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Paper

WHAT EFFECT DOES WATERJET CLEANING HAVE ON THE SURFACE AND SURFACE PREPARATION?

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Abstract

This paper is a refresher on the effect that pressurized water has on the gross and microscopic details of a substrate. The paint and cleaning industry "knows" that waterjet cleaning doesn't create an anchor "profile." However, some industries, such as automotive engine parts, use a waterjet process to create the profile over which a hard coating is placed. The difference between a profile created by abrasive blast and the profile that is created, or cleaned, by waterjet will be examined. The effect on adhesion values will also be examined.

Keywords: waterjet cleaning, surface preparation, coatings, cavitation, adhesion

1 INTRODUCTION

The coatings and corrosion industries tend to learn by experience within a fairly closed network. Around 1977, when I first observed the effect of 140 MPa (20,000 psi) waterjet cleaning on new, old corroded, and painted steel surfaces, I didn't know what I was seeing. The surface looked so different from those obtained by dry abrasive blast cleaning. I read all the papers that were published by the WaterJet Technology Association in the USA and the BHRA group in Europe and thought about the traditional surface as we think of it in the coatings industry.

Many of the initial waterjet (WJ) papers were written by academicians. They were filled with equations and centered on cutting, not cleaning. The phenomenon of what happens to the surface when a droplet traveling at high velocity hits it is found in cavitation studies in the marine, rocket, and aircraft industry, but not in the coatings literature. In 1977, abrasive blasting was, and remains, the tool of choice to make the initial profile for the coatings industry. The language and concepts concerning surface preparation have changed in this 30 year time frame. This chronology points out that the concept of cleaning a previously painted or corroded steel surface has changed. We used to think that "Clean" meant to make a profile. Now we understand that we can "Clean" a surface without changing the profile. Waterjet cleaning has become the tool to achieve "clean" and to create the situation so the coatings will perform as expected. The coatings maintenance industry has moved from a process definition to a performance definition.

2 HISTORICAL 1976-1984

In 1975, 70 MPa (10,000 psi) was the top range for cleaning. Higher pressure was produced by intensifier pumps for cutting. Then, in 1983 I had the opportunity to conduct a small pseudo-scientific test to determine if water at 40 MPa (20,000 psi) could be used to prepare steel surfaces for painting and found the following (1).

- Pressurized water at 50-70 MPa (7,000 to 10,000 psi) did not deliver enough energy to the surface to disrupt the lateral bond between old corrosion from along the surface, but it was sufficient to get pits (the depth is greater than the width) cleaned out. The appearance was directly opposite to the abrasive cleaning mechanism.

- The surface did not get shinier or smoother or lighter with extended washing. It was dull gray. Old corrosion marks and scratches remained on the surface. Defects were immediately observed.

- The surface turned instantly "golden yellow" no matter how fast it was dried with hot air. This golden color and the surface appearance remained the same for days and months.

- The water wetted the entire surface. Water droplets did not form beads on the surface.

- The appearance of steel surfaces that were blasted with abrasives such as sand or glass beads were defined as looking completely "normal."

On a microscopic scale, it was very evident that something different was happening to the surface in a very fast manner. We were making more area per unit area when cleaning off with waterjetting (WJ) than with abrasive blasting (AB). In 1985, I spoke about what I, and others, were finding at SSPC, Houston Coatings Society Training/Workshop week, and NPCA (2). (Figures 1, 2, 3)

By 1989, I came to the conclusion that the surface was becoming fractal during WJ cleaning. "Cleaning with Abrasive, as described by experts in abrasive blasting, was a Gaussian distribution. This is significant because the growth of corrosion is 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 lying on the top of the metal surface. There is evidence to show that rust products are hidden under the metal folds. Particulate blasting in a Gaussian distribution from a nozzle is not predicted to be an effective method to remove corrosion initiation sites. The visible rust is removed, but the microscopic rust is not removed."(3)

My observations were, with HPWJ, crevices and deep pockets of rust are removed preferentially, leaving tightly adherent rust products on the upper tips. The older metal surface cleaned by UHP

WJ does not re-rust in the localized patterns found in particulate blasting. It is accompanied by an overall golden color associated with thin film diffraction as if a coherent metal oxide film is formed. This is strong evidence that the waterjet is removing, or redistributing in a uniform manner, the corrosion initiation sites.

