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AN ASSESSMENT OF MOLTEN METAL DETACHMENT HAZARDS DURING ELECTRON BEAM WELDING IN THE SPACE SHUTTLE BAY AT LEO FOR THE INTERNATIONAL SPACE WELDING EXPERIMENT

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INTRODUCTION

In 1997, the United States [NASA] and the Paton Electric Welding Institute are scheduled to cooperate in a flight demonstration on the U.S. Space Shuttle to demonstrate the feasibility of welding in space for a possible repair option for the International Space Station Alpha. This endeavor, known as the International Space Welding Experiment (ISWE), will involve astronauts performing various welding exercises such as brazing, cutting, welding, and coating using an electron beam space welding system that was developed by the E.O. Paton Electric Welding Institute (PWI), Kiev Ukraine. This electron beam welding system known as the "Universal Weld System" consists of hand tools capable of brazing, cutting, autogeneous welding, and coating using an 8 kV (8000 volts) electron beam. The electron beam hand tools have also been developed by the Paton Welding Institute with greater capabilities than the original hand tool, including filler wire feeding, to be used with the Universal Weld System on the U.S. Space Shuttle Bay as part of ISWE. The hand tool(s) known as the Ukrainian Universal Hand [Electron Beam Welding] Tool (UHT) will be utilized for the ISWE Space Shuttle flight welding exercises to perform welding on various metal alloy samples. A total of 61 metal alloy samples, which include 304 stainless steel, Ti-6Al-4V, 2219 aluminum, and 5456 aluminum alloys, have been provided by NASA for the ISWE electron beam welding exercises using the UHT. These samples were chosen to replicate both the U.S. and Russian module materials. The ISWE requires extravehicular activity (EVA) of two astronauts to perform the space shuttle electron beam welding operations of the 61 alloy samples. A third astronaut will provide processing feed back to the two EVA astronauts from the orbiter aft flight deck.

This study was undertaken to determine if a hazard could exist with ISWE during the electron beam welding exercises in the Space Shuttle Bay using the Ukrainian Universal Weld System with the UHT. The safety issue has been raised with regard to molten metal detachments as a result of several possible causes such as welder procedural error, externally applied impulsive force(s), filler wire entrainment and snap-out, cutting expulsion, and puddle expulsion. Molten metal detachments from either the weld/cut substrate or weld wire could present harm to a astronaut in the space environment if the detachment was to burn through the fabric of the astronauts Extravehicular Mobility Unit (EMU). Gravitational forces on the order of 0.001 that of the earth surface gravity in the space shuttle bay may decrease the likelihood of a molten metal detachment due to the decreased gravitational force acting on the molten metal drop. The dropout of the weld pool under the force of gravity would be more likely under terrestrial situations than in space welding. However, molten metal accumulation may be more likely at the end of the weld filler wire as a result of less gravity pulling on the drop at the wire end. Some possible ways of obtaining molten metal drop detachments would include an impulse force, or bump, to the weld sample, cut surface, or filler wire. If a large enough molten metal drop accumulated at the end of the filler wire could possible be shaken off, or the sample plate could be struck while welding or cutting so as to release a molten metal drop.

An accurate understanding between the weight, nearly zero gravity for space welding, of liquid metal drops and surface tension is necessary for developing a model which describes liquid metal drop detachments. If one considers a liquid metal drop hanging from a round cross-section, the weight of the drop can be related to the surface tension through a simple force balance. Since the surface tension represents the force holding up or opposing the liquid metal drop from detaching and the weight of the liquid metal drop is the force that is tending to detach the molten metal drop, an expression can be determined representing the force balance. A simple approximate expression representing the force balance can be expressed as

$$2\pi r\gamma = \rho_m g V \qquad [1]$$

where $\rho_m gV$ is the weight of the liquid metal drop which is proportional to the interfacial surface tension γ, ρ_m is the liquid metal density of the liquid metal drop, V is the volume of the drop, and g is the gravitational acceleration. This expression is somewhat approximate since it assumes that the entire drop detaches whereas in reality only a part of, not the whole, drop detaches. The drops that detach can be much smaller than the original hanging drops depending on the surface tension and liquid metal density. Assuming a detached spherical liquid metal drop, the volume V can be determined and thus the size or radius r of the drop given by

$$r = [3\gamma/2\rho_m g]^{0.5} = C[\gamma/\rho_m]^{0.5} \qquad [2]$$

where C is a numerical constant. Thus, this expression provides an estimate for the size of a freely hanging liquid metal drop.

