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Paper

CONSIDERATIONS IN THE USE OF PULSED WATER JET TECHNIQUES FOR THE REMOVAL OF HVOF COATINGS

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ABSTRACT

Thermal spray coatings are becoming increasingly common in a wide variety of industrial applications. Specifically, Tungsten Carbide - High Velocity Oxygen Fuel (HVOF) coating, which is a derivation of thermal spray technology, is currently being tested on landing gear components. The authors have conducted extensive laboratory work on the removal of HVOF coatings from landing gear pins and other aircraft/aerospace components using forced-pulsed waterjet (FPWJ). These tests were conducted at pressures ≤ 104 MPa (15 kpsi) using only pure (tap) water. Several measurements were taken to assess the performance, and to ensure that the process meets the criteria specified by the aircraft/aerospace industry. Surface roughness measurements, taken by one of the aerospace companies, indicated no significant difference between the measurements taken before and after the removal process, indicating the substrate experienced minimal to no surface damage. Post stress analysis of the substrate, using x-ray diffraction technique, showed compressive stresses initially induced by peening to improve fatigue life, was not relieved by the removal method.

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1 INTRODUCTION

Thermal-spray coatings are becoming increasingly common for coating in a wide variety of industrial applications. Specifically, Tungsten Carbide - High Velocity Oxygen Fuel (HVOF) coating, which is a derivation of thermal-spray technology, is currently being tested on landing gear components. HVOF coatings can be easily applied and are highly resistant to abrasion wear. Moreover, this coating technique is believed to have the potential to replace apparently hazardous electrolytic hard chrome [**1, 2**]. However, HVOF coating's intrinsic durability also makes it difficult to be stripped for inspection and recoating. Current coating removal methods involve a multistep process whereby the coating must undergo diamond wheel grinding, chemical dipping, grit blasting, UHP {ultra-high pressure (380 MPa, 55 kpsi)} water blasting, and possibly a repeated chemical dip, depending on the type and thickness of the coating. Although UHP blasting has been used extensively for removing metallic coatings applied by the conventional thermal-spray, it has been found to be totally ineffective for removing HVOF coatings. Encouraged by the earlier results [**3**], the present investigation was conducted at the request of several aerospace companies, particularly Messier-Dowty. The objective was to verify if FPWJ technique, using only pure (tap) water, could safely remove the coating while eliminating the chemical, grit blasting and mechanical steps. The preference to use tap water is attributed to environmentally friendly benefits that it offers. Furthermore, the reuse of filtered spent water would reduce the overall cost of operation.

In this paper, results obtained with the FPWJ on removing the HVOF coating from landing gear pins (supplied by Messier-Dowty) are highlighted. At pressures in the range of 69 - 104 MPa (10-15 kpsi), the technique is shown to be quite effective, without damaging the substrate. The results also indicate that it is effective for selective stripping, namely removing only the top layer and leaving the sublayers untouched, all the while remaining cost effective and energy efficient.

2 HVOF COATINGS: BACKGROUND

A complete description of the HVOF coatings is beyond the scope of this paper. For the sake of clarity, a brief description, taken from the report published by the U.S. Department of Defense [**1**] is given here.

The main purpose of the use of HVOF coatings is to replace electrolytic hard chrome (EHC) coating, which has been used for more than fifty years. Chromium (Cr) plating baths used for EHC coating contain chromic acid, in which the chromium exists as hexavalent chromium (hex-Cr), known to be a ***carcinogen***. It is emitted as a mist into air by the tanks, which must be removed and disposed of as a hazardous waste. Thus, EHC operations must strictly adhere to EPA (U.S. Environmental Protection Agency) and OSHA (Occupational Safety and Health Administration) permissible exposure limits (PEL). As the current PEL of 100 $\mu g/m^3$ has resulted in many deaths, OSHA is looking into reducing the PEL to less than 5 $\mu g/m^3$, which will make EHC technique prohibitively expensive. It is in this context that HVOF technique is drawing a great deal of attention, and HCAT (Hard Chrome Alternative Team) has been formed to investigate its potential for replacing EHC. The report [**1**] concludes that HVOF coatings meet most of the acceptance criteria (fatigue, corrosion, wear, impact, hydrogen embrittlement, etc.)

specified by aerospace industry. For example, fatigue tests have shown that the average number of cycles to failure at any stress level for the HVOF-coated specimens is greater than for EHC-coated specimens.

