widely viewed as being capable of replacing hard chrome are the thermal spray technologies, especially high-velocity oxygen-fuel (HVOF) thermal spraying. With this process, the coating material, in powder form, is fed into the combustion chamber of a gun where a fuel, such as hydrogen, ethylene, or kerosene, is burned with oxygen, and the heated and softened powder is expelled as a spray with the supersonic gases. Powders deposited using HVOF include pure metals, metal alloys, cermets, and certain ceramics and polymers. The reason why HVOF is the preferred thermal spray process for chrome replacement is because it produces low-porosity (<1%), highly adherent (bond strength > 80 MPa (10,000 psi)) coatings which generally have an oxide content less than 1% even for reactive metals. As a flexible dry-coating technology it avoids high-volume waste streams and provides a choice of coating materials for each application. The use of hard chrome is so widespread that there is no single replacement technology or material, but the HVOF cobalt-cemented tungsten carbides are some of the easiest materials to spray and have shown the widest range of successful applications.

Establishment of DoD Program and Generic Materials Testing

Within the U.S. Department of Defense (DoD), the Hard Chrome Alternatives Team (HCAT; www.hcat.org) was formed in 1996 under the principal sponsorship of the DoD Environmental Security Technology Certification Program. Its objective is to demonstrate and validate HVOF coatings as a cost-effective and technologically superior alternative to hard chrome in most maintenance operations at Navy, Air Force, and Army aircraft overhaul and repair (O&R) depots and in manufacturing operations at DoD OEMs. The organizations that comprise the HCAT include DoD research laboratories, aircraft depots, aircraft OEMs, materials testing laboratories, an HVOF equipment manufacturer and an FAA-certified repair facility that has chrome plating and thermal spray capability.

The HCAT initially sought a more generic qualification of HVOF coatings by selecting base materials that were representative of the families of materials onto which hard chrome is deposited, applying two different HVOF coatings, and then conducting materials testing to demonstrate equivalent or superior performance. The base materials that were selected were AISI 4340 high-strength steel, 7075-T73 aluminum alloy, and PH13-8Mo stainless steel. The HVOF coatings were WC/Co (83%/17%) and Tribaloy 400, a cobalt-molybdenum-chromium alloy, deposited to a thickness of 100 µm (0.004”). The microhardness values for the three coatings were as follows:

• Hard chrome	10.1 GPa
• WC/Co	12.8 GPa
• Tribaloy 400	5.7 GPa

Extensive fatigue, corrosion, and abrasive wear testing was conducted on the coated materials compared to hard chrome deposited to the same thickness in accordance with standard specifications for aircraft components. In previous papers[1,2] the results for the fatigue studies on the 4340 steel, and the corrosion and abrasive wear results for all substrate/coating combinations were reported. These indicated that the fatigue performance of the HVOF coatings far exceeded that of the hard chrome, with virtually no fatigue debit. The cabinet corrosion testing (ASTM B117) indicated virtually no difference between the three coatings and the abrasive wear testing indicated superior performance for the HVOF WC/Co because of its higher hardness.

Figure 1 shows the results of the fatigue testing on the 7075 aluminum alloy. The specimens were 0.63-cm (0.25”)-diameter smooth round bars with a 1.9-cm (0.75”) length to the gage area. Specimens were tested in axial loading for both low-cycle and high-cycle fatigue, and S/N curves were generated over a wide range of maximum load conditions.

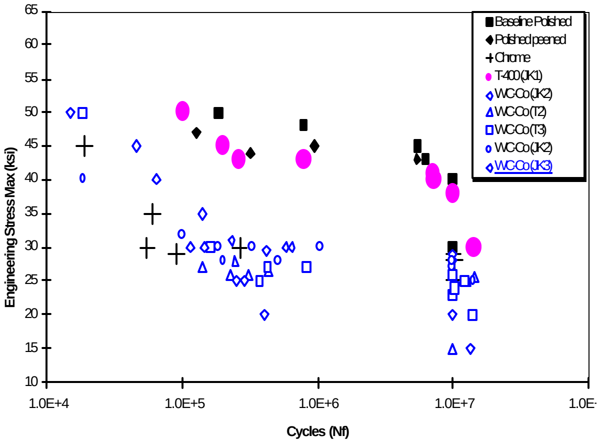

Figure 1. Fatigue of 7075-T73 Al, smooth gage; small filled symbols are for uncoated material either peened or unpeened; large filled symbols are for Tribaloy 400; open symbols are for WC/Co; crosses are for hard chrome

