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POTENTIAL FOR EMU FABRIC DAMAGE BY ELECTRON BEAM AND MOLTEN METAL DURING SPACE WELDING FOR THE INTERNATIONAL SPACE WELDING EXPERIMENT

Prepared By: James M. Fragomeni, Ph.D.

Academic Rank: Assistant Professor

Institution and Department: The University of Alabama
Department of Aerospace Engineering & Mechanics

NASA/MSFC:

Laboratory: Materials and Processes
Division: Metallic Materials and Processes
Branch: Metallurgical Research & Development

MSFC Colleague: Arthur C. Nunes, Jr., Ph.D.

Introduction

As a consequence of preparations concerning the International Space Welding Experiment (ISWE) studies were performed to better understand the effect of molten metal contact and electron beam impingement with various fabrics for space suit applications. The question arose as to what would occur if the electron beam from the Ukrainian Universal Hand Tool (UHT) designed for welding in space were to impinge upon a piece of Nextel AF-62 ceramic cloth designed to withstand temperatures up to 1427 °C. The expectation was that the electron beam would lay down a static charge pattern with no damage to the ceramic fabric. The electron beam is capable of spraying the fabric with enough negative charge to repel further electrons from the fabric before significant heating occurs. The static charge pattern would deflect any further charge accumulation except for a small initial amount of leakage to the grounded surface of the welder. However, when studies were made of the effect of the electron beam on the insulating ceramic fabric it was surprisingly found that the electron beam did indeed burn through the ceramic fabric. It was also found that the shorter electron beam standoff distances had longer burnthrough times than did some greater electron beam standoff distances. A possible explanation for the longer burnthrough times for the small electron beam standoff distance would be outgassing of the fabric which caused the electron beam hand-tool to cycle on and off to provide some protection for the cathodes. The electron beam hand tool was observed to cycle off at the short standoff distance of two inches likely due to vapors being outgassed.

During the electron beam welding process there is an electron leakage, or current leakage, flow from the fabric. A static charge pattern is initially laid down by the electron beam current flow. The static charge makes up the current leakage flow which initially slightly heats up the fabric. The initially laid down surface charge leaks a small amount of current. The rate at which the current charge leaks from the fabric controls how fast the fabric heats up. As the ceramic fabric is heated it begins to outgass primarily from contamination/impurities atoms or molecules on and below the fabric surface. The contaminant gases ionize to create extra charge carriers and multiply a current of electrons. The emitted gas which ionized in the electron leakage flow promotes further leakage. Thus, the small leakage of charge from the fabric surface is enhanced by outgassing. When the electron beam current makes up the lost current, the incoming electrons heat the fabric and further enhance the outgassing. The additional leakage promotes additional heating up of the ceramic fabric. The electrons bound to the ceramic fabric surface leak off more and more as the surface gets hotter promoting even greater leakage. The additional electrons that result also gain energy in the field and produce further electrons. Eventually the process becomes unstable and accelerates to the point where a hole is burned through the fabric.

Low Pressure Gas Effects

When modeling the penetration effect of the electron beam impingement on the surface of the ceramic cloth, various assumptions can be made to simplify the modeling. It can be assumed that the heat of the fabric i.e., the heat that goes into the fabric comes from placement of beam current with the leakage current. If the cloth is heated an amount due to the beam power $i\varepsilon$ then the change in temperature over the corresponding change in time is given by:

$$dT/dt = \sim(i\varepsilon - q_L)/\rho a \omega C_p \qquad [1]$$

where q_L is the conduction heat loss per unit volume per unit time, i is the current, ε is the voltage, a is the cross-sectional area of the cloth that is impinged by the electron beam, ω is the width of the ceramic fabric, ρ is the density of the ceramic fabric, and C_p is the specific heat of the ceramic fiber. Nextel AF-62 ceramic fiber cloth has a specific heat C_p' of 1000 J/kg/°K and a density ρ' of 820 kg/m^3, and is able to withstand temperatures up to 1427°C (2600°F). The current i in equation [1] can be determined by the expression