HVOF is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel, usually hydrogen, propylene or kerosene. The powder particles accelerated to high speed, soften in the flame and form a dense, well-adhered coating on the substrate after impact. The coating material is usually a metal or alloy (e.g., Tribaloy or stainless steel), or a cermet (for instance, a cobalt-cemented tungsten carbide, WC/Co). The higher the flame velocity, the denser and harder the coating becomes, which is evident from the high values of elastic modulus {typically of the order of 270 GPa (39,000 kpsi)} of HVOF coatings [**2**]. Furthermore, the hardness of the coating, as measured by Vickers indenter, is quite high {≈12.8 GPa (1,855 kpsi) for WC/Co on the 4340 steel substrate} - up to seven times higher than the substrate itself [**2**]. From this brief description, it is clear that the main purpose of HVOF coating is in improving the life and performance of in-service parts by resisting wear from mechanical abrasion, extreme heat or, chemical corrosion. HVOF coatings are considered to be high performance coatings as compared to regular plasma or, flame-sprayed coatings.

It must also be pointed out in passing that because of very high hardness, the UHP technology is not effective for removing HVOF coatings. However, as pointed out in the following section, when HVOF coatings are subjected to FPWJ, high-frequency pulses penetrate and remove the coating with relative ease.

3 FPWJ TECHNIQUE

The authors have reported the method used for producing FPWJ in several publications [**3**]. Basically, the method consists of modulating a stream of water flowing through a regular nozzle (Fig. 1A). The modulation is achieved by placing an ultrasonic probe (called 'microtip') in the nozzle [**4**]. The microtip is energized by a transducer placed outside of the nozzle. An ultrasonic generator, rated to operate at a maximum power of 1.5-kW at 20-kHz, in turn powers the transducer. For a given set of flow conditions, when the input ultrasonic power is optimum, well-defined fully developed pulsed waterjet is produced (Fig. 1B). The shape of each pulse is like a mushroom, the size increasing with the standoff distance. The efficacy of FPWJ stems from:

1. The waterhammer pressure generated by the pulse at the point of impact on the workpiece is considerably higher than the stagnation pressure (≈ pump pressure) of a continuous waterjet. For instance, if the pump pressure is 69 MPa (10 kpsi), theoretically the magnitude of the waterhammer pressure is of the order of 560 MPa (82 kpsi).

2. The increase in diameter of each pulse with standoff distance (Fig. 1B).

3. High frequency (20-kHz) of impacts, which contributes to cyclic loading of the workpiece.

A general view of the 2020-RFM (retrofit module) FPWJ generator, which can be used at pressures up to 138 MPa (20 kpsi), is depicted in Fig. 2 [**4**]. It consists essentially of an ultrasonic generator (1.5 kW, 20-kHz), an air compressor (to cool the transducer) and, other control elements to deliver safely electrical pulses to the transducer mounted on the nozzle (see Fig. 3). When connected to an end-user's pump, high-frequency pulses emerge from the nozzle. In the tests described below, it was connected to a Pratisolli pump, which was capable delivering 50 litre/min of water at pressures up to 104 MPa (15 kpsi). Maximum hydraulic horsepower is of the order of 82 kW (110-hp).

4 STRIPPING WITH THE FPWJ

4.1 Initial Trials

Before attempting to remove the HVOF coating on the landing gear pins, preliminary tests were conducted on 300M steel coupons coated with 180 μm (0.007 in) thick WC-Co-Cr HVOF coating to find out if the criteria (concerns) specified by the aerospace industry could be satisfied. A close-up photograph of the coupon illustrated in Fig. 4 clearly shows that FPWJ has removed the hard coating to bare metal finish. The coupon, at the vicinity of coating-metal interface (Fig. 4), was also examined under the scanning electron microscope at IMI-CNRC (Institute for Industrial Materials - National Research Council of Canada). The surface profile, depicted in Fig. 5, is considered to be the same as the original grit-blasted profile, implying that FPWJ did not alter it. The rough shapes of the peaks and valleys would obviously enhance adhesion of the new coating.

4.2 Tests Conducted on Landing Gear Pins

4.2.1 Landing Gear Pins

A number of landing gear pins were provided by Messier-Dowty in Canada. Figure 6 shows typical appearance of the HVOF coated (WC-Co-Cr) and highly polished gear pins. Technical specifications of the pins were:

Substrate material:	Type 4330 C steel
Profile:	127 μm (0.005 in) - grit blast - 120-140 Ra or μm surface roughness
Average thickness:	381 μm (0.015 in)

4.2.2 FPWJ Parameters and Procedure

The operating conditions were:

Pressure:	104 MPa (15 kpsi)
Orifice diameter:	1.37 mm (0.054 in)
Flow rate:	36.3 litre/min (9.6 usgpm)

Hydraulic power: 62.4 kW (84 hp)
Standoff distance: 142 mm (5.6 in)

The procedure involved traversing the nozzle at various feed rates {maximum = 3 in/min (76 mm/min)} over the pin, which was rotated in a turning device (similar to a lathe) at various rotational speeds (maximum = 525 RPM).