It is clear from the data in figure 1 that there is virtually no fatigue debit for the Tribaloy 400 coatings whereas the fatigue debit for the hard chrome and the WC/Co are comparable. It was initially believed after the first set of data for WC/Co that the substrates had been overheated during processing, but subsequent runs where the substrate temperature was carefully monitored and controlled to less than 150° C showed the same behavior. It is currently believed that the fatigue debit of the WC/Co on the aluminum alloy is most likely due to the strong mismatch in elastic modulus between the coating and substrate.

Although the results of the cabinet corrosion testing have previously been reported, atmospheric corrosion testing was recently completed on the various coating/substrate combinations, with the results being somewhat different. In this case, the test coupons consisted of 10 cm by 15 cm (4” x 6”) flat plates onto which the three coatings were deposited to a thickness of 100 µm. The specimens were mounted onto atmospheric test racks near the seashore at the Navy Marine Test Facility in Key West, FL. Some of the specimens were sprayed with a salt water solution once a week to accelerate the corrosion.

Figure 2. Representative specimens of 4340 steel plates coated with HVOF WC/Co and Tribaloy 400, and hard chrome after 18 months atmospheric exposure plus once weekly spraying with salt water

It can be seen in figure 2 that both the hard chrome and the Tribaloy coatings have extensive corrosion whereas the WC/Co coatings are virtually pristine. This result is significantly different from that of the cabinet testing, which might be a further indication that the B117 test does not accurately reflect corrosion behavior in the real world.

Execution of Separate Projects on Qualification of HVOF Coatings as a Hard Chrome Replacement

All of the studies previously reported and indicated above demonstrate what might be called the technological viability of HVOF coatings as a replacement for hard chrome plating. But it was clear through discussions with individuals who make up the stakeholder community within the DoD aerospace sector (e.g., repair depot technical representatives and engineering authorities, weapons systems program managers, and structural engineers from the three services and the OEMs) that it would not be possible to have a generic qualification of HVOF for all types of aircraft components. Because hard chrome plating does in fact protect a variety of aircraft components, this means that different stakeholders would be involved in the qualification process for each type of component. As a result, the HCAT has established partnerships with two other DoD organizations that execute projects related to qualifying and inserting technologies that can have an impact related to environmental concerns (e.g., pollution prevention) and also life-cycle costs. The first is the Joint Group on Pollution Prevention (JG-PP; www.jgpp.com) and the second is the Propulsion Environmental Working Group (PEWG; www.pewg.com).

The partnership with the JG-PP has led to the establishment of separate projects related to qualification of HVOF thermal spray coatings on the following classes of aircraft components:

- Landing Gear – inner cylinders, axles, pins, actuators (in conjunction with Boeing and the landing gear manufacturers, BF Goodrich/Menasco, Heroux and Messier-Dowty).
- Propeller Hubs (in conjunction with Hamilton Sundstrand)
- Hydraulic actuators for systems other than landing gear (OEMs to be identified)
- Helicopter Dynamic Components - including transmission and rotor head components (in conjunction with Boeing Philadelphia and Sikorsky)

The partnership with the PEWG has led to a project related to replacement of hard chrome on gas turbine engine components and is being executed in conjunction with GE Aircraft Engines, Pratt & Whitney, and Rolls-Royce Allison.

The execution plan for each project first involves the development of Joint Test Protocols (JTP) following a methodology developed by the JG-PP. The JTP defines all of the testing required for full qualification of the alternative process which generally includes both materials testing on coupons for fatigue, corrosion, wear, and other properties, and actual component testing involving installation of coated components into test rigs and into operational aircraft where performance is tracked over extended periods of time. In addition to preparation and execution of the JTPs, the projects also involve establishing production-level HVOF facilities at the appropriate military aircraft maintenance facilities, training personnel at those facilities, analyzing costs, and developing standards and specifications for application, grinding, and stripping of the HVOF coatings on the categories of aircraft components.

