Hard Chromium Alternatives Team Update - Improving Performance While Reducing Cost

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The Hard Chrome Alternatives Team (HCAT) is a joint effort by the defense departments of the U.S. and Canada, aerospace companies, and military overhaul depots to replace chrome on landing gear, propeller hubs, hydraulics, and engines with high velocity oxy-fuel (HVOF) thermal spray coatings. Although the original aim was to replace chrome plate with a coating of equivalent performance and acceptable cost, it has been found that performance is usually better and total production cost lower. This talk will outline the current status of the work, with data on fatigue, wear, and corrosion, and discussion of progress in qualification and definition of standards.

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Introduction

The increasing environmental and worker safety pressures on chrome plating are leading companies in many industries to adopt alternatives. While environmental issues are important, what really sells these alternatives is the realization that the correct choice of alternative can lower cost while improving performance.

Improved performance results from such changes as lower wear, improved corrosion, reduced fatigue, and better hydraulic seal life. Lower cost can simply reflect lower processing cost, or it can be more subtle - lower cost of ownership, or faster overhaul and less frequent maintenance, resulting in more revenue-earning uptime.

The Hard Chrome Alternatives Team (HCAT) is DoD's primary program for replacing hard chrome plating, which is used by aerospace original equipment manufacturers (OEMs) on factory parts, and in military overhaul and repair (O&R) depots for rebuilding worn components. The team comprises all of the critical decision-makers and stakeholders, including various aerospace manufacturers, military depots and approval agencies, and laboratories in the US and Canada, who are working together to generate and share all of the data needed to validate High Velocity Oxygen Fuel (HVOF) and other thermal spray coatings as hard chrome replacements in OEM and O&R use. The US half of the team is concentrating on HVOF WC-17Co (and to a lesser extent Tribaloy 400) for military depot O&R use, while the Canadian half is concentrating on HVOF WC-10Co4Cr for OEM landing gear, of which Canada is the world's leading supplier.

HVOF is a thermal spray technology in which 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 expelled as a spray with the supersonic gases. 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 cobalt-cemented tungsten carbides are some of the easiest materials to spray and have shown the widest range of successful applications.

Rather than attempt the impossible task of validating HVOF WC-Co as a universal chrome replacement, or on the other hand, the impossibly expensive task of validating HVOF on every single item, HCAT is concentrating on validating the alternative for classes of components associated with specific aircraft systems, namely

- Landing gear - inner cylinders, axles, pins, actuators (in conjunction with Boeing and the landing gear makers, BF Goodrich/Menasco, Heroux and Messier-Dowty).
- Turbine engines (in conjunction with the Propulsion Environmental Working Group, PEWG, whose members include Pratt and Whitney, GE Aircraft Engines, and Rolls Royce-Allison).
- Propeller hubs (in conjunction with Hamilton Sundstrand)
- Hydraulics
- Helicopter rotary head components

These are the team's current areas, but we may expand into other systems, or into non-aerospace components as future needs arise.

Requirements for aircraft chrome replacement

Chrome plating is used in several different ways in the aircraft industry:

- As a wear-resistant coating, typically 75 µm (0.003") thick, mostly for external wear areas
- As a rebuild coating, up to 0.5 mm (0.020") thick, to bring worn components back to their specified dimensions
- As a light abrasion/corrosion barrier for many internal areas (thin dense chrome or flash chrome, typically 7.5µm (0.0003") 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.
- IDs of hydraulic and landing gear outer cylinders (frequently thin, dense chrome)

Experience with HVOF for replacing chrome

There is a growing body of experience with HVOF, especially, but not exclusively, WC-Co and WC-CoCr for replacing chrome plating on aircraft. This experience includes the following:

- For some years, Boeing has used HVOF coatings in place of hard chrome for various spot-problems on landing gear.
- Boeing 767 and 777 landing gear are now supplied with HVOF WC-CoCr coatings in place of hard chrome.
- Most of the major airlines are flight testing aircraft with HVOF instead of hard chrome on landing gear cylinders, pins, or axles.
- Boeing now has a repair specification permitting HVOF WC-Co or WC-CoCr in place of chrome plate for landing gear rebuilds up to 0.015" thick.
- Lufthansa intends soon to require that new aircraft be substantially chrome-free.

OEMs are adopting HVOF as a chrome replacement for several reasons:

- To get out of the chrome plating business with its attendant risks and regulations.
- To reduce production cost while improving product quality.
- To satisfy customer demand.

