GHTA Spot-Welding Experiments of Aluminum and Titanium Plates under a Simulated Space Environment

By Yoshikazu SUIITA,1) Teppi KUROKAWA,2) Junko SATO,2) Shinitiro SHOBAKO,2) Teppi KOHNO,2) Yoshiyuki TSUKUDA,1) Noboru TERAJIMA1) and Koichi MASUBUCHI3)

1)Department of Electro-Mechanical Systems Engineering, Takamatsu National College of Technology, Takamatsu, Japan
2)Advanced Course of Mechanical Electrical Systems Engineering, Takamatsu National College of Technology, Takamatsu, Japan
3)Department of Ocean Engineering, Massachusetts Institute of Technology, Massachusetts, USA

(Received November 19th, 2001)

GHTA (Gas Hollow Tungsten Arc) welding experiments were conducted under a simulated space environment that consists of vacuum and microgravity. A vacuum chamber for the experiments was placed in the aircraft cabin. Aluminum and titanium plates were employed as work pieces. The experiments prove that the arc discharge phenomena, the welding phenomena, and the microstructure of welded metal receive almost no effect from gravity. Moreover, it is also demonstrated that the weld metal of the plate welded under the simulated space environment hangs down less than that of the plate welded on the ground.

Key Words: GHTA Welding, Space Welding, Simulated Space Environment, Microgravity, Aluminum, Titanium

1. Introduction

The International Space Station (ISS) is now being constructed and will be completed by 2006. All ISS structural modules will be assembled by the mechanical joining method because the ISS design was planned in about 1980 when the space application of welding technology was considered to be impracticable. It is necessary however to establish space welding technology with a view to repairing and maintaining the ISS and to constructing other space structures.1)

It is about 40 years since the former Soviet Union first recognized the need of space welding technology and developed space electron beam welding.2, 3) The United States has also been pursuing similar research and development of electron beam welding4) and laser welding5) for space applications. Some problems remain unresolved, however, such as an astronaut’s exposure to X-rays from electron beam welding equipment and the low-energy efficiency of laser welding. Furthermore, NASA provided its space shuttle with an electron beam welder developed by the former Soviet Union and planned to inaugurate space welding experiments in October 1997, although details have since emerged of the unexpected announcement in April 1997 to postpone these experiments indefinitely.6) Meanwhile, when conventional GTA (Gas Tungsten Arc) welding is applied to welding in a vacuum, there are problems,7) such as the expansion of arc and the impossibility of obtaining an arc discharge for use as a welding heat source. Therefore the authors previously proposed the method of gas hollow tungsten arc (GHTA) welding8, 9) that involve trace argon gas being delivered from only the tip of the hollow tungsten electrode. We have conducted welding experiments in a ground vacuum environment and clarified the arc welding phenomena and melting phenomena10–12) in a vacuum condition. Moreover, we recently succeeded in GHTA welding experiments in an aircraft-borne simulated space environment (flying laboratory) and examined the effects of space environment on the arc discharge state and the melting/solidification phenomena of stainless steel.13)

For space development, aluminum alloy and titanium alloy, which have high specific strength, are widely employed. Therefore, to apply GHTA welding in space, it is essential to carry out GHTA welding experiments under a simulated space environment, vacuum and microgravity, by using these space structural materials. Accordingly, we conducted GHTA spot-welding experiments on aluminum and titanium plates under a simulated space environment in the flying laboratory. In this paper, we report the results of these experiments, such as the arc discharge phenomena, melting/solidification phenomena, and the macro- and micro-structure of welded metal.