Execution of Project on Landing Gear

The remainder of the paper will be concerned with the execution of the project related to qualification of HVOF thermal spray coatings as a chrome replacement on landing gear since. This is a joint project between the United States and Canada. In 1997, the Canadian Department of National Defence (DND) and Industry Canada (IC) became interested in the HCAT program because of the considerable number of military aircraft in DND and because Canadian companies manufacture more than two thirds of the landing gear on military and commercial aircraft in North America. As a result, a formal Project Arrangement was established between the two countries and a Canadian team (C-HCAT) was formed to execute some of the testing.

In July 1998 a meeting was held that involved members of the U.S. and Canadian HCAT teams and representatives from all of the DoD, DND and OEM stakeholders for the purpose of developing the JTP for landing gear. It was decided that it would be issued in two parts, with the first part describing the materials (coupon) testing and the second part describing the component (rig and flight) testing. Part I was completed and was endorsed by the stakeholders in 1999 and testing is in progress. Results for some of that testing are presented here.

Only two types of HVOF coatings are being evaluated in the landing gear project on three base materials. Testing is also being conducted on hard chrome plating as a baseline. The U.S. team is evaluating WC/Co (83%/17%) and the Canadian team is evaluating WC/CoCr (86%/10%-4%) deposited onto 4340, 300M, and Aermet 100 steels. Materials testing includes fatigue, corrosion, sliding wear, impact (both particle erosion and ball drop), and hydrogen embrittlement. (The entire 50-page JTP is available at www.hcat.org).

In order to ensure reproducibility in the test results, the JTP specifically defines all aspects of the specimen preparation, coating deposition, and testing parameters. For coupon preparation, the machining, heat treatment, grinding, etching, shot peening (if applicable), and grit blasting (if applicable) are all described. Deposition of the hard chrome is specified to be in accordance with Military Standard 1501 supported by commercial standard QQ-C-320. Deposition of the HVOF coatings is specified to be in accordance with Boeing Aircraft Corporation Standard 5851, Class 2, Type I with hydrogen used as the fuel gas. Coating thicknesses are specified at either 75 μm (0.003") or 250 μm (0.010").

Because the majority of components onto which hard chrome is currently applied are fatigue-sensitive, special attention has been paid to the internal stress of the HVOF coatings. Based on the generic studies conducted earlier that showed a correlation between compressive stress and improved fatigue, it was determined that when the coatings are applied to coupons or components, they should also be simultaneously applied to almen strips (which are commonly used for measuring stress induced by shot peening). For the HVOF coatings being evaluation in the landing gear project, almen N values ranging from 3 to 12 (compressive stress) are specified.

Surface Finish

Surface finish is a critical issue, especially for items such as hydraulic rods that run against seals. For this type of application chrome plate is typically specified with a 0.2-0.4 μm (8-16 μ") finish (average roughness, or Ra value). This permits the surface of the chrome to hold some hydraulic fluid in its pattern of microcracks. However, because of its higher hardness, a WC/Co surface with a finish greater than 0.2 μm can potentially damage the seal material. Therefore, in the JTP, the surface finish for the HVOF coatings is specified at either 0.1 or 0.2 μm.

It is becoming clear, however, that merely defining the Ra value is inadequate and that for these types of coatings it may be necessary to adopt a more thorough specification of surface finish to better define the topography.

Fatigue

The fatigue tests are being conducted in accordance with ASTM E466-96 which specifies axial load control at constant amplitude. The number of stress levels to be evaluated is four, with five specimens tested at each stress level. In general, hourglass geometry is used for the specimens, although in a few cases smooth gage is used. Coating thicknesses are either 75 or 250 µm, the R values for the fatigue test are either –1 or 0.1, and the environment is either laboratory air at ambient temperature or –40^{o} C, or immersion in a 3.5% NaCl solution at ambient temperature. More than 1300 separate fatigue tests will be conducted.

