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Paper

STRIPPING COATINGS WITH HIGH-FREQUENCY FORCED PULSED AND ULTRA-HIGH PRESSURE WATERJETS: A COMPARAIVE STUDY

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ABSTRACT

MRO (Maintenance-Repair-Overhaul) operations of aircraft parts require stripping of several types of specialty coatings, ranging from simple epoxy sealants to hard coatings, such as chrome and HVOF. The conventional methods of stripping these coatings are chemical stripping, machining (grinding), grit-blasting and ultra-high pressure continuous waterjet (UHPCWJ) blasting. More recently, extensive work done in the laboratory for several aerospace companies has shown that stripping with the high-frequency forced pulsed waterjet (HFPWJ) is highly promising. In this paper stripping results obtained with the UHPCWJ and HFPWJ are compared. As exemplified by the values listed below, all coatings can be stripped with the HFPWJ at low pressures (≤ 103-MPa), low water and power consumption (≤ 56-kW), with good surface finish resulting in significant savings in operating and maintenance costs.

HFPWJ at 69-MPa & 18.6-kW	**UHPCWJ at 248.4-MPa and 13.4-kW**
Substrate: Steel, Base coat: Epoxy, Top coat: Rubber	
Area removal rate ≈ 9.2-m^2/hr	Area removal rate ≈ 0.214-m^2/hr.
Specific Energy ≈ 7.2-MJ/m^2	Specific Energy ≈ 225.4-MJ/m^2

1. INTRODUCTON

Special thermal spray coatings are being used in aircraft engines to protect the engine parts from wear, erosion, corrosion and high temperatures. The applied coatings have to be renewed during engine shop visit, which requires stripping old coatings. The traditional (old) stripping processes are:

1. Machining (grinding),
2. Gritblasting,
3. Chemical stripping,
4. Ultra-high pressure continuous waterjet blasting (UHPCWJ).

Processes 1, 2 and 3 have the following disadvantages:

- The processes take a lot of time (depending on the part and the applied coating),
- The base material of the parts is usually damaged,
- Chemical stripping is an environment unfriendly process with considerable occupational health issues.

Process 4 (UHPCWJ) was a major step forwards in stripping coatings in MRO operations with the following benefits:

- Short stripping times (compared to the other three processes listed above),
- Ease of control of the surface finish,
- Environment friendly process with no occupational health issues.

However there are some disadvantages of this process:

- Use of ultra-high pressure intensifiers which needs special maintenance,
- Very high nozzle wear requiring frequent change of sapphire orifices (could be improved by the use of diamond orifices) and thus contributing to downtimes,
- Not possible to strip HVOF coatings without damaging base material,
- Not possible or, highly uneconomical to strip Electro Hard Chrome (EHC) coatings (plating), which needs to be replaced with HVOF or other coatings as the coating process has proven to be carcinogenic (Refs. 1 & 2).

Recent work conducted for both industrial and government sectors has shown that high-frequency forced pulsed waterjet (HFPWJ), operating at fairly low pressures, offers as a new promising technique for MRO operations. The brief comparative study presented in this paper confirms this perspective.

2. BACKGROUND

2.1 UHPCWJ

The structure of a continuous waterjet (CWJ) has been has been thoroughly investigated since the very inception of waterjet technology (Ref. 3). However, for the sake of comparison with the HFPWJ, the basic structure of the UHPCWJ is illustrated in Fig. 1. As is clear, depending on the pressure, the velocity decreases rapidly both in the axial and radial directions. Furthermore, the effective diameter of the jet also decreases {that is, depending on the pressure, the standoff distance (S_d), can be quite short}. In fact, if one examines the swath (width of the stripped track), one can see some degree of erosion at the centre of the swath caused by the high central velocity (Figure 5, the swath at 380-MPa = 55,000kpsi; see also Fig. 17). Since orifice diameters are quite small, single-orifice nozzles are rarely used for stripping coatings. In practice, either fanjets or, multiple orifice jets are used for stripping applications {for instance, at KLM, the so-called Tony-Tip, consisting of 6-orifices (d = 0.1524-mm of each orifice) is used for stripping coatings (see Figure 17); At Pratt, often, oscillating nozzles are used for stripping (see Run#4 in Figure 8)}.

2.2 HFPWJ

As extensive details have been published in the literature on the method of generating HFPWJ (Refs. 4 to 10), only a brief description is given here to highlight its characteristics compared to the UHPCWJ. The pulses are generated by inducing ultrasonic waves upstream of the orifice using a probe connected to a transducer, driven by an ultrasonic generator (Refs. 4, 5 & 6). For a given set of optimum operating parameters fully developed pulses are formed as illustrated in Figure 3A and B (Ref. 7). The advantages of using HFPWJ stem from the fact:

- The pulse is shaped like a mushroom with a fairly flat velocity profile (similar to turbulent profile inside a tube),
- For a given magnitude of hydraulic power (H_p), the diameter of the pulse increases with distance, giving a good range of S_d. In fact, depending upon the pressure and flow, S_d can be as high as 150-mm. This is important in situations where accessibility is an issue (stripping from narrow areas of the parts). This will become evident from the wide stripped swaths of coating described below,
- Repeated impacts of the pulses, 20-kHz, in the present case (the ultrasonic generator is tuned for this frequency),
- Improved nozzle life as diameters are quite large compared to those used in the UHPCWJ.