HVOF performance

Deposition

As with all coating technologies, the deposition conditions must be optimized to match the coating properties and performance to the requirements of the component and its use conditions. Most of the work in the HCAT has been done with hydrogen-fueled Sulzer Metco Hybrid Diamond Jet (DJ) guns, although there has been some use of other equipment, including Jet-Kote guns and TAFA kerosene-fuel guns. For each gun the spray conditions have been optimized to ensure that the material sprayed is the same - similar structure, porosity, hardness, adhesion, and stress.

Because most chrome replacements are used on fatigue-sensitive parts, we have paid special attention to the internal stress of the coating, measuring it on simultaneously-sprayed almen strips (which are commonly used for measuring stress induced by shot peening). The data show a clear correlation between compressive stress and improved fatigue, leading to a **specification that requires an Almen N value of 3-12 compression**.

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 0.1-0.4μm (4-16μ") finish. This permits the surface of the chrome to hold some hydraulic fluid in its pattern of microcracks. However, a WC-Co surface with such a finish is an efficient cutting tool for the seal material. Experience shows that the surface of WC-Co should be 0.15μm (6μ") Ra or better (preferably <0.5μm, or 2μ"). This can be achieved by diamond grinding or superfinishing. With this type of finish the seal life is usually better than that of a seal running against hard chrome.

It is becoming clear, however, that merely defining the average roughness, Ra, is inadequate, and that for these types of coatings we need to adopt a more thorough specification of surface finish to better define the topography. While some HCAT members have adopted more rigorous specifications for their products, the team as a whole has not yet settled on a general definition.

It is important to remember that, whereas chrome can be ground with a simple carbide wheel, WC-Co requires a diamond wheel, which can be very expensive. For this reason, some users use metallic thermal spray coatings rather than the harder carbides. We have found that Tribaloy 400 can be ground or even single-point turned.

Stripping

For aircraft components, which have to be repaired periodically, it is essential to have an efficient and clean stripping method to remove the old coating prior to repair. Obviously, the coating can always be ground off, but this is labor-intensive and inevitably cuts into the underlying material.

Chrome is typically removed in a caustic or acid bath, and the residue treated as toxic waste. WC-Co and WC-CoCr can both be removed by an aerospace industry-approved electrolytic method based on Rochelle salt, with the chemistry of *Table 1*.[1] Unlike the chrome stripping solutions, the Rochelle salt solution is benign.

Table 1. Rochelle salt stripping bath chemistry.

Sodium carbonate	20 – 30 oz/gal
Sodium potassium tartrate (Rochelle salt)	8 – 12 oz/gal
pH	11 – 12
Operating temperature	130° – 150°F
Current	40 – 80 A/ft^2 DC, anodic
Voltage	4 – 6 V DC

As *Figure 1* shows, this solution strips WC-Co and WC-CoCr at a rate of about 50µm (0.002") per hour. The method has been tested on 4340 high strength steel and on PH13-8Mo stainless steel. In neither case was there any dissolution of the substrate even after etching for 10 hours.

Fatigue

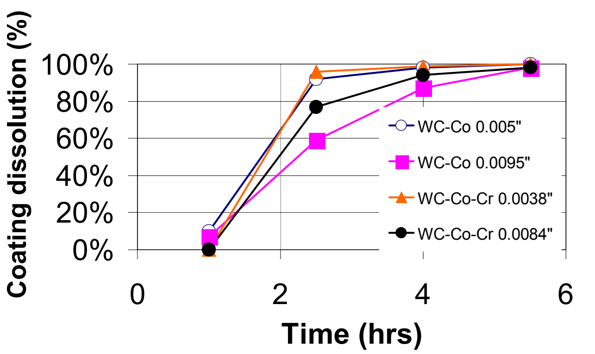

Figure 1. Rochelle salt stripping of HVOF coatings.

Fatigue performance is a critical issue for many chrome plated aircraft components, especially landing gear and hydraulic actuators. Because it is under tensile stress, chrome plate is known to cause a very significant fatigue debit, which is taken into account as a knock-down factor in designing fatigue-sensitive components. As we have noted above, the deposition parameters were designed to ensure that the coating would be under compressive stress, with the result that in most cases there is little or no fatigue debit.