$$i = enav \qquad [2]$$

where e is the charge of an electron, and v is the mean velocity of the electrons. The electron velocity can be approximated from a consideration of the electron charge and the voltage. The kinetic energy of an electron can be equated to voltage potential times the charge of the electron such that

$$0.5 m_e v^2 = eV \qquad [3]$$

Thus, the velocity of the electron(s) can be determined from the above expression as

$$v = (2eV/m_e)^{0.5} \qquad [4]$$

where m_e is the mass of an electron (9.11E10^{-31} kg), e is the charge of the electron (1.602E10^{-19} Coulombs), V is the voltage of the electron gun (8000 Volts), and v is the velocity of the electron. The velocity of the electrons coming out of the gun for 8000 volts potential would be approximately 53E10^6 m/sec.

The passage of electrons from the orifice of the UHT electron beam gun at high velocities (see equation 4) through a vacuum chamber at low partial pressures approaching 10^{-4} Torr results in electron collisions with the gas atoms/molecules dispersed throughout the vacuum chamber that are in the line of path of the electron beam. The number of electron collisions with the gas molecules/atom (say oxygen or nitrogen) will depend in part on the vacuum pressure since number density of the molecules/atoms in vacuum is proportional to the pressure. So as the vacuum pressure decreases the number of electron collisions with the gas molecules also decreases and as the vacuum pressure increases the frequency of electron collisions with the gas molecules also increases. The vacuum pressure inside the chamber is also inversely proportional the mean free path λ of the gas atoms/molecules dispersed throughout the chamber. As the vacuum pressure increases the free mean path of the gas molecules will decrease and as the pressure decreases the free mean path increases. The gas in the chamber is assumed to be monatomic oxygen and nitrogen. Thus as the vacuum pressure decreases in the chamber more electrons are able to reach the target because the free mean space between the molecules increases and the thus the number of electron collisions with the gas molecules decreases. The mean free distance between the gas molecules in the chamber can be determined in terms of the number of gas molecules per cubic volume and the collision cross section. The collision cross section σ of electrons colliding with gas monatomic molecules is given by the expression

$$\sigma = \pi r^2 \qquad [5]$$

where r is the radius of the molecule that has been hit by an electron. Thus the collision cross section for electrons colliding with gas containing monatomic oxygen (r = $1.8E10^{-10}$ m) would be equal to $1.02E10^{-19}$ m^2. The collision cross section for electrons colliding with monatomic nitrogen (r = $2.13E10^{-10}$) would be equal to $1.43E10^{-19}$ m^2. If there are n molecules per unit volume, the number of collisions per unit time, or the collision frequency z, is

$$z = \sigma n v \qquad [6]$$

where v is the average speed of the gas molecules. The mean free path between collisions i.e., the average distance between collisions, is equal to the total distance covered in some interval time divided by the number of collisions in that time and would thus be equal to

$$\lambda = 1/\sigma n \qquad [7]$$

The number of gas molecules at standard pressure and temperature can calculated from the ideal gas equation as

$$n = p/kT \qquad [8]$$

where k is Boltzman's constant ($1.38E10^{-23}$ J/K), p is the pressure, and T is the temperature. Thus if p is 1 atm. and T is 273 K, then n is approximately $2.7E10^{+25}$ molecules/m^3. Thus, the number of oxygen molecules at a vacuum chamber pressure of 10^{-5} Torr can be determined from the expression

$$n_2 = (p_2/p_1)n_1 \qquad [9]$$

Therefore, if p_1 is 1 atm, and p_2 is 10^{-4} Torr, and n_1 is $2.7E10^{+25}$ molecules/m^3, then n_2 would be equal to $3.553E10^{+18}$ molecules/m^3 of oxygen molecules. The free mean path of gas in the vacuum chamber can thus be calculated from equation (2.8) for monatomic oxygen as λ = 2.759 m (or 9.053 ft.), and for monatomic nitrogen as 1.968 m (or 6.458 ft.). If the gas pressure in the vacuum chamber was decreased to say 10^{-5} Torr then the free mean path would be λ = 27.59 m (or 90.53 ft.) for monatomic oxygen and would be λ = 19.68 m (or 64.58 ft) for monatomic nitrogen. However, if gas pressure in the vacuum chamber was increased to say 10^{-3} Torr, then the free mean path would be λ = 0.2759 m (or 0.9053 ft.) for monatomic oxygen and would be λ = 0.1968 m (or 0.6458 ft) for monatomic nitrogen. Thus, changes in the partial pressure can have indeed a large effect on the free mean path distance.

