Stripping of coatings and prepping of surfaces with waterjets: basic considerations

Vijay, M., A. Tieu, W. Yan, B. Daniels and M. Xu
VLN Advanced Technologies Inc., Ottawa, Canada, K1J 9M7

ABSTRACT

Over the past several years, working with a number of aerospace organizations, the authors have conducted extensive work on stripping of a variety of coatings from metallic substrates with the forced pulsed waterjet (FPWJ) and continuous Waterjet (CWJ). This has resulted in understanding the effect of both operating variables and microstructural properties of coating and the substrate materials on stripping and prepping processes. The investigations have clearly indicated the close relationship between the stripping and coating processes. The irregularities in stripping and prepping (for example, surface profile after stripping) are due to the irregularities in the coating process itself.

1 INTRODUCTION

As elegantly stated by Torpey (***1***), "as water is the oldest cleaning medium known to man," interest in using water for cleaning belongs to history. To appreciate where the technology is today for stripping and prepping, it is equally fitting to note the statement by Gronauer (***2***), "Obviously since water has no abrading power, well bonded materials such as paint, epoxy, vinyl, etc., cannot be removed with water alone, ***regardless of the pressure***." As is evident from the references listed in this paper (listed chronologically), it is now possible to strip epoxy coatings at pressures of the order of 15MPa (3**,** 4**,** 5) and, very hard coatings (7 to 13, 15 to 20, 26), prepping (22, 24, 27, 28, 29, 30) and peening (21, 23, 25) at pressures of the order of 69MPa with the FPWJ. It is quite likely that in the not too distant future FPWJ (27) or, coating particle (not grit)-entrained *cp*FPWJ (28, 30), could replace grit blasting for prepping the surfaces, as there appears to be some concern about the safety of grit blasting (14).

Working with several international collaborators in aerospace sector (starting with ATK Thiokol, sub-contractor to NASA in 2002-2003), the authors have conducted extensive series of tests on stripping coatings, etc., with the FPWJ technique (typical appearance of the high-frequency pulses is illustrated in Fig. 1). Some of the challenging applications are depicted in Fig. 2 (also Table 1). Where possible, its efficacy has been compared to that of the CWJ (3, 9). Observations from these investigations have led to the basic (rather preliminary) understanding of the stripping and consequently prepping the surface, including peening (this work is still in progress). Although a great deal of attempt has been made to understand the mechanism of removal of a coating (13), it would be virtually impossible to arrive at complete understanding as the coating process is quite complex (6). For example, coating a component (substrate) with Chrome (coated by Chromic acid) is quite different compared to coating it with HVOF (for example, using WC-Cr-Co particles). The mechanism of removal of Chrome appears to be different compared to HVOF. While Chrome comes off as flakes (spalling), the ground HVOF is removed more uniformly (that is, grain by grain). However, spalling occurred when stripping "as-deposited" HVOF. The spalling may be due to the removal of each consecutive layer of coating (from top to bottom) as the total thickness of coating on the part (coupon) is obtained by multiple passes of the coating gun. That is, spalling is probably due to delamination of successive layers. In any case, while spalling does improve removal rates, does it contribute to other irregularities observed in the investigations?

In this paper, highlights of these irregularities (remnant coating in the substrate, surface profile, etc.) are presented. Although the data considered are based on stripping and prepping (peening is still under investigation) with the FPWJ, it is believed that these observations are equally valid for stripping with the CWJ. It should be noted in passing that these investigations are quite expensive.

2 MAGNITUDE OF REMNANT COATING

In one of the investigations on testing the effect of stripping on fatigue life of the coupons (Fig. 9), close-up examination showed (barely visible with the naked eye), some tungsten particles remained in the substrate (4340 steel). However, it was not clear how much coating remained and what is the allowable tolerance (ppm), for example, in large parts such as landing gears (not only by the CWJ, FPWJ but also conventional mechanical and chemical removal methods). In order to resolve this concern, stripping tests were conducted on small sections, distributed on the perimeter, as indicated in Fig. 3. The objective was to find out if anisotropy of the coating (hardness, thickness, microstructure of WC-Cr-Co and surface profile of steel) in the axial and radial directions would influence stripping. Typical results obtained with the EDS spectrum and SCM are illustrated in Fig. 4. Close-up photographs of the pin in Fig. 4G show the defects in the coating.

While Figure 4A shows EDS spectrum of the coating before stripping, Fig. 4B shows after stripping. Figure 4C shows striations in the coating caused by grinding. All discs cut from the cylindrical pin shown in Fig. 3 had a small percentage of tungsten more or less uniformly distributed in the steel (Fig. 4D). Figure 4E shows microfractures (or, surface profile after stripping) in the substrate and Fig. 4F shows particles of W (Tungsten), possibly imbedded in the microfractures of iron forced by the jet. Although not indicated in Fig. 4A, the area over which the scan was made is $\approx 0.01\text{-mm}^2$ located somewhere in an area of 4.41-mm^2. The number of particles (counts) of W in this area was of the order of 200, which is about 0.02ppm/mm^2, which is considered to be insignificant (according to one confidential source, 10-percent of remnant coating is believed to be acceptable). The EDS also found that the percentage of remnant particles varied around the circumference, indicating the deficiencies in the coating (could be due to varying bond strength; as discussed elsewhere, thickness or hardness do not appear to influence stripping significantly). It is not clear if the grinding process influences stripping (it appears to influence hardness of the coating). It is interesting to note that in one of the scans of a small area, the number of iron particles before stripping was about 1300 and after stripping about 900, indicating loss by erosion. This is how the surface profile occurs, that is, by erosion. In summary, in large industrial parts, it would not be possible to conduct EDS and, if the remnant coating is an issue, all one has to do is to strip it again at the same operating parameters (pressure, horsepower and standoff distance) perhaps at a higher traverse speed.