Theoretical Model

A way of producing a molten metal detachment would be by an impulse or bump to weld sample. During the welding of a sample, it is possible that a quantity of molten metal could become detached by splashing the molten metal out from the weld puddle. This would in part depend on how secure the weld samples are fastened or bolted. Properly securing the weld samples will greatly minimize the effect an impact could have on lifting the molten metal above the weld puddle. If the samples are not securely bolted down and fastened then it becomes more easier for an impact force (i.e. a bump) to cause molten metal to be lifted up and possibly splashed from the weld puddle. It is possible to estimate the amount of liquid molten metal that could be displaced from a weld puddle in terms of the width and depth of the weld puddle. If the weld puddle has a depth equal to W/2 and a width equal to W then the maximum volume V_{ps} of liquid metal that could be displaced from the puddle would be equal to

$$V_{ps} = \pi W^3/12 \qquad [3]$$

and it may be anticipated that about 50% of this volume would exit the puddle as a molten drop.

During the welding operation, it is possible that the filler wire which is partially emerged into the molten metal weld pool might be snapped out of weld puddle so as to entrain and release a liquid metal drop with an initial velocity. As the filler wire is lifted from the weld pool it is wetted by the molten metal. As a consequence some of the molten metal comes up with it. At a certain height that the liquid metal is lifted, the normal level of the weld pool surface becomes unstable above the weld pool and breaks away. The minimum force to achieve this detachment would be equal to the weight of the filler metal wire plus the weight of the liquid metal that is being lifted. If the filler wire, which is emersed into the molten metal weld puddle, is lifted up out of the weld puddle then a given volume of molten metal will be lifted out of the weld puddle and then become detached. The volume of molten metal V_{we} that could be lifted up and become detached would be equal to

$$V_{we} = \pi a^3/3 \qquad [4]$$

where a is radius of the filler wire emerged into the weld puddle. The above equation would describe the maximum amount of molten metal that would be removed from the weld pool as a result of the filler wire being dipped into the weld pool and then lifted out of the weld pool.

If the filler metal wire is not in the weld puddle for a given length of time it is possible that molten metal can accumulate at the end of the filler metal wire. In order for this to occur, the filler wire must remain lifted far enough and long enough away from the molten metal weld puddle for molten metal to accumulate. If the molten metal accumulation comes in contact with the weld puddle surface, then due to surface tension the molten metal accumulation will be pulled directly into the weld puddle. However, if the filler wire is held for a long enough time away from the weld puddle, the growth rate of the metal volume on the end of the filler wire can be written in terms of the filler wire velocity, area, and time. If the volume is expressed in terms of the radius of the molten metal accumulation at the tip of the filler wire, then the rate of growth of the molten metal drop can be expressed as

$$4\pi r^3/3 = \upsilon A t \qquad [5]$$

where υ is the filler wire feed rate or velocity, A is the filler wire cross-sectional area, t is the time, and r is the radius of the molten metal accumulation at the end of the filler wire. A large drop could be defined as a drop with a radius approximately three times equal to or greater than the radius of the filler wire. The impact velocity to detach a large molten metal drop from the end of the filler wire would be approximately equal to

$$v = a\{2(\lambda+1)\pi\gamma/\rho_m V\}^{0.5} \qquad [6]$$

where v is the impact velocity required to detach a large drop from the end of the filler wire, V is the volume of the drop, a is the filler wire radius, γ is the interfacial surface tension, and λ has a value of order 1 to 2 . This expression provides a measure of the difficulty to detach or separate large drops that have grown in size at the end of the filler wire from the electric arc during electron beam welding.

During an electron-beam cutting exercise of the metallic sample, molten metal droplets can develop on the edges of the metal sample where the cutting has occurred. If a large impact or impulse force is applied to the metal sample, the molten metal droplets can pull away from the edge. If struck hard enough, the sample plate with molten metal pool or droplets on the side that is struck might release a drop of molten metal. In order for a liquid metal drop to detach, a given amount of energy must be expended to the drop to overcome the surface energy holding the drop in place. The amount of energy required to detach a molten metal drop would depend on the interfacial surface free energy γ and the surface area of the drop and be approximately equal to $\gamma \Delta a_{surface}$. The change in the surface area $\Delta a_{surface}$ of the drop before and after detachment is

$$\Delta a_{surface} = a_{drop} + a_{residual} - a_{initial} \quad [7]$$

where a_{drop} is the surface area of the detached drop, $a_{initial}$ is the initial surface area of the drop prior to being detached, and $a_{residual}$ is the residual surface area of molten metal left over on the surface after the drop has become detached. During an electron beam cutting process, the liquid metal drops that form on the edges of the cut on the sample often are diamond shaped rather than spherical. A drop can be considered as two cones joined together at a common base with a height h. The residual and initial drops are diamond shaped whereas the detached drop is spherical. Thus, for molten metal drops formed during the cutting process, $\Delta a_{surface}$ can be expressed as

$$\Delta a_{surface} = 4\pi(d_1/2)^2 + \pi d_3\{h^2 + (d_3/2)^2\}^{0.5} - d_2\pi\{h^2 + (d_2/2)^2\}^{0.5} \quad [8]$$