Furthermore, as the technique uses fairly low pressure and highly reliable plunger pumps (≤ 103-MPa), maintenance costs are quite low.

3.0 COATINGS & STRIPPING METHODS

In the aircraft and aerospace (rockets) sectors, a variety of different thermal spray and galvanic plating coatings are used to protect the components against high temperature, wear, impact and erosion. Often the coatings also function as dimensional restoration, abradable or, as machine clearance control coating. In MRO operations, all old coatings have to be stripped before reapplication. Examples of traditional stripping methods of some coatings are given in Table 1. Depending on the coating and the stripping method, the stripping times can vary from a couple of hours to a couple of days. On the other hand, Table 2 shows results obtained with the UHPCWJ in stripping several types of coatings from various parts in MRO operations at KLM. It is obvious that stripping with the UHPCWJ compared to the traditional methods is far better {some of the parts stripped with the HFPWJ are reported by Vijay, et al (Ref. 9)}.

4.0 COMPARISON OF STRIPPING WITH THE UHPCWJ AND HFPWJ

In this paper an attempt is made to compare the performance of HFPWJ with the UHPCWJ based on limited set of results obtained at KLM, Pratt and VLN laboratories. However, an examination of Table 2 shows that several nozzle configurations (static & rotating fanjets) and rotating multiple orifice nozzles (at Pratt oscillating nozzles) have been employed to strip a wide variety of coatings (top and bond coats). In order to make an appropriate and accurate comparison, similar nozzles (both dynamic and geometric) must be used for stripping with the HFPWJ. Even if such nozzles were available, it would be difficult to make an accurate comparison because the nature of the coatings may differ (see the variations in the values of E_s listed in Table 2). For this reason, stripping results obtained with the single-orifice nozzles were used for comparison (this would also confirm the fundamental distinction between continuous and pulsed waterjets). Both metallic (HVOF & plasma; Tables 1, 2 &3) and non-metallic coatings (epoxy) were used in the study.

5.0 RESULTS AND DISCUSSION

The results are depicted graphically in Figures 4 to 16 with the relevant operating parameters and other relevant observations (Fig. 17 is used just for illustrating striation patterns). The photographs are important to visualize the appearance of the test samples before and after stripping. The observations are listed below. The indicators for comparing the performance of HFPWJ with the UHPCWJ are (see Nomenclature for definition of the variables):

A_s = Rate of stripping = W_sV_{tr} (m^2/hr)
$E_s = H_p/A_s$ (MJ/m^2)
$E_m= Q/A_s$ ($litre/m^2$)
R_a = Mean surface roughness values of the substrate after stripping, μm (R_a = NA implies that it could not be measured with the existing roughness meter in the laboratory).

In calculating the values of these parameters, spalled areas of the top coat were not considered (this happens predominantly with the HFPWJ, depending on the brittleness of the coating material). It should also be noted that if water is filtered and reused (recycled), the magnitude of E_m would be irrelevant. In stripping the coatings with the UHPCWJ, illustrated in Figs. 10 to 16, the diameter of the single-orifice was kept at 0.254-mm, equal to the value used in the 4-orifice rotating nozzle employed at KLM (see Table 2).

Figure 4: These steel plates were coated with epoxy (bond coat) with hardened rubber as topcoat (to simulate coatings used on rocket boosters). Single-pass Run #178 and multiple-adjacent Run #179 were conducted with the UHPCWJ at 248.4-MPa (H_p = 13.4-kW) and maximum V_{tr} = 3600-mm/min. Runs #98 to 108 were conducted with the HFPWJ at 69-MPa (H_p = 18.6-kW) at V_{tr} ranging from 19,000 to 50,800-mm/min. Although both methods produced bare metal finish, HFPWJ produced good surface profile at all traverse speeds. The calculated values of A_s, E_s, and E_m (at the maximum traverse speed) are: **HFPWJ:** *9.2, 7.2, 105.6* **UHPCWJ:** *0.21, 225, 927.8*, which clearly show the benefit of pulsing the jet.

Figure 5: This Figure illustrates stripping baked enamel from a steel plate at the operating conditions as indicated (at the same values of H_p). Comparison of test A with B clearly indicates that the surface finish achieved the HFPWJ is fairly uniform (due to flat velocity profile). Since V_{tr} is constant for both tests, the area removal rate achieved with the HFPWJ is almost 6-times that of UHPCWJ, with corresponding reductions in the magnitudes of E_s and E_m.

Figure 6: This is a marine steel sample with six layers of hard epoxy coatings (tests conducted for the US Navy). The operating parameters are listed in the Figure. Run#1 and #3 were single-pass tests conducted respectively with the HFPWJ and UHPCWJ at the same traverse speed of 50,800-mm/min. Runs #2 and 4 were multiple-pass adjacent runs to strip 25.4-mm wide swaths. Based on the total number of passes, the stripping rates achieved with the HFPWJ and UHPCWJ were respectively 9.7 and 2.4-m^2/hr (Ref. 8). The magnitudes of E_s and E_m respectively are: 7.8 & 31.5-MJ/m^2 and 102 & 113.5litre/m^2, once again confirming the benefit of using the HFPWJ for stripping marine coatings.