3 INFLUENCE OF HARDNESS OF COATING

Variation of Vickers microhardness (H_v) in the axial direction of several HVOF (WC-Cr-Co) 300M steel pins is shown in Fig. 5. The variation does not come as a surprise as the measurements depend on the size of indenter and, where it indents on the pin. For example, the Vickers hardness of WC is approximately 2100 and that of Chromium is ≈ 1000. Therefore, if the indenter strikes WC, the hardness would be higher. Also, as pointed out before, the grinding of the coated pin is believed to influence the hardness (see the striations in Fig. 4C). Several tests were conducted to find out if hardness has any effect on stripping process, particularly the surface profile {measured by R_a and R_z; from the standpoint of bond strength of the coating, R_z is more relevant (6)}. Typical results are listed in Fig. 6. Observations are:

- Effect of grinding the coating (polishing) does not have a significant effect on the surface profile (R_z values are slightly lower at section #5);
- For any section, roughness values of the substrate are higher than the coating, indicating generation of surface profile by erosion;
- There is no significant variation in the values of R_a and R_z indicating that hardness does not influence the stripping process. These values are considered to be excellent for achieving good bond strength of HVOF (18).

These observations are encouraging as hardness of the coating by any coating technique is not easy to control (6).

4 INFLUENCE OF THE THICKNESS OF THE COATING

Depending on the application of the part, the thickness of the coating can vary from 0.05 to 0.2-mm (note: in the thermal barrier coatings, the thickness of the top ceramic coating can exceed 1.0-mm; however, since ceramic is very brittle, stripping it with the jet is quite easy). On one of the pins, shown in Fig. 7, thickness of the WC-Cr-Co varied from 0.0432 to 0.114-mm. The R_z values of the coated pin varied somewhat from section to section as indicated (probably due to grinding). However, after stripping (shown by the bands), there is no systematic variation in the values of R_z. As mentioned elsewhere, the lower values of 10.4 and 10.7-µm, could be due to the defects in the coating. This is emphasized in Fig. 7B. At identical operating conditions (P = 103.5-MPa), while the coating was stripped effectively in one section of the pin, several spots of the coating remained in the other section.

5 RESIDUAL STRESSES BEFORE AND AFTER STRIPPING

On some of the bands on the pins residual axial and hoop stresses were measured, by XRD (X-ray diffraction), before and after stripping. The measurements were at the centres (indicated by the dotted line) of nine, equally spaced locations, indicated in Fig. 8. The results, obtained at three sets of operating conditions, are summarized in the table below Fig. 8. The observations are:

- The scatter in the data once again confirm the anisotropy of the substrate itself, perhaps contributed by the coating process;
- All residual stresses, both axial and hoop, are compressive. This is encouraging as tensile stresses are undesirable (see **Section 6**);
- The values at locations 1 and 9 are higher compared to the other lines. This is probably due to the proximity of these lines to the coating;
- However, the magnitudes have decreased compared to the pre-shot peened and post-shot peened values. Whether this reduction is significant or not, is not clear because, according to Hultman and Sundgren (6), the coating process itself will alter the magnitudes of the post-shot peened values (the stresses at the interphase of the coating and the substrate must be balanced. Otherwise delamination of the coating will occur. Further discussion on this is beyond the scope of this paper);
- Generally, the coating process will reduce the magnitudes of the compressive stresses, especially for HVOF process (due to high temperature of the flame). As an example, if 20-percent reduction occurs after coating, then for P = 69MPa, the average post-shot mean $\sigma_c \approx$ -900MPa and the stripping reduces the magnitude to an average value of -498 (45%);
- If one disregards the scatter in the data, conceptually, the magnitude of σ_c can be correlated with the magnitude of R_z (6). The magnitudes of R_z for the third set (103.5MPa) and the first set (69MPa) are respectively 13.3 and 16.0μm. Therefore, the reduction in the magnitude of σ_c from -554 (587) to -498 (461) bears this out.
- It is obvious from these results that peening with waterjet of the substrate will not happen if erosion (necessary for prepping) occurs. Peening will definitely happen (simple work hardening) if the pressure is kept below the threshold pressure (inception of erosion). Further discussion ensues in **Section 7**.
- The fact that the stresses are compressive implies that stripping by the FPWJ will not significantly affect the fatigue life of the component (substrate). If it does, then peening the component with the CWJ (21, 23, 25) or, FPWJ (study in progress) following stripping will enhance fatigue life.

6 FATIGUE TESTS

Fatigue bars used for this investigation are illustrated in Fig. 9 (it appears that shapes vary from one organization to the other). The first series of tests was conducted on an ***ad-hoc*** basis, without paying any attention to the changing geometry of the bar. The data listed in Table 2 were obtained at variable traverse speeds at constant values of: P = 103.5, d = 1.37, S_d = 146 and N_r = 60, selected randomly.

In this series of tests, the robotic arm was not programmed to follow the curvature and consequently the S_d varied from the cylindrical section to the gage section. Also, since N_r is constant, for a given V_{tr}, the dwell time over the gage section is higher than the cylindrical section.

For the stresses listed in the first column, comparison of the cycles (N_f) clearly shows there is great deal of irregularities. For instance, for the Ti 6AL-4V with as sprayed HVOF, N_f = 150,800. The values were 134,400 (***b***) and 279,000 (***c***) after stripping. Why it decreases for τ = 0.1092 and increases for τ = 0.1422 is hard to explain. The same is true for the 15-5PH coated with the HVOF (last two rows).