4.2.3 Results

Productivity: Obviously, this is quite important. The dimensions of the finished pins shown in Fig. 7 were: 203 mm (8 in) in length and 45 mm (1.75 in) in diameter. The average time taken to finish each pin was about 16 minutes. The multi-step process (chemical, grinding, etc.) described above would probably take a few hours to achieve the same performance.

Surface Finish: Surface roughness (finish) measurements were taken at the top and bottom locations (Fig. 8) prior to and after removal of the coatings. The average values were:

Ra (1): before coating application (that is, grit-blasted substrate) = 3.43 μm (135 X 10^{-6} in)
Ra (2): after the removal of coating = 3.35 μm (132 X 10^{-6} in)

The magnitudes surface roughness are within the range of original grit blasted values (120-140 Ra). Figure 9 shows typical appearance of the pin (finished substrate) examined with a stereoscope. The finish is uniform, free of erosion and pitting damage. These results indicate that once the operating parameters of the FPWJ are optimized, the substrate will experience minimal or no damage.

Dimensional Stability: Several dimensions of the pins were measured as listed below:

D1:	Average outside diameter **before** HVOF coating - **top**:	45.695 mm (1.7990 in)
D2:	Average outside diameter **before** HVOF coating - **bottom**:	45.756 mm (1.8014 in)
D3:	Average outside diameter **after** HVOF coating - **top**:	46.076 mm (1.8140 in)
D4:	Average outside diameter **after** HVOF coating - **bottom**:	46.124 mm (1.8159 in)
D5:	Average outside diameter ***after HVOF stripping*** - **top**:	45.733 mm (1.8005 in)
D6:	Average outside diameter ***after HVOF stripping*** - **bottom**:	45.802 mm (1.8032 in)

The changes in dimensions after stripping the coating from the top and bottom locations are respectively 0.08% and 0.1%. These results unquestionably indicate that the changes are far less than the allowable tolerances, confirming once again, that FPWJ does not alter the original dimensions of the components.

Measurement of Surface Stresses: Measurement of residual (surface) stresses of one of the stripped pins was made using XRD (x-ray diffraction) technique (Fig. 10). Measurements were taken at the top, middle and bottom locations of the pin (Fig. 8). The results are listed below:

Location	Longitudinal Stress, MN/m^2 (kpsi)	Transverse Stress, MN/m^2 (kpsi)
Top	-469.2 (-68.0 ± 1.0)	-462.3 (-67.0 ± 1.0)
Middle	-407.1 (-59.0 ± 1.0)	-441.6 (-64.0 ± 1.0)
Bottom	-441.6 (-64.0 ± 1.0)	-489.9 (-71.0 ± 1.0)

These results indicate that the FPWJ stripped surfaces are in state of compression, both in the longitudinal and transverse directions. This is highly encouraging as surface stresses must be compressive to prevent premature failure of components by fatigue, especially in aerospace industry [**5**].

5 OTHER CONSIDERATIONS

Erosion of Substrate: A major concern with respect to stripping any coating, which is considerably harder than the substrate, is excessive erosion of the latter. However, as the results definitely indicate, this problem did not occur with the use of FPWJ.

Repeatability: Obviously, this is quite important. Surface roughness measurements and microscopic examination of the substrates (Figs. 4, 5 and 9) clearly show that FPWJ satisfies this requirement.

Hydrogen Embrittlement (HE): Briefly, hydrogen embrittlement is a process by which various metals, most importantly high-strength steel, become brittle and crack following exposure to hydrogen. The mechanism begins with hydrogen atoms diffusing through the metal. When these hydrogen atoms recombine in minuscule voids of the metal matrix to form hydrogen molecules, they create pressure from inside the voids. This pressure can increase to levels where the metal starts to lose its ductility leading to formation of cracks. Hydrogen embrittlement can happen during various manufacturing operations or operational use, anywhere where the metal comes in contact with atomic or molecular hydrogen (electroplating is an example). In the case of aerospace components the cracks can act as stress risers. However, according to Department of Defense report [**1**] since high temperatures are involved in the process of HVOF coating, this is concerned to be less of a problem compared to EHC coatings. Obviously, as the FPWJ stripped components are re-coated at high temperatures, **HE** will not be a problem.

