Demonstration, validation and certification of forced pulsed waterjet technique for the removal of coatings from aircraft/aerospace components

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Abstract

Extensive work is in progress in the laboratory to investigate the feasibility of using forced pulsed waterjet (FPWJ) technique for removing a variety of coatings (Chrome, HVOF, plasma) from aircraft/aerospace components. Airworthiness, that is, certification of the technique as safe for aerospace applications requires: (1) demonstration that the FPWJ does indeed remove the coatings without damaging the substrate material and (2) validation that it will not alter the properties of the components (dimensions, compressive stresses, etc.). While demonstration stage has been completed successfully, further work continues to validate FPWJ as airworthy and green technique for the removal of coatings.

1 INTRODUCTION

The collaborative work reported in this paper has been in progress for more than five years (**1, 2 & 3**). The major goal of the work is to seek certification from regulatory agencies in aviation industry to use the patented forced pulsed waterjet (FPWJ) technique for the removal of Chrome, HVOF (high-velocity oxy-fuel) and other types of coatings from aircraft/aerospace components. A number of studies have indicated that hexavalent Chromium, which occurs through oxidation of lower valence Chromium compounds during plating, causes, among other health risks, lung cancer. Therefore, OSHA has issued a final rule on permissible exposure limit (PEL) of 0.5-μg/m^3 (**4, 5, 6 & 7**). Implementation of such stringent requirement would not only make Chrome plating prohibitively expensive, but also would substantially increase turnaround time (TAT) of processing of components. In order to circumvent this problem, several alternative coatings, particularly hard and highly wear resistant HVOF coatings, consisting of Tungsten Carbide (WC), Cobalt (Co) and other thermal spray particles, have been proposed (**5, 6, 7 & 8**). However, as explained by Tieu, et al. (**2**), HVOF coating's intrinsic durability also makes it difficult to be stripped for inspection and recoating. Current stripping methods involve multiple processes such as grinding, wet chemical baths (which may require repeat dips) and grit blasting, depending on the type and thickness of coating. Ultra-high pressure (UHP) continuous waterjet (CWJ), which is used extensively for stripping conventional thermal-spray metallic coatings, has been found to be inefficient for removing HVOF coatings. Preliminary investigations conducted at the request of several aerospace/aircraft companies have shown that FPWJ has a great potential for removing HVOF and other coatings (**1**). The final implementation of the FPWJ technique for stripping of these coatings on a regular basis (both commercial and military), however, will depend on its certification as safe (airworthy) by both national and international regulatory agencies (OEM, FAA, USAF, etc.). Certification requires demonstration and validation (***Dem/Val***) of the technique, which are briefly described in the following **Section**.

2 PROCEDURES FOR CERTIFICATION

Simply stated, the procedures are:

- Demonstration of the technique that it does function as claimed by the provider (OEMs or government organizations) of the technique;
- Qualification, which involves evaluating the technique for (a) performance (effectiveness compared to other existing or proposed techniques), (b) safety (airworthiness, which is legal) and (c) environmental compliance {meeting the requirements of organizations such as, EPA (Environmental Protection Agency of USA)} and (d) operator friendly.

In practice the certification procedure could be quite complex, starting from (**9**):

- Design generation (customer requirements and negotiations with regulatory agency);
- Release of product definition, which involves analysis of design;
- Substantiation of design by calculation and tests, which may involve design changes;
- Substantiation of changes made after tests and before production to meet certification standards;
- Verification and approval by the customer;
- Incorporation of changes into the prototype;
- Certification by the provider and the regulatory agency.

In the case of FPWJ technique for stripping the coatings from aerospace/aircraft components, satisfying the following requirements is quite essential.

