The coatings and corrosion industries tend to learn by experience within a fairly closed network. Around 1977, when this author first observed the effect of waterjet cleaning (WJ) at 140 MPa (20,000 psi) on new, old corroded, and painted steel surfaces, the surface obtained looked very different from that obtained by dry abrasive blast cleaning (AB). The visible appearance of steel, as created by AB, was the only accepted surface preparation. Did WJ produce a substrate that could be repainted? Could the coatings industry accept a surface preparation method that gave steel such a different appearance?

Many of the initial WJ papers that the author studied were complex, filled with equations, and focused on cutting, not cleaning. What happens to the surface when hit by a droplet travelling at high velocity appeared in cavitation studies in the marine, rocket, and aircraft industries, but not, as of 1977, in the coatings literature. In 1977, AB was, and remains, the method of choice to make the initial profile for the coatings industry. The AB process was the only indu-

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try standard. Since 1977, however, the language and concepts concerning surface preparation, including AB and WJ, have changed.

This article describes the history of WJ cleaning, discusses the effect that pressurized water has on the gross and microscopic details of a substrate, and examines a profile created by AB and one cleaned, or, created, by WJ. The article integrates papers from the Waterjet Technology Association in the U.S. and BHRA in Europe with articles from the JPCL and documents from SSPC and NACE.

**Historical: 1976-1994**

In 1975, 70 MPa (10,000 psi) water pressure was the high end of the range for cleaning. Intensifier pumps could produce higher pressures for cutting operations. In 1983, this author conducted a small pseudo-scientific test to determine if water at 140 MPa (20,000 psi) could prepare steel surfaces for painting, with the following results.¹

- Water at 50–70 MPa (7,000–10,000 psi) did not deliver enough energy to the surface to disrupt the lateral bond between old corrosion and the surface but was sufficient to clean out pits.
- At 140 MPa, the appearance of the WJ-cleaned surface differed completely from that achieved by AB. The surface cleaned by WJ did not get shinier or smoother or lighter with extended cleaning but was dull gray. Old corrosion marks and scratches remained on the surface. Defects were immediately observed.
- At 140 MPa, the surface turned instantly "golden yellow" no matter how fast it was dried with hot air. The color and surface appearance remained the same for days and sometimes months.
- At 140 MPa, the water droplets did not form beads on the surface; instead, the water wetted the entire surface.

- Compared to steel surfaces cleaned with WJ at 140 MPa, surfaces prepared by AB were uniform and were the goal (to meet SSPC VIS-1 and ISO 8501-1).

On a microscopic scale, it was evident that, compared to AB, WJ was doing something different to the surface very quickly. In the study, WJ cleaned more area per unit area than AB (Figs. 1–3).²

By 1989,³ this author was reaching the conclusion that the surface produced during WJ was, at a microscopic level, becoming fractal (geometric pattern repeated at ever smaller scales to produce irregular shapes and surfaces). In contrast, AB reshapes malleable metal, creates microscopic flat surfaces, and erodes the metal surface in distinct, larger-than-microscopic patterns (i.e., in thousandths of inches) and visible to the eye as compared to patterns that require a magnified view to see.

This author wrote that the effect of WJ on steel "is significant because the growth of corrosion is thought to be fractal. Solid particulate blasting is quite effective in creating the initial pattern on steel substrates, perhaps more by the ductile and malleable properties of the metal than by cutting and gouging. Solid particulate blasting is effective in removing brittle rust products and coatings lying on the top of the metal surface. There is evidence that rust products can be hidden under the metal folds. Particulate blasting in a Gaussian [bell-shaped] distribution from a nozzle is not predicted to be an effective method to remove corrosion initiation sites [any point on a metal where there is a 'potential difference,' necessary for corrosion to occur]. The visible rust is removed, but the microscopic [initiation site] is not removed."³

The author observed that with high-pressure (HP) WJ (70 MPa), crevices and deep pockets of rust were removed preferentially, leaving tightly adherent rust products on the upper tips. The older metal surface cleaned by ultra-high pressure (UHP) WJ at 140 MPa (as defined then) and fan jets did not re-rust in the
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years. The panels were at 100% relative humidity. A little condensate formed and dripped on the panels. Sometime during year 5, the water finally evaporated. Light gelatinous rust spots from condensate were visible on the steel cleaned by WJ. The sections cleaned with abrasive blasting or pressure washed prior to abrasive blasting look remarkably the same. There is no evidence that pressure washing changed the corrosion pattern. The WJ-cleaned plate has discrete sites with only the light golden hue from the original WJ (Figs. 4–6).