Costs: The fact that it took only 16 minutes to strip the pin suggests that the stripping with FPWJ would lead to considerable savings in cost of refurbishing aerospace components. Furthermore, as the hydraulic power was of the order of 60 kW (80 hp), the total energy consumed for processing one pin is of the order of 16 kW-hr. Obviously, both the cost and energy consumption would be considerably less than the multi-step stripping process mentioned above (in the case of chemical dipping, one needs to consider the costs of ventilation and disposal of toxic waste!).

Other factors such as compactness of the FPWJ equipment, low maintenance costs due to fairly low pressure, etc., result in considerable savings. Further savings can be achieved by synergically integrating FPWJ stripping and thermal spray systems, which would allow sharing robotic arms, control systems, etc.

Environmental Concern: Waterjet technique in general uses only pure (tap) water. Since operations with FPWJ are quite fast, it uses less water (if the waste water is filtered and reused, water issue does not even arise). Use of less energy consumption with no chemicals implies reduced emission of CO_2 {CO_2 loading of the environment is: 0.255-kg/kW-hr (0.42 lbm/hp-hr) of energy consumption} and, no chemical vapors into atmosphere or, workplace. Thus, FPWJ stripping process can be considered as operator friendly green viable technology.

6 CONCLUSIONS

The main conclusions from this preliminary investigation are:

- FPWJ technique can remove thermal coatings, in this case, hard HVOF coatings, without causing damage to the substrate at fairly low pressure and energy consumption.
- The surface finish of the substrate is uniform, repeatable and satisfies the requirements of the aerospace industry.
- The stripping process retains the dimensional stability of the components and does not affect the material surface stresses.
- The FPWJ equipment is compact, portable and can be easily integrated with the thermal spray systems to reduce the overall costs of stripping.
- FPWJ uses only pure (tap) water and therefore is a green viable technique for stripping of hard coatings.
- Further work is in progress to certify the technique as safe for applications in aerospace industry.

7 ACKNOWLEDGMENTS

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8 REFERENCES

1. Anon, "Replacement of Chromium Electroplating on landing Gear Components Using HVOF Thermal Spray Coatings," Environmental Security Technology Certification Program (ESTCP) - Cost and Performance Report (PP-9608), U.S. Department of Defense, May 2004.

2. Sartwell, B.D., P.M. Natishan, I.L.Singer, K.O. Legg, J.D. Schell and J.P. Sauer, "Replacement of Chromium Electroplating Using HVOF Thermal Spray Coatings," Paper, AESF Plating Forum, HCAT, March 1998.
3. Yan, W., A. Tieu, B. Ren and M. Vijay, "High-Frequency Forced Pulsed Waterjet Technology for the Removal of Coatings," JPCL (Journal of Protective Coatings & Linings), Vol. 20, No.1, January 2003.
4. Vijay, M.M., W. Yan, A. Tieu and B. Ren, "Ultrasonic Waterjet Apparatus," International Publication Number WO 2005/042177 A1 (May 2005) and U.S Patent Application Publication No. US 2007/0063066 A1, March 2007.
5. Nascimento M.P., M.A.S. Torres, R.C. Souza and H.J.C. Voorwald, "Effect of Shot Peening Pre-treatment on the Fatigue Behaviour of Hard Chromium on Electroless Nickel Interlayer Coated AISI 4340 Aeronautical Steel," Materials Research, Vol. 5, No.2, June 2002.

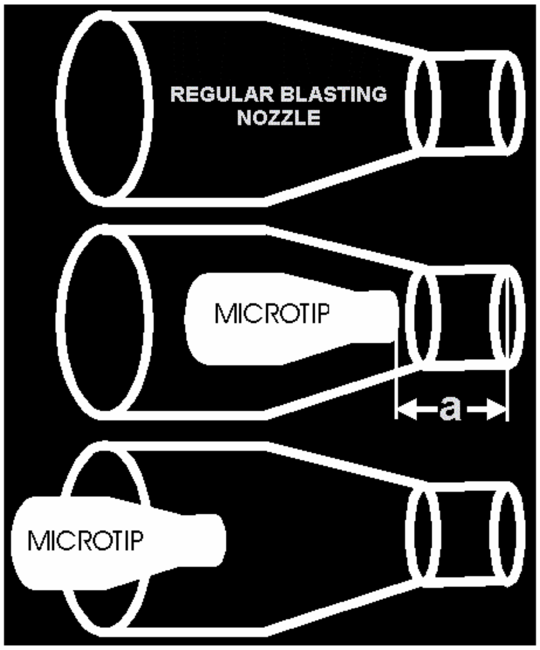

Fig. 1A Modulation method used for producing the FPWJ.