- No significant alteration in surface texture (specifications by organizations such as ASME B46.1) – to be evaluated using surface roughness measurements, metallography and SEM/EDX analysis of the surface of the substrate;
- Mass loss expectation – no measurable dimensional changes of the parts (diametric and weight measurements before and after stripping, etc.);
- Does not alter surface compressive stresses of the parts, that is, does not cause premature failure of parts processed with FPWJ by fatigue – to be established by fatigue testing of standard bars (conducted by the end-user);
- Does not cause failure of the parts by hydrogen embrittlement – to be tested by the end-user;
- Does not alter surface and material defects, permitting routine inspections;
- Reproducibility of performance (consistent surface finish, etc.);

- Reliability of the equipment and environmental compliance.

In this paper, highlights of the work done to date are described in the following **Sections**. It must be stated in passing that names of corporations or government agencies for whom or, with whom the work was conducted are not disclosed (due to confidentiality agreements) in this paper (except ES3 and Messier-Dowty).

3 TECHNICAL BACKGROUND

The method used for generating FPWJ by modulating a continuous stream of water has been reported in several publications (**10**). As described thoroughly by Bai, et al. (**11**) and by Vijay, et al. (**12**), high-frequency pulses of water are generated by modulating a CWJ by locating a probe (microtip) inside the nozzle driven by an ultrasonic transducer-generator assembly. When a pulse of water impinges on a target, the pressure of impact is the waterhammer pressure, which is considerably higher than the normal stagnation pressure. For example, if the operating pressure of the pump were 69-MPa, the impact pressure of a pulse would be of the order of 550-MPa. Although the duration of each impact is quite short (≈ 1-μs), the combination of high frequency (20-kHz) and high impact pressure makes the material to yield quite readily. In simple terms, this means that if a certain job can be done with a CWJ, the same job can be done at much lower pressures using FPWJ. As a consequence, the pulsed waterjet machines are compact in size, portable, safe to operate, environmentally compatible, user friendly, and as affirmed by Messier-Dowty, is green viable technology (**2**). Furthermore, these machines offer another attractive feature. That is, they can be operated in FPWJ mode or, CWJ mode simply by turning on or off the ultrasonic generator. Thus, the machines can be used for the removal of hard or soft coatings (**10**).

4 EXPERIMENTAL WORK

4.1 Demonstration

As stated above, the purpose of demonstration is to prove to the end-users the effectiveness and potential of FPWJ for stripping a variety of coatings from aircraft/aerospace components without damaging the substrates. From this perspective, some of the interesting and most challenging applications are illustrated in Figs. 1 to 7. All tests were conducted on an X-Y gantry or, using a five-axis Kawasaki robot or, using a hand-held gun to illustrate all operating possibilities. The highlights are:

Figure 1: These simple tests were conducted for an airline corporation. FPWJ removed the 1.27-mm thick HVOF (WC-Co) coating quite readily at 103.5-MPa. The surface finish achieved in tests #11 & 12 were considered to be excellent by the airline.

Figure 2: The results depicted in Fig. 2 were obtained for a landing gear company. A single-orifice nozzle (d = 1.372-mm) at P = 69-MPa was used to remove the HVOF coating from the landing gear pin. The surface finish (profile) was considered to be excellent by the client (Fig. 2C).

Figure 3: Removing epoxy coating from landing gear components is illustrated in Fig. 3. The coating was effectively removed to Cadmium base at a pressure of only 69-MPa. The surface finish, depicted in Figs. 3B, C, E and F, was considered to be excellent by the client.

Figure 4: In this figure removing HVOF coating from an aircraft frame is depicted. The magnitudes of A_s and E_s were respectively were the order of 0.4-m^2/hr and 85.0-kWhr/m^2 at a pressure of only 69-MPa.

Figure 5: A hand-held gun consisting of a dual-orifice (d = 1.02-mm of each orifice) rotating nozzle at 69-MPa was used for stripping hard coatings (e.g., aluminized epoxy and varnish) from the outer surfaces of the propeller gear box and housing.

Figure 6: To remove several types of coatings from the complex parts shown in Fig. 6 was quite challenging. Soft coatings shown in Fig. 6A, were removed with the FPWJ at pressures $\leq$ 34.5-MPa. HVOF coatings on the bore of the PT support (Fig. 6C) and the balance piston wheel teeth (Fig. 6E, F) were removed (including the grooves) at pressures of the order of 90-MPa, the durations ranging from 30 to 150-s. Plasma coating on the inner surface of the compressor was removed at 83-MPa in less than 90-s. The surface finishes of all the parts were assessed to be excellent by the aircraft corporation.

