Journal of Technology and Operations Management 7(2), 56-68 (2012)

DRY-ICE BLASTING AN OPTIMAL PANACEA FOR DEPURATING WELDING ROBOTS OF SLAG AND SPATTER

Nazim Baluch
Che Sobry Abdullah
Shahimi Mohtar
School of Technology Management and Logistics,
UUM College of Business,
University Utara Malaysia

ABSTRACT

Though MIG welding robots are extensively applied in the automotive assemblies **'***Spot Welding' is the most common welding application found in the auto stamping assembly manufacturing. Every manufacturing process is subject to variations – with resistance welding, these include; part fit up, part thickness variations, misaligned electrodes, variations in coating materials or thickness, sealers, weld force variations, shunting, machine tooling degradation; and slag and spatter damage. All welding gun tips undergo wear; an elemental part of the process. Though adaptive resistance welding control automatically compensates to keep production and quality up to the levels needed as gun tips undergo wear so that the welds remain reliable; the system cannot compensate for deterioration caused by the slag and spatter on the part holding fixtures, sensors, and gun tips. To cleanse welding robots of slag and spatter, dry-ice blasting has proven to be an effective remedy. Presently, CO_2 / dry ice blasting is being effectively used in a wide array of applications from heavy slag removal to delicate semiconductor and circuit board cleaning. This process can be used on-line without damaging equipment or requiring a machine "teardown". Unlike conventional toxic chemicals, high-pressure water blasting and abrasive grit blasting, CO_2 / dry ice blasting uses dry ice particles in a high velocity air flow to remove contaminates from surfaces without the added costs and inconvenience of secondary waste treatment and disposal. This paper describes MIG and Spot welding process and analyses the slag and spatter formation during robotic welding of stamping assemblies; and concludes that the dry ice blasting process's utility in cleansing of welding robots in auto stamping plant operations is paramount and exigent.*

Keywords: *CO_2 / Dry-Ice, Dry Ice Blasting, Welding Robots, Robotic Assemblies, MIG weld, Spot Weld*

INTRODUCTION

Dry ice is the solid form of Carbon Dioxide (CO_2), which is a colorless, tasteless, odorless gas found naturally in our atmosphere. Though it is present in relatively small quantities (about 0.03% by volume), it is one of the most important gases we know of. In the early 1930's, the manufacture of solid phase CO_2 became possible. During this time, the creation of "dry ice" was nothing more than a laboratory experiment. As the procedure for making dry ice became readily available, applications for this innovative substance grew. Obviously, the first use was in refrigeration, and dry ice is still widely used in the Food Industry for packaging and protecting perishable foods today. 1945 saw stories of the U.S. Navy experimenting with dry ice as a blast media for various degreasing applications. In May 1963, Reginald Lindall received a patent for a “method of removing meat from bone “using” jetted CO_2 particles. In November 1972, Edwin Rice received a patent for his "method for the removal of unwanted portions of an article by spraying with high-velocity dry ice particles". Similarly, in August 1977, Calvin Fong received a patent on "Sandblasting with pellets of material capable of sublimation". The work and success of these early pioneers led to the formation of several companies in the early 1980's that pursued the development of dry ice blasting technology. In 1986, Cold Jet®, Inc. was founded in the State of Ohio by Mr. Newell Crane. Dry ice pelletizers and dry ice blasting machines entered the industrial markets in the late 1980's. At that time the blasting machines were physically large, expensive, and they required high air pressure for operation (pressures greater than 200 psi or 13.8 bar). As the CO_2 / dry ice blasting technology advanced, the dry ice blasting machines' size and cost dropped, and presently, the latest nozzle technology has made blasting effective at shop air pressures of 80 psi or 5.5 bar (Snide, 1992).

Nowadays, CO_2 / dry ice blasting is being effectively used in a wide array of applications from heavy slag removal to delicate semiconductor and circuit board cleaning; a process that can be used on-line without damaging equipment or requiring a machine "teardown". Unlike conventional toxic chemicals, high-pressure water blasting and abrasive grit blasting, CO_2 / dry ice blasting uses dry ice particles in a high velocity air flow to remove contaminates from surfaces without the added costs and inconvenience of secondary waste treatment and disposal. Virtually any item that is part of a production process and is difficult to clean on-line or during production hours by traditional means may be an excellent dry ice application such as removing weld slag from Robotics, Fixtures, and Carriers (Ackerman, 2013).

