Ice Blast Technology for Precision Cleaning

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Abstract

Small ice particles have special properties that can be optimized to effect critical cleaning without chemical solvents or surfactants. The mechanisms of ice blast cleaning are described and some theoretical considerations are discussed to provide a basis for process optimization. Ice blast applications are described in general as well as with respect to precision cleaning. A case study on the application of ice blast to improve the metallurgical bonding of bimetallic zirconium alloy tubing is also presented. The evaluation shows that ice blast cleaning is superior to conventional acid etching for the critical cleaning of metallic surfaces.

Introduction

The concept of ice blast has been around for some time as evident by a 1955 U.S. patent on a car wash machine utilizing ice particles [1]. In reality, ice blast is relatively novel. This is most likely due to the fact that small ice particles are difficult to handle and many mechanical devices designed to improve the handling of such particles were not reliable. In fact, the early ice blast machines used dry ice which in pellet form is much easier to handle. The subject of this paper is the application of small crystalline ice particles made from water for the purpose of doing precision cleaning work.

Ice particles have properties ranging from the softness of snow to the hardness of ice that sank the Titanic. Evaluation of the static, dynamic, and impact properties of small ice particles show that they have the requisite properties for precision cleaning. In addition, there is now commercial equipment capable of delivering these small ice particles consistently and reliably to ensure statistically and individually reproducible results required by precision cleaning.

A case study on improving the metallurgical bonding of bimetallic zirconium alloy tubing is also presented. Improving the bond integrity is important not only for the in-service properties of the tubing but also for reducing the yield loss and rework costs for the manufacturer. Ice blast gives manufacturers the ability to improve the product quality and eliminate the environmental liabilities associated with the typical metal cleaning process of etching in acid solutions. This is important to any metal manufacturer that performs bonding, welding, or plating operations.

I. Introduction to Blast Cleaning Processes

Industrial blast cleaning processes all have one thing in common: a projectile (blast media) hitting a target (part to be cleaned). Cleaning is the result of impact interaction. When the impact is essentially elastic, light surface cleaning is usually accomplished and is generally described as displacement work. Inelastic impact causes media breakdown and/or part damage. In general, media breakdown without part damage produces mechanical or frictional work and frequently a lot of dust. The process is called abrasive blast cleaning when part damage is intentional; for example, in some metal surface preparations like sand blasting.

The impact properties of both the projectile and target must be considered to fully understand the nature of impact work. However, the target properties are fixed in most manufacturing situations so the only variables to consider are those associated with the blast media. A thorough understanding of the blast media is very important in specifying a proper blast cleaning process for the job.

Blast media can be continuous or discrete. Water is a familiar continuous blast media. Discrete blast media include, among many others, sand, plastic chips, walnut shell, glass beads, dry ice pellets, and crystalline ice particles made from water. Only dry and crystalline ice do not generate dust on impact because they undergo a phase change. Blast media that generates dust cannot be used for precision cleaning because of the high probability of recontamination. Thus, dry ice pellets and crystalline ice particles can be used for precision blast cleaning. Crystalline ice particles can do a superior cleaning job in the presence of inorganics typical of most manufacturing environments because the particles undergo a phase change from solid to liquid water. The phase change provides a medium to dissolve and contain the inorganics.

In more tangible terms, crystalline ice blast is much more cost effective. The operating cost of a commercial ice blast machine, such as model MX 90 manufactured by UNIVERSAL ICE BLAST, amounts to about $1 per blasting hour in addition to the cost of compressed air. Since ice particles are generated on demand there is also no media to purchase, handle, or inventory. The crystalline ice blast cleaning process can be implemented to operate continuously as long as power, water, and air are supplied.

II. Ice Particles as Blast Media for Precision Blast Cleaning

The blast media must perform two types of impact work to provide precision cleaning: displacement and frictional scrub. A liquid rinse further enhances the result.

Water in its liquid state is not an ideal media for precision blast cleaning because it lacks the frictional scrub capability even though it can be made to generate a very high momentum for displacement work. This is true in general for fluids.