Figure 7: Removal of thermal barrier coating from the combustion chamber outer liner is illustrated in Fig. 7. It is obvious from the close-up view of the chamber that FPWJ at a pressure of the order of 100-MPa was quite effective in removing the coating without damaging the surface.

In summary, the tests under “demonstration” did confirm that FPWJ is indeed quite effective for removing several types of coatings from complex aircraft/aerospace parts.

4.2 Qualification

The first series of tests to qualify the FPWJ process was conducted in collaboration with Messier-Dowty (**2 & 3**). The samples were landing gear pins (Fig. 8) coated with 0.38-mm thick WC-Co-Cr (as sprayed). The observations from this very preliminary and limited study were:

- The surface finish of the substrate was excellent (see Fig. 8).
- The surface residual stress measurements made with XRD (X-ray diffraction) showed that cyclic loading of FPWJ did not alter the compressive material surface stresses of the pin.

Following these highly encouraging observations, further work was conducted in collaboration with ES3. Typical results achieved in this collaborative project are depicted in Figs. 9 to 15. Relevant data and observations are summarized in **Table 1**.

5 DISCUSSION

Qualitatively, close-up photographs are useful for recording visual observations of the substrate (damage, finish, flash rust, etc.). Although excessive damage (deep pitting etc.) disqualifies the process of stripping, certain degree of erosion (which needs to be quantified by microscopic measurements and metallography) is necessary for creating good surface profile. On some coupons flash rust did occur, which can be eliminated by adding rust inhibitors to water (in the case of HVOF coating, the rust would not be problem). The term “excellent” stated in **Table 1** was based on visual observation of the coupons after stripping with the FPWJ. The photographs also assist, to some extent, to understand the mechanism of removal of the coatings from the substrate material.

Although a detailed description is beyond the scope of this paper, the dominant mechanism appears to be peeling (flaking) for Chrome and, erosion in the case of HVOF (that is, removing particles from the substrate). To summarize, visual observation of the surface of the coupon after conducting a test at a particular set of operating parameters was useful in assessing the quality of surface finish obtained (see Fig. 14).

Quantitative assessment of the effectiveness of FPWJ for stripping was based on measuring before and after stripping: (1) surface roughness, (2) dimensions of the coupons and (3) mass of coupons. The term "excellent" in **Table 1**, based on the measurements of R_a, dimensions and masses of the coupons before and after stripping, implies that FPWJ would meet the "surface texture" criterion required for qualification (see Fig. 14). However, from the standpoint of productivity and energy consumption, the magnitudes of A_s and E_s are also quite important. The following observations are noteworthy:

- As anticipated, depending upon the type of coating, the magnitudes of A_s and E_s vary significantly.
- For hard Chrome on 4340, the values of A_s and E_s were better for the 1.372-mm orifice compared to the 1.626-mm orifice. For Chrome on 300M, on the other hand, the reverse seems to be the case. The magnitude of A_s increased from 0.61 to 4.87-m^2/hr (by a factor of eight) when the orifice diameter was increased to 1.626-mm. It is not clear if this variation is due to the variation in the method of plating the coupons. Further work is obviously required to confirm this effect.
- The stripping rates of HVOF from 4340 steel (as sprayed or ground) were observed to be higher than the rates of stripping of HVOF from 300M. It appears that while 300M was sprayed with WC-Co using the JP8000 system, 4340 was sprayed with WC-Co-Cr using the DJ2600 system. It is not clear whether this difference in composition and particle size distribution or, the method of coating contributes to this difference in performance. It is also quite likely that the adhesion process of particles in HVOF coating is not well understood, and may be the reason for performance variation. Finally, the difference in performance could be due to the differences in microstructural material matrices of 4340 and 300M steels. Understanding these factors would make it possible to enhance the performance of stripping with FPWJ.
- Another interesting observation in the case of 4340-HVOF is increasing the thickness from 0.127 to 0.254-mm did not decrease the stripping rate (it remained constant at 0.362-m^2/hr). This observation suggests that adhesion (bond) strength, rather than the thickness, is probably more important from the standpoint of stripping.
- In the case of HVOF on 300M, the effect of thickness on A_s is not clear. When the thickness increased from 0.076-mm to 0.216-mm, the stripping rate decreased from 0.121 to 0.06-m^2/hr. However, for the 0.4445-mm thick coating, stripping rate increased to 0.093-m^2/hr. A plausible explanation is that the process of coating thick layers may be different than coating thin layers.
- The magnitudes of E_s varied significantly in stripping the coupons, the minimum & maximum being respectively 13.6 to 1,035-kWhr/m^2, the goal being to keep it as low as possible. There are several steps to accomplish this goal. As the stripping rate is a function of the width of coating removed per pass and traverse speed of FPWJ, it is possible to increase both by increasing the pressure for a given nozzle diameter. Other possibilities are employing single-orifice oscillating or, dual-orifice rotating nozzles.

