Effects of Mars Atmosphere on Arc Welds: Phase 2

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CO$_2$ carbon dioxide

D/W   depth to width (ratio)

FZ   fusion zone

GTAW   gas tungsten arc welding

UTS   ultimate tensile strength

TECHNICAL MEMORANDUM

EFFECTS OF MARS ATMOSPHERE ON ARC WELDS, PHASE 2

1. INTRODUCTION

In today's Space Age and in our modern world there is a great push towards the expansion of the capability of humans in outer space. This expansion of capabilities in outer space requires many years of diligent research in order to understand the effects of different extraplanetary or space environments on humans, structures, and manufacturing processes.

The ultimate goal of NASA is to send humans to deep-space locations, such as the Moon and Mars, and return them to Earth safely. Therefore, the Martian atmosphere effects on equipment that must be deployed on the surface of Mars must be understood. One way to quantify the effects of the Martian atmosphere on equipment is to compare it directly to the effect on the same or similar equipment and processes by the atmosphere here on Earth.

As shown in table 1, the Martian atmosphere contains far less nitrogen and far greater carbon dioxide (CO_2) than the terrestrial atmosphere. This difference in atmospheric composition has an effect on the weldability of materials and the properties of welds.

Table 1. Experimental matrix for Mars welding experiment.[1,2]

	Nitrogen	Oxygen	Argon	CO_2	Carbon Monoxide
Terrestrial atmospheric composition (%)	78	21	0.90	0.04	–
Mars atmospheric composition (%)	2.70	0.13	1.60	95.32	0.08

This experiment focuses on analyzing these atmospheric gas effects without consideration for atmospheric pressure or gravitational effects. The simulated Martian atmosphere and terrestrial atmosphere are maintained at the standard temperature and pressure of Earth. One effect of the variation in atmospheric gases is the change in density of the gases between the simulated Martian gas environment and terrestrial environment, both at terrestrial atmospheric pressure. This will be further discussed in section 4 and future reports may analyze the effects of gravity and atmospheric pressure on gas density.

Two common aerospace materials were welded in both a simulated Martian atmosphere and a terrestrial atmosphere: (1) AA2219-T87, of interest because of its vast use in the Orion capsule, and (2) Ti-6Al-4V, of interest because of its use in water filtration systems. AA2219-T87

is also used to manufacture the core stage and many other components of the fuel tanks and transition joints of heavy-lift rockets. Therefore, knowledge of its weld behavior within the atmosphere of Mars is needed due to its prevalence in mission components.

Knowledge of welding these two materials in a simulated Martian atmosphere could save the lives of astronauts in the event of an emergency that may require repairs and welds while on the Martian surface.

For long-term colonization of Mars by the private and public aerospace sectors, manufacturing of rocket components and manufacturing in general will become a necessity on the Martian surface. In that event, any knowledge of the effects of the Martian atmosphere on weld quality and in gas tungsten arc welding (GTAW) will greatly help NASA missions, and beyond that, the permanent colonization of Mars.

This research focuses on GTAW because it is a versatile arc welding process. All arc welding processes exhibit kinetic metallurgical processes (nonuniform heat flow, thermal expansion and contraction, nonequilibrium solidification, solid-state phase transformations, etc.) and thermodynamic effects due to the high heat inherent to the process.[3] This Technical Memorandum will discuss the change in material properties, such as tensile strength and hardness, due to kinetic metallurgical processes, thermodynamic differences, and atmospheric differences between welding in terrestrial and Martian atmospheres. It will also consider other potential differences in the gases of both the terrestrial and Martian atmospheres.