Some of the results have been obtained for the fatigue testing on the HVOF WC/Co coatings. Figure 3 provides the data on cycles to failure at different stress levels for the 75-µm-thick coatings on Aermet 100 steel and for uncoated Aermet 100.

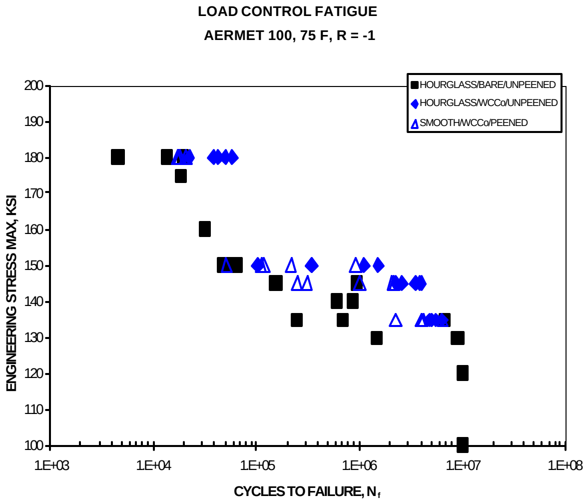

Figure 3. Results of fatigue testing for uncoated, peened Aermet 100 specimens and HVOF WC/Co-coated unpeened hourglass specimens and WC/Co-coated peened smooth gage specimens.

Although the data for the hard chrome is not yet available, it is clear that the application of the HVOF coatings does not induce any loss of fatigue strength for this material, a critical factor in considering its use on landing gear components.

Wear Testing

Wear tests are being conducted to provide information on manufacturing variables and wear conditions including coating material, surface finish, lubrication, side loads, velocities, type of wear, and other wear environment factors. Two test methods are being employed:

- Oscillating piston/bushing at low frequency and long stroke (see figure 4)
- Fretting test at high frequency and short stroke (see figure 5)

The piston and bushing oscillating wear test is being used to reflect typical conditions of use under a side load. The fretting wear test is being used to reflect typical actuator piston dithering or vibration movement.

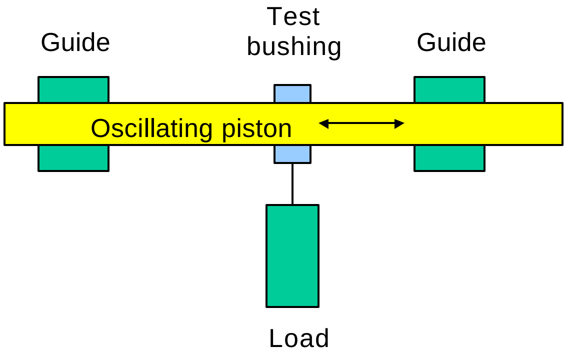

Figure 4. Cross sectional schematic of piston and bushing oscillating wear test.

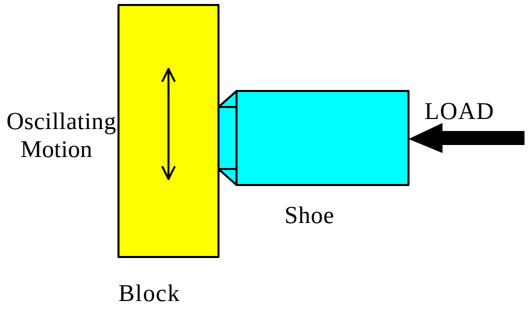

Figure 5. Cross sectional schematic of the fretting wear test.

The shoe and block materials correspond to the piston and bushing/seal materials. The base material for the piston and shoe is 4340 steel and the hard chrome and HVOF coatings are applied to only these components. Table 1 provides the wear material test matrix.

