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Surface Finishing of Tungsten Carbide Cobalt Coatings Applied By HVOF for Chrome Replacement Applications

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Tungsten Carbide Cobalt coatings applied by HVOF are increasingly used in applications for chrome replacement. One of the operational concerns with such coating applications is seal life where the coating is in contact with a sliding or rotational seal. A study was conducted to evaluate the relative surface finish properties of hard chrome electroplate and a tungsten carbide cobalt based coating over a range of surface finishes. The study includes finishes that were obtained with standard grinding methods for each coating, as well as hand polishing and mechanical superfinishing. A summary of the properties achieved and anticipated performance is presented.

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Introduction

Electroplated hard chrome has been a standard in the aviation industry for the past 5 decades to provide a surface that is hard, smooth, resistant to abrasion and wear, and provides some degree of corrosion protection. Though its residual tensile stresses can cause a debit in the fatigue strength of the base material to which it is applied, it is used throughout aircraft systems on structural and flight critical hardware. Because of the environmental and health risks associated with the application and handling of chrome processing materials, efforts have intensified to reduce or eliminate its use.

During the 1990s, tungsten carbide coatings (WC) applied by high velocity oxygen-fuel (HVOF) thermal spray systems were tested extensively as a potential replacement for hard chrome plating. These coatings do not pose the environmental risks of chrome plating, and have the added benefit of requiring less processing steps and time to produce. Testing has consistently shown that when applied using proper materials, application techniques and parameters, the HVOF coatings provide less fatigue debit, more corrosion resistance, and better wear resistance than chrome plate. The improved performance characteristics and reduction in application time offer significant opportunities for manufacturers and operators; whether eliminating the increasing health and environmental liabilities of a chrome plating facility, or reducing the maintenance requirements of various systems and equipment.

As a result of positive test data obtained in comparing HVOF coatings to chrome plate, a number of aircraft applications are now approved for new manufacture, overhaul, and rework. These applications include highly loaded, fatigue critical items such as main landing gear cylinders, axles, and truck beam pivot pins. Because some components such as the main cylinder are in sliding contact with a hydraulic seal, there is concern for the seal life, or the potential for premature leakage.

Studies conducted on seal wear with HVOF coatings have determined that seal life can be improved when finer surface finishes are employed than those traditionally used on chrome plate. Reductions of 2 to 4 times in the Ra value typically used with chrome have proven to be effective. In areas where a chrome finish would be specified at 0.40 μm (16 μin) Ra or finer, HVOF finishes of 0.20 μm (8 μin) Ra or even 0.10 μm (4 μin) Ra or finer are desirable to enhance seal life. While this seems contrary to concerns that extremely fine finishes do not provide sufficient oil retention to lubricate a seal adequately, testing and experience prove otherwise.

These fine finishes are achieved by conventional grinding methods using diamond wheels, or by supplemental polishing. Because of the increasing demand for low Ra values on the HVOF coatings, the use of superfinishing equipment to supplement conventional grinding was investigated.

This paper outlines a study undertaken to evaluate the surface finish properties of HVOF tungsten carbide coatings compared to comparable finishes on chrome plate. Further finish improvements attainable by the use of superfinishing equipment are also documented. Also included are reports and data from various tests and service evaluations of HVOF coatings.

Laboratory Testing Background

Based on the service requirements of aircraft components that are currently chrome plated, the primary mechanical property concerns regarding substitution with HVOF coatings are:

- Substrate fatigue performance
- Substrate and coating corrosion resistance
- Wear properties

In evaluating these properties, a baseline must be established for the selected substrate material with hard chrome plating applied. That data can then be compared to test data for the HVOF coating to determine if the tungsten carbide's performance is as good as or better than hard chrome. Once that comparison has been completed, the decision can be made to proceed with in-service testing, or implementation of HVOF coating as a fully approved process.

A large number of combinations of test methods and parameters have been employed with the materials involved. A sampling of typical results is presented here for reference.

Fatigue Testing

Fatigue testing has generally been conducted by 2 methods: axial fatigue and flexural fatigue. A wide range of specimen materials and configurations has been employed. The example shown in Figure 1 represents the results of a fatigue test comparing HVOF coated 4340 to bare, and chrome plated 4340. All of the specimens were shot peened prior to coating application. The bare baseline was also shot peened.