The electron beam directed through the randomly dispersed gas in the vacuum chamber will interact with the gas molecules and scatter some of the molecules. The probability that the electron beam will scatter an atom or molecule will be σ/A, and the volume of the electron beam directed through the vacuum at a distance λ would be given by λA. The total number of electrons scattered by the beam would be $\lambda A n_{gas}$. The probability that the entire electron beam would be scattered would be

$$(\lambda A n_{gas})(\sigma/A) = 1 \qquad [10]$$

The free mean path can thus be determined from the above equation as

$$\lambda = 1/n_{gas}\sigma_{gas} \quad [11]$$

If an electron beam of current i_o starts out across the vacuum chamber, in distance interval dx an attenuation di occurs of the local current i proportional to the ratio of the distance interval dx to the mean free path. The drop in current di can be expressed in terms of the travel interval distance dx of the total length of the beam as

$$di = -i(dx/\lambda) \quad [12]$$

or

$$di = -i\, n_{gas}\sigma_{gas}\, dx \quad [13]$$

If equation [13] is integrated, the results is given by

$$i = i_o \exp\{-x/\lambda\} \quad [14]$$

Thus the ratio of the beam current to the leakage current can be expressed as

$$i/i_o = \exp(-x/\lambda) \quad [15]$$

where the ratio of the beam current to the leakage current represents the percent of residual power in the beam. Table 1. shows some calculations comparing different standoff distances to the percent residual power to the beam for different vacuum chamber pressures, pressures starting from within the normal UHT operating range below 10^{-5} Torr (depending upon the capability of the vacuum chamber) and rising to 10^{-3} Torr.

Table 1 Percent Residual Power to the Beam for various electron beam gun standoff distances for three different vacuum chamber pressures for monatomic nitrogen.

x, standoff distance, in.	percent residual power to the beam, % (10^{-3}Torr)	percent residual power to the beam, % (10^{-4}Torr)	percent residual power to the beam, % (10^{-5}Torr)
2	77	97	100
6	46	93	99
12	21	86	98
24	5	73	97
48	0	54	94

Table 1 demonstrates that the attenuation of the electron beam causes the beam to lose it potency at long standoff distances. For example with a vacuum pressure of 10^{-4} Torr and a standoff distance of 48 inches roughly only half of the beam current power reaches the target. However, the above analysis suggests that the electron beam may not lose its potency for lower vacuum chamber pressures.

The translational kinetic energy associated with a molecule of mass m and velocity v_m is $0.5m\ v_m^2$. If the mean translational kinetic energy of a molecule is equated to the available kinetic energy 1.5kT for three translational degrees of freedom then the approximate speed of a molecule at some temperature heated above room temperature would be

$$v_m = (3kT/m)^{0.5} \qquad [16]$$

where k is Boltzman's constant ($1.38E10^{-23}$ J/°K), and T is the absolute temperature for a surface heated above room temperature. If nitrogen gas in the vacuum chamber is considered, then v_m can be determined based on the Atomic Mass Units (AMU) of the gas, which for a nitrogen gas molecule would be 28. Thus, $v_m=\{[3(1.38E10^{-23}\ J/°K)(600°K)]/[(28AMU)(1.673E10^{-27}Kg/AMU)(1Jsec^2/m^2/Kg)]\}^{0.5}=728$ m/sec. It is hard to know for sure what gas(s) is emerging from the cloth, but if water or oxygen were emerging then the appropriate AMU should be used (AMU = 18 for water, AMU = 21 for oxygen). Correspondingly for water v_m = 908 m/sec, and for oxygen v_m = 841 m/sec. Thus, the velocity of gas molecules at 600°K in the vacuum chamber would be in the range of about 700-900 m/sec for a gas mixture consisting of oxygen, nitrogen, and water molecules.