Table l. Wear test material matrix

Piston/coating material (Fretting Shoe/Coating)	Bushing material (Fretting Block)
4340/Hard Chrome Plate	4340 steel
4340/HVOF WC-CO	AMS 4640 (Al-Ni-bronze)
4340/HVOF WC-10Co-4Cr	Anodized aluminum
	Caron B on Al bronze
	Nitrile/PTFE T-seals in 4340

Because there are so many variables in the wear testing, a statistical design-of-experiments methodology is being followed. During testing of the piston/bushing, the coefficient of friction is monitored and then subsequent to the test, the coatings are examined to measure the extent of wear, if any. Some preliminary results have been obtained and figure 6 presents friction data for the 4340 piston coated with hard chrome, WC/Co and WC/CoCr sliding against a bare 4340 bushing with a normal load of 130 kg (288 lbs).

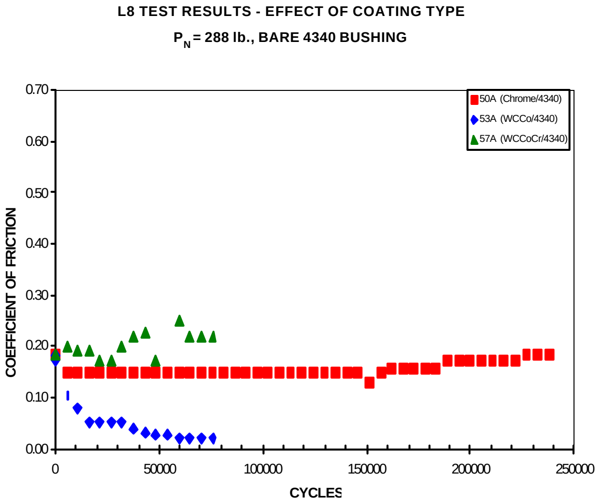

Figure 6. Friction coefficient as a function of cycles for rod/bushing test.

It can be seen that there are substantially different results for the two HVOF coatings, with the WC/Co exhibiting much lower friction than the WC/CoCr and the hard chrome plate.

Hydraulic Actuator Testing

Separate testing outside of the HCAT program has been conducted on evaluating the performance of several HVOF coatings compared to hard chrome. To measure wear performance under real conditions, rig tests have been run at Greene, Tweed & Co.[3] using hydraulic actuators with several rod coatings and two types of seals. A sequence of 50 million rod movements incorporated strokes of 0.08 to 7.5 cm at frequencies of 0.5 Hz for the long strokes to 6 Hz for the short strokes. Seal leakage was measured during the test, and coating degradation checked periodically.

The materials and seals used in the tests are summarized in Table 2. Note that the surface finishes on the coatings were different for different materials. This is very important, since it is known that too smooth a finish on chrome prevents proper lubrication, leading to overheating and severe rod and seal wear. On the other hand, a carbide coating that is too rough rapidly damages the seal. The Tribaloy 400 was finished in the same way as the hard chrome.

Table 2. Coatings and seals used in hydraulic tests; base material was 4340 steel

Coatings	
Hard chrome	0.1 µm Ra finish
HVOF Tribaloy 400	0.1 µm Ra finish
HVOF WC/17Co	0.05 µm Ra finish
HVOF WC/10Co4Cr	0.05 µm Ra finish

Seals	
ACT seal	Elastomeric nitrile seal PTFE backup
Enercap seal	PTFE seal, nitrile energizer

In hydraulics there are two critical wear problems, both of which lead to leakage:

1. wear and damage on the seal
2. wear and scratching of the rod

Leakage was measured as a function of time (cycles), while the actuators were checked periodically for wear of the seals and rods.

Figure 7 shows the average leakage as a function of time. Leakage is dependent on both the coating and the seal type. The peaks in leak rate correspond to seal failures for the ACT elastomeric seals, as does the inflection point in the PTFE chrome curve. With the PTFE seal the WC-Co and WC-CoCr both performed far better than chrome. However rapid seal failure of the elastomeric seals made the carbide performance unacceptable. The Tribaloy was acceptable with both types of seal, with its performance being better than chrome, but not as good as the carbide coatings. Average seal life is shown in Figure 8, which clearly shows the superior performance of the HVOF coatings with PTFE seals.