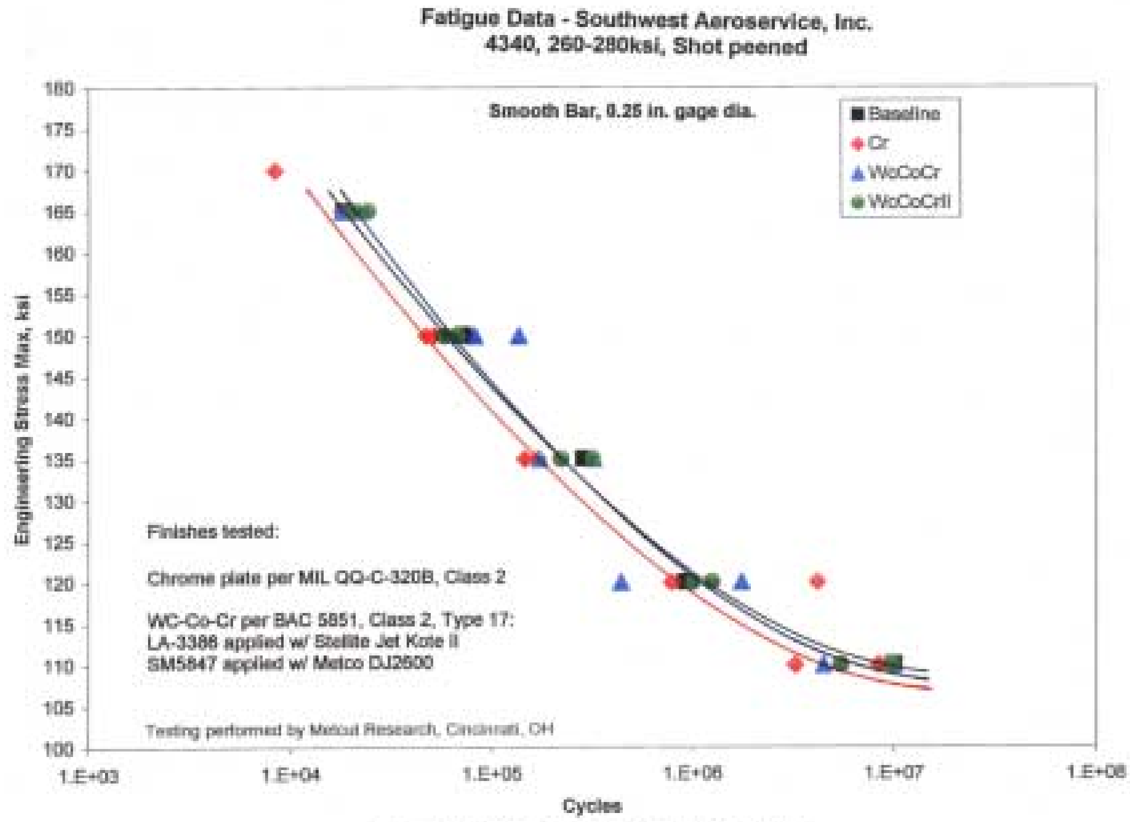


Figure 1 – Axial Fatigue Results on 4340 Smooth Bar

In this particular test, 2 different HVOF spray systems and powders were used to further investigate coating properties from different material/system combinations. The results show similar results from both sprayed coatings with properties rivaling those of the bare baseline, and better than chrome plate across the range of applied stresses.

Corrosion Testing

An obvious concern for components that are exposed to the elements is their susceptibility to corrosion. Tests have been conducted on HVOF tungsten carbide coatings using different test methods to best simulate aircraft applications.

In ASTM B117 Salt Fog Tests using a 4340 steel substrate, results indicate that the WC-17%Co coating performs notably better than the comparative chrome baseline. (Figure 2) [1]