2.1 Corrosion or Re-Rusting on Steel, Corrosion Initiation Sites

I predicted in 1989 that WJ would remove corrosion initiation sites more effectively than abrasive blasting. In 2000, three heavily corroded steel sections from a marine barge were blasted to ISO SA-3 (SSPC-NACE SP-5) “White Metal”; washed with 31 MPa (4500 psi) water to remove salts and then abrasive blasted to white metal; or cleaned to approximately NACE-SSPC WJ-1. They were then placed in individual sealed containers over water and stored indoors for 6 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. You can see the light gelatinous rust spots from condensate. 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. (Fig 4, 5, 6)

3 1994 FORWARD TO DATE

By 1994, equipment had been developed that made removal of coatings and rust from economically feasible. Higher-pressure pumps, rotating heads, and remote controls were becoming commercial. Environmental issues were forcing a change. The coatings and waterjet industries (up to that time largely confined to industrial cleaning) found each other.

3.1 Nozzle and Flow-Pressure

There are two actions in waterjet cleaning- the direct impact due to the velocity of the jet and the sideways flow or shear that is controlled by the volume. (Fig 7)

To “Cut through or Abrade” the coating or rust, there must be enough impact induced erosion to break down the **cohesion** of whatever you are removing from the surface. There is Shear stress that develops against the vertical pit walls to produce hydraulic lifting. This shear stresses the **adhesion** forces.

Borowski illustrated the focused path of a multi-orifice rotating nozzle (4).

3.1.1 Water Streams and Stresses

R. Lever discussed the relation of velocity and shear in 1995 and produced a clear illustration of the rotational effect and collected some of the terms. (5) (Fig 8)

Lever was trying to take the mystery out of “how much pressure or volume should be used” and turn the selection into a rational process. Surface Cleaning can be accomplished by lower Pressure and higher volume- 21 Mpa-70 MPa (3,000 to 10,000 psi). Lower pressure and higher volumes do not degrade coatings very much. The volume adds to the shear stress that develops against vertical pit walls. The hydraulic lifting will stress the adhesion forces of the coating. Pore Pressure is the shear stress that builds in much smaller microscopic cracks of the coating or substrate. Pore pressure stresses the coating adhesion forces or works tangential to the pit of the substrate.

The revolving jet stream is traveling transversely so it flexes the coating repetitively. The jet stream loads and unloads and stresses the tensile flexure of the coating. The coating is rapidly loaded and unloaded as the jet passes over the areas. In areas of low adhesion over hidden blisters or under coating rusting, the coating pops off. The coating is loaded and unloaded as the head goes around from 1500 to 3000 rpm. Brittle coatings crack.

Lever observed as you go to higher pressure (higher velocity) and lower flows, the concentrated jet energy goes up. The Jet Energy Intensity erodes coatings and stresses the binding or cohesion force of the coating. You overcome the binding force with the energy intensity. More volume tends to shear or hydraulically lift the coating; more velocity from a smaller orifice tends to erode the surface.

3.2 Energy of The Surface- Peening or Wetting

In 1983, I saw that the surface prepared by WJ cleaning wetted- that is to say, beads of water did not form on the surface. Coatings required a surface that can be wetted to be effective.

3.2.1 International Paint

By 1994, International Paint (IP) had become very vocal on the performance of coatings over Waterjet Cleaned surfaces. International Paint issued their in-house photos. In 1994, at a US Navy conference in Bremerton, Washington, Dr. John Kelly emphasized that coatings adhered well to WJ cleaned substrates. IP was getting higher than expected adhesion values over cleaned surfaces and light flash rust. An IP Vice-President said at a NACE Marine Technology Exchange meeting: “Adhesion begins at the bottom of the pits.” International Paint recognizes that HP WJ cleans the pits.