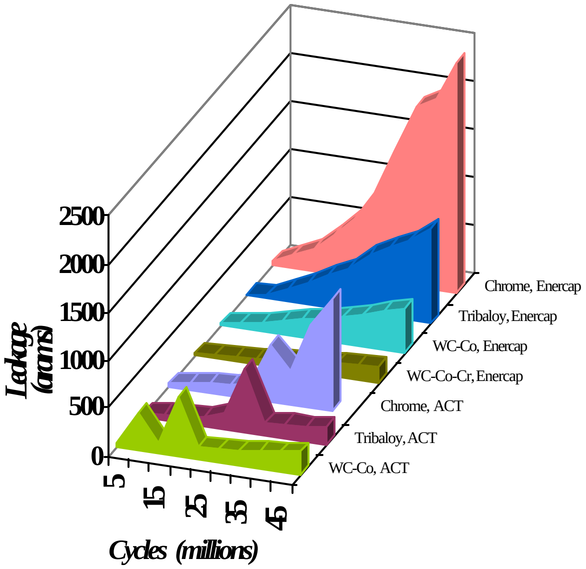

Figure 7. Hydraulic fluid leakage in rig test.

Obviously, performance may also be strongly affected by surface finish, and superfinishing of the HVOF coatings may make them acceptable when used with elastomeric seals. However, at this point Greene, Tweed's recommendation is that the HVOF carbide coatings not be used in actuators equipped with elastomeric seals without further testing.

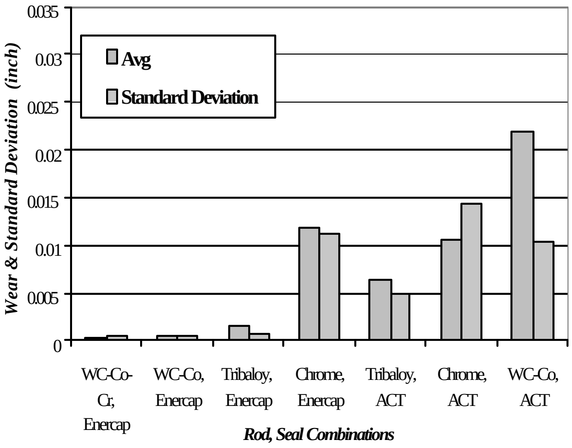

Figure 8. Seal life for various coating/seal combinations.

Production, Lifetime, and Cost Issues

Several analyses have been made in recent years of the cost of HVOF coatings compared with chrome plating. Based on different types of components and different scenarios their results reflect the wide range of situations in which chrome is used. For most manufacturers, total production cost, rather than process cost alone, is the most important issue, while for most users, life-cycle cost (or cost of ownership) is the critical issue.

For aerospace OEMs the primary cost savings tend to come from elimination of the need to heat treat high strength steels to prevent hydrogen embrittlement. This reduces production time with its associated inventory and cost-of-money. This makes HVOF especially cost-effective for large items such as landing gear and hydraulics.

For users, the primary cost savings in extending time between overhauls and reducing the loss of revenue-generating time to overhaul. At Jacksonville Naval Aviation Depot there have now been several occasions when a previously-chromed item has been coated with HVOF WC-Co, with the result that it has never returned for overhaul. The permissible life of many aircraft components is often defined by fatigue limits (maximum allowable flight hours) or by repair limits (maximum number of repairs or total thickness of repair). When the repair coating life is 3-5 times that of chrome, it becomes possible to protect the component with a "lifetime coating" that will last the entire life of the item, eliminating further strip-down and repair costs.

Summary

Currently, there are several ongoing DoD/industry programs to qualify HVOF thermal spray coatings as a chrome replacement on different types of aircraft components. Testing to date has shown that HVOF WC/Co coatings demonstrate superior performance to hard chrome with regard to fatigue, corrosion, and wear, although for hydraulic actuators it is not certain that these coatings can be used for all types of seals. As more and more data is generated and the results are obtained from rig and flight testing, the qualification process should accelerate, leading to actual insertion of this technology in manufacturing operations and at military overhaul and repair depots. The higher performance of HVOF-coated components should ultimately lead to reduced maintenance, lowering the total-cost-of ownership to DoD for its aircraft.

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