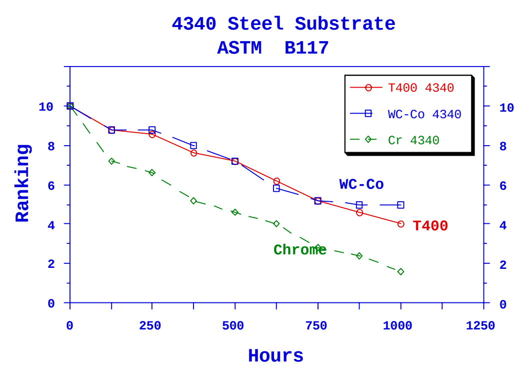
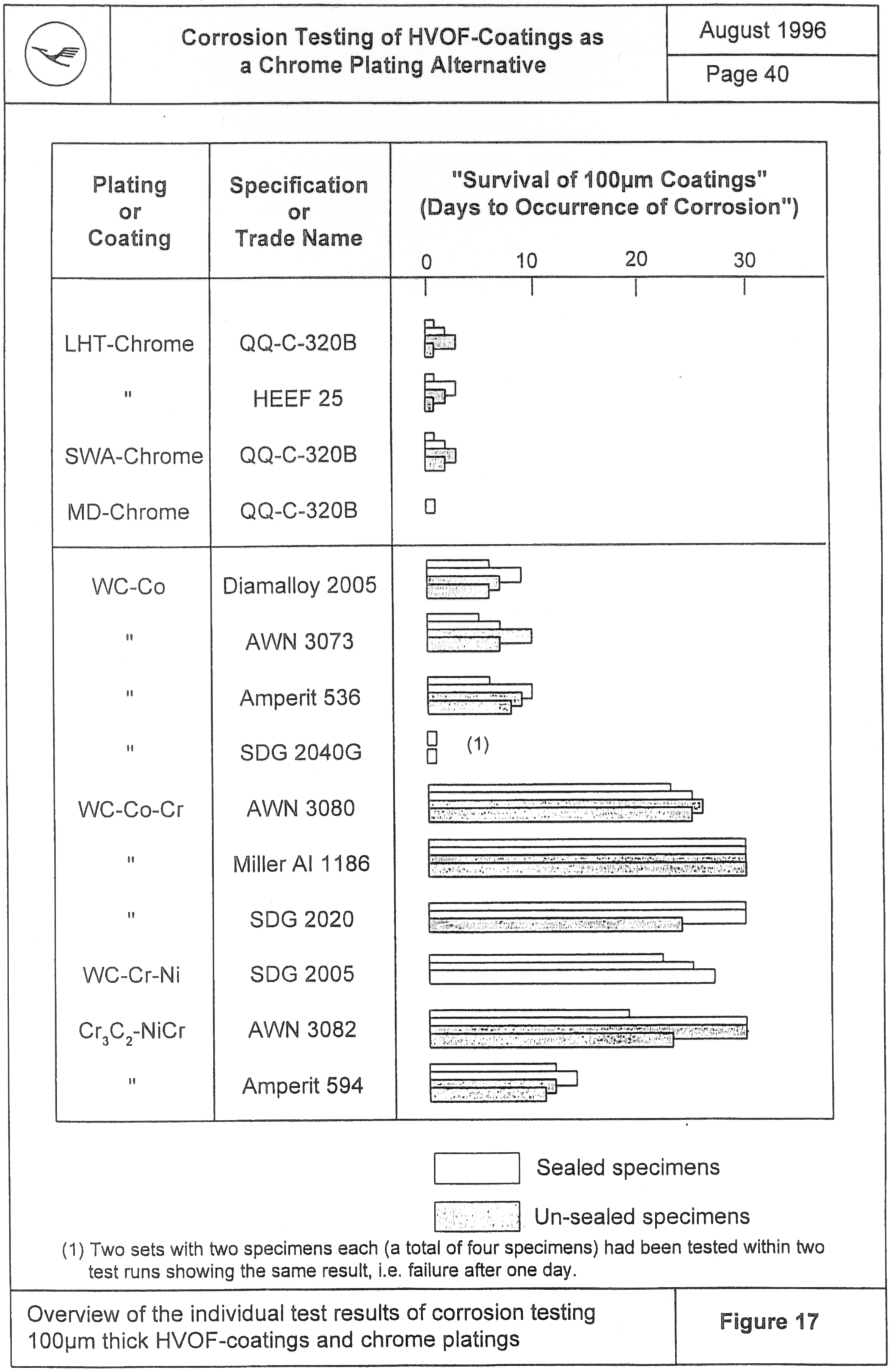


Figure 2 - Appearance rankings for coatings on 4340 steel substrates subjected to ASTM B117 cyclic test.

Other corrosion studies undertaken by organizations such as Lufthansa Technik also evaluated the other HVOF material of choice for chrome replacement: 86%WC-10%Co-4%Cr. In their study, the WC-Co-Cr performed not only better than chrome plating but also better that the WC-17%Co material. (Figure 3) [2] This has led some users to select the coating with 4% chrome content for additional protection in highly exposed and vulnerable areas. It should be pointed out, given the environmental concerns regarding chrome, that the chrome content



Corrosion Testing of HVOF-Coatings as a Chrome Plating Alternative	August 1996
	Page 40

"Survival of 100µm Coatings" (Days to Occurrence of Corrosion")

0 10 20 30

Plating or Coating	Specification or Trade Name
LHT-Chrome	QQ-C-320B
"	HEEF 25
SWA-Chrome	QQ-C-320B
MD-Chrome	QQ-C-320B
WC-Co	Diamalloy 2005
"	AWN 3073
"	Amperit 536
"	SDG 2040G (1)
WC-Co-Cr	AWN 3080
"	Miller Al 1186
"	SDG 2020
WC-Cr-Ni	SDG 2005
Cr_3C_2-NiCr	AWN 3082
"	Amperit 594

Sealed specimens

Un-sealed specimens

(1) Two sets with two specimens each (a total of four specimens) had been tested within two test runs showing the same result, i.e. failure after one day.