2. EXPERIMENTAL PROCEDURE

The procedures used in this experiment follow methods similar to the experimental procedures used in phase 1, reported in Technical Memorandum, "Mars Atmosphere Effects on Arc Welds: Phase 1."[4]

First, an experimental matrix shown in table 2 was formulated and to it were added weld joints and filler metal to help further prove the capability of using GTAW in a simulated Martian environment. Rather than bead-on-plate welds, all welds for phase 2 were made along square butt weld joints with the addition of appropriate filler metal. AA2219-T87 and Ti-6Al-4V were used because they are commonly utilized in the aerospace industry and because they were the weld materials tested in phase 1 of this experiment. The terrestrial welds were welded with a No. 7 shielding cup and an HW20 torch (common weld torch for GTAW). The simulated Martian welds were made with a ceramic shielding cup and an HW20 torch. The filler metal used for the AA2219-T87 welds was 3/32-in-diameter 2319 per AWS A5.10[5] and the filler metal used for the Ti-6Al-4V was 1/16-in-diameter ERTi-5 per AWS A5.16[6].

Table 2. Terrestrial and Martian atmospheric compositions.

Phase 2	Aluminum 2219 (Pure Tungsten Electrode 1/8 in)					
Weld joints	AlWeld 6M	AlWeld 7M	AlWeld 8M	AlWeld 6E	AlWeld 7E	AlWeld 8E
Thickness (in)	0.25	0.25	0.25	0.25	0.25	0.25
Torch shield gas (weld grade argon) (ft^3/hr)	30	20	10	30	20	10
Atmosphere	Mars	Mars	Mars	Earth	Earth	Earth
Weld current (A)	170	170	170	170	170	170
Testing	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness
Weld position	Flat	Flat	Flat	Flat	Flat	Flat
Weld length (in)	6	6	6	6	6	6
Phase 2	Titanium 64 (2% Thoriated Tungsten Electrode)					
Weld joints	TiWeld 6M	TiWeld 7M	TiWeld 8M	TiWeld 6E	TiWeld 7E	TiWeld 8E
Thickness (in)	0.19	0.19	0.19	0.19	0.19	0.19
Torch shield gas (weld grade argon) (ft^3/hr)	30	20	10	30	20	10
Atmosphere	Mars	Mars	Mars	Earth	Earth	Earth
Weld current (A)	75	75	75	75	75	75
Testing	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness	Tensile, macro/ hardness
Weld position	Flat	Flat	Flat	Flat	Flat	Flat
Weld length (in)	6	6	6	6	6	6

Arc length, voltage, and travel speed controlled by welder to the best possible consistency.

The terrestrial welds were all made in open air to best represent the terrestrial environment, and the Martian welds were made in a glove box purged with simulated Martian gas. The glove box used is shown in figure 1. All simulated Martian and terrestrial welds were made at terrestrial standard temperature and pressure so the atmospheric gas effects alone could be analyzed. Future experiments should take Martian atmospheric pressure into account by using a vacuum to achieve reduced atmospheric pressure at 600 Pa and should use a hollow tungsten electrode to allow the shielding gas flow through the electrode and adequately shield the arc in a low-pressure environment.[2,7]

Figure 1. Purged glove box prior to beginning Martian welds.

Following welding, both in the terrestrial and simulated Martian environments, each weld was tested in multiple ways. The welds were visually inspected for defects, and also were imaged with radiographic testing to check for internal defects. They were then sectioned into tensile samples and microscopy samples. Weld joints and tensile testing were used in phase 2 to understand the effects of the atmospheric environment on weld strength rather than just hardness as in phase 1. The tensile results data were then graphed and the microscopy samples were microhardness tested and analyzed for microstructural phenomena. The weld depth-to-width (D/W) ratio was also measured using the microscopy samples. The atmospheric compositions used for the terrestrial and simulated Martian environments are shown in table 1. The flow chart in figure 2 shows the progression from one phase to the next for this experiment. Following testing for the welds in phase 2, data were compiled into graphs and tables for analysis.