Figure 7: The coating on the cylindrical coupons depicted in this Figure is HVOF (Ref. 9). It is quite clear that HFPWJ produces an excellent surface finish ($R_a \simeq 0.37$) compared to the UHPCWJ ($R_a \simeq 3.6$). In fact, as noted by the second author (KLM), it is not possible to remove HVOF coating with good surface finish with the UHPCWJ. Even if it does, the process is considerably slow as observed in the current tests. The removal rate at 380-MPa is of the order of 0.0007-m^2/hr (E_s = 85,900, E_m = 227,142) compared to 0.046-m^2/hr (E_s = 5,440, E_m = 52,565) achieved with the HFPWJ.

Figure 8 (Results from Pratt): The operating parameters and the observations are indicated on the Figure. For appropriate comparison, Run #3 is compared with Run #C as Run #4 was stripped with an oscillating nozzle. The results are: UHPCWJ (A_s = 0.002, E_s = 117,000 & E_m = 308,450) and for HFPWJ (A_s = 0.043 E_s = 3,433 & E_m = 49,800). The benefits of using the HFPWJ for stripping the HVOF from the base metal Nickel Alloy are immediately obvious.

Figure 9 (Results from Pratt): As indicated in the Figure, at Pratt, twin oscillating UHPCWJ orifices were used to remove the honeycomb material (only a sample result is reported in this paper). The results are: UHPCWJ (A_s = 0.078, E_s = 6,460 & E_m = 17,000) and for HFPWJ (A_s = 1.74, E_s = 70.3 & E_m = 1,020). The magnitudes of E_s and E_m for the UHPCWJ would be considerably higher if stripping with a stationary (non-oscillating) nozzle were considered. Furthermore, the fact that often the stubbles did remain on the substrate, requiring grinding for removal, indicates that HFPWJ is far better for this application.

Figures 10 to 16: The coatings listed in these Figures encompass those used on various parts in aircrafts (see Table 2). All the relevant results are listed in the Figures. In all of the runs with the UHPCWJ, the very narrow kerfs are clearly visible (see also Fig. 17). Therefore, based on the fact that HFPWJ strips much wider paths, the magnitudes of A_s, E_s and E_m are expected to be significantly better. Furthermore, if spalling of the top coat is taken into account (see Figs. 12, 14, 15 & 16), HFPWJ contributes significantly to the stripping rate. Since the major interest is in stripping the bond coats, spalled areas were ignored in calculating the performance indicators. As already pointed out elsewhere, HFPWJ produces better surface finish than the UHPCWJ. It should also be pointed out that occurrence of erosion (see, for instance, Figs. 12 and 14) implies that traverse speed (feed rate) could be significantly increased or, the pressure could be decreased to achieve specific values of R_a.

In summary, in order to highlight the benefits of HFPWJ for stripping several types of coatings the magnitudes of A_s, E_s and E_m are listed in Table 3.

6.0 CONCLUSIONS

The conclusions from the limited comparative tests conducted at the laboratories of KLM, Pratt and VLN Tech are:

- Stripping coatings with the HFPWJ offers several advantages compared to the UHPCWJ,
- As HFPWJ uses low pressures (~ 103-MPa) generated by highly reliable plunger pumps, maintenance and operating conditions would be significantly better than UHP pumps.
- HFPWJ is a user and environmentally friendly technique.

7.0 ACKNOWLEDGMENTS

The authors are thankful to KLM Royal Dutch Airlines and Pratt & Whitney Automation (USA) for the results included in this paper.

8.0 REFERENCES

1. Anon, “OSHA’ Final Rule for Hexavalent Chromium,” Spear Consulting, Magnolia, Texas, USA.
2. Anon, “Chrome Plating Alternatives: Thermal Spray, Electroless Plating and Others,” A Thintry Market Study, Thintry Inc., New York, USA, 2005.
3. Shavlovsky, D.S., “Hydrodynamics of High Pressure Fine Continuous Jets,” Paper A6, Proc. 1st International Symposium on Jet Cutting Technology, BHRA Fluid Engineering, Canfield, Bedford, England, 1972, pp. 81-92.
4. Vijay, M., “Fundamentals and Applications of Cavitating & Forced Pulsed Watejet Technologies” Technical Note, VLN Tech., 2010 (revised periodically).
5. Vijay, M.M., W. Yan, A. Tieu and B. Ren, “Ultrasonic Waterjet Apparatus,” US Patent #7,594,614 B2, September 29, 2009 (also Canada, China, Europe and Japan).
6. Vijay, M.M., A. Tieu, W. Yan and B. Daniels, “Method and Apparatus for Prepping Surfaces with High-Frequency Forced Pulsed Waterjet,” US Patent Application Publication #US 2010/0015892 A1, January 21, 2010.
7. Vijay, M.M., M.K.Y. Lai & M. Jiang, “Computational Fluid Dynamic Analysis and Visualization of High Frequency Pulsed Water Jets,” Paper 39, Proc. 8th American Water Jet Conference, Water Jet Technology Association (WJTA), St. Louis, USA, 1995.
8. Vijay M.M., “Doing More With Less: Pulsed Jet Technique, Par 1,” Cleaner Times, The Journal of High Pressure Water Applications, February 2005, pp. 28-31.
9. Vijay, M., A. Tieu, W. Yan, B. Daniels, J. Randolph, F. Laguines, D. Crawford, C. Pessetto, J. Merrill, R. Eybel, K. Bucknor and M. Game, “Demonstration, Validation and Certification

of Forced Pulsed Waterjet Technique for the Removal of Coatings from Aircraft/Aerospace Components,” Proc. 19th International Conference on Water Jetting, BHR Group Limited, UK., pp. 203-216.