Overview of the individual test results of corrosion testing 100µm thick HVOF-coatings and chrome platings

Figure 17

Figure 3 – Lufthansa Corrosion Testing of Chrome Plating and Thermal Sprayed Coatings

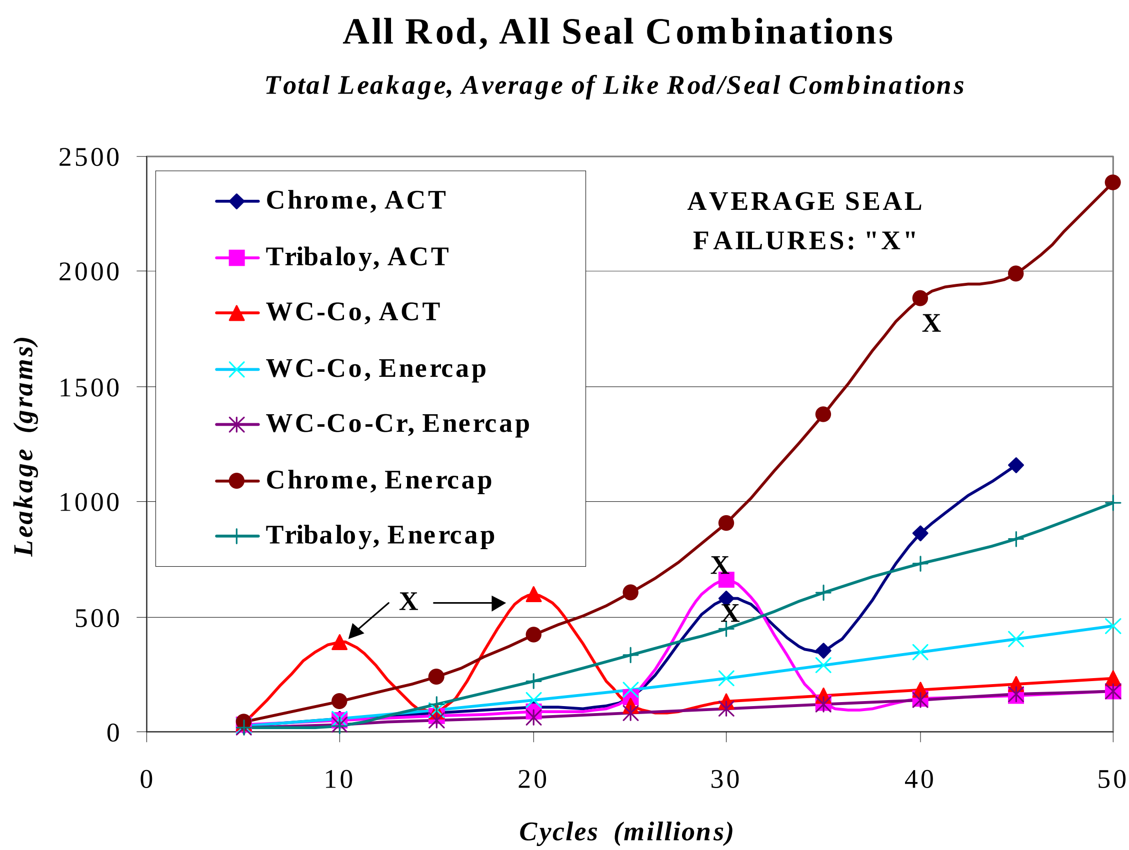


Figure 4 – Greene, Tweed & Co. Seal Wear Study on Chrome Plating and HVOF Coatings

found in thermal spray powders is in a stable metallic state. By contrast, the chrome in plating baths that is of environmental concern is in an ionic, hexavalent state. There are currently no environmental regulations in place that specifically regulate the thermal spray application of powders containing chrome.

This demonstrates another benefit of HVOF coatings: the ability to select different material compositions that best suit the environment and the application. Whereas chrome is a "one-size fits all" in its use as a corrosion, wear, or seal bearing surface, HVOF coating compositions can be selected for their best properties, by application.

Wear Testing

A wide range of test methods have been used to characterize the wear properties of HVOF compared to chrome, both standardized as well as specially developed methods.

Of particular interest in sliding hydraulic seal wear applications is the effect of the HVOF coating on seal life. Studies conducted by seal companies like Greene Tweed have demonstrated that when HVOF is mated with the proper seal material, it can significantly improve seal life over that obtained on a chrome plated surface. (Figure 4) [3]

Process Control

The caveat that must be emphasized with all of these results is that they are not a given. The HVOF process for all its simplicity is in-fact quite complex, containing numerous interdependent variables. These variables must be understood and controlled carefully to achieve the satisfactory performance results illustrated. Because HVOF systems are commercially available, the tendency may be to believe that you can plug it in and go. This is far from the case and companies such as Boeing have addressed this issue by establishing qualification tests for spray suppliers that desire to work on fatigue sensitive components such as landing gear. These tests evaluate the combination of spray equipment, powder utilized, and spray application parameters to produce a coating with satisfactory performance characteristics. Once approved, the process is frozen and may not be changed without additional testing or study.

In-Service Evaluations

Lufthansa

Lufthansa put the first-ever HVOF coated B737-300 NLG inner cylinder into service on January 3, 1996 for a two year evaluation. The cylinder was coated with WC-17%Co applied by Southwest Aeroservice, Tulsa, OK. (Figure 5)
Lufthansa was motivated by environmental concerns as well as processing issues related to chrome. Typically the process flow time is six days for the chrome plating cycle on this part. That is because of the need for special masking and supplementary anodes to plate the cylinder and then the axles. This process flow time is reduced to less than four hours when applying an HVOF coating resulting in a significant life cycle cost reduction for the part.