- Surface finish and dimensional stability (that is, no significant changes in the outside diameters of the coupons) were considered to be excellent. Additionally, weight measurements of stripped coupons showed that material loss due to FPWJ stripping process was negligible.
- It should be noted from Fig. 15 that CWJ at the same operating parameters as FPWJ was ineffective in stripping the HVOF coating from the 300M coupon.

6 CONCLUSIONS

Basically, the main conclusions from the continuing investigations are:

- All demonstrative tests have clearly shown that FPWJ is very effective in removing several types of coatings from a variety of complex aircraft/aerospace components.
- Tests conducted to date to affirm qualification of the FPWJ for stripping are highly promising.
- Stripping results (finish etc.) were highly uniform and reproducible.
- Mass loss and dimensional changes caused by the stripping process were within acceptable levels.
- Performance, as measured by removal rate and specific energy values, are significantly better than the values achieved by other processing techniques (chemical dipping, grinding, etc.)
- FPWJ process is environmentally and user friendly as it only uses water (green viable technology).
- More extensive work is required to receive certification from regulatory agencies (prior to submitting this paper, cursory tests on coupons for fatigue and hydrogen embrittlement evaluation of the FPWJ stripping process have been completed. These results will be available by the end of this year).

7 ACKNOWLEDGMENTS

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9 NOMENCLATURE

A_s: Removal rate of the coating, m^2/hr
d: Orifice diameter, mm
E_s: Specific energy, kWhr/m^2
P: Pump pressure, MPa
R_a: RMS value of surface roughness, μm
S_d: Standoff distance, mm
V_{tr}: Traverspeed of the nozzle, mm/min
T_c: Thickness of coating, mm