Phase 1: Make AA2219-T87 and Ti-6Al-4V welds in both a terrestrial and a Martian environment. Martian welds will be simulated in a purged chamber with simulated Martian gas. All welds shall be bead-on-plate and created in terrestrial pressure in order to simplify the experiment. The welds will also be autogenous so the effect of the atmosphere can be clearly observed. All welds will be visually and radiographically inspected and analyzed metallo-graphically. After metallography, all of the welds will be microhardness tested. Lastly, the titanium welds will be sent out for oxygen/nitrogen analysis of the fusion zone.

Phase 2: Make AA2219-T87 and Ti-6Al-4V welds in both a terrestrial and a Martian environment. Martian welds will be simulated in a purged chamber with simulated Martian gas. All welds shall be butt welds. Welds shall be created in terrestrial pressure in order to simplify the experiment. The welds will use filler metal to better simulate real-world welding procedures. Weld joints will be used instead of bead-on-plate welds in order to truly analyze the effects of the atmosphere on a weld joint. All welds will be visually and radiographically inspected and analyzed metallographically. Tensile testing will also be done on all butt welds to analyze weld strength. After metallography, all of the welds will be microhardness tested.

Phase 3: Make AA2219-T87 and Ti-6Al-4V welds in a Martian environment. Use weld data from first two phases for terrestrial welds. All welds will be made in a vacuum purged with Martian gas to better represent the Martian atmospheric conditions. Butt welds will be made so tensile strength tests can be performed. The primary purpose of this phase will be to analyze the effects of low atmospheric pressure on Mars for GTAW capability. Welds will be made with a hollow tungsten electrode torch to ensure proper argon shielding. All welds will be subjected to metallography, tensile testing, microhardness testing, and oxygen/ nitrogen/carbon analysis.

Figure 2. Flowchart describing the basic elements of each phase of this experiment.

Phase 3 shown in figure 2 will also attempt to assess gravitational effects by simulating the welds and calculating the effects of gravity on surface tension and molten metal flow.

3. RESULTS

Figure 3 shows plane view images of the welds produced with the GTAW process. Weld length indicated by marks seen in figure 3(a),(c),(e), and (g) is 7 inches and all other welds were of similar length. Weld labels are based on the material welded, the order in which they were welded beginning with the first welds from phase 1, and the environment in which they were welded.

Figure 3. Sample weld images prior to cutting of welds (image scales vary):
(a) AlWeld6E, (b) AlWeld6M, (c) AlWeld8E, (d) AlWeld8M,
(e) TiWeld6E, (f) TiWeld6M, (g) TiWeld8E, and (h) TiWeld8M.

Figure 4 shows radiographic images of four randomly picked welds from this phase 2 study. Welds were only partial penetration so the weld joint is visible down the center of the welds. All radiographic testing found no defects in the welds that would adversely affect the weld properties.

Figure 5 shows the aluminum weld cross sections. The variations between the simulated Martian and terrestrial aluminum welds will be further discussed in section 4.

Figure 4. Example of radiographs for AA2219-T87 welds: (a) AlWeld6E and (b) AlWeld6M, and Ti-6Al-4V welds: (c) TiWeld6E and (d) TiWeld6M.

Figure 5. Macroscopic optical images of AA2219-T87 welds: (a) Al6E_25X, (b) A16M_25X, (c) A17E_25X, (d) Al7M_25X, (e) A18E_25X, and (f) Al8M_25X.

Figure 6 shows the titanium weld cross sections. The variations between the simulated Martian and terrestrial titanium welds will be further discussed in section 4.

Figure 6. Macroscopic optical images of Ti-6Al-4V welds: (a) Ti6E_25X, (b) Ti6M_25X, (c) Ti7E_25X, (d) Ti7M_25X, (e) Ti8E_25X, and (f) Ti8M_25X.

Figure 7 shows graphs of the hardness values for both the aluminum and titanium welds and compares the differences between the welds made in the simulated Martian environment and those made in the terrestrial environment. The hardness values for each of the two materials were taken using a consistant indenter load so the simulated Martian and terrestrial welds could be directly compared for each of the materials.