Small ice particles are ideal for precision blast cleaning because they impact the target surface as solids, then deform to the surface structure in a frictional scrubbing action, and finally melt to water as shown in Figure 1. In technical terms, they perform displacement work before phase change, they perform frictional work during phase change, and they perform rinsing work after phase change. The ability to perform frictional scrub is the reason ice blast can provide a high level of cleanliness with a minimum amount of media. For example, a commercial ice blast machine such as model SX 110 manufactured by UNIVERSAL ICE BLAST requires only about 20 gallons of water per hour of blasting work. This is only a small fraction of the volume of water required by a high pressure water blaster.

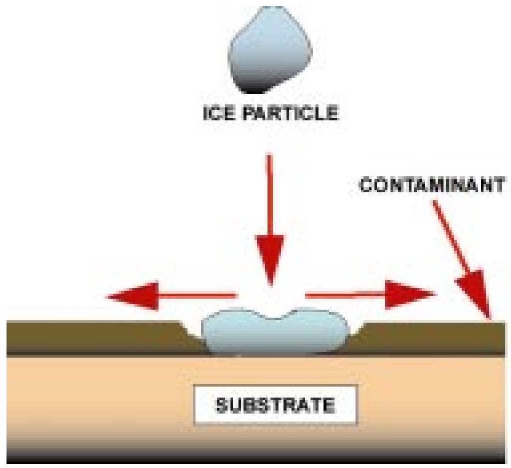

Figure 1 - Mechanisms of Ice Blast: Impact-Deformation-Rinsing

To optimize blast cleaning with ice particles, it is necessary to consider the relative requirement of displacement work with respect to frictional scrub work. Consider a planar surface to be cleaned with deposits along the surface. The displacement force (*F*) provided by an ice particle can be shown to have the following form:

$$F \approx 1.14\left(\frac{9m^3v^6RE^2}{16k^2}\right)^{1/5}\cos\theta$$

where *E* and *k* represent material constants, *m* the mass, *R* the effective radius, *v* the velocity of the ice particle, and θ the angle between the approaching ice particle and the plane of the surface. The equation can be simplified as shown below.

$$F \approx R^2v^{1.2}\cos\theta$$

The frictional scrub pressure (*P*) can be represented by the following extended and simplified forms of the equations.

$$P \approx 1.14\left(\frac{9m^3v^6RE^2}{16k^2}\right)^{1/5}\left(\frac{\sin\theta}{R^2}\right)$$

$$P \approx v^{1.2}\sin\theta$$

This suggests that ice particles should have a small approach angle for maximum displacement force while maximum frictional scrub pressure is achieved at essentially a normal approach. It is particularly interesting to observe that maximum displacement work is obtained with larger ice particles while maximum frictional scrub work is achieved independent of ice particle size. In both cases higher ice particle velocity gives improved efficiency.

Precision blast cleaning requires sufficient displacement cleaning, maximum frictional scrub, and minimal recontamination. The ice blast stream should be directed at an angle favoring high frictional scrub pressure while maintaining sufficient forward component of the blast force for displacement cleaning to achieve a very high level of cleanliness. The rinse water should also have sufficient forward momentum to minimize any chance of spray contamination. In practice, it is not always possible to have a large approach angle because of part configuration and other spatial constraints. In this case some compromise must be made and a higher air pressure may need to be used to provide higher ice particle velocities. Alternatively, longer dwell times, reduced average particle size, or increased ice particle flux can be considered.

Finally, it is important to remember that the cleanliness of the part is no better than that of the air and water quality used in ice blast. Oil-free compressed air and deionized water must be considered for very high level of cleanliness.

III. Applications of Ice Blast Cleaning

In general, ice blast cleaning has been used in applications where a) a high level of cleanliness is required, b) minimal or no damage to the substrate is acceptable, and c) waste is to be minimized. Some applications for waste minimization include radioactive decontamination, lead based paint abatement, asbestos abatement, and hazardous chemical decontamination. In many of these applications where a negative air environment is required, the waste water produced by ice blast is as low as 1 gallon per hour of blasting. In naturally vented spaces, the typical waste water volume is about 3-7 gallons per hour. The water spray produced in these applications helps to encapsulate blast debris that is often hazardous.

The non-abrasive impact property of small ice particles has been used to reclaim reject automotive plastic components, restore architectural structures, and restore salvaged undersea treasures. Additional applications include factory cleaning and equipment maintenance.