Robot welding is a relatively new application of robotics; it is the branch of technology that deals with the design, construction, operation, and application of robots as well as computer systems for their control, sensory feedback, and information processing. Even though robots were first introduced into US industry during the 1960s, the use of robots in welding did not take off until the 1980s, when the automotive industry began using robots extensively for spot welding. Since then, both the number of robots used in industry and the number of their applications has grown tremendously. Investing in welding automation can be a relatively quick way for companies to achieve greater productivity, improve weld quality and reduce costs. But protecting that investment is the key to maintaining these benefits over the long term. Preventive and predictive maintenance programs are an easy and cost-effective way to help. These programs not only protect against costly downtime, but they can also help lower labor costs, reduce waste and minimize rework (Nocks, 2007). The robot may weld a pre-programmed position, be guided by machine vision, or by a combination of the two methods. However, the many benefits of robotic welding have proven to make it a technology that helps many original equipment manufacturers (OEM) increase; accuracy, repeat-ability, and throughput (Cary & Helzer, 2005).

WELDING PROCESS – MIG and SPOT RESISTANCE WELDING

Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the work pieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the work pieces to form a bond between them, without melting the work pieces (Weman, 2003).

MIG and Spot Resistance Welding – are the two most widely used methods applied to join metal assemblies in various manufacturing operations. Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding, is a welding process in which an electric arc forms between a consumable wire electrode and the work piece metal(s), which heats the work piece metal(s), causing them to melt, and join. Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from contaminants in the air. The process can be semi-automatic or automatic. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations.

Spot Welding - Resistance Spot Welding (RSW) is a process in which contacting metal surfaces are joined by the heat obtained from resistance to electric current. Work-pieces are held together under pressure exerted by electrodes. Typically the sheets are in the 0.5 to 3 mm (0.020 to 0.12 in) thickness range. The process uses two shaped copper alloy electrodes to concentrate welding current into a small "spot" and to simultaneously clamp the sheets together. Forcing a large current through the spot will melt the metal and form the weld. The attractive feature of spot welding is a lot of energy can be delivered to the spot in a very short time (approximately ten milliseconds). That permits the welding to occur without excessive heating to the remainder of the sheet (Weman, 2003). During spot welding, the large electric current induces a large magnetic field, and the electric current and magnetic field interact with each other to produce a large magnetic force field too, which drives the melted metal to move very fast at a velocity up to 0.5 m/s. As such, the heat energy distribution in spot welding could be dramatically changed by the fast motion of the melted metal (Li *et al.* 2007).The amount of heat (energy) delivered to the spot is determined by the resistance between the electrodes and the amperage and duration of the current. The amount of energy is chosen to match the sheet's material properties, its thickness, and type of electrodes. Applying too little energy won't melt the metal or will make a poor weld. Applying too much energy will melt too much metal, eject molten material, and make a hole rather than a weld. Another attractive feature of spot welding is the energy delivered to the spot can be controlled to produce reliable welds (Shannon, 2007).

INDUSTRIAL ROBOTS IN WELDING and ASSEMBLY

Industrial robots are programmable, multi-function manipulators designed to automate tasks such as welding or the movement of materials through variable programmed motions. There are two popular types of industrial welding robots. The two are articulating robots and rectilinear robots. Robotics controls the movement of a rotating wrist in space. Rectilinear robots move in line in any of three axes (X, Y, & Z). In addition to linear movement of the robot along axes there is a wrist attached to the robot to allow rotational movement. This creates a robotic working zone that is box shaped. Articulating robots employ arms and rotating joints. These robots move like a human arm with a rotating wrist at the end. This creates an irregularly shaped robotic working zone.

There are many factors that need to be considered when setting up a robotic welding facility such as; accuracy and repeatability, number of axes, reliability, fixtures, programming, seam tracking systems, maintenance, controls, weld monitors, arc welding equipment, positioners, and part transfer. A robotic welding system may perform more repeatably than a manual welder because of the monotony of the task. However, robots may necessitate regular recalibration or reprogramming. Robots should have the number of axes necessary to permit the proper range of motion and the robot arm should be able to approach the work from multiple angles. The axes of movement that a robot has are referred to as degrees of freedom. Typical vertically articulated robots feature a 6-axis configuration, or six degrees of freedom. Six Industrial Robot Configurations include: Vertically Articulated; Cartesian; SCARA; Cylindrical; Polar; and Delta. Robotic welding systems are able to operate continuously, provided appropriate maintenance procedures are adhered to. Continuous production line interruptions can be minimized with proper robotic system design and robust maintenance management system in place. Besides quick weld tip change over, planning for the following contingencies needs to be completed; rapid substitution of the inoperable robots, installing backup robots in the production line and redistributing the welding of broken robots to functioning robots close by.