10. Vijay, M.M, W.Yan, B.Ren, A. Tieu and B. Daniels, “Removal of Hard Metallic and Non-metallic Aerospace Coatings with High-Frequency Forced Pulsed Watejet Machine,” Proc. 18h International Conference on Water Jetting, BHR Group Limited, UK, pp. 367-379.

9.0 NOMENLATURE

A_s	Area removal rate (stripping rate), m^2/hr
d	Orifice diameter, mm
E	Total energy consumed in stripping (H_p X T), MJ
E_m	Volume of water used per unit stripped area (Q/A_s), litre/ m^2)
E_s	Energy consumed per unit stripped area (E/A_s), MJ/m^2
H_p	Hydraulic power, kW
P	Pump (nozzle) pressure, MPa
Q	Flow rate, litre/min
R_a	Mean surface roughness of the substrate after stripping, μm
S_d	Standoff distance, mm
T	Time of exposure (duration) of the test sample to the jet, hr
V_{tr}	Traverse speed of the nozzle, mm/min
W_s	Width of coating stripped, mm
τ	Total thickness of coating, mm

Table 1 – Traditional old Stripping methods

Examples of stripping coatings	**Methods**
Al	Sodiumhydroxide
NiAl	Nitric Acid
CuNi	Nitric Acid
CuNiIn	Nitric Acid
NiC	Nitric Acid
CuAlFe	Chromium Acid
NiCrAl	Machining
CrC	Manual grinding/grit blasting
WC	Enstrip A-TL + Sodiumhydroxide
NiCrAlY	Aqua-regea (double acid)
ZrO	Gritblasting
EHC	Chromium acid

Table 2. Stripping coatings from typical aircrafts parts with the UHPCWJ (Source: KLM)

Part Description & Operating Parameters	Dome CF6-50	Outer Liner	3-9 Spool	Shroud	HPC Disk	Thermal Shroud	LPT Case	Air/Oil Seal	11-13 Spool	HPC Case
Surface	Area 1-8	Outer Dia	Lands	Inner Dia	Dia U	Knife Edge	Rail #1	Knife Edge	Lands	HX-HW
Base Material	Hastaloy X	Hastaloy X	Titanium	Al	17-4 PH	René41	Inc718	Inc718	Inc718	Steel
Bondcoat	NiCrAlY	NiCrAlY	NiAl	NiAl	WC	NiAl	Inc718	NiAl	NiAl	NiAl
Topcoat	YO/ZrO	YO/ZrO	Al	Poly/Al		AlO	CrC	AlO		Al
Average dia of part, mm	615	750	500	1300	150	1000	1230	600	600	750
Height of the part, mm	20	400	800	62	50	80	12	60	175	1000
Spray Width, mm	12	12	40	40	40	25	12	15	25	40
Peripheral Speed, m/min	1.7	1	2	10	1	2	0.25	2	1	4
Rotational Speed, RPM	0.9	0.4	1.3	2.4	2.1	0.6	0.065	1.1	0.5	1.7
Overlap (%)	70	50	70	99	90	95	75	80	75	75
Number of hits/area	3	2	3	67	10	20	4	5	4	4
Nozzle Speed, mm/min	3.17	2.55	15.28	1.47	8.49	0.80	0.19	3.18	3.32	16.98
Flow Capacity of the pump, litre/min	6.00	6.00	6.00	6.00	6.00	6.00	7.60	6.00	6.00	7.60
Pressure, MPa	370	370	370	275	370	370	370	370	370	370
Number of Orifices	1	1	4	4	4	4	1	3	4	5
Diameter of orifice, mm	0.508	0.508	0.254	0.254	0.254	0.254	0.508	0.254	0.254	0.2286
Type of Nozzle	Fanjet Rotate	Fanjet Static	4-Jet Rotate	4-Jet Rotate	4-Jet Rotate	4-Jet Rotate	Fanjet Static	3-Jet Rotate	4-Jet Rotate	5-Jet Rotate
Equivalent diameter of orifices, mm	0.508	0.508	0.508	0.508	0.508	0.508	0.508	0.4318	0.508	0.508
Calculated Flow, litre/min	6.80	6.80	6.80	5.86	6.80	6.80	6.80	5.10	6.80	6.88
Calculated Power, kW	41.93	41.93	41.93	26.87	41.93	41.93	41.93	3145	41.93	42.46
Calculated Stripping Time, min	6.3	157.1	52.4	42.2	5.9	100.5	618	18.8	52.8	58.9
Calculated Energy Consumed, MJ	16	395	132	68	15	253	156	36	133	150
Area Stripped, m^2	0.039	0.942	1.257	0.253	0.024	0.251	0.046	0.113	0.330	2.356
E_s = Area/Energy, MJ/m^2	411	419	105	269	629	1006	3355	314	403	64

Table 3. Summary of experimental results for comparison.

