Electron Beam and Gas Tungsten Arc Welding under Microgravity†

Hidetoshi FUJII*, Yasuhiro AOKI** and Kiyoshi NOGI***

Abstract

Electron beam (EB) and gas tungsten arc (GTA) welding were performed using both microgravity and terrestrial conditions and the effects of gravity on bead shape and bubble behavior were investigated. The drop-shaft type system was used to obtain a 10s microgravity of 10^{-5}G at the Japan Microgravity Center (JAMIC). Small-sized systems for both EB welding and GTA welding were developed, and EB welding was carried out in a high vacuum under microgravity, which simulates conditions very similar to those in space. It was found that a flat bead is formed is formed under proper conditions and a large amount of metal can be welded at once in any welding position. When aluminum alloys were welded in a high vacuum under microgravity, several pores were observed in all the welds including the bead-on-plate welds. It was established that the bubbles were formed by the production of Al_2O gas. By comparing the pore distribution in the terrestrial environment with that in the microgravity environment, the bubble behavior in the molten pool was investigated and the following conclusions reached. Blowholes grow by combining with other blowholes after their formation, though wormholes do not combine with other wormholes or blowholes. Gravity does not significantly affect either the movement or the combination of bubbles smaller than a critical size. Gravity does affect the movement of bubbles larger than a critical size, though it does not affect their combination.

KEY WORDS: (Microgravity) (Bead Shape) (Bubble Generation) (Bubble Behavior)(Aluminum Alloys) (Small-sized EB System) (Blowholes)(Wormholes)

1. Introduction

The construction of the international space station (ISS) commenced in 1998 and is anticipated to be completed by 2004 through the cooperative efforts the USA, Russia, Europe, Canada and Japan. In such circumstances, a welding technique in space will be essential for the construction and repairs of space structures such as the ISS. In order to establish the welding technique in space, welding experiments in space were started in 1969 by the USSR[1)] and then in 1973 by the USA[2)]. In Japan, welding experiments in a microgravity environment were started in 1990, though the experiments have not yet been carried out in space. For example, Abe *et al.*[3)] performed the gas tungsten arc (GTA) welding in a microgravity environment. Kaihara *et al.*[4)] successfully performed the gas metal arc (GMA) welding as well as the GTA welding.

The authors have also started welding experiments in a microgravity environment since 1996. As a result, they have clarified the effects of gravity on welding phenomena including bead shape[5)], microstructure[5], pore distribution[6)], bubbles behavior[6)] and arc shape[7)]. A small-sized electron beam welding system was also successfully developed[8)]. This paper is a review of our recent work on welding experiments in a microgravity environment.

2. Experimental Apparatus and Procesure

Although microgravity environments can be achieved by several methods, a drop-shaft microgravity system was used in our studies, as shown in **Fig. 1**. The system can maintain a 10 s microgravity of less than 10^{-5} G. The quality of microgravity is very high and is similar to the space environment. The drop capsule is composed of a double structure consisting of an inner and an outer capsule and a vacuum is maintained between them so that the free fall velocity of the welding apparatus in the inner capsule will not be affected by the air drag.

Figures 2 and **3** show the GTA and the EB welding systems, respectively. These systems were developed in our studies. The size of the apparatus is $0.87\text{m}^w \times 0.87\text{m}^l \times 0.92\text{m}^h$. The GTA welding system consists of a welding power source, a welding chamber, a shielding gas supply, current type welding power source is supplied with a

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battery and a welding control system. The constant 2.4kW (AC100V, 3000VA) from the battery. The EB welding system consists of an electron beam gun, a high voltage power supply, a vacuum chamber, a vacuum pump, a battery, and a system controller. The total size of the gun is about 0.37 m, including the anode gird and a focusing coil. The electron beam welding system can be operated at a maximum voltage of a negative 20kV and a maximum steady-state beam current of 80mA.

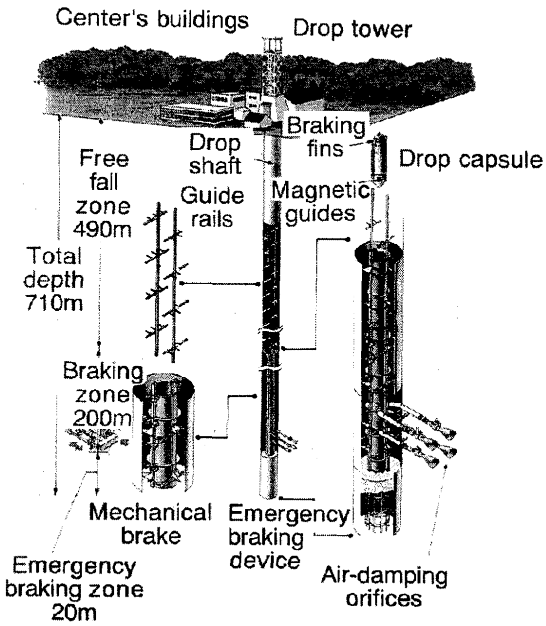

Fig.1 Schematic illustration of the free fall system.