Figure 7. Average FZ hardness values taken from seven hardness tests: (a) Aluminum welds and (b) titanium welds.

Figure 8 shows graphs comparing the weld metal tensile strengths of terrestrial welds versus simulated Martian welds for both aluminum and titanium. The tensile strength values were adjusted based on the cross-sectional area of the broken tensile samples by applying the equation: stress = force / area. Area reduction and elongation were minimal because the welds were only partial penetration.

Figure 8. Weld metal tensile strengths based on actual weld cross-sectional area. UTS of: (a) aluminum welds and (b) titanium welds.

Figure 9 shows graphs of the D/W ratio of the terrestrial and simulated Martian welds for both aluminum and titanium.

Figure 9. D/W ratio measurements: (a) Aluminum welds and (b) titanium welds.

4. DISCUSSION

The set of weld images in figure 3 shows that most of the welds did not exhibit any clear visual defects. Figure 3(h) shows TiWeld8M, which had a different surface appearance than any of the other welds. This weld also experienced an arc instability during the welding procedure which is possibly attributed to differential pressures between the external atmosphere and the shield gas (the shielding gas adds pressure in the vicinity of the arc because the overall atmosphere is contained within the glove box although the experiment was performed at atmospheric pressure), or to the metal/alloy weld pool to arc rod potential and/or current transients, or both simultaneously. While the arc plasma and shield gas is fluctuated or alternatively quenched by reactions between the arc, base metal, and surrounding atmosphere, the local weld pool environment is affected strongly by these fluctuations, and additionally by the impingement of the external atmosphere which is relatively magnified by such fluctuations. These varying external atmosphere and internal shield gas and arc interactions have been reported to occur albeit for differing GTAW atmospheric gases, shielding gases, and alloys and weld conditions.[8,9]

At some pressure it is suggested that the above-reported impacts of effects, such as observed arc instability, resulted in the atmospheric (carbon) contamination of the weld pool from the predominantly CO_2 (95.3%) simulated Martian atmosphere. Other factors affecting this contamination are the differential pressures of a simulated atmospheric pressure impinging upon a reduced shielding gas pressure, and the shielding gas being designed to shield against an external atmosphere at a constant standard temperature and pressure.

Additionally, and in more detail, as during TiWeld8M welding, the arc appeared unstable and the width of the arc was slightly decreased. The concurrent effects as discussed above were the greater differential between the atmospheric gas and the shield gas pressures. The effective decreased argon shield gas flow, which potentially had the effect of increasing the heat necessary to maintain a weld puddle in Ti-6Al-4V, was then an additional contributing factor. This may be due to an increased pressure on the arc from the surrounding atmosphere because of the decreased shielding gas flow rate which can increase the field strength and heat emission.[10] As the decreased shielding by the shield gas occurred, and as the increased need for heat to melt and maintain the weld pool in the titanium alloy occurred, the arc simultaneously 'became,' or was observed to be, unstable. These concurrent effects (as above) then—claimed as a possible mechanism—allowed CO_2 from the surrounding atmosphere to penetrate the arc.

The effect of CO_2 penetrating the arc is discussed further later in this section. Additionally, the impingement of the simulated Martian atmosphere on the titanium—due to higher atmospheric pressure (caused by shielding gas adding to the glove box overall pressure) and higher atmospheric density—may also have affected this arc instability by other mechanisms not considered here.

The dissociation of CO_2 into carbon and oxygen while in a high temperature environment, such as an arc, is further discussed later in this section. Such a mechanism is reported elsewhere albeit for different gases and weld GTAW conditions[8,9] and references 11–17.