Coating Materials	**Substrate**	**HFPWJ**		**UHPCWJ**	
		E_s	**E_m**	**E_s**	**E_m**
Rubber (top coat) Epoxy (bond coat)	Steel (Fig. 4)	7.2	105.6	225	927.8
HVOF (WC-Co-Cr)	300M Steel (Fig.7)	5,440	52,565	85,900	227,142
Tungsten Carbide	Nickel Alloy (Fig. 8)	3,433	49,800	117,000	308,450
Honeycomb	Hastelloy Ni Alloy (Fig. 9)	70.3	1,020	6,460	17,000
NiCrAl (Electric Arc)	Inconel 718 (Fig. 10)	313	76	1,580	4,168
NiCrAl (Plasma)	Al 443 (Fig. 11)	71	17	1,580	4,168
NiCrAl (Plasma)	Steel 410 (Fig. 12)	457	108	∞	∞
Al-Polyester (top coat), NiAl (bond coat)	Al 6061-T6	71	17	1,580	4,168
NiAl	Steel (Fig. 14A)	416	6,000	∞	∞
CuZnAg	Steel-410 (Fig. 14B)	209	3000	1,580	4,168
NiCrAlY	Steel-410 (Fig. 16)	502	7250	∞	∞

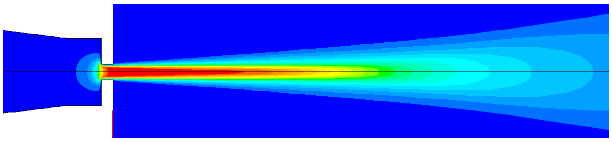


Figure 1. Typical radial velocity distribution of UHPCWJ - Red: 800, Yellow: 500, Green: 350 and Light blue: 200-m/s (Ref.1).

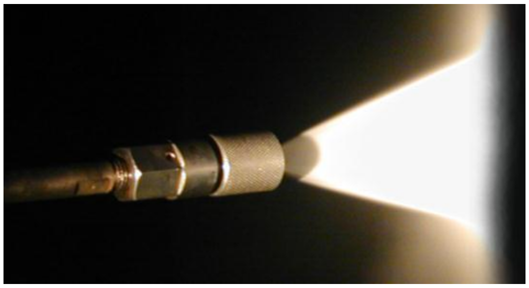


Figure 2. Typical appearance of a fan waterjet at UHP.

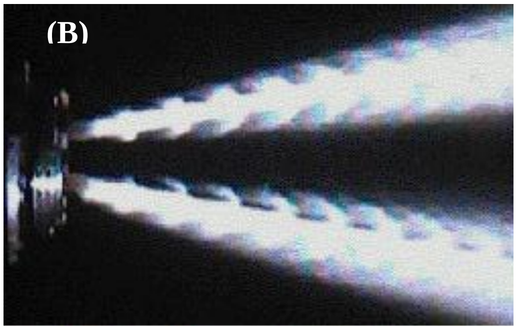


Figure 3. Typical appearance of HFPWJ. (A) Issuing from a single-orifice nozzle, (B) Issuing from a dual-orifice nozzle.

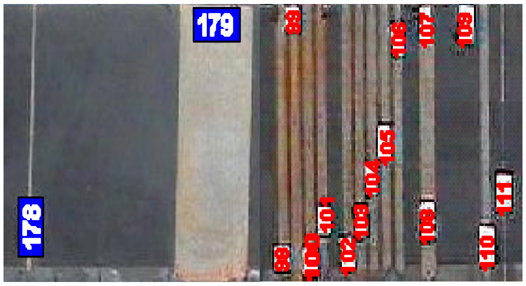


Figure 4. Comparison of UHPCWJ @ 248-MPa (#178 & 179) and HFPWJ @ 69-MPa for stripping epoxy (base coat) and rubber (top coat) from steel.

Figure 5. Baked enamel stripped from a steel plate. (A) HFPWJ @ 31-MPa (10.8-kW), (B) UHPCWJ @ 207-MPa (10.8-kW).

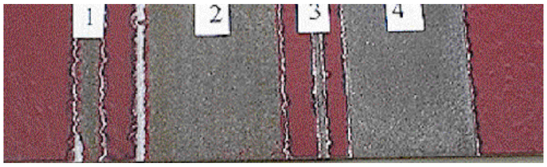
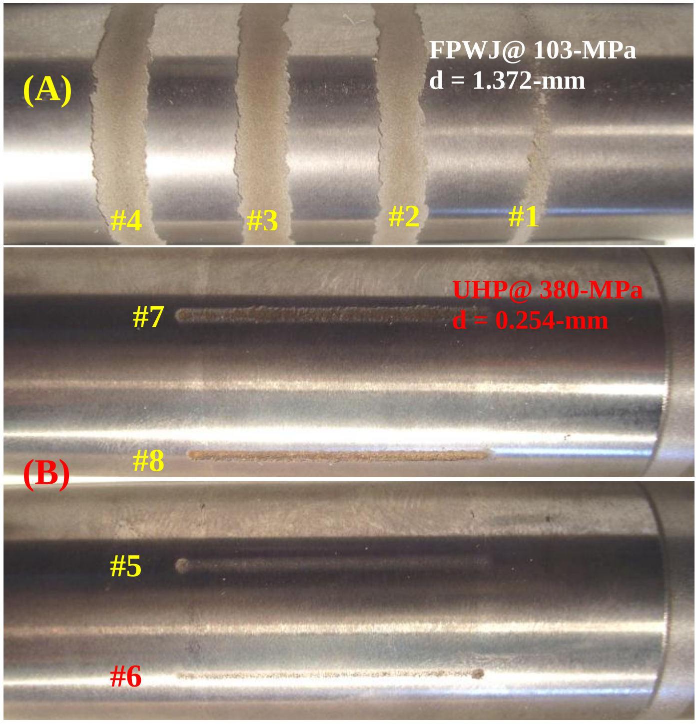


Figure 6. Six layers of marine coatings stripped from a steel plate. #2: HFPWJ @ 76-MPa (21-kW), #4: UHPWJ @ 276-MPa (21-kW).



