1995

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

PARTICULATE ELECTRON BEAM WELD EMISSION HAZARDS IN SPACE

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Introduction

The electron-beam welding process is well adapted to function in the environment of space. The Soviets were the first to demonstrate welding in space in the mid-1980's. Under the auspices of the *International Space Welding Experiment (ISWE),* an on-orbit test of a Ukrainian designed electron-beam welder (the Universal Hand Tool or "UHT") is scheduled for October of 1997. The potential for sustained presence in space with the development of the international space station raises the possibility of the need for construction and repair in space. While welding is not scheduled to be used in the assembly of the space station, repair of damage from orbiting debris or meteriorites is a potential need. Furthermore, safe and successful welding in the space environment may open new avenues for design and construction. The safety issue has been raised with regard to hot particle emissions (spatter) sometimes observed from the weld during operations. On earth the hot particles pose no particular hazard, but in space there exists the possibility for burn-through of the space suit which could be potentially lethal. Contamination of the payload bay by emitted particles could also be a problem.

Experimental Evidence and Parameters of the Problem

Experiment has suggested a correlation between metal gas content and sparking during electron beam welding.[1] When dissolved gas was intentionally introduced to a metal by an unshielded tungsten-arc weld, particle emissions were observed during electron-beam welding of the same region. Furthermore, anecdotal evidence suggests that the presence of dissolved volatiles in targets decreases the quality of films formed by electron-beam evaporation. The presence of hydrogen contamination has also been reported to be associated with sparking during welding and hydrogen is known to be a source of porosity during welding.[2] Data from the international space welding experiment contamination tests suggest a correlation between butt welding and sparking. One possible interpretation is that butting two metal plates together forms little pockets of contaminants due to the surface roughness at the interface. Residual surface contaminants such as machine oil may vaporize during heating thus forming gas bubbles in the advancing weld pool.

The UHT is not intended to operate in the keyhole formation power density regime more common of electron beam welding. Keyholing should be avoided so that the beam does not pass through the sample and impinge another surface. According to The Physics of Welding[3] a power density of order 10^{10} W/m^2 is needed for keyhole formation. Assuming a voltage of 8 kV and current of 100 mA for the UHT yields a power of 800 W. Hence the beam would have to be focussed to a diameter of about 0.32 mm to expect keyhole formation. However, other circumstances my alter this; for example, we observed keyhole formation in a hydrogenated sample of 304 stainless at an energy density that did not produce a keyhole in the normal material.

Four possible mechanisms of spatter are discussed. Experimental results on electron beam welding of 5456 aluminum, 304 stainless steel, and Ti-6Al-4V titanium are then presented. Finally, the results are discussed in light of the potential mechanisms.

A. Spatter by Recoil Pressure

Spatter may occur due to the impulse applied to the surrounding fluid when the small volume above the gas pore quickly vaporizes. The presence of a pore near the melt surface within the irradiated area results in increased local heating. Energy that otherwise would have been conducted away is trapped by the low thermal conductivity of the pore. The increased temperature results in enhanced vaporization above the pore. The recoil force of the vaporizing particles pushes against the melt rather like a piston forcing emission of fluid as shown in figure 1. At sufficiently high beam energy, such vaporization could occur even in the absence of a pore and drilling results.[4]

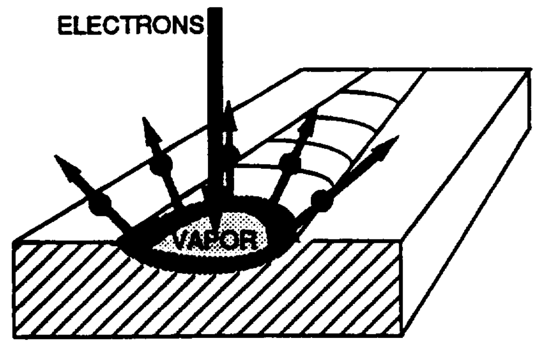

Figure 1: Vapor-pressure-induced spatter. Vapor pressure acts like a piston forcing liquid from the melt.

