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Formation and disappearance of pores in aluminum alloy molten pool under microgravity

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Abstract

With the start of construction of the international space station, a welding technique in space is becoming essential for the construction and repair of space structures. We now describe the results obtained under microgravity by electron beam welding, which is thought to be the most probable candidate for space welding. The microgravity environments were achieved using the drop-shaft system at the Japan Microgravity Center. The system can produce a microgravity of 10^{-5} G and a duration of 10 s. The sample was an aluminum–copper alloy, 2219, which is commonly used in the aerospace industry. The effective diameter of the electron beam was set at approximately 3 mm in order to prevent the keyhole formation. A significant decrease in the number of the pores in the Al alloys was observed under microgravity. All of the pores smaller than 100 μm disappeared for both microgravity and terrestrial environments. These results indicate that there exists a new bubble formation mechanism, consisting of a reaction between the molten Al and Al_2O_3 forming Al_2O gas, and that the convection due to the Marangoni flow is negligible in an Al molten pool.

Keywords: Microgravity; Drop-shaft; Electron beam welding; Interfacial tension; Convection; Aluminum alloy; Al_2O; Bubble size

1. Introduction

The construction of the international space station has been underway since 1998 through the cooperative efforts of the USA, Russia, Europe, Canada and Japan. Under such circumstances, a welding technique in space is becoming essential for the construction and repair of space structures. Welding experiments in space were started in 1969 by the USSR [1] and then in 1973 by the USA [2]. However, detailed information on these welding phenomena has not been reported due to the military restrictions. The authors have also performed gas tungsten arc welding under microgravity using a drop-shaft type microgravity system and have clarified the effect of gravity on various welding phenomena including the bead shape [3], the microstructure [3], the arc shape [4], and the bubble behavior [5,6].

Porosity in a weld is one of the welding defects that significantly affects the mechanical properties of the weld. For aluminum alloys, which will be commonly used in space due to their low specific weight, high tensile strength and corrosion resistance, hydrogen is usually a major cause of porosity formation due to the decrease in its solubility in the molten pool during cooling. In general, under microgravity, the number of the pores is greater than in a terrestrial environment, because the pores cannot be released to the outside of the molten pool due to the lack of convection [5–7]. Accordingly, it is necessary to determine the details of the bubble behavior under microgravity for the coming space age.

Because space is a vacuum, electron beam welding should be the most effective method in space [8], though arc welding is most commonly used in terrestrial environments. Recently, it was pointed out that when an aluminum alloy is welded in a vacuum as in electron beam welding, the Al_2O_3 film on the surface of the aluminum alloys could be a source of bubbles, because the number of the bubbles increases with the increasing thickness of the oxide film [9]. Although, aluminum alloys will be commonly used in space, its oxide film cannot completely be removed even in a terrestrial environment. In addition, in low earth orbit (LEO), where spacecraft travels, the spacecraft surfaces will be damaged by atomic oxygen, micrometeoroids and debris bombardment [10,11]. Atomic oxygen, which is formed by

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the photodissociation of molecular oxygen, is the dominant species in LEO [12]. Because atomic oxygen has an average energy of 4.5–5 eV at the ram impact velocities and is extremely reactive [10], the damaged part will be oxidized by the atomic oxygen. Under such severe circumstances as LEO, a welding technique will be essential for the repair of space structures, and more bubbles will be formed in LEO than under terrestrial conditions. Thus, it seems that bubble formation from an aluminum oxide film is a very important issue for predicting the success of space welding in the future. Accordingly, in this study, the behavior of the bubbles formed during electron beam welding under microgravity is investigated in detail.

2. Experimental procedure

Microgravity environments were achieved using the drop-shaft system at the Japan Microgravity Center. The system can produce a microgravity level of 10^{-5} G and a duration of 10 s. A developed welding system was loaded into the drop capsule, and then the capsule was dropped 710 m below ground level.

For loading into the drop capsule of the microgravity system, some restrictions are imposed on the size and the weight of the apparatus (under 870 mm × 870 mm × 918 mm and 500 kg), power consumption (only battery), and durability (8 G). In this study, a new system was developed within these restrictions. It is much smaller than an ordinary electron beam welding apparatus. The miniaturization of the system is also important for actual transportation into space. Fig. 1 shows the developed electron beam welding system and its electron beam gun [13]. The system consists of an electron beam gun, a focusing coil, a vacuum chamber, a vacuum pump, a high voltage power supply and a battery. The gun is a triode focusing electrode, and a ground potential anode providing the electron acceleration. The distance from the filament cathode to the sample is only 370 mm. The vacuum chamber is equipped with a specimen and a worktable. An ion pump was selected for the evacuating system because it is free of oil and mechanical vibration that lowers the quality of microgravity. The high voltage power supply provides up to negative 20 kV at 100 mA. The effective diameter of the electron beam was set at about 3 mm so that the energy density should be low. Under this condition, the weld pool is expected to be shallow and wide like in arc welding rather than deep and narrow like in ordinary electron beam welding. Such heat conductive melting is suitable for welding in outer space because defects such as porosity and spiking are reduced.