Kelly in 1996 wrote, “…the coating must come into intimate contact with the substrate to allow adhesive bonds to be formed. … The coatings must wet …out to give …the best chance to perform by allowing them to properly adhere to the surface..” (6)

3.2.2 Wetting

McGaulley looked at coating over new, smooth surface prepared by grit blast, shot peen, roto peen, wire wheel, grinder, water jet, and solvent clean. (7) All the methods had comparable adhesion values even though the WJ and Solvent clean had no detectable profile by Testex method, and had very smooth comparable surfaces. However, something had happened to the surface. They included a photo of the comparison of surface wetting between WJ cleaning and solvent cleaning. “During surface preparation, the wetting characteristics of the surface changed significantly. Prior to water jetting, the 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, meaning more complete wetting was achieved, thus the surface energy of the substrate was increased.” “Water jetting may affect substrate surface energy. It is not known at this point what this means for coating adhesion, though it does indicate increased wettability of the surface. High wettability results in intimate contact between coating and bare steel, which directly correlates to increased pull-off adhesion."

3.2.3 Residual Stess, Peening

The above is the large-scale observation. McGaulley didn't have an explanation for the wetting. From other industries, we find that waterjet cleaning is used to "peen" surfaces, reduce residual stresses, and change the energy of the substrate. Typically an aluminum alloy is used as a test material rather than steel because it requires less velocity to get the results.

What do we find? There is a change in the energy of the surface. The fatigue strength is enhanced. In addition, there may be erosion that is dependent on the nozzle and the waterjet stream.

S. Kunaporm looked at Aluminum Alloy 7075-T6 material as the target surface (8). The magnitude of erosion on the material surface was strongly dependent on the applied peening conditions. The waterjet peening can enhance the fatigue strength by 20-30% to that of unpeened AL 7075-T6 Material. Waterjet peening is capable of inducing surface plastic deformations similar to shot peening. The degree of fatigue life improvement by waterjet peening was found to be dependent on peening conditions i.e. jet pressure, standoff distance, nozzle type, jet velocity, and peening time.

3.3 Regions of Water Exiting from the Nozzle

There are multiple regions in a "continuous" high speed water jet. Just as the water exits from 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 is traveling at the speed of sound in air. It is not uncommon to see velocities of 2 –3 times the speed of sound, so there are conditions of ultrasonic compression/decompression when the water hits the substrate. There will be some water droplets that have entrapped air with the consequence that there will be additional energy provided by imploding droplets with partial vacuum bubbles.

3.4 Cavitation –

3.4.1 SonoChemistry

The effects of cavitation within the fluid jets can be minimized or enhanced depending on the nozzle and the overall systems. SonoChemistry and sonoluminescence arises from acoustic cavitation: the formation, growth, and implosive collapse of bubbles in a liquid.

Maynard published a popular press article on "SonoChemistry." SonoChemistry is the emerging study of chemical reactions powered by high-frequency sound waves. (10) Ultrasonic waves in liquids cause the formation of tiny bubbles that collapse so quickly, [on the order of 10 E-10 sec] and with such enormous temperatures and pressures, that novel chemical reactions are generated.

SonoChemistry is 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. "…ultrasonic cavitation in water has its own unique qualities. 'Water is fairly volatile and the products that you get from sonolysis of water, hydrogen atoms and hydroxyl radicals, are extremely reactive and so they dominate the chemistry,' Suslick [University of Illinois at Urbana-Champaign] said."

3.4.2 What does the cavitating droplet look like?

This extraordinary picture of a single water drop shows why researchers say a 100-micron diameter water droplet appears to hit the surface as a 5-10 micron particle. (10) (fig 9) On the contrary, a 100-micron solid abrasive (4 mil, 100 mesh) cannot physically get into a hole less than 100-micron diameter. So that pit, or crack remains uncleaned unless you can fill the hole with "clean" solid dust from the impact and breakup of the abrasive.

Summary: Combining the SonoChemistry and sonoluminescence thoughts with my observations. In 1983, I saw a seemingly instantaneous formation of a light golden color over the entire surface of the steel when water traveling at the ultrasonic speed of 522 m/sec (70 MPa) (1.5 x speed of sound in air) hit the steel. The golden color turned out to be a thin film with a diffraction pattern. One explanation is that droplets within the stream are collapsing in the 10 E-10 to 10E-12 sec time frame; to give a very localized energy spike that results in a thin layer, very tightly adherent, of oxides or hydroxides being formed on the surface instantaneous. It doesn't surprise me that once a surface has been cleaned with HP WJ, it remains resistant to new corrosion.