The tests in the second series of tests were conducted more carefully and systematically, programming the robot to closely follow the profile. Furthermore, the fatigue bar had the hour-glass shape with a gradual variation in the curvature (31). As comprehensive set of results has been reported by Field, et. al (26), only sample results are listed in Table 2. These results basically confirm the observations made in **Section 5**, that is, variations in fatigue life are due to the reduction in residual stresses after stripping. The fatigue life can be improved by reducing the operating pressure from 103MPa (to ≈ 69MPa). Furthermore, as pointed out in that **Section 5**, peening after stripping, would improve fatigue life. It should be noted that fatigue life of FPWJ stripped coupons appear to be significantly better than mechanical stripping (grinding). In summary, stripping the coatings with the FPWJ will not deteriorate fatigue life of the components if appropriate steps are taken.

7 PREPPING THE SURFACES

As is well known, the main purpose of prepping a surface is to ensure strong adherence of the coating to the substrate material (22**,** 24, 29***;*** the latter is an excellent reference). However, generally these publications refer to prepping surfaces by grit blasting. More recent work seems to suggest that surfaces can be prepped by CWJ (22). Experimental work is in progress to investigate the efficacy of prepping the surfaces with the FPWJ (27). Figures 10A, 10B and 10C clearly show that it is possible to prep metallic surfaces to any degree of roughness with the FPWJ at pressures of the order of 69MPa. Figures 10D and 10E show the prepped internal surfaces of aluminum alloy bores. While the former was prepped with the CWJ at 380MPa, the latter was achieved the FPWJ at 69MPa. Although FPWJ can prep the metallic surfaces, the rate of prepping would be considerably slow for hard metals such as steels. This can be circumvented by using AFPWJ (abrasive-entrained forced pulsed waterjet) for prepping. However, the abrasive particles are not conventional grit particles. As explained by Vijay (28, 30), the particles are the same as the substrate material, albeit harder. This would eliminate the problem of imbedding a foreign particle (grits such as aluminum oxide) in the atomic matrix of the substrate, which could become stress concentration points. Figure 10F shows outer surface of a tube prepped at pressures of the order of 21MPa by entraining Tungsten particles in the AFPWJ (*cp*FPWJ; *cp* indicates '*coating particle*' as Tungsten particles are used for coating).

In order to verify if prepping with the FPWJ would enhance the adherence of the coating, as shown in Fig. 10G, etc., a few 25.4-mm diameter aluminum bond plugs were prepped with the FPWJ (G, I, J) to various profiles (too rough to be measured by profilometer). Plug H was prepared by conventional grit blast to 4μm. Aluminum cold spray powder was applied (tests conducted at the University of Ottawa). Preliminary results of pull test showed plug H failed at the coating and substrate interface (H1), meanwhile plugs G, I, J all failed at glue (G1, I1, J1) at higher loads, suggesting significantly higher bond strength. In fact, when plasma coating was used, the bond strength improved almost by a factor of eight. Further work is in progress for other coating techniques.

8 CONCLUSIONS

The conclusions from the extensive work conducted on stripping over a period of more than a decade are:

- The irregularities observed in stripping the substrates are due to the deficiencies that occur in the coating process itself.

- CWJ (although at very high pressures) and FPWJ are quite safe for removing hard coatings.
- The prepping achieved with the FPWJ and *cp*FPWJ appear to enhance the bond strength of the coating compared to that of grit blasting.

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10 NOMENCLATURE

A_p: Area removal rate of coating, mm^2/min
*cp*FPWJ: Coating particle (not grit such as, garnet) entrained pulsed waterjet

d: Diameter of the orifice, mm
H_p: Hydraulic power, kW
N_r: Rotational speed of the sample, RPM
N_f: Number of cycles in fatigue measurements (to failure or, where the testing was stopped)
P: Operating pressure, MPa
R_a: Root mean square surface roughness, μm
R_z: Peak to valley surface roughness, μm
S_d: Standoff distance, mm
V_{tr}: Traverse speed of the jet, mm/min
σ_c: Residual stress, MPa (-ve value indicates compressive)
τ: Thickness of coating, mm

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Table 1. Several types of coatings removed from various substrates.

Substrate Materials	Coating	Comments
Inconel 625	TBC	The coatings listed have been removed from rectangular, cylindrical and complicated aircrafts parts with the FPWJ. These investigations have been conducted and continue to be conducted for both military and commercial organizations. Surface finishes have been accepted as excellent. Not listed are: several types of marine epoxy coatings investigated for the navy, both Canadian and US (see for example, Refs. ***3***, ***4***). See Figs. 2 and 10 for typical appearances of surface finish.
Inconel 718	WC-Co	
Inconel 718	718 Inc. HVOF	
Inconel 718	73 mxc Arc Wire Spray	
Inconel 718	T-800	
Inconel 718	Cr-C	
Inconel	NiCrAlY	
1020 Steel	1343VM HVOF	
410 S.S	SermeTel “W”	
300M	WC-Co-Cr	
300M	Cr	
300M	WC-Co-Cr	
4340	Cr	
4340	WC-Co-Cr	
4340	WC-Co-Cr	
4340	Cr	
4340M	WC-Co-Cr	
Magnesium Alloy	Aluminized epoxy enamel	
15-5PH	WC-Co-Cr	
15-5PH	Cr	
Ti 6AL-4V	WC-Co-Cr	
Ti 6AL-4V	CuNiIn	
Al 6061	NiAl	
Al 1100	WC17Co	
Composites	Epoxy coatings	Aircrafts

Table 2. Some fatigue data.