Table 1. Summary of relevant experimental data

Surface finish: ***<u>EXCELLENT</u>***

Figure #	P (MPa)	S_d (mm)	V_{tr} (mm/min)	Remarks
9 Chrome-steel	96.6 ≈100	≈ 100	0	d = 1.016 Exposed for 60-s. No damage.
10 Chrome on 4340 steel	86.2	76.2	127.0	d = 1.626 T_c = 0.076-0.127 $1.93 \leq R_a \leq 2.39$ $A_s = 0.604$, $E_s = 110.8$
Chrome on 4340 steel	96.6	101.6	254.0	d = 1.372 T_c: same as above $A_s = 1.217$, $E_s = 46.6$
11 Chrome on 300M steel	86.2	76.2	1,016.0	d = 1.626 T_c = 0.076-0.127 $0.91 \leq R_a \leq 1.22$ $A_s = 4.87$, $E_s = 13.64$
Chrome on 300M steel	96.6	101.6	127.0	d = 1.372 T_c: Same as above $1.02 \leq R_a \leq 1.75$ $A_s = 0.61$, $E_s = 92.70$
12 HVOF on 4340 steel	103.5	146.0	76.2	d = 1.372 T_c = 0.076-0.127 $2.56 \leq R_a \leq 3.45$ $A_s = 0.362$, $E_s = 172.6$
HVOF on 4340 steel	103.5	146.0	76.2	***<u>Increased thickness</u>*** d = 1.372 T_c = 0.203-0.254 $A_s = 0.362$, $E_s = 172.6$
13A HVOF on 300M steel	103.5	146.0	25.4	d = 1.372 T_c = 0.076-0.127 $2.11 \leq R_a \leq 2.49$ $A_s = 0.121$, $E_s = 517.7$
13B HVOF on 300M steel (as sprayed)	103.5	146.0	12.7	d = 1.372 T_c = 0.216 $2.84 \leq R_a \leq 3.76$ $A_s = 0.06$, $E_s = 1035.4$
13C HVOF on 300M steel (as sprayed)	103.5	146.0	12.7	$3.56 \leq R_a \leq 3.86$ Same results as **13B**, indicating good reproducibility.
13D HVOF on 300M steel (as sprayed)	103.5	146.0	19.05	d = 1.372 T_c = 0.4445 $2.24 \leq R_a \leq 2.39$ $A_s = 0.093$, $E_s = 673.4$

Fig. 1. Removal of 1.27-mm thick HVOF (WC-Co) coating from steel substrate at 103.5-MPa at various traverse speeds (tests conducted for a US airline).

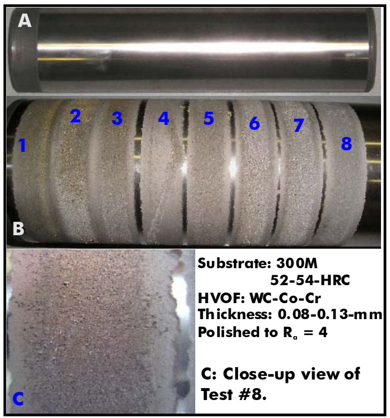
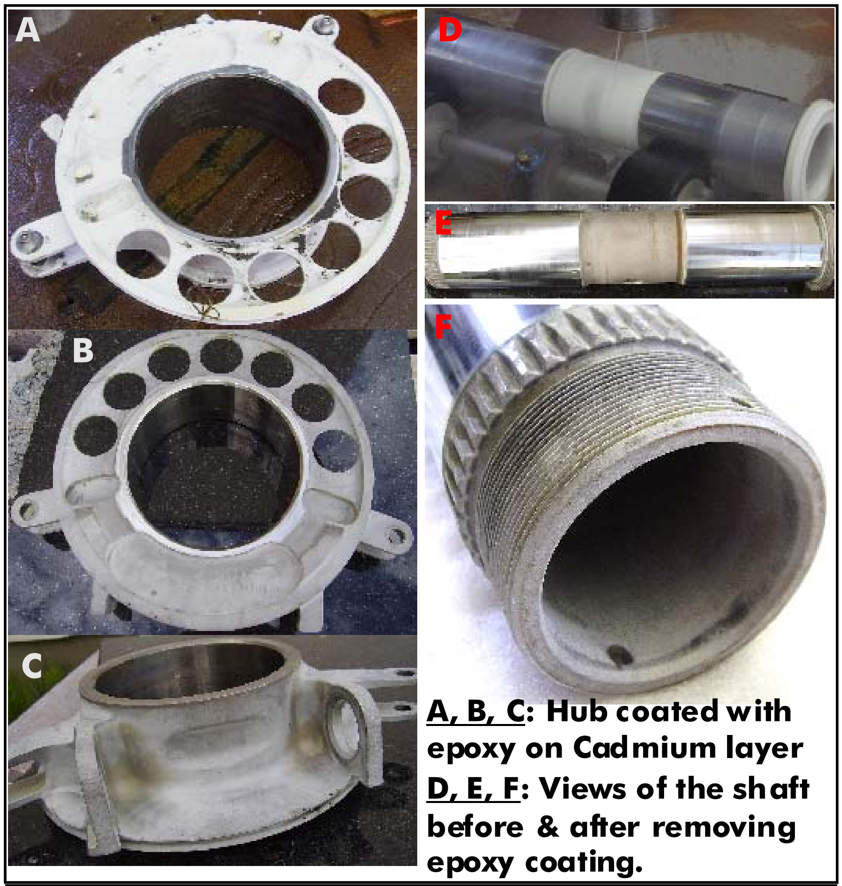


Fig. 2. Removing HVOF coating from highly-polished landing gear pin.