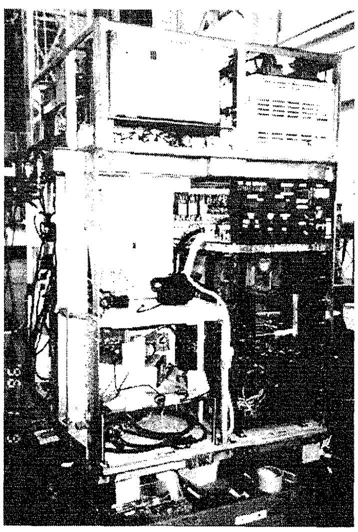

Fig.2 Gas tungsten arc welding apparatus for use in microgravity environment. 1: welding power source, 2: welding chamber, 3:battery, 4:welding control system, 5:video tape recorder

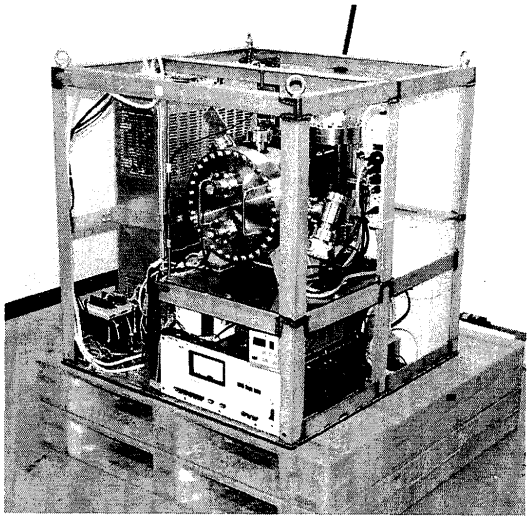

Fig.3 Electron beam welding apparatus for use in microgravity environment. 1:high voltage power supply, 2: vacuum chamber, 3: vacuum pump control system, 4: battery, 5: system controller

The materials used were aluminum alloys (A2219, A5083). Bead-on-plate welding and butt welding were performed. The polarity in GTA welding was direct current electrode negative (DCEN).

3. Results and Discussion

3.1 Weld shape under microgravity

Figures 4 (a) and **(b)** show transverse sections of butt welds formed using GTA welding in both environments. The shielding gas was helium and the welding position was horizontal. In a terrestrial environment, as shown in Fig. 4 (a), the weld bead is hollowed out in the upper part and is bulged very much in the lower part. In this case, the molten metal drops in the gravity direction and is solidified there. In a microgravity

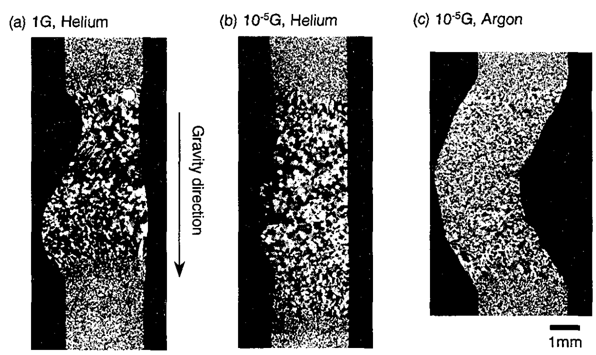

Fig.4 Transverse sections of butt welds formed with GTA welding in horizontal position.

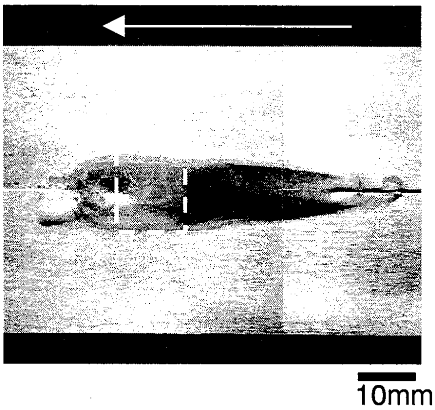

Fig.5 Typical bead appearance welded with developed system in a horizontal position under microgravity.