1st Series of conducted on an *ad-hoc* basis (sample results)				
Substrate	**Coating**	**Thickness (τ)**	**Cycles in fatigue testing (N_f)**	**Remarks**
a: Ti 6Al-4V Stress: 759MPa	No coating (bare)	Not applicable	150,800	**See "*b*" below.**
b: Ti 6Al-4V Stress: 759MPa	WC-10Co-4Cr ***As sprayed***	≈ 0.1092	134,400	**See "*a*". V_{tr} = 25.4**
c: Ti 6Al-4V Stress: 759MPa	Bare	Not applicable	158,000	**See "*d*"**
d: Ti 6Al-4V Stress: 759MPa	WC-10Co-4Cr	≈ 0.1422	279,000 Life increased	***See "c"*** V_{tr} = 25.4
e: 4340 Stress: 966MPa	Bare	Not applicable	142,600	**See "*f*"**
f: 4340 Stress: 966MPa	WC-10Co-4Cr **As sprayed**	≈0.1422	1,000,000 Incredible!	**See "e". V_{tr} = 7.62**
g: 4340 Stress: 966MPa	Bare	Not applicable	102,600	**See "*h*".**
h: 4340 Stress: 966MPa	WC-10Co-4Cr	≈0.1422	1,000,000 Incredible	**See "*g*". V_{tr} = 6.35**
i: 4340 Stress: 966MPa	Bare	Not applicable	1,000,000	**See "*j*".**
j: 4340 Stress: 966MPa	Chrome	≈0.1422	894,900 Comparable	**See "*i*". Two runs were made on this bar at V_{tr} = 10.16**
k: 4340 Stress: 966MPa	Bare	Not applicable	1,000,000	**See "*l*".**
l: 4340 Stress: 966MPa	Chrome	≈0.1422	1,000,000	**Fatigue life same as "*k*". V_{tr} = 12.7**
m: 4340 Stress: 966MPa	Bare		1,000,000	**See "*n*".**
n: 4340 Stress: 966MPa	Chrome	≈0.1422	366,000 Very low.	**See "*m*"** **V_{tr} = 15.24**
o: 15-5PH Stress: 1035	Bare	Not applicable	940,000	**See "*p*".**
p: 15-5PH Stress: 1035	WC-10Co-4Cr	≈0.1422	124,000 Very low	**See "*o*"** **V_{tr} = 25.4**
Fatigue tests conducted by ES3 in collaboration with VLN (*19, 26*): Stress = 897-MPa				
Inconel 718	Bare	Not applicable	≈ 16,000	-----
Inconel 718	Bare Peened	Not applicable	≈ 70,000	-----
Inconel 718	T-800	≈0.076-0.127	≈ 65,000	P = 103.5, S_d = 89 V_{tr} Variable
Inconel 718	T-800	≈0.330-0.381	≈ 50,000	P = 103.5, S_d = 89 V_{tr} Variable
Inconel 718	Cr-C	≈0.076-0.127	≈ 50,000	P = 103.5, S_d = 89 V_{tr} Variable
Inconel 718	Cr-C	≈0.330-0.381	≈ 45,000	P = 103.5, S_d = 89 V_{tr} Variable
Inconel 718	T-800 Mechanical Strip	≈0.0.76-0.127	≈ 30,000	Operating variables not known
Inconel 718	T-800 Mechanical Strip	≈0.330-0.381	≈ 30,000	Operating variables not known

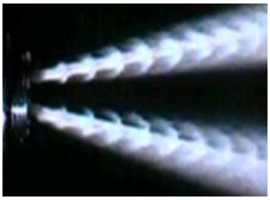


Fig. 1. General appearance FPWJ at 20-kHz issuing from a Twin-orifice rotating nozzle.

Fig. 2. Photographs showing the efficacy of the FPFJ in processing the surfaces.
(A) Rust from infrastructures, (B) Corrosion from turbine blades, (C) Epoxy and
(B) Elastomer coatings and seals from helicopter components, (D) Copper from helicopter pats, (E) Thermal barrier coatings from aircraft engines and (F) epoxy coatings from composite surfaces.

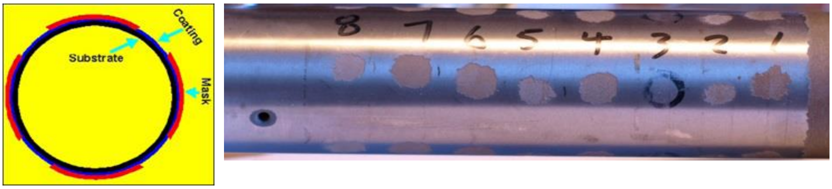


Fig. 3. Stripping the HVOF coating from the periphery of the cylindrical pins for SCM study.