<u>A, B, C</u>: Hub coated with epoxy on Cadmium layer

<u>D, E, F</u>: Views of the shaft before & after removing epoxy coating.

Fig. 3. Removing epoxy coat on Cadmium base of landing gear components.

Fig. 4. Removing HVOF coating (specification not known) from aircraft frame.

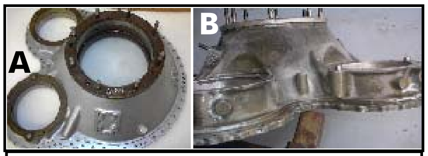


Fig. 5. Stripping of hard coatings (aluminized epoxy and varnish) from propeller gear box and housing.

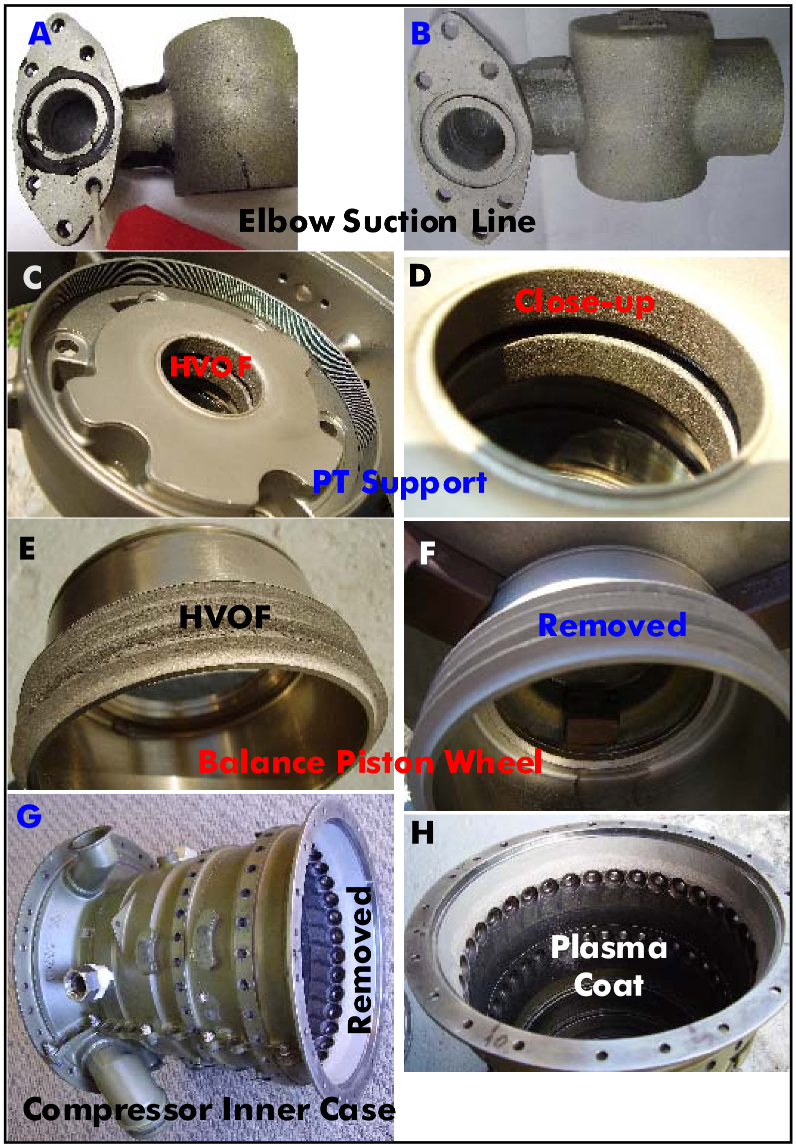


Fig. 6. Removing several types of coatings/sealants from a variety of aircraft parts.