3.5 Making a Profile

When I originally sectioned through surfaces cleaned by 140 MPa (20,000 psi), I found what I described as a micro-profile that was much smaller than the larger "peak-to-valley" profile that is measured in the coatings industry. I didn't have a good explanation, but thought that cavitation might play a role. As the years went on, producing the primary profile in softer metals has become accepted and provides an explanation for the micro-profile.

3.5.1 VanKuiken (Profile and Adhesion)

VanKuiken discusses making a profile in aluminum with HP WJ by itself. The patents can be downloaded from www.uspto.gov. The patents include this illustrative profile and a comparison between AB and WJ produced profiles. (11) The photos comparing the abrasive and waterjet surfaces will be given in the presentation, but are not of sufficient quality to use in the printed paper.

"The high velocity, high pressure water jet blast not only cleans the surface of machining debris and lubricants, but also surprisingly attacks the pores of the microstructure, that is, the interstices of relatively small pits with undercuts as compared to a grit-blasted surface. These pits with undercuts provide an excellent surface with superior mechanical/adhesive qualities for the application of a thermal-sprayed metal alloy coating. The finely pitted surface provides both increased surface area for metal/metal adhesion and increased texture for mechanical interlocking between the metal casting and coating."

VanKuiken used aluminum oxide, glass, silicon carbide, or chilled iron of 30-80 mesh size to prepare a "standard" surface on aluminum pieces such as Alloy 319 used in engine blocks. The prepared piece will be coated with a high velocity oxy-fuel (HVOF) thermal spray. For comparison, VanKuiken also used 245-350 MPa (35,000-50,000 psi) HP WJ through multiple orifices (preferably 0.13 mm (0.005 inches) diameter) to roughen the surface. The exit speed was up to 923 m/sec (3000 feet/sec). The 8-orifice nozzle consumed 3.5 l/minute (0.928 gal per minute).

On the WJ surface, the peak-to-peak spacing is about 20 microns to 50 microns. The peak-to-valley depth is 10 to 75 micron. The photo 3A [in the patent] is prepared by crushed steel grit of 60 mesh size at 100 psi for 30 seconds. The peak-to-peak spacing is 230 microns.

"We have measured the stress required to strip the thermal spray coating off the typical grit-blasted surface and find it is on the order of 3,000 psi. In contract, the stress to remove thermal spray coatings on the water-jet treated surface is of the order of 6,000 psi. There is a marked difference in the size and number of pits per unit surface area that are formed by grit blasting versus water-jet blasting."

3.5.2 Taylor -Threshold Pressure for Hard Metals

In 1995, Taylor, looked at the erosion of Inconel (IN 718) and titanium (Ti- 6AL-4V) with 345 MPa (50,000 psi) pure waterjet. (12) Taylor was concerned about individual droplets and cleaning [removal] of surface oxides from turbine blades. The threshold pressure for IN 718 was determined to be around 207 MPa (30,000 psi), with a velocity around 650 m/sec. This threshold of a water drop velocity threshold is compared to plexiglass at 150 m/sec, and for aluminum at 200 m/sec. Taylor reports "Excellent bonding of a thermal spray overlay was obtained with this surface preparation having an absolutely clean interface."

"The striking point is that the detail of the eroded surface increases with increasing magnification, suggest the waterjet erosion produces a fractal surface. The highest magnification micrographs show a multitude of granular features of about 2 μm is size and rather micro-faceted. There is no indication of ductile fracture, but there are no long-running cleavage facets indicating brittle fracture either."

"The structure of the waterjet-eroded surface is compared to the conventional alumina grit blasted surface in Figure 8[in Taylors's paper] at the same magnification…. The feature size is at least an order of magnitude finer in the waterjet surface. In contrast, the grit-blasted surface would actually appear smoother as the magnification is increased, going from a long-range roughness pattern to smooth plateaus and facets, although there is micro-grooving due to the abrasion of the grit particle. The roughness of the grain blast surface is about 5.3 μm, while the waterjet surface is about 6.0 μm, much the same in magnitude but substantially different in detail."