Ice blast has been also used in precision cleaning applications to deburr and clean small motor armatures, to deflash and clean fuel pump housings, and to improve the metallurgical bonding of bimetallic zirconium alloy tubing as described in the following case study.

IV. Zirconium Alloy Bimetallic Tubing

Bimetallic tubing allows for the optimization of properties that a conventional tube cannot achieve in severe applications. One application of bimetallic tubing is for zirconium alloy (Zircaloy) fuel cladding in light water nuclear reactors. The economic incentive to decrease fuel-cycle costs has resulted in increased fuel burn-ups that may exceed the corrosion performance of conventional zirconium alloys. The desired performance can be achieved by using a bimetallic or duplex tube with a bonded outside layer of an improved corrosion resistant zirconium alloy. The bulk of the tube is made of Zircaloy-4 that provides the mechanical properties while the thin outer layer of extra low Sn (ELS) Zircaloy provides the enhanced corrosion performance [2].

This case study focuses on the development of a cleaning process to improve the metallurgical bond between the thin outer liner and base material of bimetallic tubing. A high quality bond is necessary since bonding defects may cause a deterioration of the heat flux across the wall thickness of the cladding tube. The non-uniform temperature gradient could cause localized hydriding and eventual fuel cladding failure. Both intermediate and final size cladding tubes are 100% non-destructively tested using ultrasonic techniques to detect non-bonding delaminations. For example, a final size tube of 10.75 mm outside diameter (OD) x 0.88 mm wall thickness (W) is typically tested with a 0.1 mm width x 20 mm length notch. The liner thickness on this size of tube is approximately 0.1 mm [3]. Improvement of the cleaning process was intended to enhance the bonding performance of material ultrasonically tested at the intermediate size.

V. Cleaning Process for Bimetallic Tubing

The typical manufacturing steps for cleaning and bonding the ELS liner and Zircaloy-4 base components are shown in Figure 2. The liner and base components are typically machined into matched cylindrical sets with tight dimensional tolerances. The components are cleaned, assembled, and joined into a billet by electron beam welding the end joints in a vacuum.
Metallurgical bonding occurs during extrusion through a conical die at 550-750°C and high pressure. Typical reduction ratios are 5-10:1 for a 63.5 mm OD tube having a 2-3 mm thick outer liner bonded to the base component. Several cold working (pilgering) and annealing steps are typically performed to convert the material to final size tubing.

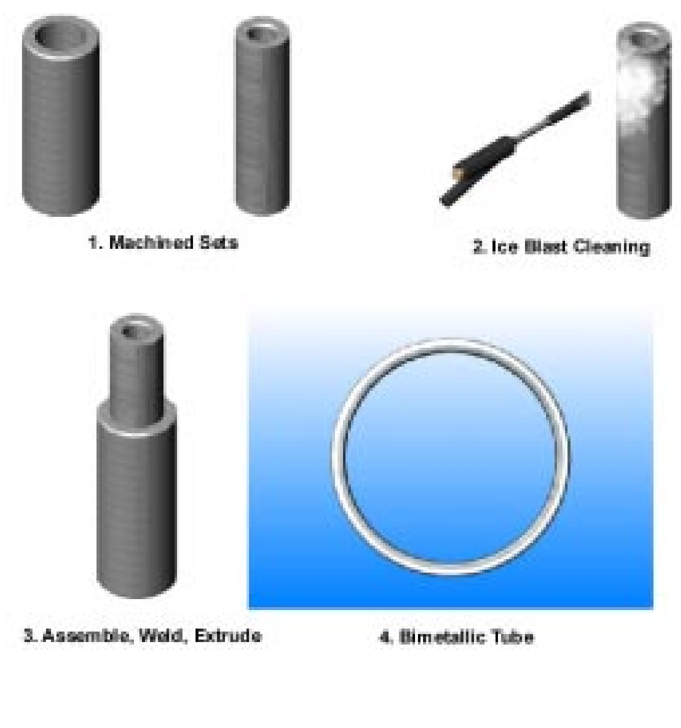

Figure 2 - Manufacturing Process

The standard cleaning process for cleaning Zircaloy components involves etching in mixtures of hydrofluoric-nitric acids to a bright silver appearance. Typically, the base and liner components are loaded onto stainless steel racks and dipped into large tanks of caustic cleaners, acid solutions, and hot deionized water. The use of acids requires physical protection of operators from the acid as well as significant ventilation to reduce the exposure of volatile nitrogen oxides (NOX). The corrosive nature of the chemicals can influence the equipment and material located in the facility. For example, cranes, light fixtures, and tool cabinets can all experience accelerated corrosion.