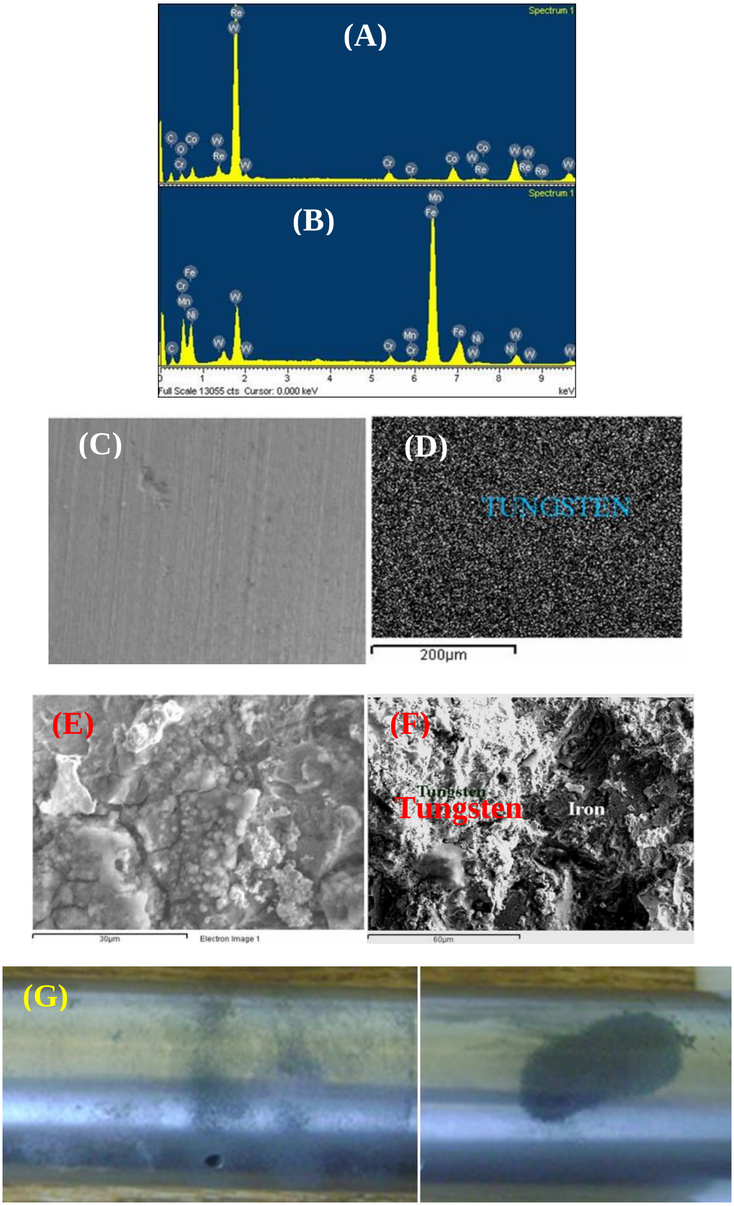


Fig. 4. (A) EDS spectrum of coating on steel before stripping, consisting mostly of W with minor amounts of Cr and Co, (B) Spectrum after stripping showing some remnant tungsten particles, (C) SCM photo of the surface before stripping showing striations, (D) Map showing the distribution of tungsten particles in the coating, (E) Photo of surface after stripping showing cracks in iron (substrate), (F) Remnant tungsten (believed to be imbedded in the cracks of iron and (G) Close-up views of the defects in the coating of some pins.

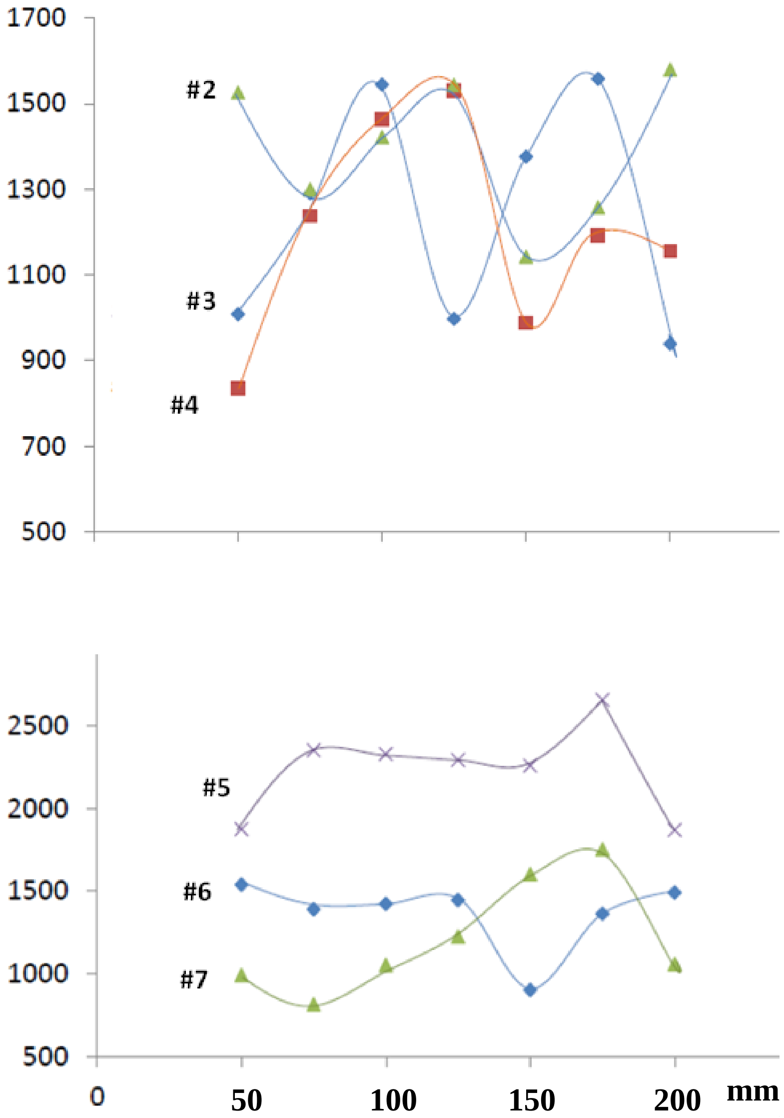


Fig.5. Variation of microhardness (Vickers) along the length of the pins.