Fig. 7. Removing thermal spray barrier coating from the inside surface of a combustion chamber.

Fig. 8. Removal of 0.381-mm thick HVOF coating (WC-Co-Cr) from a tapered landing gear pin (300M steel, HRc 53-55). Conducted in collaboration with Messier-Dowty.

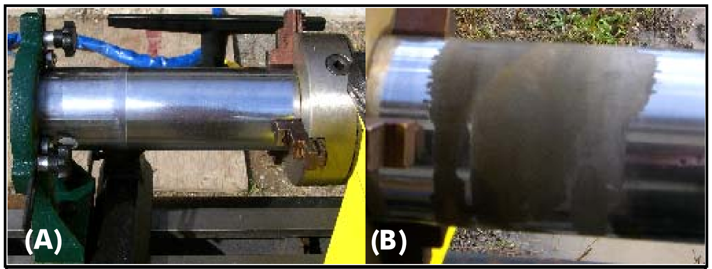


Fig. 9. Removal of 0.24 to 0.38-mm Chrome from cylinders (rejected landing gear parts). (A) before exposure to FPWJ, (B) surface finish after removal. Conducted in collaboration with ES3.

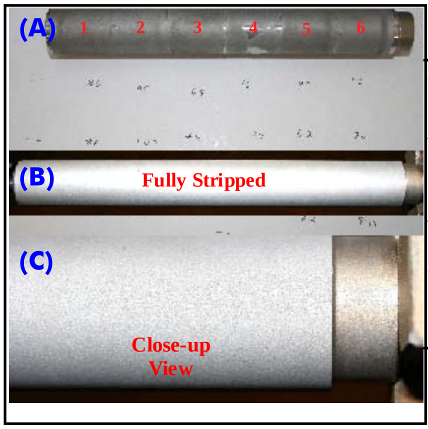


Fig. 10. Stripping 0.076 to 0.127-mm thick Chrome from 4340 steel cylindrical coupons. The handwritten numbers in (B) are the R_a values measured before and after removing the coating. Pressure = 86-MPa Conducted with ES3.

Fig. 11. Stripping 0.076 to 0.127-mm thick Chrome from 300M steel cylindrical coupons. R_a values are indicated.
Pressure = 86-MPa. Conducted with ES3.

Fig. 12. A close-up view of the 4340-steel cylindrical coupon from which 0.076 to 0.127-mm thick HVOF (WC-Co or, WC-Co-Cr) coating was removed at 103.5-MPa. Conducted with ES3.

Fig. 13A. Removal of 0.076 to 0.127-mm thick HVOF from 300M. Conducted with ES3.

Fig. 13B. Same as in Fig. 13A, except thickness = 0.203-mm.

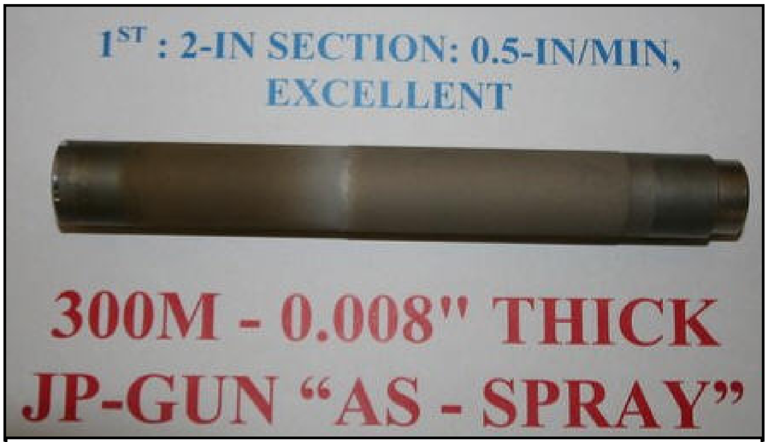


Fig. 13C. Same as in Fig. 13B, except for different method of coating.