Figure 4 shows four example radiographic images of the welds made for this experiment. All four images show no evidence of any internal defects aside from incomplete penetration which was expected to occur at the low weld currents used. The weld joint line shown down the center of the weld in figure 4(a) is evidence that the weld did not fully penetrate through the thickness of the weld joint. A less distinguishable weld joint line indicates that the weld metal penetrated further into the weld joint. This variation in weld penetration was unavoidable because the weld travel speed was controlled by the welder and therefore may change throughout the weld. All attempts were made to maintain consistency; a certified welder performed the welds in order to ensure weld quality. All other radiographic images showed no evidence of defects.

The optical images shown in figure 5 display a clear difference in weld cross section between AA2219-T87 welds made in a simulated Martian environment and those made in a terrestrial environment. The depths of the welds vary which may be due to a reverse in the Marangoni convection mode.[8,9] The color of the grains also varies from the darker terrestrial welds to the lighter simulated Martian welds. This color variation must be caused by the difference in the environment, which means that it may be caused by the high amount of nitrogen found in the terrestrial atmosphere that may have diffused into the weld metal during welding like CO_2.[8,18] The simulated Martian AA2219-T87 welds also exhibit a presence of dark precipitates that do not appear in the terrestrial AA2219-T87 welds. These precipitates may be aluminum carbide which would explain the greater tensile strength of the simulated Martian AA2219-T87 welds shown in figure 8(a). This may be confirmed in future work with the use of scanning electron microscopy to analyze the precipitate composition. As tensile strain is applied to the weld, the aluminum carbide precipitates that formed during welding/cooling may resist tensile strain and may utilize Zener pinning to pin dislocations, thus increasing tensile strength.[19] AlWeld8M shown in figure 5(f) exhibits a greater number of these precipitates and its tensile strength is just below the tensile strength of AlWeld7M. The greater number of precipitates shown in AlWeld8M may be due to decreased argon shielding gas, which may have allowed the CO_2 in the simulated Martian atmosphere to more easily have penetrated the arc, where it then dissociated into carbon and oxygen. Carbon and oxygen in the arc has the ability to dissolve into a weld puddle.[8] Additional experimentation is necessary to determine why the visible precipitates are as large as they are and whether additional precipitates will allow for greater tensile strength.[1,2,8,9,16,17,20–22]

Aluminum carbide precipitates have been found to penetrate the surface of a molten weld puddle but are limited in how far they diffuse into the material.[20,22] This may be why the aluminum carbide precipitates are mostly segregated to the surface of the fusion zone (FZ) in AlWeld6M and AlWeld7M. Due to decreased shielding gas, the CO_2 contamination in AlWeld8M may have been great enough to allow the aluminum carbide precipitates to diffuse further into the FZ, as shown in figure 5(f). The decreased shielding coupled with the high atmospheric pressure on Earth may have allowed more simulated Martian gas to penetrate into the arc and then the heat from the arc may have driven diffusion of the dissociated CO_2 into the weld metal.[20–22]

The optical images of the Ti-6Al-4V welds shown in figure 6 display a difference in appearance between the simulated Martian welds and the terrestrial welds. The simulated Martian welds appear to have darker grains than the terrestrial welds. From TiWeld6M to TiWeld8M, the shade of the grain structure darkens. This corresponds to a decrease in argon shielding gas. This decrease in shielding gas caused the simulated Martian gas to impinge more greatly on the arc and weld puddle, thus causing a change in grain color. With decreased shielding gas, the arc would have lower pressure immediately surrounding it and this may cause the pressure of the surrounding simulated Martian gas to flow towards the arc more rapidly than it had when higher shielding gas rates were used. TiWeld8M has drastically darker and finer grains than TiWeld8E. This trend is seen in TiWeld6M and TiWeld7M but is much more obvious in TiWeld8M. TiWeld8M used a shielding gas flow rate of 10 ft^3/hr, which was low enough to cause extreme contamination from the simulated Martian gas. This same observation was easily made during the visual inspection of TiWeld8M. A clear transition happened in TiWeld8M due to excessive CO_2 contamination of the weld. This caused the weld to appear darker as shown in figures 3(h) and 6(f). The change in color of the TiWeld8M was associated with a higher tensile strength as shown in figure 8(b). This effect may be attributed to titanium carburization. Titanium has been found to carburize easily in comparison to aluminum, which would explain why the change in weld appearance was severe when low argon shielding was used.[11–15]