Welding Robots - though MIG welding robots are extensively applied in the automotive assemblies ‘Spot Welding’ is the most common welding application found in the auto stamping assembly manufacturing. While it is commonly used in the automotive industry to join sheet metal frames together, the spot welding application has a variety of project uses. Automating spot welding is quick, easy and a great economic solution. Spot welding robots have the ability to overcome difficult welds while providing consistent quality. A spot welding robot is cost effective and various kinds offer floor space savings, which is why so many automotive manufacturing companies have incorporated this kind of robot into their plant. When specifying for heavier loads, consideration should be given to: Number of axis; Payload; H-Reach; Repeatability; and Robot Mass.

A robotic welding cell is devoted to producing products requiring similar operations; these welding cells, a type of cellular manufacturing, represent an alternative structure that reduces manufacturing lead times, improve product cost and quality. Modern welding cells provide a high level of flexibility, allowing for potential engineering and future design changes. They also have reduced manpower requirements. The robotic welding cells have been the bridge needed to achieve the quality, throughput and machine reliability required. Assembly robots have expanded production capabilities in the manufacturing world. The assembly process is faster, more efficient and precise than ever before. End of arm tooling can be customized for each assembly robot to fit any assembly needs. Robots have saved workers from tedious and dull assembly line jobs, while increasing production and savings in the process (Steed, 2013). However, the new ultra high strength steels (UHSS) are presenting the welding engineer with new challenges, i.e. smaller welding windows (less robustness), more complicated fracture mechanisms, potentially weaker welds, different fatigue behaviour and more complex quality checking in production. The classic problems at resistance spot welding, such as electrode alignment, the presence of adhesives and sealants as well as various types of zinc coatings have a larger effect on the welding of UHSS compared to conventional mild steels; nevertheless, weld performance can be improved with adaptive controls.

PERNICIOUS RAMIFICATION OF WELD SLAG AND SPATTER

Slag - is the residue left on a weld bead from the flux; flux shields the hot metal from atmospheric contaminants that may weaken the weld joint. Slag can also be globules of molten metal that are expelled from the joint and then re-solidify on the metal surface. Slag inclusions are non-metallic solid material entrapped in weld metal or between weld metal and base metal. Slag inclusions are regions within the weld cross section or at the weld surface where the once-molten flux used to protect the molten metal is mechanically trapped within the solidified metal. This solidified slag represents a portion of the weld's cross-section where the metal is not fused to itself. This can result in a weakened condition which could impair the serviceability of the component. Inclusions may also appear at the weld surface. Like incomplete fusion, slag inclusions can occur between the weld and base metal or between individual weld passes. In fact, slag inclusions are often associated with incomplete fusion (MDOT, 2012).

Spatter - is essentially little droplets of molten material that are generated at or near the welding arc. Spatter is generally regarded as a nuisance and is a critical factor that needs to be taken into consideration when developing an application. Some of the problems associated with spatter include; spatter balls sticking to work pieces or tooling, spatter burning auxiliary wire and connectors, loss of material from the arc and weld, and excessive clean up of spatter. Most manufactures strive to reduce the amount of spatter generated, if not eliminate it all together.

Spatter is caused by several factors, the main factor being a disturbance in the molten weld pool during the transfer of wire into the weld. Typically this is caused by the relationship between amperage and voltage. This is usually seen when the welding voltage is too low or the amperage is too high for a given wire and gas combination. In this situation, the arc is too cold to keep the wire and pool molten and causes a stubbing effect of the wire. This can occur at both high and low current ranges. Spatter may be generated as a result of the gas selected. In GMAW, the use of CO_2 increases the arc energy and is very cost effective yet creates more weld spatter. Argon is commonly used to counter balance the spatter generated from CO_2. During MIG welding, one of the most common causes of excessive spatter is using too much wire. If one is getting spatter everywhere during a MIG weld, try slowing down the wire feed speed. If that doesn't work, the excessive spatter might be the result of arc blow, which occurs when magnetism in the base metal affects the quality of arc. To combat arc blow, try welding toward ground clamp. If that doesn't do the trick, switch welding machine to alternating current (Minnick, 2007).