**1994 to Date**

By 1994, new WJ equipment for surface preparation made removal of coatings and rust economically feasible. Higher-pressure pumps, rotating heads, and remote controls were becoming commercial. Environmental issues (e.g., dust control) were forcing changes, and the coatings and WJ industries found each other. In January 1995, *JPCL* published “New Hydroblasting and Slurryblasting Standards Issued” (pp. 64–69), and SSPC-SP 12/NACE 5, “Surface Preparation and Cleaning of Metals by Waterjetting Prior to Recoating,” was issued.

**Nozzle and Flow Pressure**

WJ cleaning has two actions: the direct impact from the velocity of the jet and the sideways flow or shear controlled by the volume of water flowing (Fig. 7, p. 49). To “cut through or abrade” coatings or rust products, impact-induced erosion must be sufficient to break down their cohesion. Shear stress that develops against the vertical pit walls produces hydraulic lifting and stresses the adhesion forces. (Also, see ref. 4.)

**Water Streams and Stresses**

In 1995, R. Lever discussed the relation of velocity and shear and produced a clear illustration of the rotational effect. Lever was turning the selection of "how much pressure or volume of water should be used" into a rational process. Lever noted that surface cleaning can be accomplished by lower pressure and higher volume—21 Mpa–70 MPa (3,000 to 10,000 psi)—although lower pressure and higher volumes do not degrade coatings very much. The revolving jet stream travels transversely, so it flexes the coating repetitively. The jet stream loads, unloads, and stresses the tensile flexure of the coating. In areas of low adhesion over hidden blisters or under-coating rusting, the coating pops off because of the tensile flexing, even if the coating is not breached.

Lever observed that as pressure increases (higher velocity) and flow decreases, the concentrated jet energy increases. The jet energy intensity erodes coatings and stresses the binding or cohesion force of the coating. More volume tends to shear or hydraulically lift the coating; more velocity from a smaller orifice tends to erode the surface.
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Energy of the Surface—Wetting or Peening

During the testing in 1983, the author saw that the surface prepared by WJ wetted—that is to say, beads of water did not form on the surface. Coatings require a surface that can be wetted for effective adhesion, and the good adhesion obtained on a WJ-cleaned surface was confirmed in July 1994, by International Paint at a Naval Sea Systems Command (PERA-CV) “Water Jet Workshop” conference in Bremerton, WA: adhesion values were higher than expected over surfaces after WJ, and light flash rust formed. Kelly later wrote about the need for the coating to wet out to achieve proper adhesion.6

Wetting

In 2001, McGaulley et al. looked at coating over new, smooth surfaces prepared by grit blast, shot peen, roto peen, wire wheel, grinder, water jet, and solvent cleaning.7 The results are complex. The authors found that all the methods had comparable adhesion values even though the WJ and solvent cleaning had no profile detectable by either the Testex tape or profilometer. They noted, however, that “During surface preparation, the wetting characteristics of the surface changed significantly. Prior to water jetting, water was observed to bead on the surface meaning incomplete wetting was achieved and the substrate had low surface energy. After the surface was water jetted, however, water was observed to spread quickly over the surface...”7 Hence, increased wettability was achieved, and the surface energy of the substrate increased.

Residual Stess, Peening

Although McGaulley et al. had no explanation for the wetting,7 it is known from other industries that WJ is used to “peen” surfaces, reduce residual stresses, and change the energy of the substrate. Typically an aluminum alloy has been used as a test material rather than steel because it requires less velocity to get the results.

As indicated in some of S. Kunaporn’s findings when studying WJ peening on aluminum alloy 7075-T6,8 the energy of the surface changes. The fatigue strength is enhanced. In addition, there may be erosion that depends on the nozzle and the WJ stream.