The successful development of ice blast technology has replaced acid etching as the cleaning process of Zircaloy bimetallic tubing. This process change represents a significant change in cleaning philosophy for Zircaloy materials. The old mentality of cleaning by material removal has been replaced with a process to critically clean the surface of machining oils and foreign contamination. Removal of surface contamination on Zircaloy components is assured using the typical ice blast parameters of less than 10 minutes blast time at 12 bar (180 psig). Drying of the components is necessary before assembly since ice blast is a wet process. Radiant heat can be employed to remove the moisture prior to billet assembly [4].

Besides the obvious environmental and quality benefits, ice blast technology allows for mechanization or automation of the cleaning process. For example, the base or liner component can be rotated on turntables or wheels while the ice blast nozzle traverses the length from a movable fixture. This process assures quality by maintaining a constant speed, blast angle, and stand-off distance. Ideally, ice blast for critical cleaning applications should be performed in a blast booth with air exhaust and sound deadening features. The booth provides protection from foreign contamination, contains the water spray, and reduces the blast noise to acceptable levels.

VI. Comparison of Cleaning Processes

Ultrasonic testing of intermediate size tubing manufactured by acid etching and ice blasting reveals significantly different results. Acid etched material tends to have significantly more bondzone delaminations than material cleaned by ice blast. Failure analysis of ultrasonic indications shows that most delaminations in acid etched material tend to form as localized voids. A typical delamination shown in Figure 3a has dimensions of 0.165 mm width x 0.004 mm height x 1.5 mm length. Further evaluation by electron microscopy techniques has revealed significant clustering of zirconium-fluoride particles in the delamination. Individual zirconium-fluoride particles have been also detected in the metallurgically bonded interface. The zirconium-fluoride particles are believed to be a residue that is coating the surfaces of Zircaloy components after etching in hydrofluoric-nitric acids. The data suggests that the residue prevents metallurgical bonding in areas containing a high density of zirconium-fluoride particles.

Zircaloy components that are cleaned by ice blasting show essentially no delaminations during intermediate size ultrasonic testing. This amazing improvement has been verified by destructive testing. Evaluation of samples by optical microscopy as shown in Figure 3b reveals a clean interface without any defects. Ice blast cleaning has removed all surface contamination.

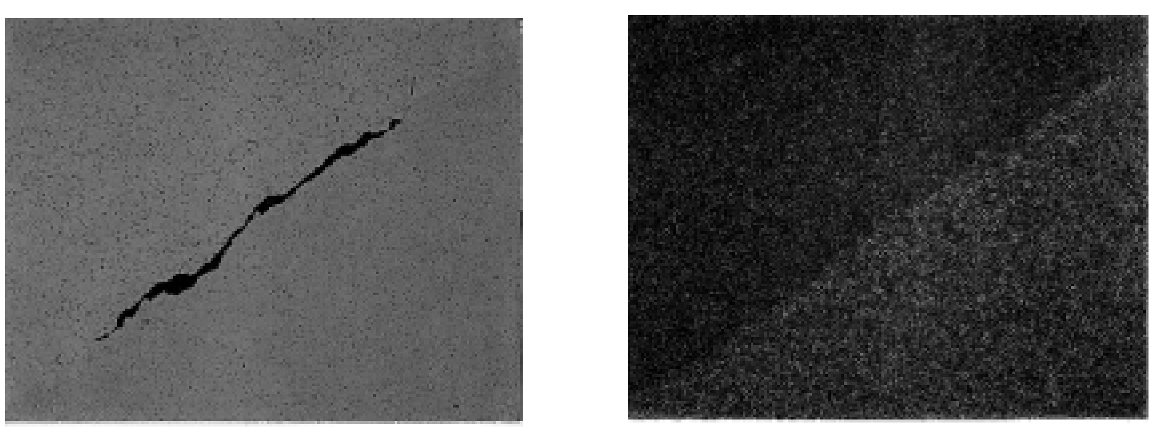

Figure 3 - Metallography of interface between liner and base components, 500:1 magnification: (a) delamination typical of acid etch process, and (b) clean interface typical of ice blast process.