To ensure integrity of welds, it is vital to remove weld slag as many products are constructed from a series of stamped and formed panels that are spot-welded together making a unibody frame. An epoxy sealer is applied between the panels before they are spot welded; this sealer is splattered along with welding slag during the welding process. After a period of time, this "spatter" builds up on the robot joints and other ancillary equipment. It can become difficult to perform regular maintenance on the equipment and the range of motion of the robot will be reduced. The production line may need to be shut down to remedy problems caused by this excess accumulation of slag and sealant. As auto frames pass through welding lines they can catch on this slag build-up, robots apply sealant in the wrong locations and weld quality is therefore compromised. During preventative maintenance, skilled electricians and mechanics spend a disproportionate amount of time cleaning troubled areas rather than focusing on items requiring repair/maintenance. E-coat is another problem area whereby epoxy coating builds up and affects the effectiveness of holding clamps and contact shoes. Traditional cleaning methods tend to damage the delicate sensors and electrical devices in the area. Manual scraping and wiping doesn't clean very effectively and it is very time consuming. Though adaptive resistance welding control, aided by signature image processing for weld consistency, automatically compensates to keep production and quality up to the levels needed as gun tips undergo wear; these systems can not compensate for the deterioration in weld quality due to slag and spatter damage to guns and sensors (Moore, 2012 & Simpson, 2008). Dry ice blasting method, explained in the following paragraph, is highly effective to rid welding guns and fixtures of slag and spatter.

DRY ICE BLASTING

Dry ice is the solid form of Carbon Dioxide (CO_2), which is a colorless, tasteless and odorless gas found naturally in our atmosphere. Though it is present in relatively small quantities (about 0.03% by volume), it is one of the most important gases we know of. With a low temperature of -109° F (-78° C), solid CO_2 (dry ice) has an inherent thermal energy ready to be tapped. At atmospheric pressure, dry ice sublimates directly to vapor without going through a liquid phase. This is a unique property meaning that the blast media simply disappears, leaving only the original contaminant to be disposed off. In addition, blast cleaning in water sensitive areas is now practicable. The grade of CO_2 used in dry ice blasting is the same as that used in the food and beverage industry and has been specifically approved by the FDA (Food and Drug Administration), the EPA (Environmental Protection Agency) and the USDA (United States Department of Agriculture). Carbon dioxide is a non-poisonous, liquefied gas that is both inexpensive and easily stored at work sites. Of equal importance is its non-conductive and non-flammable nature. CO_2 is a natural by-product of several industrial manufacturing processes such as fermentation and petro-chemical refining. The CO_2 given off by the above production processes is captured and stored without losses until needed. When the CO_2 is returned to the atmosphere during the blasting process, no new CO_2 is produced. Instead, only the original CO_2 by-product is released (Ackerman, 2013).

Methodology

Cleansing with dry ice is new development which is expanding around the world. The system uses small rice size pellets of dry ice shooting them out of a jet nozzle with compressed air. It works somewhat like sandblasting or high-pressure water or steam blasting, with superior results. The frigid temperature of the dry ice -109.3°F or -78.5°C "blasting" against the material to be removed causes it to shrink and lose adhesion from its sub surface. Additionally when some of dry ice penetrates through the material to be removed, it comes in contact with the underlying surface. The warmer sub surface causes the dry ice to convert back into CO_2. The gas, having 800 times greater volume, expands behind the material speeding up its removal. Paint, oil, grease, asphalt, slag, spatter, tar, decals, soot, dirt, ink, resins, and adhesives are some of the materials removed by this procedure. Only the removed material must be disposed off, as the dry ice sublimes into the atmosphere (Ackerman, 2013). In dry ice blasting, there are several methods used to manufacture the dry ice blasting media. One technique is to shave dry ice granules from a solid CO_2 (dry ice) block at the blasting machine. This generally produces sugar-crystal sized dry ice granules, which must be used quickly due to rapid sublimation; which is due to their high surface area-to-volume ratio. Another technique is to manufacture hard pellets of dry ice in a pelletizer then immediately blast with the pellets or store the pellets in an insulated container until they are needed. These dry ice pellets are generally on the order of 0.08" to 0.12" (0.2cm to 0.3cm) in diameter, and 0.1" to 0.4" (0.25cm to 1cm) in length.

Pelletized dry ice is manufactured by flashing pressurized liquid CO_2 into snow, and then compressing the snow into solid form. The snow is either directly nuggetized into pellets (mechanical compression) or is extruded into solid pellet form through a die under hydraulic pressure. The latter process allows for a more efficient conversion from the liquid phase to the solid phase. Generally, it is desirable to have dry ice pellets that are well compacted to minimize the entrapment of gaseous CO_2 and/or air which may affect product quality. The yield achieved when flashing liquid carbon dioxide into snow increases as the temperature of the liquid CO_2 decreases, so it is important to pre-chill the incoming liquid CO_2 via heat exchangers with the outgoing CO_2 vapor.