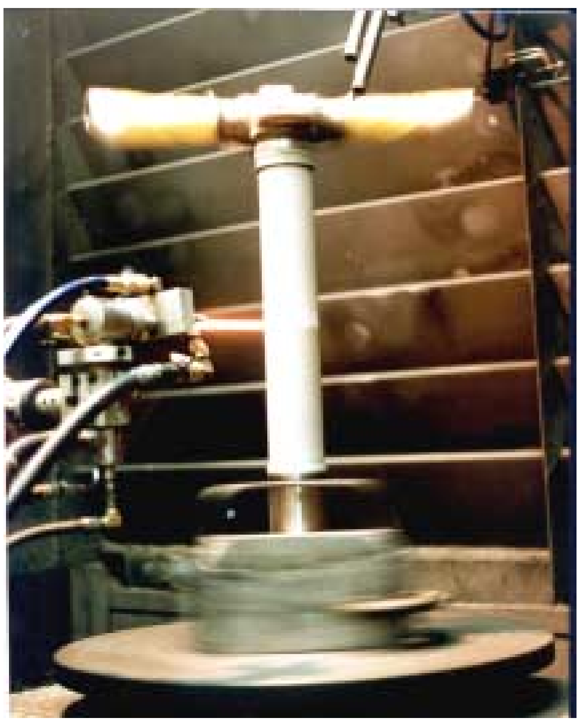


Figure 5 – Application of HVOF Coating to 737 Nose Gear Inner Cylinder

The cylinder went into service with a surface finish of 0.10 to 0.15 µm (4 to 6 µin) Ra. The cylinder was then inspected at 6-month intervals throughout the period of evaluation. This inspection consisted of raising the nose of the airplane to achieve full extension of the gear. The wheels and the bearings were removed and a penetrant inspection (red dye check) was performed to detect possible cracks. No rejections were found during the dye checks. All surfaces were inspected for visible defects such as chipping, flaking of the coating, and wear marks but no defects were found.

Lufthansa has traditionally replaced seals after 900-1100 flight cycles. During this evaluation seal life was extended to 1910 flight cycles. The cylinder was removed in April 1998 after completing 4701 flight cycles. The cylinder was inspected for visible defects similar to the 6-month inspections and no defects were found. Surface roughness had increased to an average of 0.25 µm (10 µin) Ra with a brownish discoloration evident on the surface due to imbedded particles of Teflon from the seal.

A fluorescent penetrant inspection (FPI) showed indications on the aft side of the cylinder that were not readily apparent with the dye check used at the 6-month intervals. Upon magnification the fluorescent streaks were in fact small crack like indications. In an effort to determine the extent of this cracking the cylinder was returned to Boeing, Seattle for a Barkhausen inspection.

The Barkhausen test measures the stress presence in the substrate using a generated magnetic field. If cracks had indeed continued to the substrate, as in the case of chrome plate, the Barkhausen would have shown a reading to that effect. Since it was determined that these indications did not go all the way to the substrate it was concluded that the cracks themselves were confined to the thickness of the splat layer. The only way to confirm this suspicion is to cross section the part where the indications are and examine them under the microscope. Since the Barkhausen tests did not warrant this the part was returned to Lufthansa for continued service. The cylinder was returned to service on 21 August 1998. Another inspection of the component was conducted on the aircraft on 21 September 1999 with no structural defects noted.

Delta Airlines

Delta Airlines has been active in terms of the number of parts that have been put into service evaluation status. A summary of the parts that have been put into service starting in December of 1997 along with the coating(s) applied is listed in Table 1.

The service evaluation cycle is a 2-year period with an inspection at 6-month intervals. The inspection consists of dismantling the component assembly and performing a dimensional check of the coating along with surface roughness measurements. In addition, a fluorescent penetrant inspection is made on the coated surface to detect any cracking of the coating.

Table 1
Delta Airlines HVOF Service Evaluations

1. 737 Nose Landing Gear Inner Cylinders
   WC-Co-Cr

2. 737 Nose Landing Gear Lower Bearing
   Triballoy T-400

3. 757 Main Landing Gear Axles
   WC-Co-Cr

4. 757 Main Landing Gear Axle Sleeves
   WC-Co-Cr/T-400

5. 767 Main Landing Gear Axles
   WC-Co-Cr

6. 767 Main Landing Gear Axle Sleeves
   WC-Co-Cr/T-400

In the case of the main landing gear axles for the 757 and 767, thermally coated axles are installed on one side of the airplane and the standard chrome plated axles on the other side. This arrangement affords a side by side comparison of thermal coatings with chrome under identical circumstances.

In this situation dimensional checks have indicated no wear loss of the thermal coatings. Surface roughness readings on the static axle surfaces have shown a very slight increase as compared to the chromed surfaces. This increase is due mainly to material transfer from the 15-5PH axle sleeves in direct contact with the thermal coating as a result of fretting. No such material transfer was observed on the chromed axles. Fluorescent penetrant inspection shows the resultant material transfer as a streak on the coated surface. No indication of coating cracking or failure has been detected on any part that has been in service.