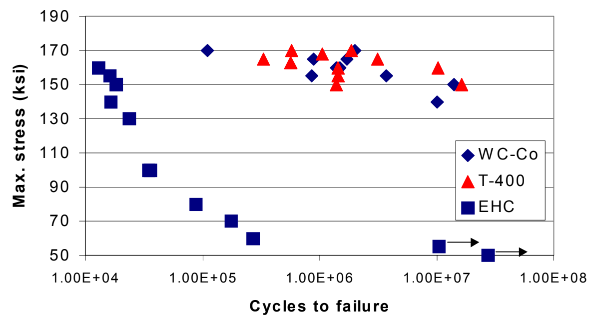

Figure 2. Fatigue of coated 4340 high strength steel, ***hourglass*** *specimens.*

Fatigue data for 4340 high strength steel coated with hard chrome and with HVOF Tribaloy 400 and WC-17Co is shown in Figure 2.[2] Unlike our earlier data, which was taken with smooth round and rectangular specimens, this data was taken with hourglass-shaped high cycle fatigue specimens required for validation of the process. Data has not yet been acquired for the uncoated baseline, but on the basis of our earlier work[3], we expect it to show that the HVOF coatings caused little or no fatigue debit. Note that this is in strong contrast with chrome plating, which causes a very significant debit.

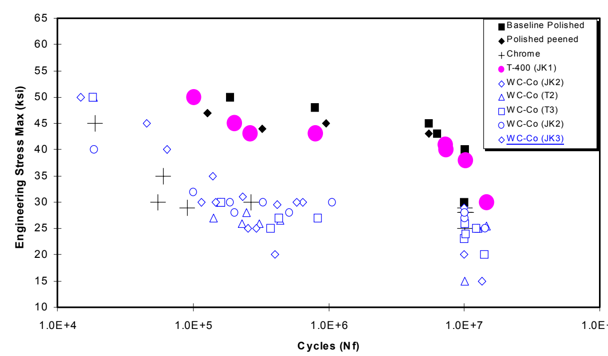

Figure 3. Fatigue of 7075-T73 Al, ***smooth gauge****. Filled symbols baseline; crosses EHC; large circles T-400; open symbols WC-17Co.*

For aluminum 7075-T73 alloy the situation is quite different. (Figure 3). When early data showed WC-17Co to have the same fatigue debit as chrome, our expectation was that the WC-Co coating had overheated the alloy. Extensive testing showed that there was little or no difference between the chrome and the HVOF WC-Co produced by different vendors and equipment, with very careful temperature control. The Tribaloy 400, on the other hand, is almost indistinguishable from the uncoated baseline material. We believe that the behavior of the WC-Co is most likely due to the strong mismatch in elastic modulus between the coating and the substrate.

The fatigue data clearly show that one cannot simply use WC-Co as the universal chrome replacement. The coating should match the requirements of the application, varying as necessary with conditions of use and substrate material.

Wear and hydraulic testing

Wear tests are currently under way to simulate wear between the different materials in hydraulic actuators in two wear regimes:

1. Fretting wear - small stroke, simulating dithering in fly-by-wire systems.
2. Oscillating piston/bushing wear - simulating long-stroke actuator motion.

The tests are being run under conditions defined to explore the effect of lubrication, side-load, and coating surface finish. An initial design of experiment matrix is presently being analyzed.

The purpose of the wear testing is not to measure true wear rate (which can only be done in a real wear system), but to understand the importance of variables such as wear couple and surface finish.

To measure wear performance under real conditions, rig tests have been run at Greene, Tweed & Co.[4] using hydraulic actuators with several rod coatings and two types of seals. A sequence of 50 million rod movements incorporated strokes of 0.03” to 3” 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.

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

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 for the reasons noted above. 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, a Co-based alloy coating, was finished in the same way as hard chrome. Leakage was measured as a function of time (cycles), while the actuators were checked periodically for wear of the seals and rods.

Table 2. Coatings and seals used in hydraulic tests - 4340 rods.

Coatings:	
Hard chrome	3.9 Ra standard rod finish
Tribaloy 400	8.9 Ra finish
HVOF WC-17Co	3.8 Ra finish
HVOF WC-10Co4Cr	6.5 Ra finish
Seals:	
ACT seal	Elastomeric nitrile seal, PTFE backup
Enercap seal	PTFE seal, nitrile energizer

Figure 4 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 (Enercap)-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