How Does Dry Ice Blasting Work?

The Basic Process of dry ice blasting is similar to sand blasting, plastic bead blasting, or soda blasting; in that a media is accelerated in a pressurized air stream (or other inert gas) to impact the surface to be cleansed or prepared. With dry ice blasting the media is solid CO_2 particles. One unique aspect of using dry ice particles as a blast media is that the particles sublimate (vaporize) upon impact with the surface. The combined impact-energy dissipation and extremely rapid heat transfer between the dry ice pellet and the surface causes the instantaneous sublimation of the solid CO_2 / dry ice into gas. The gas then expands to nearly eight hundred times (800x) the volume of the dry ice pellet in a few milliseconds in what is effectively a "micro-explosion" at the point of impact. Because of the solid CO_2 vaporizing, the dry ice blasting process does not generate any secondary waste. All that remains to be collected is the contaminant that is being removed. As with other blast media, the kinetic energy associated with dry ice blasting is a function of the particle mass' density and impact velocity. Since CO_2 / dry ice particles have a relatively low hardness, the process relies on high particle velocities to achieve the needed impact energy. The high particle velocities are the result of supersonic propellant or airstream velocities (Snide, 1992).

Unlike other blast media, the CO_2 / dry ice particles have a very low temperature of -109° F (-78.3°C). This inherently low temperature gives the dry ice blasting process unique thermodynamically induced surface mechanisms that affect the coating or contaminate in greater or lesser degrees, depending on the coating type. Because of the temperature differential between the dry ice particles and the surface being treated, a phenomenon known as "fracking" or thermal shock can occur. As a material's temperature decreases, the material becomes brittle, enabling the particle impact to break-up the coating. Also, the thermal gradient or differential between two dissimilar materials with different thermal expansion coefficients can serve to break the bond between the two materials. This thermal shock is most evident when blasting a non-metallic coating or contaminate bonded to a metallic substrate. Quite often companies examining the dry ice blasting process are concerned with the effect the thermal shock will have on the parent metal. Studies have shown that the temperature decrease occurs on the surface only, so that there is no chance of thermal stress occurring in the substrate metal (Snide, 1992). The efficiency and effectiveness of this process depends on the thermal conductivity of the substrate and contaminant. The rapid change in state from solid to gas also causes microscopic shock waves, which are also thought to assist in removing the contaminant. The ice used can be in solid pellet or shaved ice block forms. The shaved ice block produces a less dense ice medium and is more delicate than the solid pellet system.

Blast Machine Types

There are two general classes of dry ice blasting machines as characterized by their method of transporting pellets to the nozzle; the two-hose and the single-hose systems. In either type of system, the proper selection of blast hose is important because of the low temperatures involved and the need to preserve particle integrity as the dry ice particles travel through the hose. In the two-hose system, dry Ice particles are delivered and metered by various mechanical means to the inlet end of a hose and are drawn through the hose to the nozzle by means of vacuum produced by an ejector-type nozzle. Inside the nozzle, a stream of compressed air (supplied by the second hose) is sent through a primary nozzle and expands as a high velocity jet confined inside a mixing tube. When flow areas are properly sized, this type of nozzle produces vacuum on the cavity around the primary jet and can therefore draw particles up through the ice hose and into the mixing tube where they are accelerated as the jet mixes with the entrained air/dry ice particle mixture. Advantages of this type of system are relative simplicity and lower material cost, along with an overall compact feeder system. One primary disadvantage is that the associated nozzle technology is generally not adaptable to a wide range of conditions (i.e. tight turns in a cavity, thin-wide blast swaths, etc.). Also, the aggression level and strip rate of the two-hose system is less than comparable to single-hose blast machines. In a single-hose system, particles are fed into the compressed air line by one of several types of airlock mechanisms. Reciprocating and rotary airlocks are both currently used in the industry. The stream of pellets and compressed air is then fed directly into a single hose followed by a nozzle where both air and pellets accelerate to high velocities. Advantages of this type of system are wide nozzle adaptability and the highest available blast aggression levels. Disadvantages include relatively higher material cost due to the complex airlock mechanism.