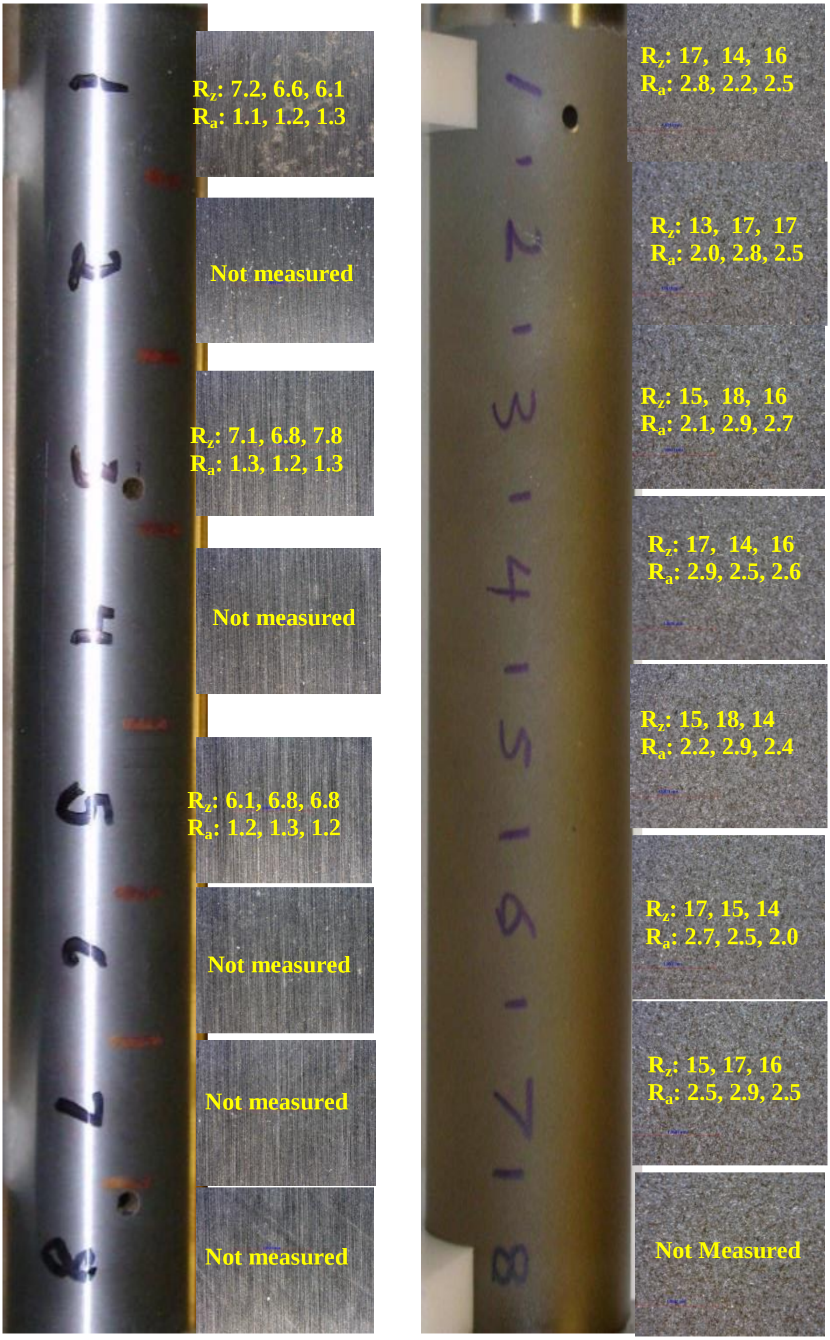
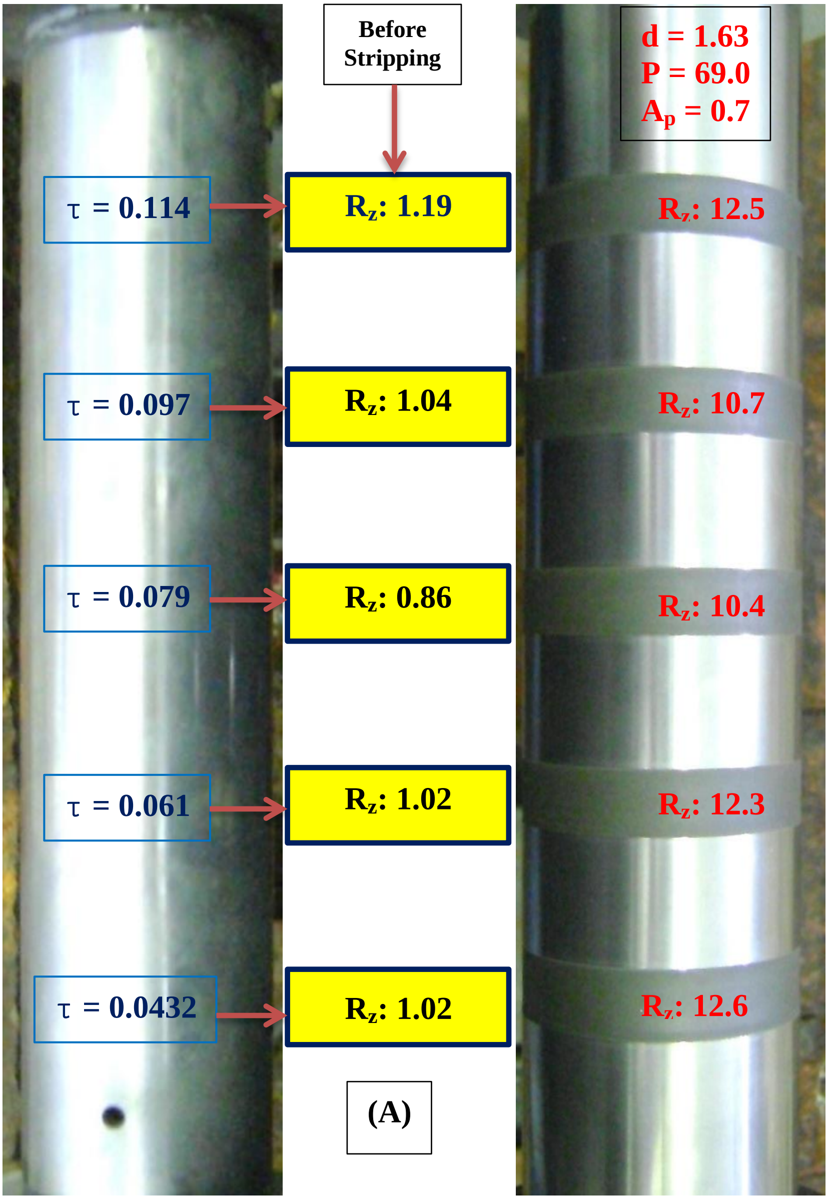