Regions of Water Exiting from the Nozzle

Other researchers describe multiple regions in a “continuous” high-speed water jet. As the water exits the orifice, there is an initial region of a core jet, then a transitional region where the continuous flow has a droplet layer around the core jet, and, finally, a zone consisting of droplets and air.9

Starting around 70 MPa (10,000 psi), the water travels at the speed of sound in air. Velocities of 2–3 times the speed of sound are common, so there are conditions of ultrasonic compression/decompression when the water hits the substrate. Some water droplets will have entrapped air, resulting in additional energy provided by imploding droplets with partial vacuum bubbles.9

Cavitation—SonoChemistry

The effects of cavitation—the formation,
growth, and implosive collapse of bubbles in a liquid—within the fluid jets can be minimized or enhanced, depending on the nozzle and the overall systems.10

Maynard described SonoChemistry as being based on the effects of cavitation, the creation and collapse of bubbles in a liquid subjected to ultrasound. Because the bubbles are so small compared to the volume of surrounding liquid, the heat dissipates rapidly, and ambient conditions remain essentially unaffected, giving unique qualities to ultrasonic cavitation in water.10

Eighteen years earlier, Suslick had shown why pressurized water can get into cracks and why it is “different” from solid abrasives. A 100-micron diameter water droplet appears to hit the surface as a 5–10 micron particle.10 In contrast, during AB, a 100-micron solid abrasive (4 mil, 100 mesh) cannot physically get into a hole less than 100 microns in diameter, leaving a pit or crack uncleansed unless “clean” solid dust from the impact and breakup of the abrasive can fill it.

The present author could now rationalize her previous observations of UHP WJ cleaning with that of SonoChemistry. In 1983, a light golden color seemingly formed instantaneously over the entire steel surface when struck by water travelling at the ultrasonic speed of 522 m./sec (70 MPa), or 1.5 times the speed of sound in air. The golden color, as in a soap bubble film, was a thin film caused by a diffraction pattern. The academic explanation is that droplets within the stream are collapsing in the 10E10 to 10E12–second time frame, giving a very localized energy spike that results in a thin, very tightly adherent layer of oxides or hydroxides forming on the surface instantaneously and leaving it resistant to new corrosion.

Making a Profile

It is possible to profile metal with WJ alone. When the present author originally sectioned through surfaces cleaned by 140 MPa (20,000 psi), she found, but
could not explain, what she described as a micro-profile that was much smaller than the larger “peak-to-valley” profile measured in the coatings industry. She thought cavitation might play a role.

An explanation might be found in subsequent researchers’ work on the erosion/profile of exotic metals in the aerospace industry after cleaning by WJ. VanKuiken\textsuperscript{11} shows that the WJ-treated surface is very reactive for coating bonding. Taylor\textsuperscript{12} shows that surface area increases, a component Hare (discussed later) finds desirable for coatings performance. Miller\textsuperscript{13} shows that WJ removes considerably less material removed than does conventional AB. The authors caution against prolonged exposure or zero sweep rates. Draughon\textsuperscript{14} and Dupuy\textsuperscript{15} show the depth of cleaning without metal damage.

**General Discussion of Profile and Erosion**

The above studies also emphasize that the profile from WJ depends on grain size. The WJ profile was much finer than those prepared by AB. The present author’s conclusion to the coatings industry is that the major profile, the one that is measured in terms of microns (thousandths of inches), remains the same, but the microscopic details change. The crevices are open. ExTRANeous loose material is removed. WJ produces more surface area per unit area. The coating can wet the surface and adhere well.

Furthermore, the existing profile under the coating or rust is cleaned off and renewed. The author does not expect the peak-to-valley height to change during WJ, unless embedded abrasives or “hackles” were included in the original profile reading. Removal of embedded abrasives, or “hackles” could change a subsequent profile reading.

To avoid misunderstanding the making of profiles on steel while WJ cleaning, the readers should understand that the above authors are deliberately trying to maximize erosion of the substrate or tar-
get. The aircraft and rocket industries use up to 350 MPa to clean critical parts. The engineers have looked at the fatigue, removal, and profile effects on the metal surface because they do NOT want to do anything that will affect the integrity of jet aircraft engine metal substrates.