HVOF on 300M steel

Figure 7. Stripping HVOF (WC-Co-Cr) with the single-orifice HFPWJ (A) & UHPCWJ (B).

Run #1: T = 15-s; **Run #2**: T = 30-s, R_a = 0.335, A_s = 0.046; **Run #3**: T = 45-s, R_a = 0.363; **Run #4**: T = 60-s, R_a = 0.376; **Run #5**: V_{tr} = 25.4 (Coating not removed); **Run #6**: V_{tr} = 19.05 (Coating barely removed); **Run #7**: V_{tr} = 12.7, R_a = 0.871, A_p = 0.0007

Run #8: V_{tr} = 6.35, R_a = 3.61 (Substrate damaged)

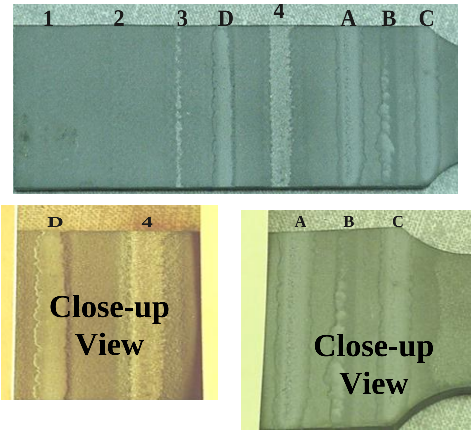


Figure 8. Tungsten Carbide (HVOF) coating stripped from Nickel Alloy with single-orifice HFPWJ (A, B, C & D) at 69-MPa (H_p = 41-kW) and UHPCWJ (1, 2, 3 & 4) at 380-MPa (H_p = 65-kW).

Run A: 1-pass, V_{tr} = 152.4 (Coating removed). Slight erosion of substrate.

Run B: 1-pass, V_{tr} = 304.8 (Coating barely removed).

Run C: 1-pass, V_{tr} = 203.2 (Coating removed). Good surface finish.

Run D: 2-passes, V_{tr} = 381.0 (Coating removed). Good surface finish.

Run #1: 1-pass, V_{tr} = 152.4 (Coating not removed).

Run #2: 2-passes, V_{tr} = 152.4 (Coating not removed).

Run #3: 3-passes, V_{tr} = 152.4 (Coating barely removed).

Run #4: 4-passes, V_{tr} = 152.4 (Coating removed). Surface finish: rough.

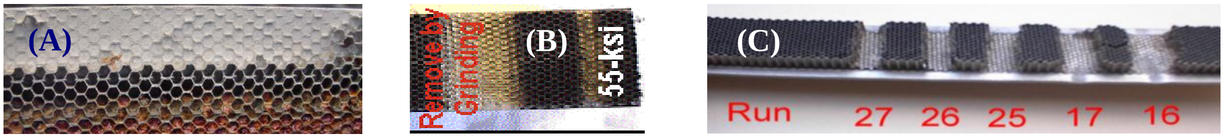
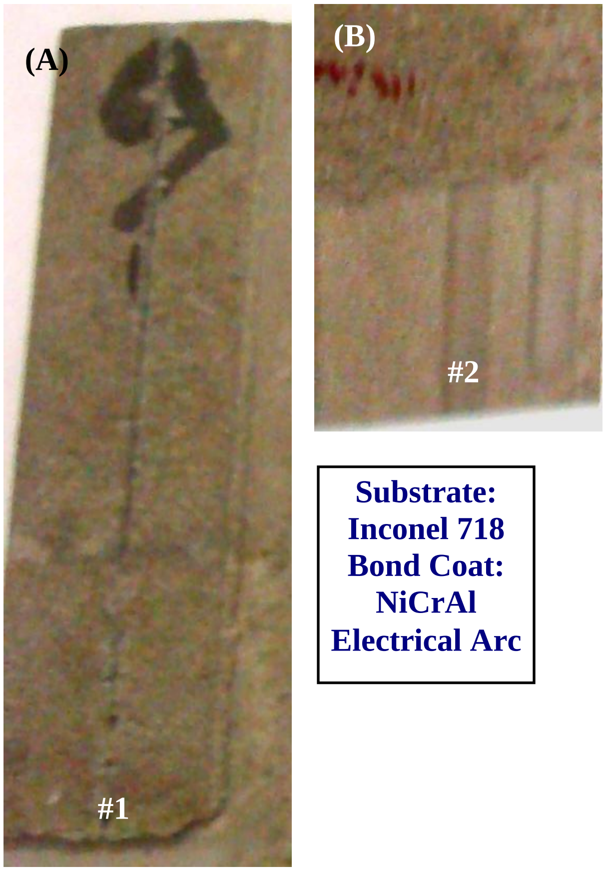


Figure 9. Stripping honeycomb (Hastelloy X Ni Alloy) from aircraft components (typical substrate: Hastelloy N Ni Alloy). Note: Honeycomb tested at Pratt (A & B) & at VLN (C) may be different.