Fig. 6. General view of the cylindrical pin #5 (Fig.5) before and after stripping to show the effect of microhardness of the coating. $\tau \approx 0.076$



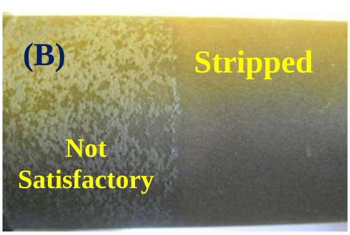


Fig. 7. Photos of pins.
(A) Effect of thickness of coating on A_p and R_z.
(B) P = 103.5. Defective pins.

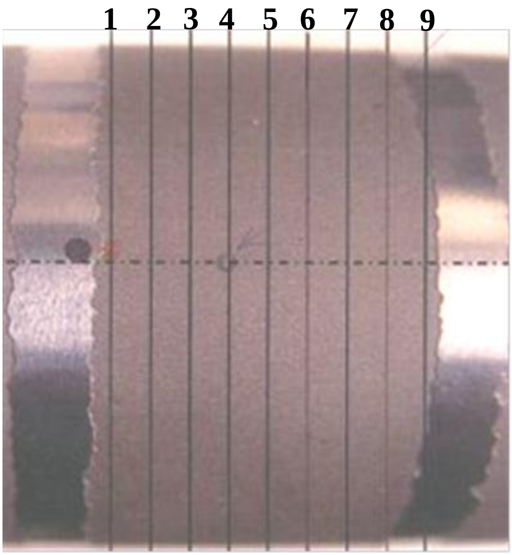


Fig. 8. Measurement of residual stresses at the stripped sections shown by X-ray Diffraction (XRD) technique (see the Table below).

Section	**P = 69, d = 1.63, S_d = 70, V_{tr} = 25.4, N = 1000**		**P = 103.5, d = 1.19, S_d = 102, V_{tr} = 25.4, N = 500**		**P = 103.5, d = 1.19, S_d = 102, V_{tr} = 50.8, N = 1000**	
	Hoop	Axial	Hoop	Axial	Hoop	Axial
Pre-shot peen*	-842	-842	-856	-869	-807	-814
Post-shot peen*	-883	-918	-925	-918	-904	-918
1	-600	-607	-586	-642	-600	-642
2	-476	-524	-331	-407	-545	-580
3	-435	-442	-352	-386	-511	-573
4	-455	-469	-365	-373	-531	-566
5	-421	-455	-345	-359	-538	-559
6	-448	-448	-352	-373	-531	-531
7	-435	-469	-373	-380	-524	-559
8	-552	-531	-400	-414	-573	-607
9	-662	-676	-662	-676	-635	-662
Average	**-498**	**-461**	**-418**	**-445**	**-554**	**-587**

*Note: These residual stresses were not measured at the same location as the stripped Section. Negative signs indicate the stresses are compressive.