Evaluation of the two cleaning processes can be quantitatively determined before bonding using a unique photoelectron emission technique. When a metallic surface is illuminated with ultraviolet light (UV) of the proper wavelength, electrons are emitted from the surface. The interaction between UV light photons and emitted electrons is known as optically stimulated electron emission (OSEE). The emitted electrons from the surface can be collected across an air gap by a biased collector and measured as a current. Thus, changes in the photocurrent (10^{-10} to 10^{-12} amps) can be measured by holding the intensity and energy of the UV light and the air gap distance constant. Surface contamination may then increase or decrease the electron emission depending on its own photoemission characteristics. In simple terms, a clean surface is a current generator while surface contamination acts as a resistor. For comparison purposes, the OSEE instruction is scaled from 0 to 999 with 0 representing severe contamination and 999 representing maximum cleanliness [5].

In-process OSEE measurements reveal significant differences in the surface contamination of cleaned components. The Zircaloy components typically have a relative OSEE value of 65 after machining. The low value is expected because of the layer of machining oil on the surfaces. Some components were conditioned with a fine abrasive and then cleaned with methyl alcohol to establish a control sample for maximum cleanliness. As expected, the relative OSEE value was 999. These control samples were then processed through the standard acid etch and ice blast processes. The acid etched samples typically had OSEE values of 375 while the ice blasted samples remained at 999 as shown in Figures 4a-b. This suggests that acid etching is contaminating instead of cleaning the components. Ice blast, meanwhile, is very effective for critical cleaning.

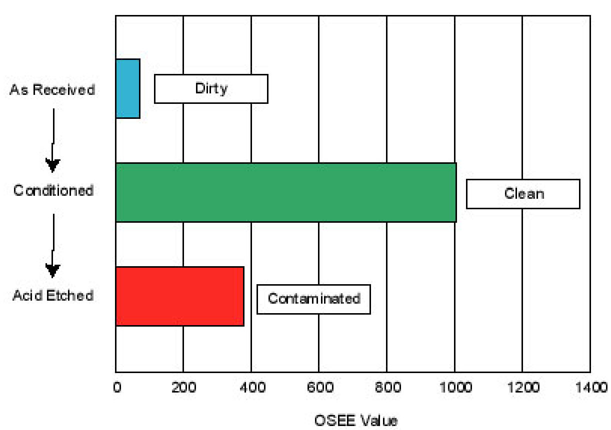

Figure 4a - Acid Etch Process

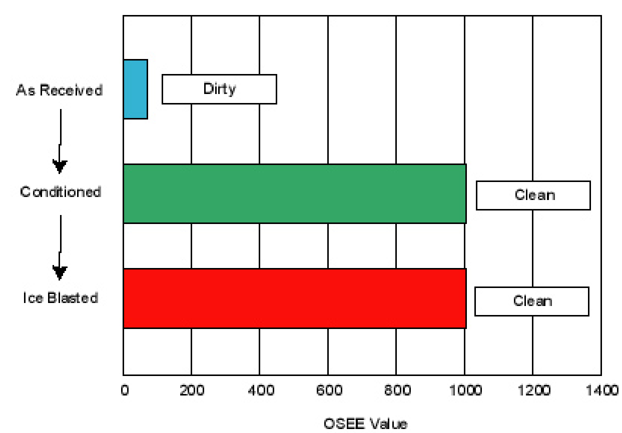

Figure 4b - Ice Blast Process

Conclusions

1. Commercial equipment capable of delivering small crystalline ice particles now exists for both general and critical cleaning applications.

2. Crystalline ice particles clean by displacement during impact, frictional scrubbing during phase change, and rinsing after phase change.

3. Application of ice blast for critical cleaning has improved the metallurgical bonding of bimetallic zirconium alloy tubing.

Acknowledgments

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