B. Spatter by Snapping Open of a Pore

One possible source of spatter is the snapping open or "popping" of a pore at the surface as shown in figure 2. Using an assumed geometry, we assumptions and assuming the radius of the initial pore is r_1, the change in surface area upon emission is $3\pi r_1^2$ and the available surface energy is the surface energy times that. In a perfectly efficient process, this could just eject (zero speed) a particle of radius $0.866r_1$. To get what we hope is a more reasonable estimate of the resultant particle emission we assumed that one half of the energy went into particle ejection and the remaining into motion in the melt. Under this assumption the maximum radius (zero speed) of an emitted particle would be $0.612r_1$. This maximum radius corresponds to emission with zero kinetic energy. If instead we assume one fourth of the available energy goes into kinetic energy and one fourth goes into surface energy (with the remaining one half still lost to the melt), then the radius of the emitted particle would be $0.433r_1$. In this scenario the speed of the emitted particle would be

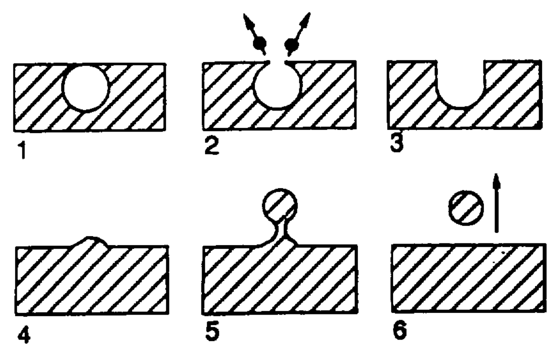

Figure 3: The bursting of a pore at the weld-pool surface may leave a cavity in the surface. The collapse of such a cavity could lead to emission of a drop as sketched.

$$v = 3.7\sqrt{\gamma/\rho r_1} \;.$$

By way of example, a pore of radius 250 μm in pure aluminum would lead to emission of a particle of 108 μm radius with speed 4.3 m/s.

D. Spatter by Change in Beam Focus

An experiment was performed prior to this work where the electron beam focus was changed during the course of a weld in one inch thick aluminum. A sudden change in focus from the bottom of the plate to 25% higher led to the formation of a hole in the surface several millimeters in diameter.

Experimental Results on Electron Beam Welds

The UHT was not available so a Hamilton-Zeiss electron beam welder was used for the performance of the following welds.

5456 Aluminum

The degree of sparking in bead-on-plate welding of 5456 aluminum depended on the focus with more sparking at tighter focus. With a sufficiently defocused beam a regime was found where sparking occurred at about one spark per eight inch weld (40kV, 10 mA and 10 in/min). Operating in this regime, a sheared butt joint showed a few sparks. Intentionally roughed joints showed more sparks. A very rough butt joint was prepared with a film of oil on half its length. Sparking was enhanced in the oil region. This may be ascribed to the oil vaporizing and forming pores in the melt. Another butt joint was prepared with various sized center punch holes along the faying surface. The joint alternated about every other inch between center punch holes and undamaged material. Our hope was that the holes would become pores in the melt. Half the plate had the holes just below the surface and the other half had holes deeper in the material. The half with the holes near the surface sparked more than the half with the holes below the surface; however, the sparks did not completely correlate with the hole locations.

304 Stainless Steel

Bead-on-plate welds of 304 stainless resulted in little sparking even at very high key-holing energy densities. A milled smooth butt joint emitted a few tiny sparks and one larger one. A rough butt joint emitted lots of small sparks; however, the welder reported that the surface appeared different with the presence of what he termed mill scale so some difference besides just edge roughness may have been involved.