3.5.3 Miller- Removal of Material during multiple passes, Average Profile

In 1999, R. K. Miller of Thiokol presented "Erosion of Steel Substrates when Exposed to Ultra-Pressure Waterjet Cleaning Systems." (13) Thiokol uses WJ to clean critical rocket engine parts for outer space. Prior to using UHP WJ, they had been cleaning the surfaces pits with dental picks. UHP WJ cleans the pits. Thiokol was concerned with damage to the metal substrate. The experiment used a target of D6AC steel with different sweep rates and rotation rates (dwell time). The plate was weighed before and after the sweep and an AVERAGE profile was calculated. Thiokol verified that the minimum allowable erosion of 0.0001 inch (2.5 micron) would **not** be exceeded during the cleaning process.

A grit blast of zirconium silicate produced an average profile of 18 micron (0.700 mil, 1 mil =0.001 inch). A single pass of 40,000 psi produced an average profile of 0.009 mil; a second pass produced 0.017 mil; three to six passes produced an average profile of 0.5 micron (0.018 mil). This paper established that two passes eroded whatever material was going to be eroded from the D6AC steel. Subsequent passes did not remove more material. Then the steel substrate remained constant. These results are different from the 1992 tests. Thus, UHP WJ does make a micro-profile, but not of the same magnitude as the abrasive.

Erosion testing conducted at the established normal operating parameters shows that the level of erosion of D6AC steel is minimal (< 0.00002 inch). This level of erosion is 98% less than that caused by the zirconium silicate, dry abrasive, blast system previously used for paint and adhesive removal. Multiple exposure testing showed that the erosion caused by the waterjet process is not linear. The data show that the initial exposure removed up to 88% more material than subsequent exposures. Failure simulation testing shows that any prolonged exposure, at zero nozzle rpm and / or zero sweep rate, will cause significant material removal, (0.0017 in./sec.).

3.5.4 General Discussion concerning Profile and Erosion

Notice that these papers emphasize that the profile is dependent on the grain size. The WJ profile was much finer than those prepared by abrasives. What I say to the coatings industry is: '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. Draughon (14) and Dupuy (15) have good photographs of a deeply pitted, but cleaned surface.

The profile that exists under the coating or rust is cleaned off and renewed. I do not expect the height of the peak-to-valley to change during WJ cleaning, unless embedded abrasives or "hackles" were included in the original profile reading. Removal of embedded abrasives, or "hackles" could change a subsequent profile reading.

Our method of measuring profile with Testex tape is based somewhat on "the larger the grit- the dirtier the surface, the higher the profile." Our profile tests measure not only peak-to-valley, but also peak-to-peak that might be due to embedded particles.

Before someone in the paint industry gets excited about making profiles on steel while WJ cleaning, let me make clear that these authors are deliberately trying to maximize erosion of the substrate or target. The aircraft and rocket industries use up to 350 MPa to clean critical parts. The engineers have looked at the fatigue and effect on the surface, as they do NOT want to do anything that will affect the integrity of jet aircraft engine metal substrates.

VanKuiken (11) shows that the WJ treated surface is very reactive for coating bonding. Taylor (12) shows that there is increased surface area, a component that Hare finds desirable for coatings performance. Miller (13) shows that the amount of material removed is much, much less than with conventional abrasives. The authors caution against prolonged exposure or zero sweep rates. Draughon (14) and Dupuy (15) show the depth of cleaning without metal damage.

3.5.5 D Wright- Profiles in Carbon Steel, Stainless Steel, and Clay Pipe.

D. Wright (16) presented real examples of the consequence of "bad" practices or "bad" nozzles (16). These are two fairly recent easy-to-read papers that feature the cleaning of carbon steel and stainless steel process pipe, and vitrified clay, PVC and HDPE sewer pipe. Wright was defining safe parameters for cleaning interior of pipes. It is very clear from these papers that profiles can be formed in steel if you are not careful.