Dry ice blasting machines are also differentiated into ‘Dry Ice Block Shaver Blasters’ and ‘Dry Ice Pellet blasters’. The Block Shaver machines take standard 60 lb (27.3 kg) dry ice blocks and use rotating blades to shave a thin layer of ice off the block. This thin sheet of dry ice shatters under its own weight into sugar grain sized dry ice particles. These particles then fall into a funnel for collection. A two-hose delivery system is used to transfer the particles at the bottom of the funnel to the surface to be cleansed. The low mass of these particles combined with the inefficient two-hose system limits the block shavers to light duty cleansing. Because the shaved ice machines deliver a dry ice particle blast with high flux density (Number of particles striking a square area of surface per second), they are effective on thin, moderately hard coatings such as air dried oil based paint. The disadvantage of the ice shaver is that the dry ice particle's size and flux density, as well as its velocity, are fixed.

In contrast, Pellet Blasting machines have a hopper that is filled with pre-manufactured CO_2 / dry ice pellets. The hopper uses mechanical agitation to move the pellets to the bottom of the hopper and into the feeder system. As stated earlier, the pellets are extruded through a die plate under great pressure. This creates an extremely dense pellet for maximum impact energy. The pellets are available in several sizes, ranging from 0.04" to 0.12" (0.1 cm to 0.3 cm) in diameter. With a single-hose delivery system, the final pellet size and blast flux density exiting the nozzle is governed by the type of blast hose (hose diameter and interior wall roughness) and nozzle used. Because of its design, the single-hose dry ice pellet blasting units are capable of "dialing-in" the correct blast type needed for a wide range of individual coatings or contaminate removals.

Dry ice blasting machines are further differentiated into all-pneumatic and electro-pneumatic types. All-pneumatic machines have a pneumatically operated dry ice particle feed mechanism and controls. This may include the use of air motors. The advantage of such a machine is the availability of compressed air at the blast locations, especially outdoors. One disadvantage is that the operation of the machine may be susceptible to disruption due to moisture or contamination in the compressed air supply. In addition, these machines are more prone to freeze-ups and are better suited for light duty spot cleansing applications. Also, if the machine is powered by an air motor, it will have a continuous exhaust of oily air. This same air motor can easily be flooded with water if the air system is not adequately dried.

Electro-pneumatic machines are truly "Environmentally Friendly" because there is no oily exhaust and these machines are more tolerant of moisture and contaminants in the air supply. The electro-pneumatic machines rarely freeze-up which makes them ideal for automated line applications where around-the-clock dry ice blasting is required. Also, these machines provide pulse free blasting for uniform cleansing and efficient use of the dry ice. There is, however, a slight inconvenience factor associated with supplying both electrical power and compressed air to the machine at each blast location.

One of the most challenging technologies associated with either type of blast machine is the achievement of smooth, continuous pellet feed. One surprising property of dry ice is that it is not smooth or slippery like water ice nor is it smooth-flowing like sand or glass bead. Instead it is somewhat resistant to flow. Because of this, dry ice blast machines tend to have various agitators, augers and other devices in the hopper to improve pellet flow. Generally, the poorer the quality of the dry ice - containing, for example, water ice build-up or a large percentage of CO_2 "fines" or snow - the more difficult its flow through a system. As dry ice will draw moisture the machine must be tolerant of repeated freeze-thaw cycles and the associated moisture build up that will take place over time. Generally, the difference between a high-quality dry ice blasting machine and a mediocre one lies in the unit's ability to do a cleansing job quickly, cost-effectively, and with the reliability of smooth and continuous dry ice pellet flow under real-world conditions.

Nozzle Technology

The nozzle is where the dry ice particles are accelerated to the highest velocity possible in order to create an effective dry ice blast stream. Figure 1 shows the schematics of the two types of nozzles used for dry ice blasting. The science of two-hose ejector nozzles compared to single-hose convergent-divergent supersonic nozzles operating under the same conditions (i.e., air volume, pressure, temperature, CO_2 particle mass...etc.) shows a significantly higher efficiency capability for the described single-hose type nozzles. This difference in capability is directly related to the two-hose ejector nozzle's overall supplied energy being used not only to accelerate the CO_2 / dry ice particles, but also to create the vacuum pulling the secondary pellet flow through the secondary hose. Then, more energy is drained to mix this low velocity particle flow with the high velocity jet flow in order to accelerate the dry ice particles through the two-hose nozzle. In simple terms, the net resultant energy available for pellet acceleration is inherently lower for two-hose systems because much of the available energy is lost simply in combining the CO_2 / dry ice particle flow with the air-jet flow (Snide, 1992).