It is known that the presence of hydrogen in a metal can lead to weld porosity. Plates of stainless were impregnated with hydrogen by heating in a hydrogen atmosphere. A normal stainless plate and a hydrogenated one were simultaneously mounted in vacuum for welding. The normal stainless did not spark at all while the hydrogenated material sparked dramatically. Additionally, the hydrogenated sample keyholed at the same power density where the normal sample did not. This was repeated at lower power density where the hydrogenated material did not keyhole, and the hydrogenated material still sparked considerably. Since the hydrogenated material also had a thick oxide layer, a non-hydrogenated sample was prepared with a surface oxide using a torch in air. The oxidized but otherwise normal 304 stainless did not spark.

Ti-6Al-4V Titanium

A bead-on-plate weld of titanium produced no sparks. An attempted rough butt weld produced at least one spark, but we had difficulty getting the puddle to bridge the gap and consistently fuse.

Conclusions

Vapor-pressure driven expulsion of liquid tentatively fits well with the observations. The presence of pores would thermally insulate the surface resulting in vaporization of material above the pore. The vapor pressure (more properly, the recoil pressure of the evaporating particles) pushes on the liquid expelling some of it. Recall that aluminum seemed to spark more readily than steel or titanium. This may be accounted for by the higher boiling temperatures of steel and titanium as compared to aluminum. While it was not part of this study, previous work has indicated that 2219 aluminum sparks less readily than 5456 aluminum. The 5456 contains magnesium which would result in higher vapor pressures at lower temperatures. Hydrogen is known to lead to porosity, so this mechanism is consistent with the sparking from hydrogen as well. We observed both emission of single droplets and emission of "sprays" of droplets that could perhaps be identified with emission of a ring of droplets that one would expect from this mechanism. Butt welds may entrap volatile material. The volatile material could possibly result in pore formation and/or increase the vapor pressure beyond its normal value for the pure material. Still, we cannot conclusively rule out contributions from the other proposed mechanisms or perhaps even mechanisms which we have not yet considered.

Finally, a few observations of some potential concern follow. Hitting a previous tack weld which had been made in vacuum resulted in sparking. There were indications that sparks were more likely at the start or finish of a weld. When the weld begins by climbing up over the edge of the plate, the energy density on the metal at the edge is increased due to the change in angle of exposure to the beam. This may sometimes account for the increased sparking at the beginning; however, there may have been cases of increased sparking when the beam was first turned on even when not climbing over the edge. The change of surface area exposed to the beam because of angle of exposure could also play a role in sparking from butt welds. This might further predict sparking in cases of undulations of the molten pool surface. Sparks resulted when the beam was cutting a channel. The possibility exists that sparking could occur from the weld root when welding in the keyhole regime. Finally, contamination on the surface from the electron beam hitting the fixture prior to the start of the weld may have contributed to sparking.

Acknowledgements: Thanks to Craig Wood for performing the electron beam welds. Thanks to George Talia of Wichita State University for performing the metallography on an emergency stop in a VPPA weld.

References

1. C. Russell, A. Nunes, and R. Carruth, "Characterization of the Molten Weld Pool Produced by Electron Beam for the International Space Welding Experiment," Materials and Processes Laboratory, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, internal report (May 25, 1995).

2. D. G. Howden and D. R. Milner, "Hydrogen Absorption in Arc Melting," British Welding Journal (June, 1963) 304-316; G. R. Salter, "Hydrogen Absorption in Arc Welding," British Welding Journal (June, 1963) 316-325; R. A. Woods, "Porosity and Hydrogen Absorption in Aluminum Welds, Welding Res. Supp. (Mar., 1974) 97-s - 108-s.

3. The Physics of Welding, 2nd ed., ed. J. F. Lancaster, (Pergamon Press, NY, 1986)307-309.

4. C. L. Chan and J. Mazumder, "One-dimensional steady-state model for damage by vaporization and liquid expulsion due to laser-material interaction," J. Appl. Phys. 62 (11) (1987) 4579-4586.