Subsequent laboratory testing has confirmed that 15-5PH steel does have a higher rate of wear against a thermal coating when compared to chrome. This observation has resulted in coating the inner diameters of certain 15-5PH axle sleeves in contact with the axle with a similar WC-Co-Cr coating, and other sleeves with a Triballoy T-400 coating for a performance comparison. There is no rotational movement in this assembly. The axle sleeves are heated and press fitted onto the axles. These combinations were recently installed and no results of the wear characteristics are available at this time.

Surface roughness values were recorded as 0.075 to 0.15 μm (3 to 6 μin) Ra on the HVOF coated axle surfaces when they went into service. At the 18-month inspection this surface roughness measurement had increased to 0.175 to 0.225 μm (7 to 9 μin) Ra. The chromed surfaces had also shown a surface roughness increase going from an initial 0.108 μm (4.3 μin) Ra to 0.35 to 0.45 μm (14 to 18 μin) Ra. The increase in roughness for the chrome was not because of material transfer, however, but due to surface wear.

Finishing Study

Field Experience

Elastomeric seals are installed in landing gear shock struts and their primary function is to contain hydraulic fluid under pressure. The inner diameter of the seal is compressed against the outer diameter of the cylinder by the use of a bearing. The typical finish callout for chrome plate is 0.40 μm (16 μin) Ra or finer. During initial trials there was no reason to believe that the surface finish of thermal coatings needed to be anything different from chrome. When components were initially coated, the 0.40 μm (16 μin) Ra or finer finish was the callout even though a few early components such as the Lufthansa cylinder went into service with a 0.10 to 0.15 μm (4 to 6 μin) Ra finish.

In two separate instances a 757 main landing gear inner cylinder and a 737 nose landing gear inner cylinder suffered seal failure shortly after being put into service with thermal sprayed tungsten carbide on the diameter that mates with the seal. The 757 had only completed 936 cycles and the 737 had completed 855 cycles. The 757 surface finish was 0.325 μm (13 μin) Ra while the 737 had a range of 0.225 to 0.30 μm (9 to 12 μin) Ra.

The seals from the 757 were examined and the results indicated that there was severe pock mark damage and abrasive wear on the crown of the seal. Pock mark degradation is typical of friction induced stress cracking which suggests that the seals had been mated against a rough surface. Unfortunately no hydraulic fluid was retained for analysis. The cylinder was stripped of its coating and an identical coating was reapplied and finished to 0.05 μm (2 μin)

Ra. The airplane was returned to service in December 1998 with no further seal problems.

The 737 airplane had a similar history with evidence of seal failure. The seals showed abrasive wear similar to that found on the 757. The powder chemistry and the coating hardness were identical. With surface roughness ranging from 0.325 μm (13 μin) Ra for the 757 and 0.20 to 0.30 μm (8 to 12 μin) Ra for the 737, it appeared that surface roughness was indeed a factor in premature seal failure.

In the case of the 737, a hydraulic fluid sample was retained for analysis. The fluid was first filtered to remove all debris and the residue was subjected to Electron Probe Micro Analysis (EPMA). In addition, a Back Scatter Electron (BSE) image was made to identify the physical make up of the filtered debris. The results of the analysis showed that 5 micron-sized (0.0002 in.) particles of tungsten carbide had been suspended in the hydraulic fluid.

The Teflon seal was examined under magnification and tungsten carbide particles were found embedded in the surface.(Figure 6) This method of analysis is typical of what has been done in the past on fluids from a system containing chrome-plated parts. However, chrome particles have never been detected in the quantity as found with the tungsten carbide and seals have not exhibited the same kind of abrasive wear damage.

Figure 6 – WC Particles Embedded in Worn Teflon Seal of 737 Nose Landing Gear.

The conclusion from this investigation is that 5 micron-sized (0.0002 in.) particles of tungsten carbide were suspended in the hydraulic fluid turning it into an abrasive cutting media. The suspended tungsten carbide particles appear to have no adverse effect on the metal surfaces they are in contact with.

Laboratory Evaluations

Because of the increasing interest in use of HVOF applied tungsten carbide based coatings to replace chrome, and the recognition that the WC coatings can produce better performance results compared to chrome when properly applied, the next question becomes, how much better than chrome can it get? Surface finishing offers an example of how technique refinement may take a good process or system and enhance its performance making it even better. Therefore from the basic investigations and field experience described, further investigations into finishing refinements have begun.

To better understand this relationship, Boeing Commercial in Seattle decided to conduct a comparative evaluation of the properties of ground chrome plate and HVOF applied tungsten carbide finishes over a range of Ra values.