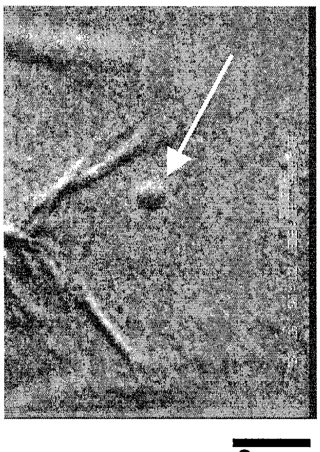

Fig.6 Radiograph of the bead in Fig.5 The arrow indicates a pore.

environment, as shown in Fig. 4 (b), on the other hand, the weld pool is maintained and a flatter weld bead is formed due to the absence of gravity. These results indicate that in a microgravity environment, a large amount of metal can be welded at once. However, even in a microgravity environment, when argon is used as a shielding gas, the arc pressure affects the bead shape as shown in **Fig. 4 (c)**. This is because the force of the arc pressure with argon shielding gas is several times larger than that with the helium shielding gas, even when the electric power is the same.

Figure 5 shows a typical bead appearance when welding with the EB system in a horizontal position in a microgravity environment. A flat weld bead was formed in a microgravity environment similar to the result of the GTAW method with helium shielding gas.

3.2 Cause of bubbles formation in Al alloy in vacuum

We propose a new cause of the bubble formation in a vacuum[6]. When welding is performed in a vacuum for aluminum alloys with an oxide layer on the surface, a gas phase of Al_2O can be formed by the following reaction[6].

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

$$\Delta G^o = 1180020 - 479.55T\ \text{(J/mol)} \qquad (2).$$

where ΔG^o is the change in the standard free energy, and T is temperature. **Figure 6** shows the radiograph of the weld shown in Fig.5. As shown with an arrow, several pores in the weld are observed. Because the pores in the bead-on-plate weld are also observed, it can be judged that the bubbles are formed by the production of Al_2O gas.

In the low earth orbit (LEO), atomic oxygen formed by the photodissociation of molecular oxygen is the most prevalent species[9]. Atomic oxygen should oxidize a damaged part of space structures. When the damaged part is repaired, the reaction between Al and Al_2O_3 can occur, producing a gas phase of Al_2O.

3.3 Effect of gravity on bubbles behavior

As mentioned in the previous section, it is necessary to investigate the bubbles behavior in space. In order to simulate the bubbles behavior in space, the GTA welding was performed using an argon - 1% hydrogen mixed shielding gas.

Figure 7 shows transverse sections of the welds in both environments. The pore distribution is significantly affected by gravity. In the terrestrial environment, round shaped pores were segregated in the upper part. Small pores were distributed in the lower part of the weld. In the microgravity environments, on the other hand, the distributions are almost the same between the upper part and the lower part.

In order to evaluate the relationship between the pore size distribution and the pore shape quantitatively, image analyses were performed. Because wormholes are formed at solid-liquid interfaces and at the last stage of the

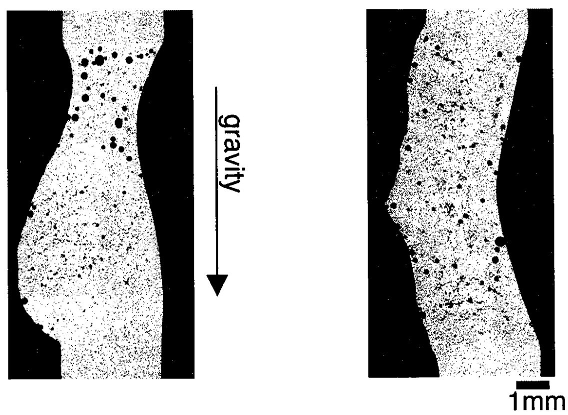

Fig.7 Transverse sections of bead-on-plate welds in horizontal welding with argon-1% hydrogen mixed shielding gas.

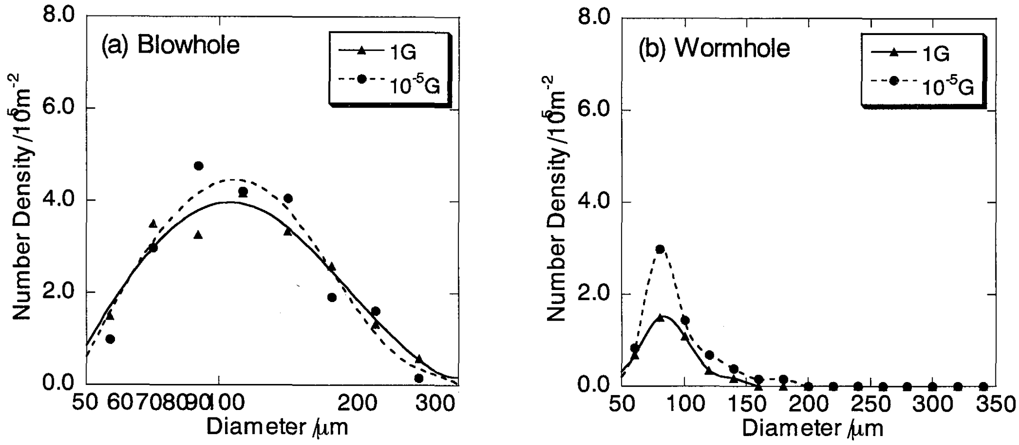

Fig.8 Blowhole and wormhole size distributions in whole cross section.