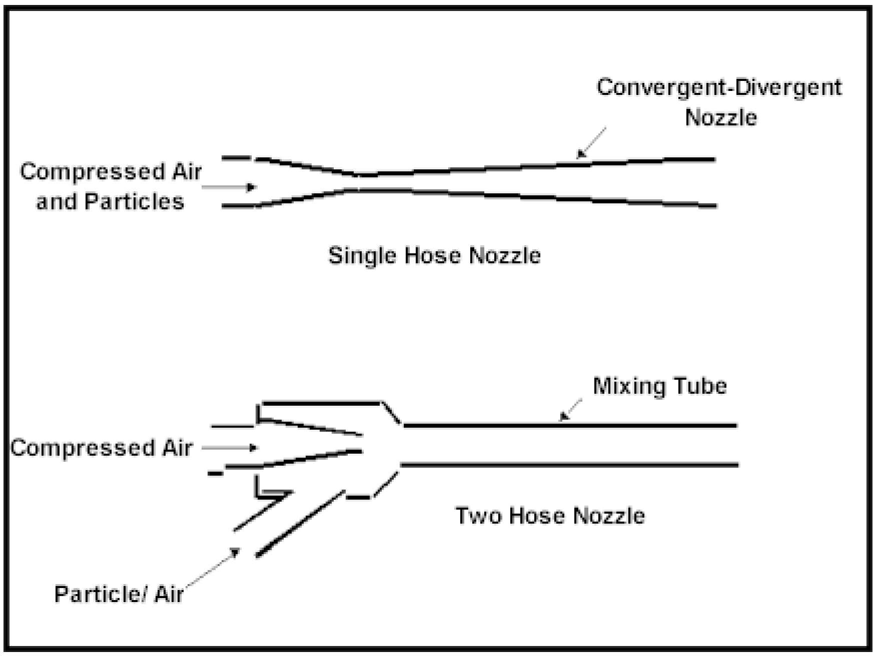

Figure 1: CO_2 / Dry Ice Blasting Nozzle Types

Since the size of the dry ice particles affect cleansing performance, a dry ice blasting system should have the flexibility to "Dial-In" the correct particle size. This can be done in a couple of different ways. First, the size of the dry ice pellet being produced by the pelletizer may be varied. Once the pellet is in the dry ice blasting machine's hopper, the size of the pellet reaching the surface to be cleansed can be varied in several ways. The diameter and type of blast hose used will either keep the pellet intact or break it up into smaller particles. Also, the nozzle may be intentionally miss-expanded to produce partially destructive shockwaves within the nozzle. Both techniques are used independently or together to optimize the dry ice particle size, blast stream velocity, and flux density for any cleansing job.

BENEFITS OF CO_2 / DRY ICE BLASTING TECHNOLOGY

Cost Reduction

The natural sublimation of dry ice particles eliminates the cost of collecting the cleansing media for disposal. Containment and collection costs associated with water/grit blasting procedures are also eliminated. Because CO_2 / dry ice blasting systems provide on-line maintenance capabilities for production equipment (online cleansing), time consuming and expensive de-tooling procedures are kept to a minimum. Dedicated cleansing cycles are no longer required as preventive maintenance schedules can be adopted, which allow for equipment cleansing during production periods. As a result, throughput is increased without the addition of labor or production equipment.

Extension of Equipment's Useful Life

Unlike sand, walnut shells, plastic beads and other abrasive grit media, dry ice particles are non-abrasive; cleansing with dry ice will not wear tooling, texture surfaces, open tolerances, or damage bearings or machinery. In addition, on-line cleansing eliminates the danger of molds being damaged during handling from press to cleaning area and back.

A Dry Process

Unlike steam or water blasting, CO_2 / dry ice blasting will not damage electrical wiring, controls, or switches. Also, any possible rust formation after cleansing is far less likely with dry ice blasting than with steam or water blasting. Also, when used in the Food Industry, dry ice blasting reduces the potential for bacteria growth inherent to conventional water blasting.

Environmental Safety

CO_2 is a non-toxic element which meets EPA, FDA, and USDA industry guidelines. By replacing toxic chemical processes with CO_2 / dry ice blasting systems, employee exposure and corporate liability stemming from the use of dangerous chemical cleaning agents can be materially reduced or eliminated completely. Since CO_2 gas is heavier than air (CO_2 gas displaces oxygen), care must be taken if blasting in enclosed areas or down in a pit.
In addition to being clean and safe, it is also important to remember that dry ice is obtained as a by product of other industrial processes - i.e. it is made from reclaimed CO_2. It does not produce CO_2 or add CO_2 to the atmosphere and therefore does not contribute to the greenhouse effect.
Dry ice blasting is the superior alternative to; Media Blasting, Solvents, Water, Steam, Hand Cleaning, Chemicals and Abrasives. Current CO_2 Blast applications include cleansing of; Molds, Dies, fixtures (food industry), Tooling, production machinery & equipment, and ink and polymer build ups (printing industry). A typical Cold Jet dry ice blast system operates at 80 psi (5.5 bar) with 150 Standard Cubic Feet per Minute [SCFM] (4.25 m^3/min), however it will depend on the application. Low flow nozzles are available, which require only 50 SCFM (1.42 m^3/min) at 80 psi (5.5 bar). Because CO_2 is 40% heavier than air, placement of exhaust vents at or near ground level is recommended when blasting in an enclosed area. In an open environment, existing ventilation is sufficient to prevent undue CO_2 buildup. Even though CO_2 is non-poisonous, it