where d_1 is the detached drop diameter, d_2 is the drop diameter before it was detached, d_3 is the residual drop diameter left on the cut edge of the sample after the drop has been detached, and 2h is the length of the initial and residual drops. As seen from the above expression, both the detached molten drop and the residual drop have the same equal length h but different size diameters whereas the detached molten metal drop is spherical. When a molten metal drop becomes detached, it acquires a velocity and thus a kinetic energy associated with the detachment. If just enough energy has been utilized to detach a drop at the interface where the drop is connected to the cut edge with no additional energy left over then the energy to detach the drop can be expressed simply in terms of the kinetic energy of the drop and thus given by

$$\gamma \Delta a_{surface} = KE_{drop} = 0.5 m_{drop} v^2_{drop} \quad [9]$$

where KE_{drop} is the kinetic energy of the detached drop, m_{drop} is the mass of the detached drop, and v_{drop} is the velocity of the detached drop. Equation [9] provides an expression of the minimum amount of energy required to detach a free hanging liquid metal drop at the cut edge of a welding sample. However, if a large enough impact force is applied to the plate and thus the sample that energy is available to both detach the drop and to propel or accelerate the drop outward away from the cut edge, then the extra energy left over after the drop has been detached will be kinetic energy available to throw the drop outward away from the plate. Thus, the above expression can be modified to include this extra kinetic energy and therefore given by

$$\gamma \Delta a_{surface} + 0.5 m_{drop} v^2_{ext} = KE_{drop} = 0.5 m_{drop} v^2_{drop} \quad [10]$$

where v_{ext} is the velocity that the drop will achieve after it has been detached due to the extra energy available after the drop has been detached. Thus the drop will accelerate as a projectile a distance horizontal in the x direction and a distance downward in the y direction. If the distance the drop goes in the x direction is X and the distance the drop travels in the y direction S, then the velocity of the drop v_{ext} relative to the plate can be expressed as

$$v_{ext} = v_{plate} - X\{g/2S\}^{0.5} \quad [11]$$

where t is the time, X is the horizontal distance, v_{plate} is the velocity of the plate to which the molten metal drop is attached, S is the vertical distance, and g is the gravitational acceleration. Thus equation [10] can thus be expressed as

$$\gamma\, \Delta a_{surface} + V_{drop}\rho_m\, X^2 g/4S + 0.5 m_{drop} v^2_{plate} - 0.5 m_{drop}\, X\{g/2S\}^{0.5}\, v_{plate} = 0.5 V_{drop}\rho_m\, v^2_{drop} \quad [12]$$

where V_{drop} is the volume of the drop, ρ_m is the molten metal drop density, v_{drop} is the drop velocity. Thus, if there is no extra energy available after the drop has been detached i.e., $v_{ext}=0$, then

$$v_{plate} = X_{max}\{g/2S\}^{0.5} = (2\gamma\, \Delta a_{surface}/m_{drop})^{0.5} = v_{drop} \quad [13]$$

Experimental Method

The experimental testing was performed in a 4 ft. X 4 ft. vacuum chamber at MSFC enabling protective garment to be exposed to the molten metal drop detachments to over 12 inches. The chamber was evacuated to vacuum levels of at least $1X10^{-5}$ torr (50 microTorr) during operation of the 1.0 kW Universal Hand Tool (UHT). The UHT was manually operated at the power mode appropriate for each material and thickness. The space suit protective welding garment, made of Teflon fabric (10 oz. per yard) with a plain weave, was placed on the floor of the vacuum chamber to catch the molten metal drop detachments. A pendulum release mechanism consisting of four hammers, each weighing approximately 3.65 lbs, was used to apply an impact forces to the weld sample/plate during both the electron beam welding and cutting exercises. Measurements were made of the horizontal fling distances of the detached molten metal drops.

Results and Conclusions

The volume of a molten metal drop can also be estimated from the size of the cut. Utilizing equations [7]-[8] calculations were made to determine $\Delta a_{surface}$ for 304 stainless steel for cutting based on measurements of metal drop sizes at the cut edges. For the cut sample of 304 stainless steel based on measurement of the drop size at the edge, $\Delta a_{surface}$ was determined to be 0.0054 in^2. Calculations have indicated only a small amount of energy is required to detach a liquid metal drop. For example, approximately only 0.000005 ft-lb of energy is necessary to detach a liquid metal steel drop based on the above theoretical analysis. However, some of the energy will be absorbed by the plate before it reaches the metal drop. Based on the theoretical calculations, it was determined that during a weld cutting exercise, the titanium alloy would be the most difficult to detach molten metal droplets followed by stainless steel and then by aluminum. The results of the experimental effort have shown that molten metal will detach if large enough of a hammer blow is applied to the weld sample plate during the full penetration welding and cutting exercises. However, no molten metal detachments occurred as a result of the filler wire snap-out tests from the weld puddle since it was too difficult to cause the metal to flick-out from the pool. Molten metal detachments, though not large in size, did result from the direct application of the electron beam on the end of the filler weld wire.