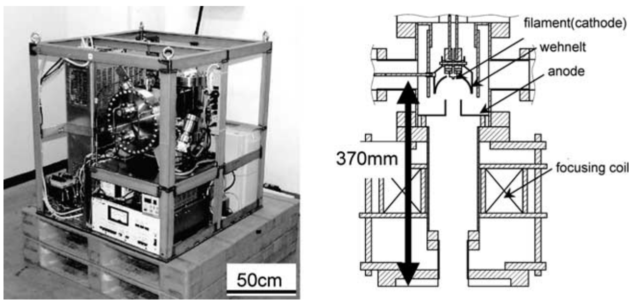

Fig. 1. Appearances of developed electron beam welding apparatus and schematic electron beam gun for use under microgravity.

Table 1
Chemical compositions of A2219 (%)

Si	Fe	Cu	Mn	Zn	Ti	Zr	Pb	V	Al
0.07	0.16	6.26	0.30	0.01	0.04	0.18	0.01	0.09	Bal

The samples were an aluminum–copper alloy, 2219, which is commonly used in the aerospace industry. Table 1 shows the chemical composition of the A2219 alloy. Sample dimensions were 50 mm × 100 mm × 3 mm. A sample was placed in the electron beam welding system, and bead-on-plate welding was performed under both terrestrial and microgravity conditions. The welding position is horizontal for the terrestrial conditions. The acceleration voltage and beam current were 11 kV and 80 mA, respectively. The welding speed was set at 5 mm/s. The vacuum level was approximately 10^{-5} Pa before welding. The distributions of the pores were observed using a transmission X-ray image system (SHIMADZU SAX-10SCT).

3. Results and discussion

3.1. Number and size of pores

Fig. 2 shows the transmission X-ray images of the beads obtained under terrestrial and microgravity conditions. For the microgravity experiments, the welding was started under the terrestrial conditions and then the environment was changed from the terrestrial to the microgvatiy environment. The number of pores under microgravity is much lower than

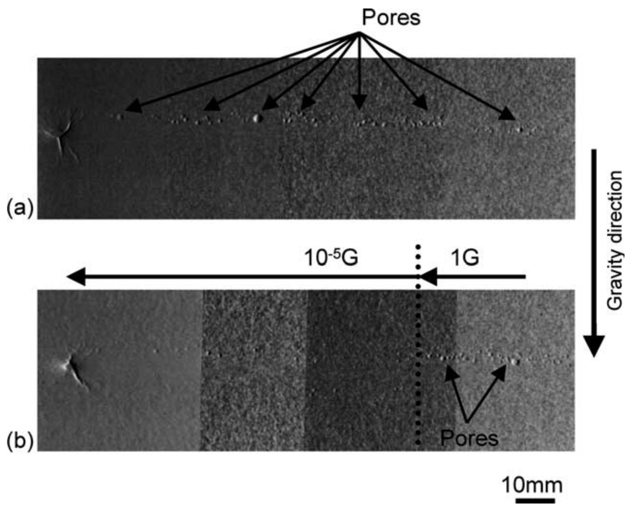

Fig. 2. Transmission X-ray images of the beads obtained under terrestrial and microgravity environments. (a) 1 G and (b) 10^{-5} G.

that under terrestrial conditions. This result is completely different from that for GTA welding with a shielding gas containing hydrogen [5]. For the hydrogen case, the number of pores under microgravity is greater than that under terrestrial conditions because the pores cannot be released to the outside of the molten pool due to the weaker convection. A similar phenomenon should have occurred during EB welding.

In general, the causes of bubble generation are considered as follows

1. Decrease in the solubility of the dissolved elements in the molten pool during cooling and solidification [14].
2. Chemical reaction [14].
3. Keyhole phenomenon [15].
4. Evaporation of the elements with a high vapor pressure [16].
5. Trapped gas between the root faces [17].
6. Physical trapping of the shielding gas [18].

It is well known that the decrease in the solubility of dissolved hydrogen in the weld pool is generally the main cause for aluminum alloys. However, it does not seem that the dissolved hydrogen is the cause of the pore formation in this case, because the change in the number of the pores under microgravity is very different from that for GTA welding with a shielding gas containing hydrogen. In addition, in this study, because a large beam diameter, 3 mm, is used, a keyhole is not formed. The A2219 alloys do not contain any alloying elements with high vapor pressures. Also, bead-on-plate welding was performed. Because electron beam welding is operated in a vacuum, there is no shielding gas. Thus, a chemical reaction seems to be the most plausible answer in this case.