2. Experimental Method

2.1. Experimental apparatus

Figure 1 shows the GHTA welding apparatus that we employed for the experiments in an aircraft. The apparatus consists of a vacuum chamber (3.2 × 10−2 m3), a rotary vacuum pump, a control box, a battery welding machine, and measuring devices. The vacuum chamber has a GHTA welding torch and a holding unit to which a work piece is fixed as shown in Fig. 2. The motor for the girth welding of pipes was not used for this experiment because only the arc spot...
welding, in which an unmoved heat source of GHTA welding was used, was conducted for the purposes of this paper. An oil-scaled rotary pump (3.6 m³/h) and a mechanical booster pump (10 m³/h) were used as vacuum pumps. Considering the electromagnetic barrier and the limit of consumable electric power, we used a battery-welding machine with DC high-voltage arc-starting unit. Four series-connected sealed batteries were used as the battery, and all welding conditions were conducted with DC electrode-negative polarity (DCEN). The welding current, welding voltage, pressure inside the chamber, and gravity were measured and recorded by a digital oscilloscope and a digital recorder. The states of welding such as arc discharge phenomena and melting/solidification phenomena were recorded with two video cameras.

2.2 Experimental procedure

The experimental apparatus was placed in the flying laboratory, so that the simulated space environment could be created for 20 seconds by a parabolic flight (6,000 m–8,000 m–6,000 m) of the aircraft. The gravity during welding experiments was about 10⁻²G. The aluminum plates and titanium plates were fixed on the holding unit as shown in Fig. 2, and spot-welded. The hollow tungsten electrode used in the welding experiments was a 2% lanthanum oxide containing tungsten electrode with outside diameter of \( D = 4 \) mm and inside diameter of \( d = 1.8 \) mm. Its tip was shaped to a 60-degree apex on an electrode grinder. The welding conditions were set as follows: welding current \( I = 100 \) A, height of electrode \( H_E = 3 \) mm, flow rate of Ar gas \( Q_{Ar} = 1.67 \) ml/s. The Positions in the experiments were with flat, as shown in Fig. 2. The arc was ignited by DC high-voltage discharge after the gravity reached 10⁻²G. The welding time was set at 13–15 s to complete solidification under the microgravity. Although the pressure in the vacuum chamber before the start of the experiments on the ground was 10⁻² Pa, for the experiments in a flying laboratory it was about 8–13 Pa so that as many welding experiments as possible could be conducted in a limited period. As a result, the pressure in the vacuum chamber after welding was about 50 Pa. The aluminum plates (A1050P) used as work pieces were 2 mm thick, 50 mm wide, and 70 mm long, and the titanium plates (TP340C) were 2 mm thick, 50 mm wide, and 70 mm long as shown in Tables 1 and 2.

### Table 1. Chemical composition (mass%) and mechanical properties of aluminum plate used.

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1050P</td>
<td>0.07</td>
<td>0.33</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>99.54</td>
</tr>
</tbody>
</table>

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>b) Mechanical properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>108</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Chemical composition (mass%) and mechanical properties of titanium plate used.

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP340C</td>
<td>0.012</td>
<td>0.083</td>
<td>0.003</td>
<td>0.025</td>
</tr>
</tbody>
</table>

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>b) Mechanical properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2% Proof stress (MPa)</td>
<td>303</td>
<td>396</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
3. Experimental Results and Discussion

3.1. GHTA welding experiments of aluminum plates

3.1.1. Arc discharge phenomena

Figure 3 shows the arc appearance during spot welding under a simulated space environment ($10^{-2} \text{ G}$) and in a ground vacuum environment (1 G) at a welding current of $I = 100 \text{ A}$, an electrode height of $H_E = 3 \text{ mm}$, and an argon gas flow rate of $Q_{Ar} = 1.67 \text{ ml/s}$. These photographs show the arc discharge state about 2 and 10 seconds after arc initiation. It is the important characteristic of arc discharge in a low pressure in which a hollow tungsten electrode is used that the arc discharge does not form a bell shape because of the low plasma density, such as that found in conventional GTA welding in the air. We first succeeded in the arc discharge experiment of aluminum under a simulated space environment by GHTA welding method as illustrated in Figs. 3(a) and 3(b). Figures 3(c) and 3(d) demonstrate the arc discharge state on the ground under the same welding conditions. From a comparison of these figures and an observation of video recording, we find that the arc discharge state is not affected by gravity. The reason for this may be that the Ar gas flow and the plasma flux caused by the Lorentz force have a greater effect on the arc discharge form than gravity does. Moreover, no effects of gravity on the welding voltage were found. This aluminum arc welding carried out with DCEN polarity was not accompanied with a vaporization of molten metal, since no cleaning phenomena occurred and the high-melting-point oxide film (alumina $\text{Al}_2\text{O}_3$) of the workpiece surface was not melt-removed. Therefore there is little difference between the arc discharge state about 2 s after arc initiation, when the molten pool is small, and the states about 10 s after initiation, when it is larger. Furthermore, the arc discharge states of aluminum are different from those of titanium and the stainless steel that accompany light emission around the molten pool.