3.6 Adhesion

Adhesion is a one good indicator of performance. It is not the only consideration. Consistently when I talk with coatings manufacturers, they are impressed with adhesion enhancement, laboratory results, and long-term performance. Most of the coatings literature uses "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. Thousands of "pull tests" have been done in the field to meet the 1000 psi requirement.

3.6.1 Factors concerning Adhesion (C. Hare)

Hare (1996) talks about molecular bonding and mechanical (or lock and key) bonding in two papers. (17) Hare cites the need for expansion of the real surface area compared to the apparent planar surface. Hare talked about expansion by scarification with sanding and abrasive blasting. "In air, thin oxide and hydroxide films will reform almost instantly on most structurally important metal substrates. Unlike rust, these films are well bonded to the metal and will serve as reactive sites that attract polar and chemically reactive groups on the polymer binder of the paint. Molecular associations between the substrate and the paint can then occur on these sites."

Hare stressed the need to remove oil from the surface. "Most substrates are rich in polar groups, which interact with the paint film binder to attain good bonding. The surfaces of all metals, except the noble metals, are chemically different from their bulk phase and are naturally covered by reaction products of the metal and its environment. Where these products are tightly adherent, such as the oxide on aluminum, they will generally contribute to good adhesion. Where the oxide surface is less adherent (e.g., on iron) as noted above, it must be removed before coating. The thin, impermeable oxide layer that immediately reforms on the newly bared iron surface is, however, when newly formed, adherent and suitable as a substrate for good adhesion."

"Expansion of the surface area increases the number of potentially reactive sites on the substrate for either primary or secondary bonding. An increased number of reaction sites, rather than purely mechanical effects, is the principal reason for improved adhesion."

3.6.2 Pen Stock, Atlas Cell Test, Adhesion

Prior to 1994, the general contracting division of PG&E had been using WJ cleaning at around 10,000 psi and high volumes for about 20 years to repair old previously lined penstocks for relining. PG&E were very satisfied and confident in the process, but wanted some test data to back up their experience. (18) PG&E & Bechtel designed an accelerated laboratory method where there was a direct comparison between the AB and the WJ cleaned surfaces. What they discovered then is still true today. Old, heavily pitted, field, penstock that had been cleaned with abrasive blasting and with 70 MPa (10,000 psi) WJ cleaning were coated with epoxy and polyurethane that were already accepted for use. The coated panels were placed on two sides of an Atlas Cell. One side was epoxy; the other was polyurethane. Aldinger 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.

This is a direct comparison of a coating over abrasive blasted and WJ surfaces. One feature was really apparent when Aldinger looked at the epoxy and urethane coatings on AB cleaned panels. The substrate is literally wet from the water that migrated through the coating that extended up into the vapor zone. The whole surface between the coating and the metal is now covered with black rust. The coating is easily peeled from the panel.

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.

PG&E felt that based on these observations, water blast cleaning would give results comparable to traditional dry abrasive blast to SSPC SP-10 "near white."

4 2004-2006

Now we are coming back full circle with Andreas Momber of Muehlan bringing new pictures of the surfaces cleaned with WJ, dry abrasive, and wet abrasive cleaning. (19) Momber shows WJ cleaning to remove embedded abrasive and the non-embedded residual material.

5 CONCLUSIONS

We have looked at:

The energy delivered to a substrate during high-pressure waterjet process.
The wetting of WJ cleaned surfaces.
The formation of a profile, under controlled conditions, for low density metals.
A discussion of creation of reactive sites.
The determination of the threshold pressure of hard metals

The difference of the profile as formed by waterjetting.

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 today, 2007, even though there are millions of square feet (square meters) that have been painted in maintenance over waterjet cleaned surfaces from "just get the loose stuff off" to "clean to bare metal."