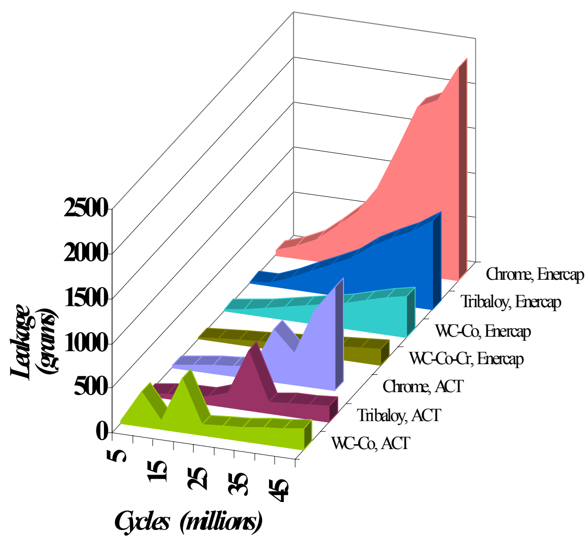

Figure 4. Hydraulic fluid leakage in rig tests.

performance being better than chrome, but not as good as the carbide coatings. Average seal life is shown in *Figure 5*, which clearly shows the superior performance of the HVOF coatings with PTFE seals.

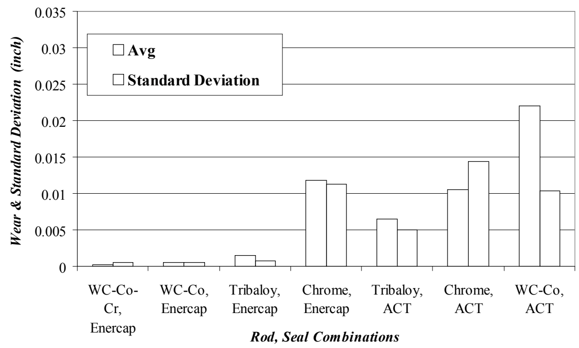

Figure 5. Seal life for various coating/seal combinations.

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 recommends that the HVOF carbide coatings not be used in actuators equipped with elastomeric seals without further testing.

Rig and Flight tests

Boeing has tested HVOF WC-Co coated pins in full scale rig fatigue testing of an F-18 landing gear[5]. These are tests of the coated pins in an actual landing gear installed in a fatigue testing rig. The HVOF coating showed no damage or wear.

A number of airlines are currently flight-testing landing gear coated with HVOF WC-CoCr, including Lufthansa and Delta Airlines. Direct comparison between the chrome plate and the HVOF coating can be made by substituting one of the two main landing gear with an HVOF coated test gear. The coatings are being evaluated for several regions

- inner cylinders
- axle journals
- actuator pins

Reports of these flight test programs are positive. In the Delta tests[6], coating wear and damage on HVOF-coated cylinders is generally non-existent, and seal wear is low. Axle journals also show no coating damage or wear. As a result Delta has now approved HVOF WC-CoCr for several landing gear overhaul applications.

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 coating 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 for heat treating 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 are 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.

Of course, in some industries elimination or reduction of repair is financially disastrous, since competitive pressures make O&R a major revenue source. Even here, thermal spray offers options. Rather than choosing the most wear-resistant repair, which is often the highest cost, the technique permits the choice of that material whose cost, life, and performance most closely match the requirements of customer and supplier. Thus, rather than eliminating the maintenance business, the technology offers the chance to improve properties other than wear (e.g. corrosion resistance, surface finish), giving a better product to the user at an acceptable cost, and a continuing income stream to the producer.

Conclusions

The advantage of chrome is that it is a single material and deposition method that can be used for a wide variety of applications. The advantage of HVOF is that it is a single technology, with a wide variety of materials that can be used to achieve just the right combination of properties for any purpose.

Our data thus far shows HVOF coatings, particularly the tungsten carbides, to be equal in performance to hard chrome in all of their measured properties, and significantly better than hard chrome in fatigue and wear.

The HCAT program is in the process of acquiring all of the data necessary for the validation and broad acceptance of HVOF coatings for OEM and O&R use. At the same time, commercial users are adopting the technology for their specific applications in landing gear and other aerospace systems.

Sources

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[2] P. Bretz and J. Schell, "HCAT Fatigue Test Program", AFOSR Grant # F49620-96-1-0298.

[3] B.D. Sartwell et. al., Proceedings of the 1998 Aerospace/Airline Plating and Metal Finishing Forum, San Antonio, March (1998), p. 97.

[4] Elwin Jang, M. Cutler, "Chromium Replacement by HVOF Spray Coatings", Final Report AF Contract # F04699-98-C-0002 CLIN 1AY, Sep 1999. Greene, Tweed work done by Tony DeGennaro.

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