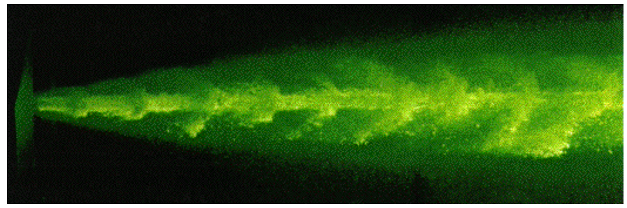

Fig. 1B Photograph of the well-defined and fully developed FPWJ taken with a pulsed Nd-Yag laser [3].

Fig. 2 Model 2020-RFM (pulsed waterjet generator) rated to operate at pressures up to 138 MPa (20 kpsi).

Fig. 3 Photograph showing the assembly of transducer (located in the black cylinder) and the nozzle mounted on a pedestal robot (courtesy of St. Louis Metallizing, USA).

Fig. 4 Close up view of the coating (left) and substrate (right) showing the clean finish achieved with FPWJ stripping.

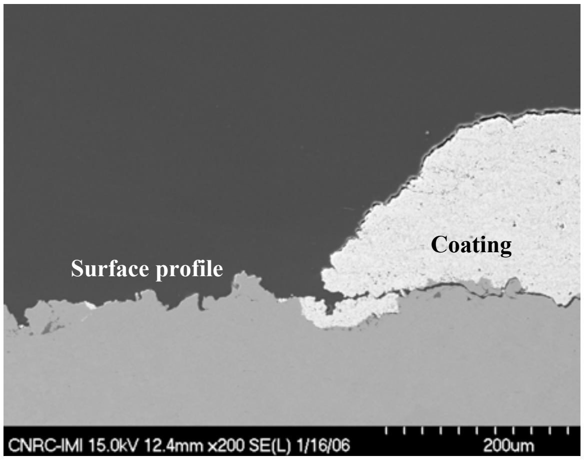

Fig. 5 SEM view of the cross-section of the interface of coating and substrate showing the original grit-blasted profile.

Fig. 6 Highly polished (foreground) and HVOF (WC-Co-Cr) coated landing gear pins received from Messier-Dowty

Fig. 7 A general view of the landing gear pins from which the HVOF coatings were removed with the FPWJ. The untouched part was used for analysis by Messier-Dowty.

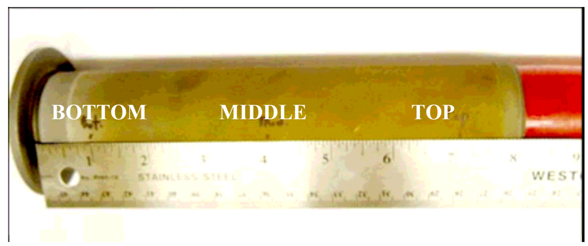

Fig. 8 Location of probes for measuring the residual stresses along the pin after stripping with FPWJ using X-ray diffraction technique.

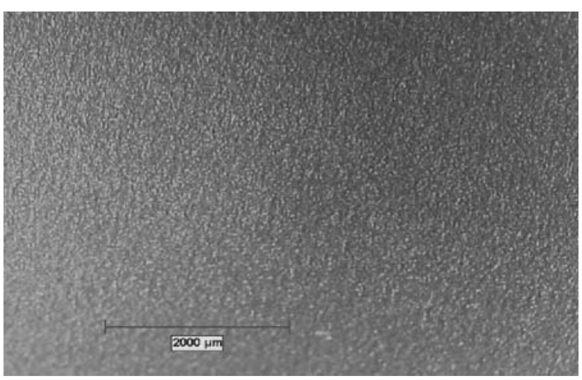

Fig. 9 Typical surface finish of the pin observed with a stereoscope after stripping of the coating with FPWJ.

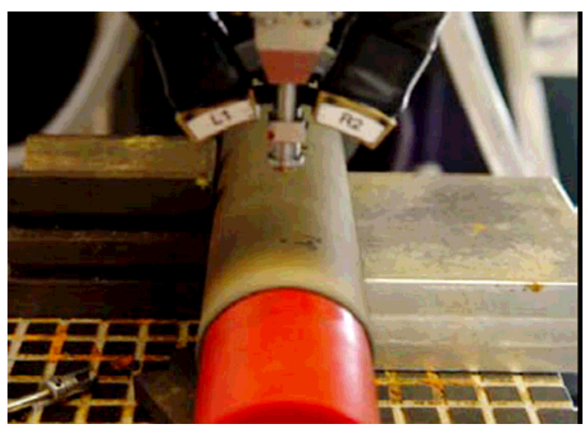

Fig. 10 Set up of the pin in the X-ray machine for measuring residual stresses.