Fig. 3 is another interesting result which shows the pore size distribution. The number of pores smaller than about 100 μm significantly decreases for both the microgravity and terrestrial environments. This result is also completely different from that for GTA welding with a shielding gas containing hydrogen [5]. It is considered from these results that the interfacial tension between the bubbles and the molten metal extinguishes bubbles smaller than the critical value. An additional pressure given to the bubbles can be calculated, as shown in Fig. 4. This pressure is calculated by the following Laplace equation $\Delta P = 2\gamma/r$ (ΔP, additional pressure; γ, interfacial tension; r, bubble radius). The required surface tension values (temperature dependence and concentration dependence) are estimated from the literature [19,20]. When the pressure exceeds the equilibrium partial pressure of the bubble, the bubbles will disappear.

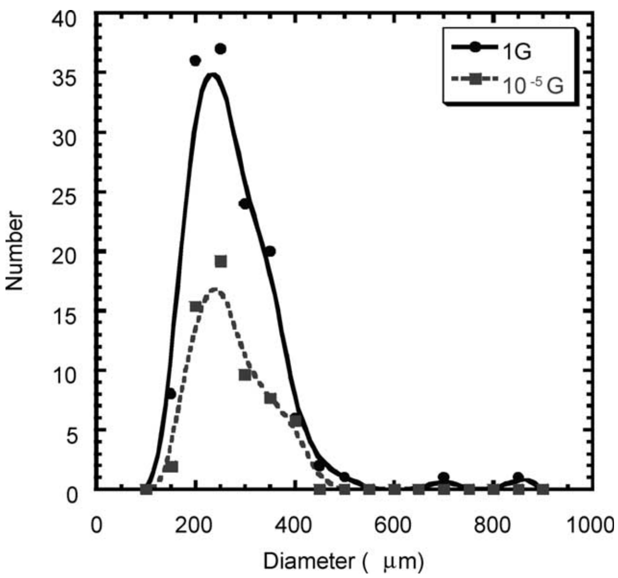

Fig. 3. Pore size distribution under terrestrial and microgravity environments.

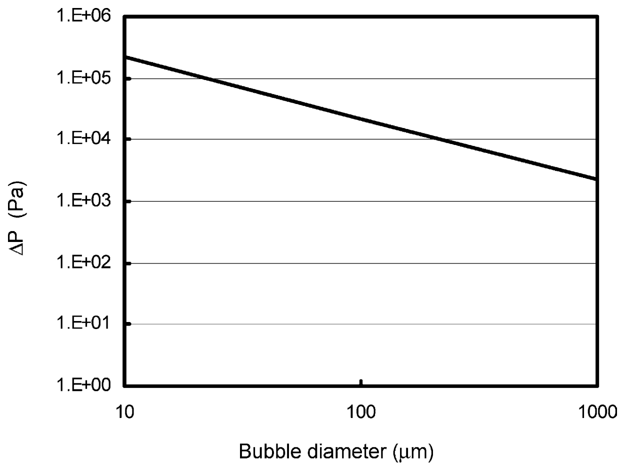

Fig. 4. Additional pressure caused by interfacial tension between bubbles and molten metal at 2273 K.

Recently, it was pointed out that when an aluminum alloy is welded in a vacuum as in electron beam welding, the Al_2O_3 film on the surface of the aluminum alloys could be a source of bubbles, because the number of the bubbles increases with the increasing thickness of the oxide film [9]. When an aluminum alloy with an oxide film is welded in a vacuum, the following reaction can occur [7,21,22,23]

$$4Al(l) + Al_2O_3(s) = 3Al_2O(g) \quad (1)$$

$$\Delta G^\circ = 1,180,020 - 479.55\ T(J/mol) \quad (2)$$

where ΔG° is the change in the standard free energy and T is temperature [23]. The equilibrium partial pressure of Al_2O gas is calculated using the standard free energy of the formation described by Eq. (2), as shown in Fig. 5. Thus, when the temperature is 2273 K, the additional force shown in Fig. 4 exceeds the equilibrium partial pressure of the Al_2O bubble, and then the bubbles smaller than about 100 μm disappear.