Coupons were made from IASI 4130 steel tubing, 7.62 cm (3 in.) long with a 1.27 cm (0.5 in.) O.D. 6 coupons were hard chrome plated on the entire O.D. surface in accordance with QQ-C-320. Another 6 coupons were coated with tungsten carbide-cobalt-chrome (86%WC-10%Co-4%Cr) using a Stellite Jet Kote II HVOF system and AI 1186 powder. The spray control specification was Boeing's BAC 5851. For convenience of application, the outer 1.27 cm (0.5 in.) of both ends of the sprayed coupons was masked leaving the middle 5.08 cm (2 in.) coated. The plating and HVOF coating were both applied to a thickness of 125 to 175 microns (0.005 to 0.007 in.).

Following application of the plating and coating, both sets of coupons were ground to achieve a range of finish values. In each set, one coupon was left in the as-plated/as-sprayed condition. The remaining 5 in each group were then ground to achieve an Ra value of 0.80, 0.40, 0.20, 0.10 and 0.05 μm (32, 16, 8, 4, and 2 μin).

The chrome coupons were ground with a 60 grit aluminum oxide wheel. Since the objective was Ra rather than dimension, the plating was ground until a uniform finish of 0.80 and 0.40 μm (32 and 16 μin) Ra was achieved on the respective specimens. To achieve finishes of 0.20, 0.10 and 0.05 μm (8, 4, and 2 μin) Ra, supplemental polishing was required. This was performed with 600 grit aluminum oxide lapping paper by hand while the coupon was still rotating in the grinder.

The HVOF coated specimens were processed similarly, however a 180 grit natural diamond wheel was used in accordance with BAC 5855. Once again finishes of 0.80, 0.40, 0.20, 0.10 and 0.05 µm (32, 16, 8, 4, and 2 µin) Ra were produced. As with the chrome, the finishes of 0.80 and 0.40 µm (32 and 16 µin) Ra were produced directly from the grinding wheel. The 0.20, 0.10 and 0.05 µm (8, 4, and 2 µin) Ra specimens received hand polishing with 45 micron diamond lapping film while turning on the grinder until the target values were achieved.

All chrome plating, HVOF coating, and finish grinding and polishing work was performed by Southwest Aeroservice, Tulsa, OK. The completed specimens were then forwarded to Boeing for analysis and evaluation.

From a detailed examination of the specimens it was apparent that the surface finish of the ground tungsten carbide coating had different physical characteristics from the chrome plated finish even though they may have the same surface roughness readings. When viewed under 500X magnification the surface of the 0.40 µm (16 µin) Ra chrome plated specimen is much smoother looking when compared to the WC-Co-Cr coating with the same Ra value. (Figures 7 and 8)

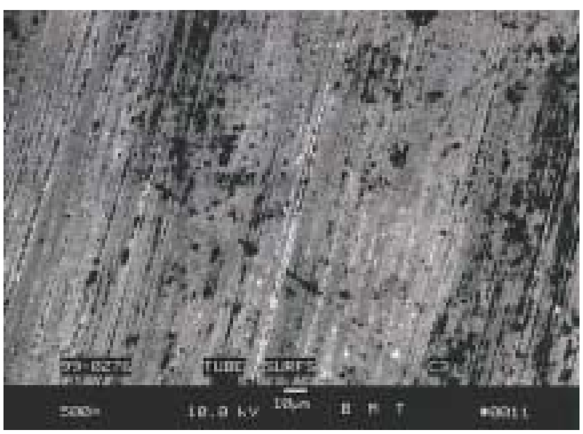


Figure 7 – Hard Chrome Plating Ground to a 0.40 µm (16 µin) Ra Finish (500X).

The grinding marks on the WC-Co-Cr are much larger and there appears to be a great deal of sharp debris just sitting on the surface. It is suspected that this debris is not tightly bound to the surface and that when the part is put into service, this debris breaks off and is suspended in the hydraulic fluid, potentially causing seal damage.

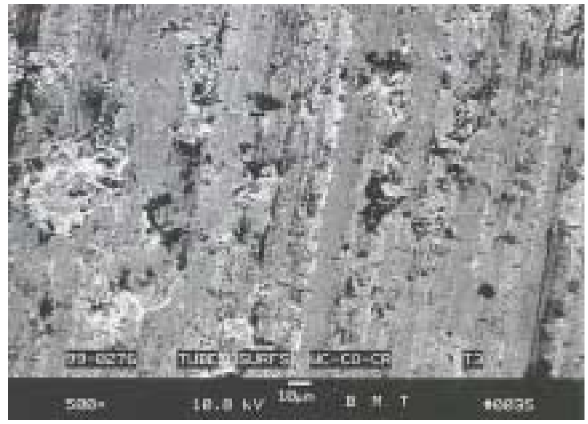


Figure 8 – HVOF WC-Co-Cr Coating Ground to a 0.40 µm (16 µin) Ra Finish (500X).

Figure 9 shows the original chrome plated specimen that was ground and polished to a 0.05 µm (2 µin) Ra finish. Figure 10 shows the original tungsten carbide coated specimen ground and polished to a 0.05 µm (2 µin) Ra finish. The chrome specimen still appears smoother and there is a definite absence of the sharp debris seen in the 0.40 µm (16 µin) Ra HVOF specimen.