Moreover, while defining safe parameters for cleaning the interiors of pipeline made of various substrates, Wright made it clear that profiles can be formed if one is not careful.\textsuperscript{16}

Adhesion

Adhesion, a good indicator of coating performance, is not the only consideration. Coatings manufacturers with whom the author has spoken are impressed with adhesion enhancement, laboratory results, and long-term performance of coatings over WJ. Most of the coatings literature refers to “pull off” tests.

In 1995, the US Navy, being concerned about flash rust, required that the adhesion of coatings applied over WJ-cleaned surfaces have a pull-off adhesion of 6.8 MPa (1,000 psi). The coating applicators had no problem meeting that test.\textsuperscript{17}

In considering factors concerning adhesion, Hare (1996) talks about molecular bonding and mechanical (or lock and key) bonding in two papers.\textsuperscript{18} He cites the need for expansion of the real surface area compared to the apparent planar surface. Hare talks about expansion of the surface by scarification with sanding and abrasive blasting; the formation of thin oxide and hydroxide films on, and well-bonded to, the surface; and reactions and molecular associations that improve the adhesion of the coating to the substrate.

Practical Example of Adhesion

Prior to 1994, the general contracting division of Pacific Gas & Electric (PG&E) had been cleaning with WJ at approximately 10,000 psi and high volumes for about 20 years to prepare old, previously lined penstocks for relining. PG&E personnel were satisfied with, and confident in, the process, but wanted some test data to back up their experience.\textsuperscript{19} PG&E and Bechtel designed an accelerated laboratory method where there was a direct comparison between the surfaces cleaned by AB and those cleaned by WJ. They cut out old, heavily pitted, field penstock initially prepared with AB; cleaned coupons partially with AB and partially with 70 MPa (10,000 psi) WJ; and applied epoxy or polyurethane coating. The coated panels were placed on either side of Atlas cells. One side was epoxy (WJ); the other was epoxy (AB) or polyurethane (WJ and AB). They exposed the coated side of the panels to the de-ionized water (DI) at 140 to 145 F with partial immersion so they could see vapor and immersed conditions. The uncoated side of the panel was held at 75 F. The simple onset of blisters turned out to be deceiving.

One feature was readily apparent when Aldinger looked at the epoxy and urethane coatings on AB panels. There were no blisters on the epoxy (AB) but the entire surface had a layer of
water under it. In essence the entire coating was one huge blister. The substrate was wet because the water had migrated through the coating that extended up into the vapor zone. The whole surface between the coating and the metal was covered with black rust. The coating was easily peeled from the panel.

The WJ panels developed blisters earlier than the corresponding AB panels. At first PG&E and Bectel said that panels from WJ had early blistering and had failed. Remember, this is 1994. However, on the WJ cleaned panels, there was water in the blisters but the blisters were localized or isolated. There was NOT a film of water on the entire panel. The coatings were tightly adherent and had to be chipped away from the surface. There were blisters because the coating was tightly adherent, so it would not shear at the substrate-coating interface. As the water migrated to the substrate the only way to make a space for the water was for the coating to expand upwards. See C. Hare (1997) for more explanation.19

PG&E thought that based on these observations, water blast cleaning would give coating performance results comparable to traditional dry abrasive blast to SSPC-SP 10, Near-White. Indeed, that was the case (or was in agreement with their field observation).

**Conclusions**

This article has briefly looked at the energy delivered to a substrate during high pressure waterjet process; the wetting of WJ-cleaned surfaces; and the formation of a profile, under controlled conditions, for low density metals.

In 1977, there was a lot of skepticism about the quality of a WJ-cleaned surface and curiosity about the black staining that remained on corroded steel. This skepticism remains in 2010, even though millions of square feet (square meters) have been painted in maintenance over WJ cleaned surfaces from "just get the loose stuff off" to "clean to bare metal."

- Over the past 30 years, the industry has changed its concept of what type of surface must be achieved in order to be "clean."
- The present author defines surface preparation as "Creating the situation so the coating will perform as expected."
- The industry used to talk about the "process" (abrasive blasting) for a clean surface; now, the industry talks about the end result—"performance" language for a "clean" surface.
- WJ cleaning has fundamentally changed our language and concept of what is occurring at the surface, and what we are trying to achieve.

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