Fabric Damage From Molten Metal Detachment

Observations were made of the interaction of 2219 aluminum droplets on 10 oz./yd^2 Teflon fabric in a vacuum chamber at pressures of 10^{-4} to 10^{-5} Torr. The metal drops were obtained from impact ejection from a horizontal weld pool onto a teflon cloth spread over the floor of the vacuum chamber. An 8000 volt electron beam, produced by a Ukrainian "Universal Hand Tool" (UHT) designed for welding in the space environment, was the source of heat for generating the weld pool. After the drops had solidified on the cloth, they were collected and measurements were made of the drop sizes and the amount of fabric damage they caused while cooling. It was experimentally observed for molten droplets of 2219 aluminum metal on the 10 oz./yd^2 Teflon fabric (0.23mm thick) that up to about 4.8 mm metal drop diameter no holes were developed in the fabric. At drop sizes of about 5 mm penetration of the fabric occurred and rapidly increased to about the diameter of the drop. However, at drop diameters less than 5 mm, the fabric was charred (both front side char and back side char), and the front side char was very roughly about half the size of the molten metal 2219 Al droplet and the back side char was very roughly about two-thirds the size of the front side char. These results appear to indicate that for a 2219 Al drop on 10 oz./yd^2 Teflon fabric a hole will burn through when the molten metal droplet size is twice the thickness of the Teflon fabric.

Depending on the chemistry involved, the process of the decomposition of the fabric is complex. The chemistry of the interaction between the molten metal and ceramic fabric is an important consideration in determining the possible amount of fabric damage. Contaminants from the surface of the fabric can outgass while the molten metal is resting on the fabric surface which can alter the conduction transfer of heat from the metal to fabric. In addition, the chemistry of the burning of the ceramic fabric, can affect the amount of potential damage to the fabric. The 10 oz./yd^2 Teflon fabric chars in the range of 300-500 °C and ablates in the range of 600 to 700 °C until nothing is left according to Differential Thermal Analysis and Thermogravimetric Analysis. However, even though the details of fabric decomposition are complex, one may evaluate in a very basic, semiquantitative manner the general features of metal and fabric interaction that control the damage process. A simple expression can be derived to relate several parameters such as the weight, pressure, force, surface tension etc. to the surface area that will first char on the fabric surface from the molten metal drop. Assuming that a spherical molten metal drop is sitting on the fabric surface and that the drop remains spherical, the weight of the metal drop can be approximated as

$$W = \rho\, g\, V = \rho\, g\, (4\, \pi\, r^3/3) \qquad [17]$$

The contact area that will first be charred from the metal drop which sits flat on the fabric surface can be expressed as

$$A_c = W/p \qquad [18]$$

where p is the internal pressure which holds the drop together, and A_c is the cross-section area of fabric which the drop sits upon i.e., the contact area. Substituting equation [17] into [18] gives the contact area as

$$A_c = \rho\, g\, (4\, \pi\, r^3/3)/p \qquad [19]$$

Equating the force the drop applies on the fabric surface with the surface tension force of the metal drop

$$p\pi r^2 = 2\pi r\gamma \qquad [20]$$

thus the pressure can be expressed as

$$p = 2\gamma/r \qquad [21]$$

Thus substituting equation [21] into [19] gives the contact area as

$$A_c = (2\pi/3)(\rho g/\gamma)r^4 \qquad [22]$$

where γ is the interfacial surface tension of the molten metal droplet. If the contact area A_c is a circular surface contact area ($\pi D^2/4$) of diameter D then the above expression can be written in terms of the contact diameter and drop diameter as

$$D = d^2(\rho g/6\gamma)^{0.5} \qquad [23]$$

Thus, for the various drop sizes of the 2219 Al alloy, the contact diameters can be computed using the above expression.