3.1.2. Melting/solidification phenomena

Figures 4(a)–(f) show oblique views from above the arc discharge and the melting states under the simulated space environment in chronological order. We find in these figures that the molten pool under the oxide film expands and hangs down as time passes [from Fig. 4(a) to 4(b)], and the surface of hanging oxide film has cracks. The flow of the molten pool was not observable because the oxide film over the molten pool was not removed. The hanging phenomenon was identified in the arc spot welding of aluminum plates in spite of the microgravity environment. But the molten pool hanging phenomenon was not identified in the
welding of stainless steel under microgravity. The reasons for these phenomena may be that the aluminum has low density and the molten pool is pushed down by the effect of plasma flux and Ar gas flow. The continuation of the arc discharge causes a hole in the base metal as shown in Fig. 4(c) but the melting zone continues to expand until the arc disappears, after which we can immediately detect “spring up phenomenon”: The hanging molten metal springs up to the opposite side. The hanging of molten metal then almost completely vanishes, as shown in Fig. 4(e) [Fig. 6(a)]. The main reason for these phenomena is that the hole in the molten pool directly under the electrode decreases the down force caused by the plasma flux and Ar gas flow that pushes the pool down.

Meanwhile, Figs. 5(a)∼(f) illustrate the melting phenomena in a vacuum on the ground in chronological order. These phenomena were also observed diagonally from above. Figures 5(a) and (b) show the expansion of the molten pool. Figure 5(b) also illustrates the cracks of the oxide film. Figure 5(c) shows the state of the molten pool observed right after the hole is made. The behavior of molten metal in a vacuum on the ground is different from under the simulated space environment because that the molten pool continues to hang from the appearance of the hole until the disappearance of the arc, and it solidifies while retaining its hanging phenomenon [Fig. 6(b)].

3.1.3. Macrostructure, microstructure, and hardness distribution

Figures 6(a) and 6(b) illustrate the macrostructure of the weld zone with a hole, welded under the simulated space environment and in the ground vacuum environment. As shown in Fig. 6, the hanging of weld metal welded under the simulated space environment [Fig. 6(a)] is much less than that in a vacuum on the ground [Fig. 6(b)].
Figures 7(a)–(c) show the microstructure of the bond, the center of the molten pool, and the middle of the metal welded under the simulated space environment and in the ground vacuum environment. The comparison between the microstructures in Fig. 7 shows no great difference between the microstructure welded under the simulated space environment and the one welded in the ground vacuum environment. The factors causing flow in the molten pool are ① the electromagnetic convection, ② the drag flow, ③ the Marangoni convection, and ④ the thermal convection. However, the effect of ② and ③ on the flow in the molten pool would be slight because the oxide film remains on the surface of the base metal in this welding experiment. Furthermore, the effect of ④, which does not occur under the microgravity environment, is much less than that of ①. For these reasons, the flow of the molten pool has not been influenced by gravity until a hole is made. Therefore the microstructure is not affected, either.

Figure 8 demonstrates the hardness distribution of the weld zone of the work piece welded under the simulated space environment and in the ground vacuum environment. The hardness distribution of under the simulated space environment is almost same as in the ground vacuum environment. This result can be expected because the microstructure of the weld metal is not affected by gravity.