Ti-6Al-4V hardness testing results (fig. 7(b)) show a greater gap in hardness between Martian and terrestrial Ti-6Al-4V welds, TiWeld8M, and TiWeld8E at the lowest shielding gas flow rate. The Martian weld hardness is greater than the terrestrial weld hardness in all cases. As stated above, this may be due to excessive contamination from the CO_2 atmosphere in the Martian weld, which led to a heavily carburized microstructure. The extent of this carburization in TiWeld8M can be observed in figures 3(h) and 6(f). The other two titanium welds, made with higher argon shielding gas flow rate, showed slightly higher hardness in the simulated Martian welds. This may also be due to carbon absorption into the weld; additional weld testing of titanium will be necessary to prove this. Future work shall include measuring carbon absorption[11–15]

The hardness test results shown in figure 7(a) clearly show that the simulated Martian AA2219-T87 welds are harder than the terrestrial AA2219-T87 welds in all cases. From 10 to 30 ft^3/hr of argon shielding, the simulated Martian welds always exhibit higher hardness. This may be due to the formation of aluminum carbide precipitates caused by carbon absorption from the simulated Martian atmosphere.[20–22] To summarize this mechanism, as the arc heated the weld, the CO_2 from the atmosphere was broken down into carbon and oxygen within the arc and then deposited into the weld pool. The carbon may have then precipitated in the weld pool, thus increasing the carbide content in the weld metal. Aluminum carbide can be observed in the micrographs shown in figure 6.[8,20–22]

As shown in figure 8(a), the ultimate tensile strength (UTS) of all the simulated Martian AA2219-T87 welds is greater than all of the corresponding terrestrial AA2219-T87 welds. Other mechanical properties found during tensile testing, such as elongation, were not considered because the welds were not full penetration and therefore would only cause negligible elongation during tensile testing. The UTS and hardness of the aluminum Martian welds also spiked at 20 ft^3/hr according to figures 7(a) and 8(a), which may be due to a higher affinity of aluminum for carbide

formation. This may also indicate that below 20 ft^3/hr shielding, contamination is great enough to cause a decrease in UTS and hardness.[20–22] This is consistent for argon shielding gas rates from 10 to 30 ft^3/hr. The simulated Martian welds were all made in a terrestrial standard temperature and pressure atmosphere made up of mostly CO_2 so the increase in tensile strength is likely related to the CO_2. CO_2 has a density of 1.98 g/L which is higher than the 1.225 g/L density of the terrestrial atmosphere.

This greater percent density of carbon (from 95.3% CO_2) in the simulated Martian atmosphere may have caused the reported material property effects here, and this is due, in part, to the greater elemental presence of dissolved carbon and carburation in the weld(s), as from when the Martian atmosphere impinged more greatly on the simulated Martian welds. This occurred due to the decreased effectiveness of shielding against the external Martian atmosphere by the argon shielding gas.[8,10,16,17]

The carbon in the CO_2 may have broken down into carbon and oxygen when it encountered the arc.[8,14] It is known that carbon introduced becomes part of the plasma arc and deposits into the weld metal. This leads to the formation of aluminum carbide precipitates within the FZ of the welds.[20–22] These carbide precipitates may cause precipitation hardening[19] and may also then act to pin dislocations during tensile testing, thus leading to increased tensile strength.[8,16,17,20–22]

The difference in atmospheric density of the elemental composition between that of the Earth and Martian atmospheres, and that in combination with the decreased effectiveness of the shielding gas as reported above in concert with arc instability, may have led to the observed contamination of the TiWeld8M and the much greater hardness of that weld. It is also well known that titanium is more susceptible to carbon contamination than other metals, which may be what caused its alloy to so significantly react with the simulated Martian atmosphere when low shielding gas was used.[11–15]