Fabric Damage Model from Molten Metal Detachment

A simple model will now be presented to describe the amount of damage done to a ceramic fabric cloth from a molten metal droplet in terms of specific material parameters and variables. In order for the metal drop to burn through the fabric to a certain volume of fabric ΔV the metal drop must provide a certain amount of energy to the fabric. The amount of energy that the metal drop must supply to burn a volume ΔV of fabric through charring and ablation would be given as

$$\rho' C_p'\Delta V\{(T_{ablat}-T_a)\}+ \rho'\Delta V(L_{char}+L_{ablat}) = \rho'\Delta V\{C_p'(T_{ablat}-T_a) + L_{char}+L_{ablat}\} \qquad [24]$$

where ρ' is the density of the fabric, C_p' is the specific heat of the fabric, T_{ablat} is the ablation temperature of the fabric, T_a is the ambient temperature, ΔV is the volume of the fabric that has been charred and ablated, L_{char} is the latent heat of charring, and L_{ablat} is the latent heat of ablation . However, the energy that is available from the drop is

$$m\, C_p \Delta T = \rho\, H_d\, C_p\, \Delta T = \rho\, (4\, \pi\, r^3/3)C_p(T_{do} - T_{df}) \qquad [25]$$

where $H_d = 4\pi r^3/3$ is the volume of the drop sitting on the fabric surface, ρ is the molten metal density, C_p is the specific heat of the metal droplet, T_{do} is the initial temperature of the drop, and T_{df} is the final temperature of the fabric. Thus, equating the energy that is available from the metal drop to the energy the drop must supply for ablation and charring yields

$$\rho'\Delta V\{C_p'(T_{ablat}-T_a) + L_{char}+L_{ablat}\} = \rho\, (4\, \pi\, r^3/3)C_p(T_{do} - T_{df}) \qquad [26]$$

where r is the radius of the metal drop. The volume of fabric that has been charred and ablated can be determined from the geometry of the damage done to the ceramic fabric. For a given thickness of fabric, w, and assuming a partial hemispherical geometric burnthrough of fabric from the molten metal drop which sits on the surface, the volume of fabric that has been damaged can be evaluated in terms of the hole radius that has been burned in the fabric. Thus, the damage volume can be determined as

$$\Delta V = \pi R^3(W/R - W^3/(3R^3)) = \pi R^2 W(1 - W^2/(3R^2)) \qquad [27]$$

where R is the radius of the hole burned in the cloth and W is the thickness of the cloth (0.254 mm for Teflon). Thus, when R=W, the volume is that of a half sphere $\Delta V=2\pi R^3/3$

However, if the fabric is only charred and no ablation takes place then the amount of energy that the metal drop must supply to char a volume $\Delta V'$ of fabric would be given as

$$\rho' C_p'\Delta V'(T_{charr}-T_a) + \rho'\Delta V'(L_{charr} + L_{htloss}) = \rho'\Delta V'\{C_p'(T_{charr}-T_a) + L_{char} + L_{htloss}\} \qquad [28]$$

where L_{htloss} is the latent heat lost by conduction of the metal drop with the metal floor of the vacuum chamber after the metal drop has burned a hole through the teflon fabric, and T_{charr} is the charring temperature of the teflon fabric. However, the energy that is available from the metal drop would be

$$m\, C_p \Delta T = \rho\, (4\, \pi\, r^3/3) C_p (T_{ablat} - T_{charr}) \quad [29]$$

Thus, equating the energy that is available from the metal drop to the energy the drop must supply for charring yields

$$\rho' \Delta V' \{ C_p'(T_{charr} - T_a) + L_{char} + L_{htloss} \} = \rho\, (4\pi r^3/3) C_p (T_{ablat} - T_{charr}) \quad [30]$$

The charring temperature is roughly 350°C and the ablation temperature is roughly 570°C. The volume of material that has been charred $\Delta V'$ can be determined from the total volume that has been both charred and ablated as well as the char radius and is given by the expression

$$\Delta V' = \pi\, R_c^2 W[1 - 0.33(W/R_c)^2] - \Delta V \quad [31]$$

or

$$\Delta V' = \pi W\{ R_c^2[1 - 0.33(W/R_c)^2] - R^2\,(1 - W^2/(3R^2)\} \quad [32]$$

where R_c is the radius from charring and W is the fabric cloth thickness. Table 2 gives the calculated values for ΔV and $\Delta V'$ based on different metal drop and hole dimensions.