3.2. GHTA welding experiments of titanium plates

3.2.1. Arc discharge and melting phenomena

Figures 9(a), (b) show the state of arc discharge of the GHTA spot welding, which was recorded 2 seconds and 10 seconds after the arc initiation under the simulated space environment. Figures 9(c), (d) show the same state in the ground vacuum environment. The welding experiment in Fig. 9 was performed under the conditions of welding current $I = 100\, \text{A}$, argon gas flow rate $Q_{\text{Ar}} = 1.67\, \text{ml/s}$, electrode height $H_{\text{E}} = 3\, \text{mm}$, and welding period $t = 13\, \text{s}$. The arc discharge right after the arc initiation (after 2 s) under the simulated space environment, as shown in Fig. 9(a), is accompanied by a slight light emission at the surface of the base metal. Figure 9(b) shows, however, as time passes and the molten pool of the titanium plate grows larger, that the arc discharge is accompanied by a greater light emission from the entire molten pool. This phenomenon is distinct from that of aluminum plate. The difference in arc discharge is not large between in the ground vacuum environments as shown in Figs. 9(c) and 9(d), and under the simulated space environment in Figs. 9(a) and 9(b). Therefore we can infer that as with the welding of aluminum plates, gravity does not affect the arc discharge of titanium plates.

Figures 10(a) and 10(b) show the melting phenomena recorded 10 seconds after the arc initiation under the simulated space environment and in the ground vacuum environment. The phenomena are observed diagonally from above. Unlike the arc spot welding of aluminum plates, the surface of the molten pool melts and the flow of the molten pool is...
observed. Examining Fig. 10(a), 10(b) and the video recording, we cannot find the marked effect of gravity on melting phenomena, except for the hanging phenomena of molten metal (explained in a later section). As we have already discussed in the previous section, the reason for these phenomena may also be that the driving force of $\Delta$, which does not occur under the simulated space environment, is sufficiently smaller than the driving force of others to cause it be ignored: $\circ$ the electromagnetic convection, $\odot$ the drag flow, $\ominus$ the Marangoni convection.

3.2.2. Macrostructure, microstructure, and hardness distribution

The macrostructure of the weld zone, welded under the simulated space environment and in the ground vacuum environment, is shown in Fig. 11(a) and 11(b). As we had expected, the comparison between Fig. 11(a), (b) clarified that the degree of hanging metal welded under the simulated space environment is smaller than in the ground vacuum environment.

Figure 12 shows the microstructures of the center of weld metal that was welded under the simulated space environment and in the ground vacuum environment. The comparison between the structure welded under the simulated space environment and the structure welded in a flat position in the ground vacuum environment shows no great difference between these structures, and both contain a coarse $\alpha$ structure that can be detected in the general weld structure of titanium. Therefore it is concluded that the weld metal microstructure of titanium plates has little effect of gravity.

Figure 13 shows the hardness distribution of the weld zone that was welded under both environments. It is clear from this figure that neither the hardness distribution nor the microstructure is affected by gravity.

4. Conclusion

We conducted GHTA spot-welding experiments with aluminum and titanium plates in a simulated space environment and in a ground vacuum environment. The results are summarized as follows:

(1) It is possible to ignite and maintain the arc discharge of aluminum and titanium plates in a simulated space environment by the GHTA welding method.

(2) The appearance of arc discharge during arc spot welding is not affected by gravity.

(3) The molten metal of aluminum is pushed down by the effect of plasma flux and argon gas flow during welding.

(4) The hanging molten metal during arc spot welding of the aluminum and titanium plates in the simulated space environment is smaller than in the ground vacuum environment.

(5) The high melting point oxide film of the surface of the aluminum plate is not removed because the cleaning phenomena do not occur in DCEN polarity welding and the vaporization that forms molten metal is not emitted.

(6) With of titanium, the arc discharge is accompanied by a greater light emission from the entire molten pool that is caused by evaporated metal.

(7) The microstructure and hardness distribution in the
weld zone of aluminum and titanium plates are not affected by gravity.

Acknowledgments

The authors would like to thank Professor Takayoshi Ohji and M. Eng. Hiroshi Nishikawa, and B. Eng. Kazuhiro Yoshida of the Osaka University graduate school for their great efforts and advice. Moreover, The authors wish to thank support of the Japan Space Forum. This study was carried out as a part of “Ground Research Announcement for Space Utilization” promoted by Japan Space Forum.

References