does displace oxygen in the atmosphere. Another concern is the temperature of the dry ice. At -109°F (-78.3°C); gloves should be used when coming in contact with the dry ice. Eye and ear protection should be worn at all times.

CONCLUSION

Dry Ice blasting creates a "No Contact Cleansing" opportunity and can remove slag and spatter in a fraction of time without the added costs and inconvenience of secondary waste treatment and disposal. Advantages include; increased line up-time from the ability to spot problems, and if a break down occurs, problems are able to be fixed quickly without having to first clean the troubled area. Robots and jigs are aesthetically better looking; the copper and brass fittings which become all nicked up from chiseling and scraping maintain a like new appearance when cleansed with dry ice jet. It is easy to clean proximity switches and tight hard to reach by hand areas such as guns and arms of the robot. Solvents used for cleaning the sealant are eliminated. In view of the strenuous nature of robotic assembly operations, it is imperative that auto stamping assembly plants incorporate dry ice (CO_2) blasting for their cleansing to ensure equipment reliability guaranteeing sustainable production. With the environmental issues and legislation becoming more and more stringent, one thing is certain; the successful shops of the future will have fully incorporated the environmentally safe and dry process of dry ice / CO_2 blasting into their operations.

REFERENCES

Ackerman, K. (2013). *Dry Ice Blasting Principles.* Retrieved on April 5, 2013 from http://www.dryiceinfo.com/cleaning.htm

Anders, A. (2003). *"Tracking down the origin of arc plasma science-II. early continuous discharges".* IEEE Transactions on Plasma Science 31 (5): 1060 9. doi:10.1109/TPS.2003.815477.

Cary, H. B. and Helzer, S. C., (2005). "Modern Welding Technology". Upper Saddle River, New Jersey: Pearson Education. ISBN 0-13-113029-3.

Li, YB., Lin, ZQ., Hu, SJ., & Chen, GL. (2007). *Numerical Analysis of Magnetic Fluid Dynamics Behaviors During Resistance Spot Welding.* J. Appl. Phys., 2007, 101(5), 053506. Retrieved on April 5, 2013 from https://en.wikipedia.org/wiki/Spot_welding

MDOT, 2012, "*Field Manual for Pile Welding 2012*", Michigan Department of Transportation, USA

Minnick, W. H. (2007). "Gas Metal Arc Welding Handbook", Textbook. Tinley Park: Goodheart–Willcox. ISBN 978-1-59070-866-8.

Moore, B. (2012). *Resistance Welding.* Retrieve on April 6, 2013 from: http://www.boschrexroth.com/country_units/america/united_states/en/Trends_and_Topics/Case_Studies_and_Tech_Papers/a_downloads_tech_papers/Resistance_Welding/Rexroth_Resistance_Welding_L.pdf

Shannon, G. (2007). Advances in Resistance Welding Technology Offer Improved Weld Quality and Reliability for Battery Manufacturers. Battery Power Products & Technology, July/August 2007, Vol 11, Issue 4, retrieved from www.batterypoweronline.com.

Simpson SW (2008) "Fault identification in gas metal arc welding with signature images", *Science & Technology of Welding and Joining*, 13(1), 87–96

Snide, J. A., "*CO_2 Pellet Cleaning—A Preliminary Evaluation*", Materials & Process Associates, Inc., October 12, 1992. Retrieved on 18 June 2013 from: http://old.coldjet.com/tech- fundamentals.html

Steed, L., 2013, "*WHAT YOU MUST KNOW ABOUT ROBOTIC WELDING*", Tregaskiss, Windsor, Ontario, Canada N0R 1L0, www.tregaskiss.com. Retrieved on 21 June 2013 from: http://www.fabricatingandmetalworking.com/2013/05/what-you-must-know-about-robotic-welding/

Weman, Klas (2003). Welding processes handbook. New York, NY: CRC Press LLC. ISBN 0-8493-1773-8.