Table 2. Fabric Damage for 2219 Aluminum Drops on 10 oz/yd^2 Teflon Fabric

Drop Size Diameter (mm)	Char Radius (mm)	Fabric Thickness (mm)	Hole Radius (mm)	ΔV Char/Ablate (mm^3)	$\Delta V'$ Char (mm^3)
3.47	0.75	0.25	0.0	0.0	0.425
4.80	1.75	0.25	0.0	0.0	2.394
4.96	1.75	0.25	0.25	0.033	2.394
5.13	3.50	0.25	2.75	6.017	3.741

A sample calculation can be done for determining the latent heats for a given metal alloy acting on the surface the specific ceramic fabric surface namely Teflon (10 oz. Per yard) which is 0.0254 cm (0.01 in.) thick. Teflon ceramic cloth has a specific heat C_p' of roughly 1046 J/kg/°K (0.25 cal/gram/°C) and a density ρ' of roughly 1.33 g/cm^3 (1330 kg/m^3 or 0.048 lb/in^3=82.9 lb/ft^3). The ambient outside temperature T_a can be taken as roughly 23°C (room temp.), the ablation temperature of teflon fabric is 570°C, the charring temperature T_c is approximately 350°C, and the effective initial drop temperature T_{do} approximated as 640°C, and the effective final drop temperature T_{df} can be approximated as 570°C. Thus, an estimated value for $L_{char}+L_{ablat}$ can be determined using the given values for the temperatures and constants. Thus, using a metal drop size of 5.13 mm diameter and drop volume ΔV of 6.017 mm^3 and from using equation [27], $L_{char}+L_{ablat}$ = 7,416,169. J/Kg (1.8 Kcal/gram). Also from using equation [31] with a drop size of

5.13 mm diameter and drop volume ΔV' of 3.741 mm^3 an estimated value for L_{char}+ L_{htloss} can be determined as 39,858,963. J/Kg (9.5 Kcal/gram). The latent heat loss L_{htloss} takes into account the heat lost through conduction of the metal drop with the metal plate floor of the vacuum chamber once a hole has been burned through the teflon fabric.

Summary and Conclusions

The effective power or potency of the electron beam was limited to about four feet under the given vacuum conditions due to electron collisions with gas molecules in the vacuum chamber.

Lower vacuum pressures result in increased electronic free mean path; thus potentially greater electron beam damage to the ceramic fabric.

The outgassing of contaminates from the ceramic fabric enhanced the fabric potency to electron beam damage.

The outgassing of the ceramic fabric which resulted in the electron beam gun cycling off at the two inch standoff distance i.e., the intermittent operation of the UHT, resulted in considerably longer burnthrough times as compared with the longer standoff distances of 6, 12, 24, & 48 inches. However, at intermediate to longer standoff distances, a tendency to outgas makes a ceramic fabric subject to electron beam damage; and just a small tendency seems adequate.

From experiments carried out concerning the molten metal detachments on the teflon fabric some additional variables were determined important and necessary to control such as the impact velocity of the drop on the fabric cloth, heat lost through the chamber floor as drop sits on the fabric surface, and the rolling motion of the metal drop on the fabric surface.

Recommendations for Future Work

Investigate electron beam damage range at lower vacuum pressures ($<10^{-5}$ Torr).

Measure/monitor the local dynamic pressure at/near the fabric surface.

Perform damage studies based on the controlled exposure of the fabric to an anvil heated to different temperatures, at different lengths of time, and different sizes of fabric contact surface area.

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