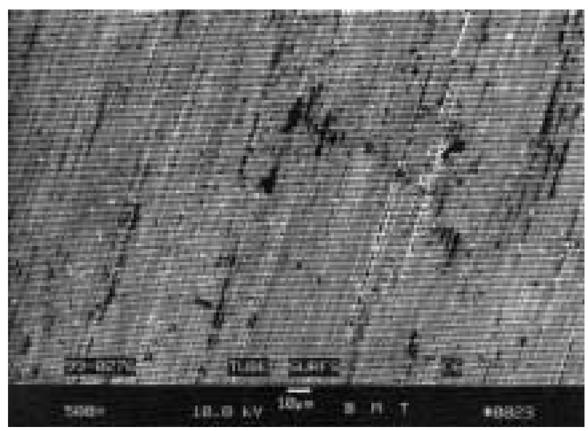


Figure 9 – Hard Chrome Plating Ground and Hand Polished to a 0.05 µm (2 µin) Ra Finish (500X).

The Superfinishing Process

"Superfinishing is a low temperature, low stock removal process which improves workpiece geometry while simultaneously producing a new surface finish, free of defects from previous operations. The process has been used for some time in the bearing and auto industries for high precision applications and is now being more widely used as workpiece tolerances become smaller and performance demands increase."

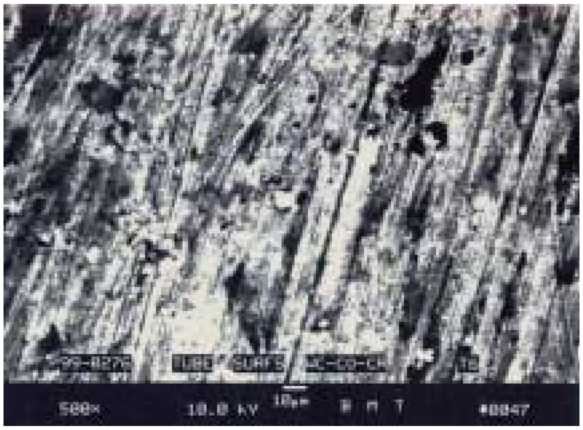


Figure 10 – HVOF WC-Co-Cr Coating Ground and Hand Polished to a 0.05 μm (2 μin) Ra Finish (500X).

"Superfinishing, sometimes referred to as short stroke honing, is characterized by the high frequency, low amplitude oscillation of an abrasive on a rotating workpiece. It is a low temperature, low stock removal process more akin to honing or lapping than higher temperature processes such as grinding. The process can achieve surface finishes (Ra) of less than 0.025 μm (1.0 μin) and expose the basic structure of the workpiece material, having the desired surface characteristics (micro-structure, hardness, etc.). In contrast, higher temperature, aggressive stock removal processes like grinding tend to heat the surface of the material, creating an amorphous layer with a lower hardness and different micro-structure. This leads to undesired surface characteristics on that portion of the workpiece where wear resistance is most critical. The superfinishing process removes the amorphous layer from previous operations, leaving a new surface in the base material while simultaneously improving the geometric form of the workpiece." [4]

In an attempt to refine the grinding process and reduce the presence of sharp debris, the 0.40 μm (16 μin) Ra HVOF specimen shown in Figure 8 was superfinished to a 0.05 μm (2 μin) Ra value by Supfina Machine Co. Inc., N. Kingstown, R.I. Figure 11 shows the dramatic difference in surface appearance as a result of this process. The depressions in the surface are the natural porosity of the coating and it is felt that these depressions can be sufficient for oil retention without seals running dry because of insufficient lubrication.

Figure 11 – 0.40 μm (16 μin) Ra Finish HVOF WC-Co-Cr Coating Following Superfinishing to a 0.05 μm (2 μin) Ra Finish (500X).

Conclusions

From the in-service seal failures and from the laboratory work it would seem that the roughness average value, Ra, may be insufficient to describe a sealing surface since it does not give any information on the shape or quality of the surface profile. For sealing situations it may be necessary to call out a Bearing Area Ratio, sometimes referred as Tp. This value is the length of a bearing surface measured at a specific depth from a reference line and expressed as a percentage of the measured length.

Future Work

Because previous studies such as the Greene Tweed study referred to earlier did not include evaluation of superfinished HVOF coatings, a test plan has been developed to investigate the relationship of bearing area ratio and surface quality on seal life. WC-Co-Cr coatings will be applied to test specimens and superfinished to a surface roughness of the 0.10 μm (4 μin) Ra or finer. The bearing area ratio, Tp, will be 0.20 μm (8 μin) equal to or greater than 90.0%. Ground chrome plating finished to the typical 0.40 μm (16 μin) Ra or less will be used as a comparative baseline. The test results will hopefully help to refine finish parameters and also give some additional insight into the materials for, and construction of the seals used in combination with these coatings.

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