- Over the past 30 years, we have changed our concept of what type of surface we must achieve in order to be "clean."
- Surface preparation is "Creating the situation so the coating will perform as expected."
- We used to talk about the "process" (abrasive blasting) for a clean surface.
- Now we talk about the end result-performance language for a "clean" surface.
- Around 1994- the industry had the "AHA" moment
  --It's waterjetting, not abrasive blasting.
- 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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Figure1 Abrasive Blast-Rounded Abrasive

Figure 2 Water Jet Cleaned-Rounded Initial Profile

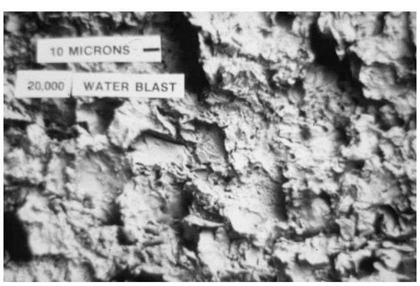


Figure 3 Water Jet Cleaned-Angular

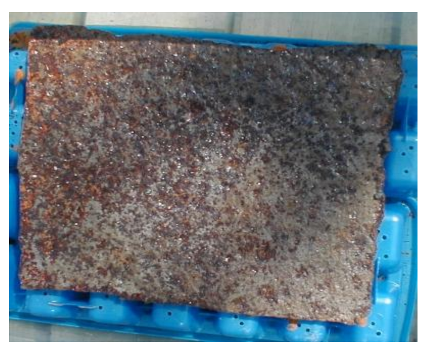


Figure 4 Marine Steel
Abrasive Blasted
Exposed to Humidity
6 years later

Figure 5 Marine Steel
Pressured Washed,
Then Abrasive Blasted
Exposed to Humidity
6 years later

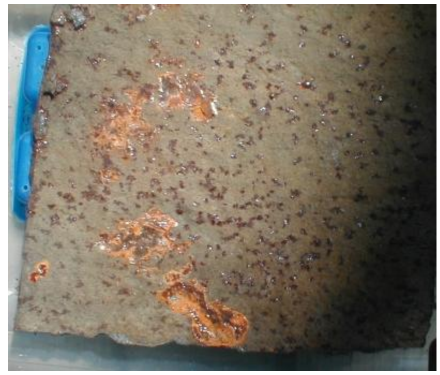


Figure 6 Marine Steel
UHP WJ Cleaned
Exposed to Humidity
6 years later

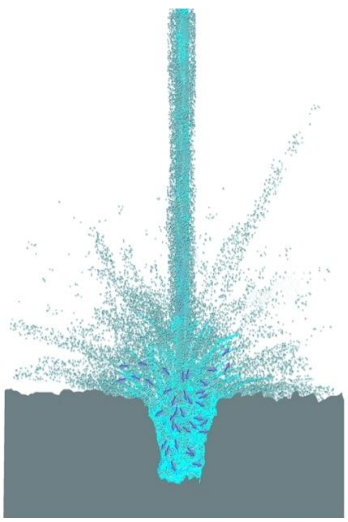
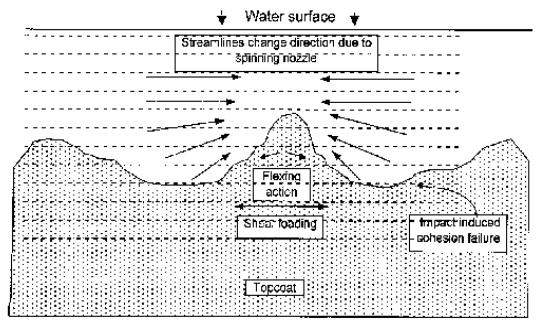


Figure 7- Flow Pattern



Horizontal flow over the irregular surface, coupled to rapid changes in flow direction as the nozzle spins and moves, induces both high shear loads at the base of any protrusion, and high bending moments.

Figure 8 Water Stream Flow (Lever 1995)

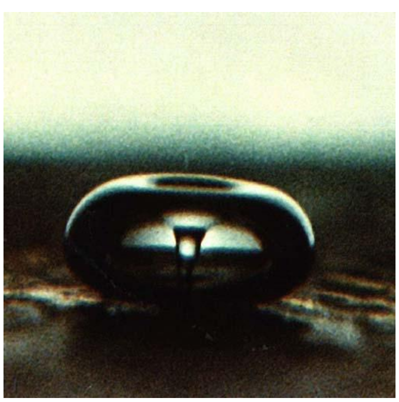


Figure 9
Formation of a microjet impact
with a velocity of approximately
400 kilometers (250 miles) per hour
L.A. Crum
www.scs.uiuc.edu/suslick/britannica.html