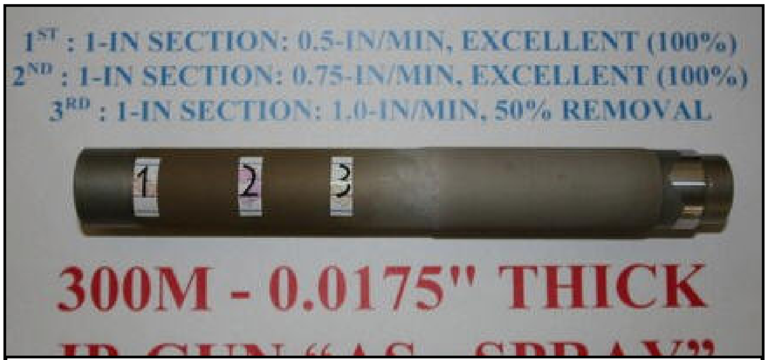


Fig. 13D. Same as in Fig. 13C, except thickness = 0.444-mm.

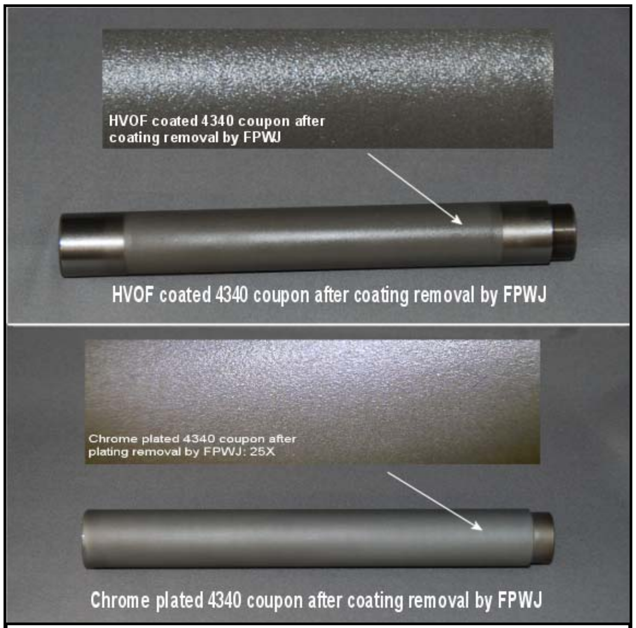


Fig. 14. Surface texture characteristics observed with a microscope. Magnification = 25.

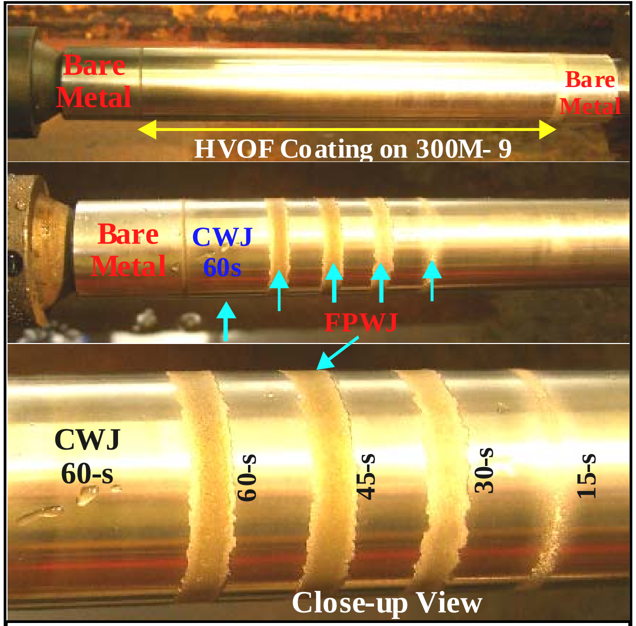


Fig. 15. Comparison of the performance of FPWJ with the CWJ for removing HVOF coating at the same operating conditions (d = 1.372-mm, P = 103.5-MPa).