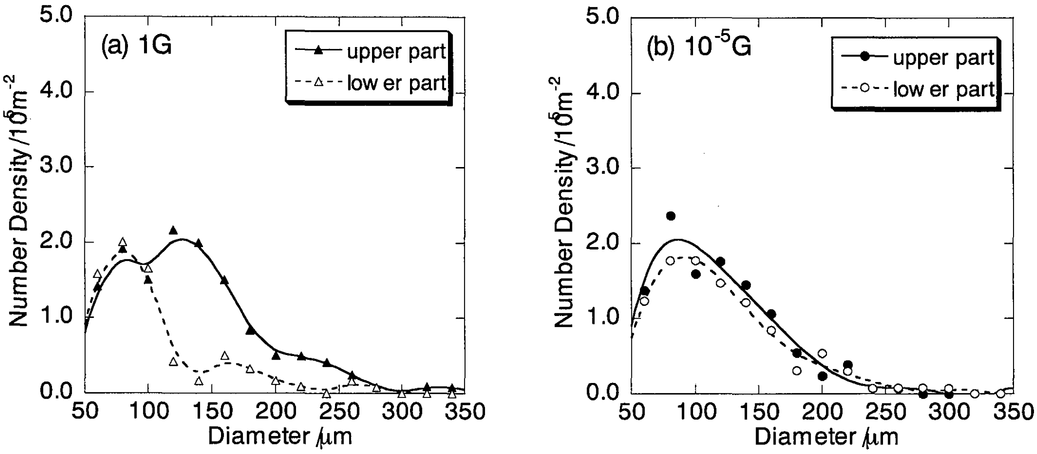

Fig.9 Blowhole size distributions separated the results in Fig.8 (a).

solidification process, wormholes cannot be affected by gravity. Accordingly, in order to analyze bubble behavior precisely, wormholes should be differentiated from the blowholes. In this study, the shape factor of 0.75 was defined as the boundary for separation between the blowholes and the wormholes. **Figures 8 (a)** and **(b)** show the blowhole size distribution and the wormhole size distribution in the whole cross section, respectively. Note that the x-axis for the wormhole size distribution is a linear scale, but that for the blowhole size distribution is a logarithmic scale. Both distributions are almost symmetrical in spite of the different scales. These results indicate that blowholes combine together after each blowhole formation and wormholes cannot combine together after each wormhole formation[6]. When two small bubbles are combined, one large bubble is formed. In this case, the number of bubbles decreases. Thus, it is natural that the number of bubbles with eight times the volume is one eighth the number of the smaller bubbles. Consequently, the distribution of the blowholes is symmetrical on the logarithmic scale.

As shown in Fig.8(a), the blowhole size distributions in both environments are very close to each other. Therefore, we can conclude that the combination mechanism of blowholes is not very affected by gravity. **Figures 9 (a)** and **(b)** are the separated distributions in the upper part and in the lower part from the results in Fig. 8(a) for both environments, respectively. In the terrestrial environment, larger blowholes are segregated by the moment from the lower part to the upper part. However, blowholes smaller than a critical value are distributed similarly in both parts. Furthermore, the distribution of the smaller blowholes is very similar to that in the microgravity environment. Thus, gravity affects the movement mechanism of larger blowholes. However, gravity does not affect the movement of blowholes which are smaller than a critical value.

7. Conclusion

By performing both the gas tungsten arc (GTA) welding and the electron beam (EB) welding for aluminum alloys in both microgravity and terrestrial environments, the following results were obtained.

(1) In the microgravity environment, a flat weld bead is formed and a large amount of metal can be welded at once when helium shielding gas is used. The EB weld bead is also formed more flatly under microgravity.
(2) When electron beam welding was performed, several pores were observed in all the welds including the bead-on-plate welds. It can be judged that the bubbles are formed by the production of Al_2O gas in a high vacuum.
(3) Blowholes grow by combining with other blowholes after their formation, though wormholes do not combine with other wormholes or blowholes. Gravity does not significantly affect either the movement or the combination of bubbles smaller than a critical value. Gravity does affect the movement of bubbles larger than a critical value, though it does not affect the combination of them.

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