Figure 8(b) shows the tensile strength variations for the Ti-6Al-4V welds. The trend for Ti-6Al-4V was nearly opposite of the trend for AA2219-T87 except for the welds made at 10 ft^3/hr argon shielding. TiWeld8M exhibited higher tensile strength than TiWeld8E, likely due to the extensive contamination of TiWeld8M by the CO_2 in the simulated Martian atmosphere, as discussed in detail above. This contamination is easily observed in the overall weld image shown in figure 3(h). This weld contamination may have been caused by titanium's affinity for carburization and the decreased argon shielding from the CO_2 atmosphere.[11–15] The other simulated Martian Ti-6Al-4V welds made with 20 and 30 ft^3/hr of argon had lower tensile strengths than the terrestrial Ti-6Al-4V welds, possibly due to adequate shielding which increased the pressure on the arc and prevented arc instability that could have been caused by CO_2 impingement into the arc plasma.[8,10,16,17]

The UTS of AA2219-T87 is 60 ksi. The tensile strength of all of the AA2219-T87 welds decreased greatly with respect to the base material. The highest AA2219-T87 tensile strength of about 32 ksi was found in AlWeld7M according to figure 8(a). This strength loss of approximately 50% may be due to the loss of the heat-treated condition during fusion welding.[23,24] Copper strengthening precipitates that are evenly distributed throughout the AA2219-T87 base metal can dissolve in the FZ during GTAW, thus decreasing weld strength.[23,24]

For SUS304 stainless steel, it has been found that adequate argon shielding without a surrounding flow of CO_2 results in very shallow and wide weld beads.[8,25] Since they are shallow and wide, the D/W ratio is very low. The opposite has been found to occur when CO_2 is flowing outside the argon shielding gas. This trend appears to apply to the Ti-6Al-4V weld D/W ratio shown in figure 9(b). The simulated Martian welds have an atmosphere of CO_2 surrounding the argon shielding so the higher pressure of CO_2, due to decreased argon shielding, easily flows into the arc and dissociates, thus causing oxygen and carbon to deposit into the weld metal.[8,9,25] This affects the flow of the weld pool because the oxygen changes the surface tension of the weld pool.[8,9] The variation in weld pool surface tension may cause the Marangoni convection mode to reverse, meaning the flow of the weld pool changes from center to edge to edge to center. At higher argon shielding gas flow rates, the pressure of the argon is closer to that of the surrounding atmosphere so it protects welds.[10,25] The terrestrial Ti-6Al-4V welds had greater protection because the density of the terrestrial atmosphere was lower than that of the simulated Martian atmosphere, thus reducing the impingement of the atmosphere on the weld arc.[16,17] Even at higher argon shielding gas rates, the simulated Martian welds still will absorb enough oxygen to increase the D/W ratio. This may be attributed to the much higher oxygen content and density in the simulated Martian atmosphere.[8–10,25]

The AA2219-T87 D/W ratios shown in figure 9(a) are inconsistent and the only simulated Martian weld that exhibits a higher D/W ratio is AlWeld8M. AlWeld8M and AlWeld8E both used very low argon shielding so the surrounding atmospheric oxygen had the greater ability to impinge upon the weld metal. The higher CO_2 content in the simulated Martian atmosphere may break down into oxygen and carbon upon heating, thus increasing the oxygen content over the 20% oxygen content in the terrestrial atmosphere. This may have caused the Marangoni convection to flow from edge to center, causing the D/W ratio to increase.[8,9] At argon shielding gas flow rates of 20 and 30 ft^3/hr, all of the weld D/W ratios were lower than both of the welds made with 10 ft^3/hr of argon shielding gas. This may indicate that 20 ft^3/hr and higher argon gas flow rate is adequate to protect the AA2219-T87 welds from both the simulated Martian or terrestrial gas environments.[8,9]