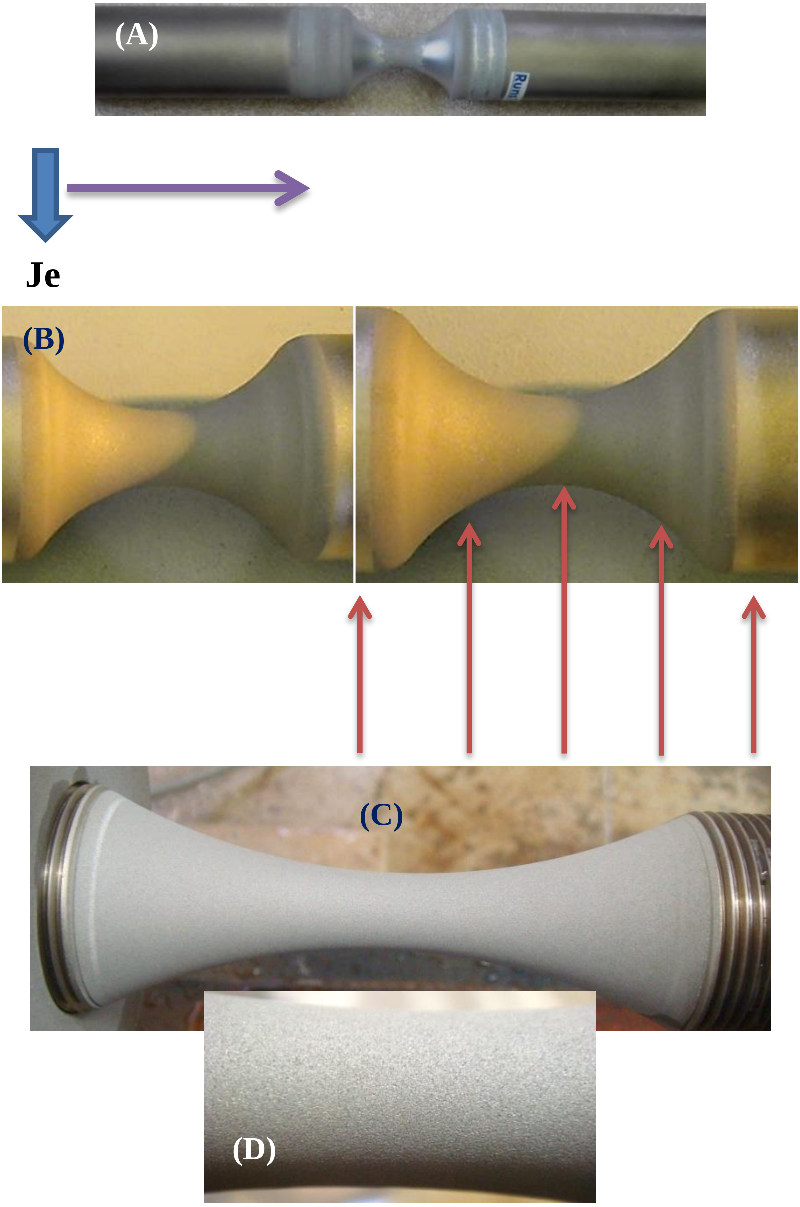


Fig. 9. Fatigue tests conducted on stripped fatigue bars.
(A) Unconventional fatigue bars, (B) Tests conducted on ad-hoc basis (S_d not varied as the jet traversed from one end to the gage section). Results are summarized in Table 1, (C) Tests conducted on hour-glass fatigue bars (***19***, ***26***) fabricated according to ASTM standard (***31***). Sample results are summarized in Table 1.

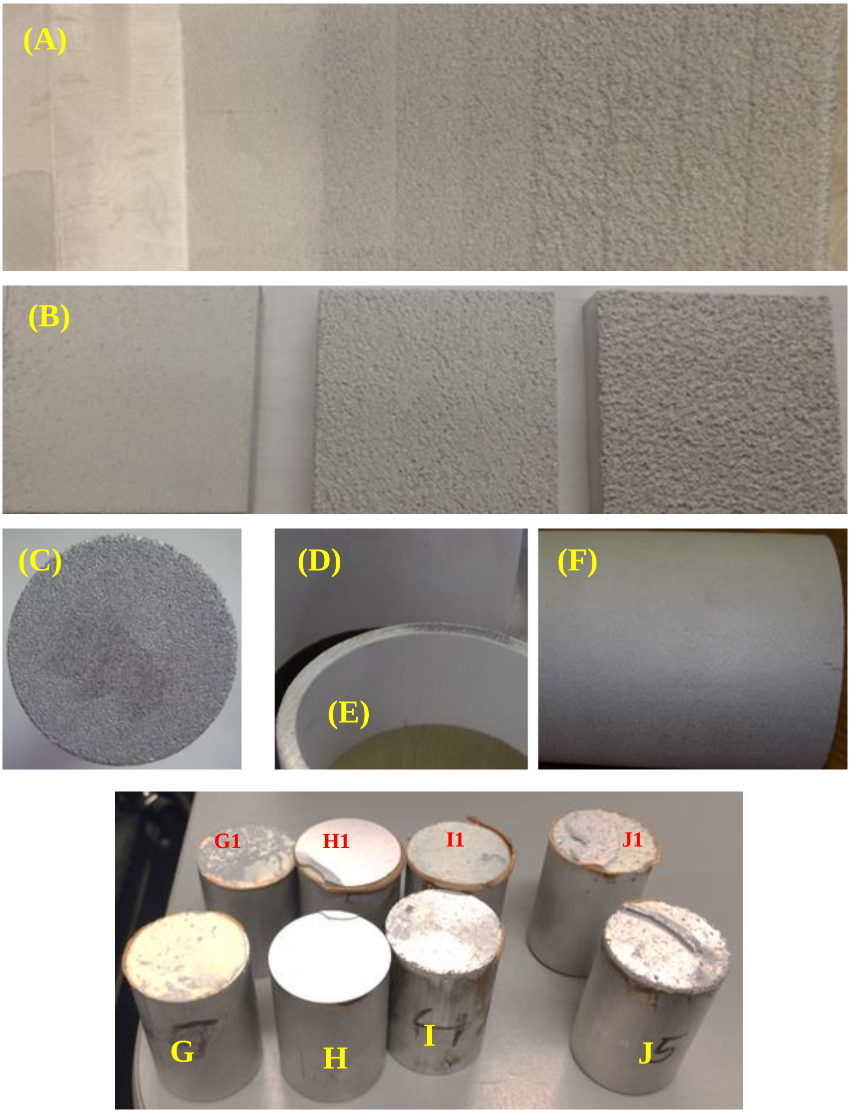


Fig. 10. Prepping substrate materials with the CWJ and FPWJ for measuring bond strength of the coatings (work in progress; see Ref. 63).

(A) General view of the Aluminum alloy substrate after prepping with the FPWJ.

(B) Close-up views of the substrates.

(C) Circular cylinders prepped with the FPWJ and also grit blasting for measuring bond strength of the cold spray coating.

(D) Interior surface of Aluminum alloy prepped with the CWJ at 380-MPa.

(E) Interior surface Aluminum alloy prepped with the FPWJ at 69-MPa

(F) Outer surface of the Aluminum alloy tube prepped with AFPWJ, using the coating particles as blasting materials (Ref. 64).

(G, H, I, J., etc.) Bond strength results.