(A) P = 380 with twin oscillating nozzles ($H_p = 140$), V_{tr} = 152.4, one pass. Stubbles of the honeycomb remained. $\underline{A_s = 0.078}$. (B) The remaining stubbles were removed by grinding (Source: Pratt).

(C) Stripped with the FPWJ. P = 69 with single-orifice nozzle ($H_p = 34$). Run #25: V_{tr} = 2540, Run #26: V_{tr} = 5080 and Run #27, V_{tr} = 7620, all one pass. Width of removal decreases as V_{tr} is increased. For Run #25 $\underline{A_s = 1.74}$.



Substrate:
Inconel 718
Bond Coat:
NiCrAl
Electrical Arc

Figure 10. Stripping with UHPCWJ (#1) and HFPWJ (#2).
#1: P = 380 (H_p = 16.7), V_{tr} = 635, A_s = 0.038, E_s = 1,580, E_m = 4,168, R_a = NA
#2: P = 69 (H_p = 53), V_{tr} = 2540, A_s = 0.61, E_s = 313, E_m = 76, R_a = 2.42.

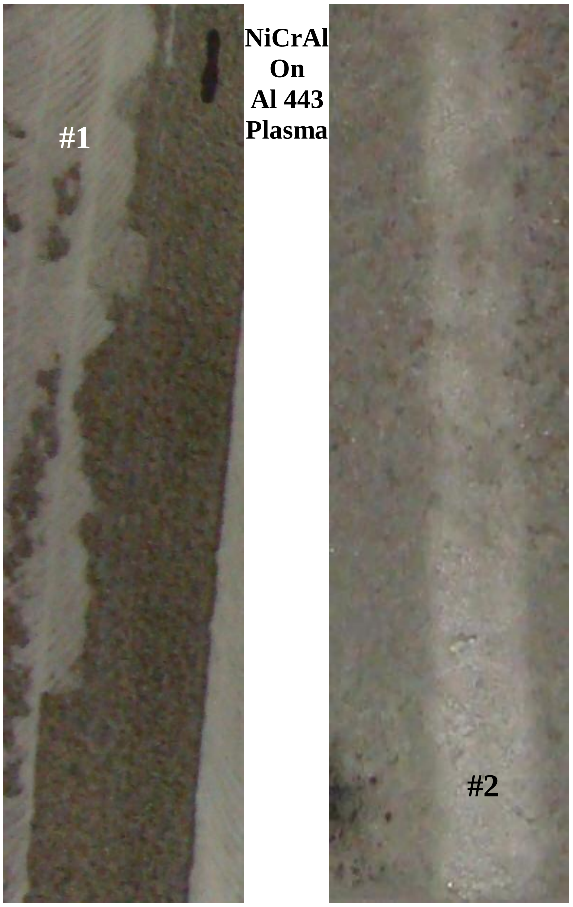
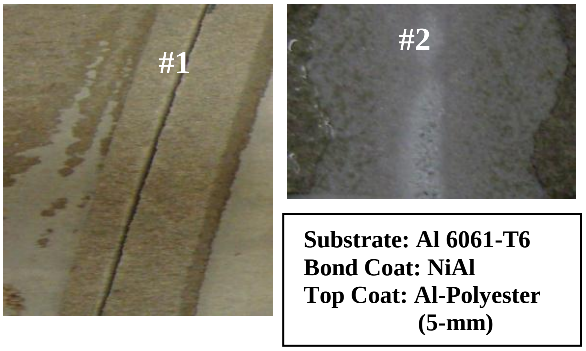


Figure 11. Stripping with UHPCWJ (#1) and HFPWJ (#2).
#1: P = 380 (H_p = 16.7), V_{tr} = 635, A_s = 0.038, E_s = 1,580, E_m = 4,168, R_a ≃ 5.
#2: P = 69 (H_p = 53), V_{tr} = 12,700, A_s = 2.7, E_s = 71, E_m = 17, R_a = 3.6 ± 5.0

Figure 12. Stripping with UHPCWJ (#1) and HFPWJ (#2).

#3 & 4: P = 380 (H_p = 16.7), V_{tr} = 635, $A_s \simeq 0$, $E_s \simeq \infty$, $E_m = \infty$, R_a = NA

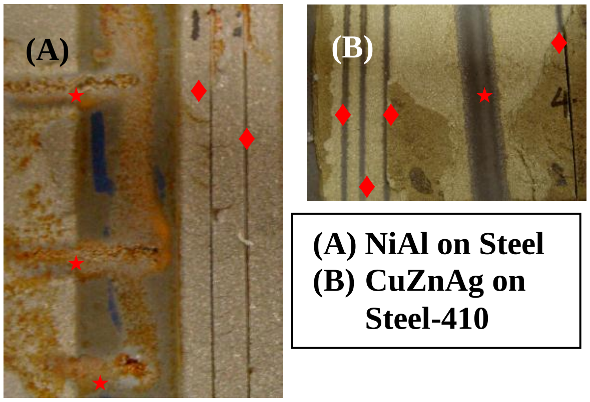
#1: P = 69 (H_p = 53), V_{tr} = 1270, A_s = 0.30, E_s = 457, E_m = 108, R_a = 2.42.