In the terrestrial environment, bubbles are moved by the convection due to gravity and consequently, they can collide with each other and then coalesce. Under microgravity, on the other hand, because there is no buoyancy, the small size

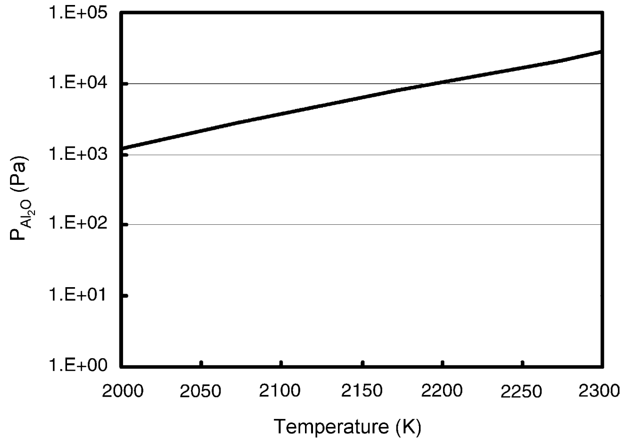

Fig. 5. Calculated partial pressure of Al_2O in equilibrium using the equation: $4Al(l) + Al_2O_3\ (s) = 3Al_2O\ (g)$.

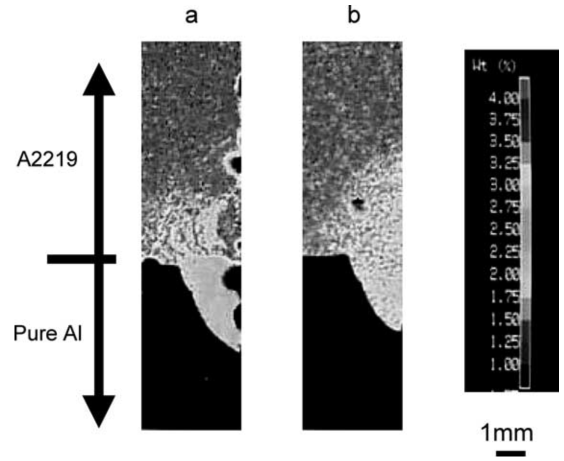

Fig. 6. EPMA analysis results of a cross section of a welded sample of pure Al (5NAl) and Al–Cu alloy (A2219) alloy. (a) 10^{-5} G and (b) 1 G.

of the pores is maintained due to the lack of coalescence, and many small-sized bubbles disappear due to the additional pressure induced by the interfacial tension between the bubbles and the molten metal.

3.2. Convection in molten pool

As mentioned before, the convection in the molten pool should significantly affect the bubble behavior. In electron beam welding, there are two driving forces for the convection: surface tension (Marangoni flow) and buoyancy. Under microgravity conditions, on the other hand, only the Marangoni flow determines the convection in the molten pool. Many researchers have concluded from their simulation results that the effect of buoyancy is negligible, compared with the effect of surface tension [24–29], although no experimental results have been obtained. For example, according to Kou's simulation [24], the velocity of convection due to surface tension about 0.1–1 m/s, while that due to buoyancy is 0.01 m/s for an aluminum alloy.

In order to experimentally investigate the effects of surface tension and buoyancy in this study, the butt-welding of pure aluminum and an aluminum–copper alloy, 2219, was performed under both terrestrial and microgravity conditions. Because copper only exists in the 2219 sample before welding, the magnitude of the stirring force can be estimated by observing the distribution of the copper concentration after welding. Fig. 6 shows the results of an EPMA analysis of cross sections of the welded sample showing the distribution of the copper concentration. Fig. 6(a) and (b) show the results obtained under microgravity and terrestrial conditions, respectively.

Under the terrestrial conditions, as in Fig. 6(b), copper in the molten pool is almost uniformly distributed, but under microgravity, as in Fig. 6(a), the distribution of copper is still discontinuous at the interface even after welding. Therefore, in this case, it can be concluded that the convection due to buoyancy is greater than that due to surface tension. This is completely different from the widely accepted notion that the convection due to surface tension is much greater. This is because the previous researchers did not consider the effect of the oxide film on the aluminum surface.

However, because of the fact that gravity actually affects the convection in the molten pool, a number of pores are left in the weld under terrestrial conditions and they disappear under microgravity due to the lack of convection. Thus, Fig. 2 also indicates that the widely accepted simulation results are not correct.

4. Conclusions

By performing electron beam welding for an aluminum alloy under both microgravity and terrestrial conditions, the bubble behavior was investigated. As a result, the following conclusions were achieved.

1. The number of pores formed during EB welding is much smaller under microgravity than under terrestrial conditions. This result is completely different form that for GTA welding with a shielding gas containing hydrogen.
2. The number of pores smaller than 100 μm significantly decreases for both microgravity and terrestrial environments.
3. The convection due to surface tension is weaker than that due to buoyancy. This is also important fact for the mechanism of the disappearance of pores under microgravity.
4. It is deduced that the bubbles are formed through the reaction: $4Al(l) + Al_2O_3(s)?3Al_2O(g)$, whose equilibrium partial pressure is very low.

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