5. SUMMARY AND CONCLUSIONS

To further human capabilities in outer space and on other planets, it is important to understand how to manufacture in nonterrestrial environments. Welding is of paramount importance for the success of nearly all forms of manufacturing. By the 2030's, NASA plans to send humans to Mars. For this reason, NASA must build a greater understanding of the effects of the Martian environment on fusion welding. This study focuses on Ti-6Al-4V and AA2219-T87 because of their extensive uses in the aerospace industry, including the core stage of heavy-lift rockets, the Orion capsule, and portions of the Environmental Control and Life Support System water filtration.

Results have shown that existing welding procedures may be used to weld in a simulated Martian gas environment. Slight variations can be observed, such as an increase in tensile strength and hardness for the simulated Martian welds with respect to the terrestrial welds. Atmospheric constituents, such as carbon, oxygen, and nitrogen, have been found to potentially affect the material properties of a weld. At low argon shielding gas, the effects of the surrounding atmosphere appear to be exacerbated. The atmospheric effects were still observed at higher shielding gas rates but were minimized. It is recommended that, for welds made with GTAW in a simulated Martian gas environment, a higher amount of argon shielding gas should be used to combat the increased impingement of CO_2 in the simulated Martian environment.

This study shows that welding of Ti-6Al-4V and AA2219-T87 is possible in a simulated Martian gas environment. Additional investigation is necessary to further determine the effects of the atmospheric pressure and elemental composition of the Martian environment on the weld metals, with a particular focus on the chemical testing of the weld metal for absorbed carbon.

6. RECOMMENDATIONS

All phases beyond this phase of this experiment will utilize a 600-Pa vacuum to simulate Martian atmospheric pressure and will utilize weld joints and layered weld geometries and configurations to simulate realistic welding applications in order to better understand the feasibility of GTAW on Mars.[2,7] Future phases may also dilute argon shielding gas with simulated Martian atmospheric gases to gain a better understanding of the critical concentration of Martian gas that is detrimental to weld properties.

Per phase 1 of this experiment, absorbed nitrogen and oxygen levels were not consistently higher in either the simulated Martian or terrestrial welds. Understanding the level of absorbed carbon in the weld metal will help to better characterize the carbon content of the black precipitates shown in figure 5(b), (d), and (f). Furthering the understanding of the differences between welding in a terrestrial atmosphere and a Martian atmosphere will translate many years of welding knowledge that has been studied on Earth. The information found in this study shows promise for GTAW of Ti-6Al-4V and AA2219-T87 in the Martian environment.

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14. ABSTRACT
Gas tungsten arc welding (GTAW) is a vital fusion welding process widely used throughout the aerospace industry. Its use may be critical for the repair or manufacture of systems, rockets, or facilities on the Martian surface. Aluminum alloy AA2219-T87 and titanium alloy Ti-6Al-4V butt welds have been investigated for weldability and weld properties in a simulated Martian gas environment. The resulting simulated Martian welds were compared to welds made in a terrestrial atmosphere, all of which used argon shielding gas. It was found that GTAW is a process that may be used in a Martian gas environment, not accounting for pressure and gravitational effects, as long as adequate argon shielding gas is used to protect the weld metal. Simulated Martian welds exhibited higher hardness in all cases and higher tensile strength in the case of AA2219-T87. This has been attributed to the absorption of carbon into the fusion zone, causing carbide precipitates to form. These precipitates may act to pin dislocations upon tensile testing of AA2219-T87. Dissolved carbon may have also led to carburization, which may have caused the increase in hardness within the fusion zone of the welds. Based on the results of this experiment and other similar experiments, GTAW appears to be a promising process for welding in a Martian gas environment. Additional funding and experimentation is necessary to determine the effects of the low pressure and low gravity environment found on Mars on GTAW.

15. SUBJECT TERMS
GTAW/TIG, welding, Mars, atmosphere, aluminum, titanium

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