Substrate: Al 6061-T6
Bond Coat: NiAl
Top Coat: Al-Polyester
(5-mm)

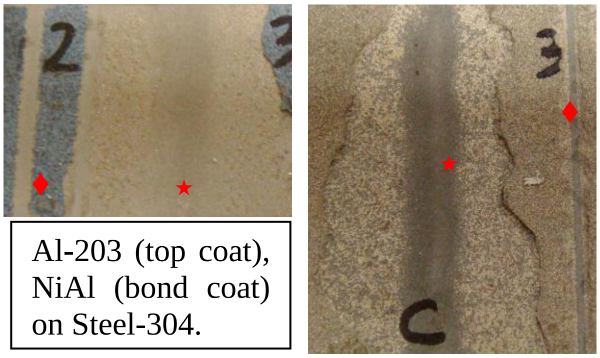
Figure 13. Stripping with UHPCWJ (#1) and HFPWJ (#2).

Run #1: P = 380 (H_p = 16.7), V_{tr} = 635, A_s= 0.038, E_s = 1580, E_m = 4,168, R_a = NA.
Run #2: P = 69 (H_p = 53), V_{tr} = 12,700, A_s= 2.7 (excluding large spalled area), E_s = 71, E_m = 17, R_a = NA (Rough).



(A) NiAl on Steel
(B) CuZnAg on
Steel-410

Figure 14. Stripping with UHPCWJ (indicated by ♦) and HFPWJ (indicated by ★).
The operating conditions are the same as in Fig. 12. Calculated values of A_s, E_s & E_m are generally of the same order of magnitudes as indicated in Figs. 10, etc.

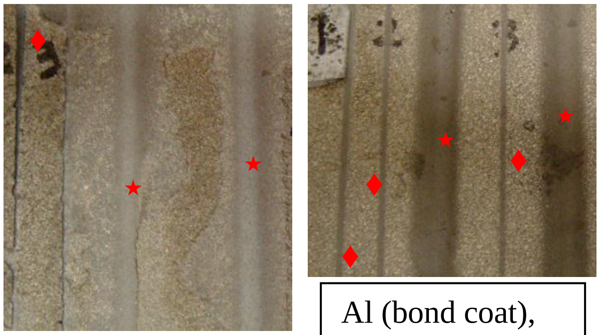


Al-203 (top coat), NiAl (bond coat) on Steel-304.

NiAl on Steel-410.

Figure 15. Stripping with UHPCWJ (indicated by ♦) and HFPWJ (indicated by ★).

The operating conditions are the same as in Fig. 12. Calculated values of A_s, E_s & E_m are generally of the same order of magnitudes as indicated in Figs. 10, etc.



NiCrAlY on Steel-410.

Al (bond coat), NiAl (top coat) on Steel-410.

Figure 16. Stripping with UHPCWJ (indicated by ♦) and HFPWJ (indicated by ★).

The operating conditions are the same as in Fig. 12. Calculated values of A_s, E_s & E_m are generally of the same order of magnitudes as indicated in Figs. 10, etc.

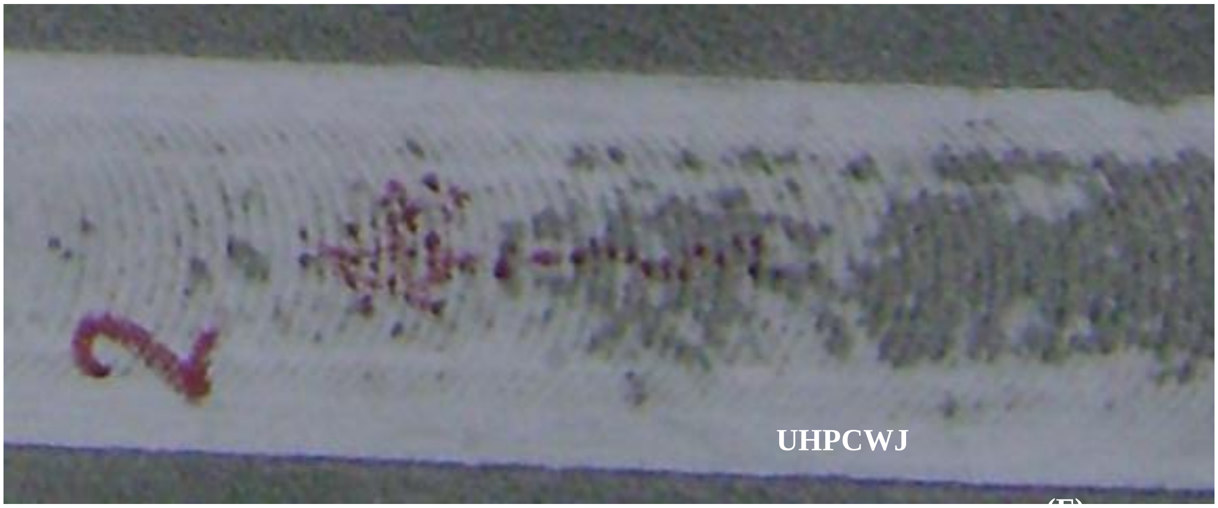


Figure 17. Photograph showing the striations (residual coating) and widths of stripped paths obtained with the 4-orifice (d = 0.2286-mm of each orifice) rotating nozzle at 276-MPa (Source: KLM). The width of the stripped path is slightly > d.