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WELDING LETTERS

Development of a Milli-Scale WAAM Method Using Constricted Gas Tungsten Arc

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In this study, a Gas Tungsten Arc (GTA)-based wire arc additive manufacturing method using constricted arc plasma and 0.3-mm-diameter wire was developed for milli-scale manufacturing. Then, beads were formed using conventional and constricted GTA, with continuous beads being successfully formed using both heat sources. However, there were differences in the range of conditions under which continuous beads could be formed. In order to investigate the reason for the differences, the current and heat input density distributions were measured. The results showed that under the conditions set in this study, constricted GTA was a concentrated arc heat source at the center of the arc compared to conventional GTA. These results exhibited that constricted GTA enabled the formation of continuous beads at lower arc currents and faster traveling speeds due to its higher central heat input density. Additionally, it suggested a faster wire melting rate compared to conventional GTA.
***Key Words*:** Additive manufacturing, Arc plasma, Fine wire

1. INTRODUCTION

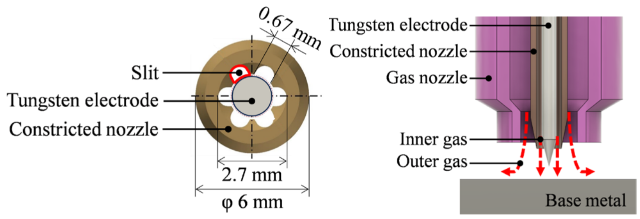
Additive Manufacturing (AM) is a method in which material layers are built based on cross-sectional data from three-dimensional models to form near-net-shaped products.

AM methods are classified according to the heat source and deposition material. Among them, the method that uses arc plasma as the heat source and wire as the deposition material is called Wire Arc Additive Manufacturing (WAAM). WAAM, which is based on overlay welding techniques, is categorized into Gas Metal Arc (GMA)- and Gas Tungsten Arc (GTA)-based methods. Compared with other AM methods, WAAM has the advantages of high deposition rates and low initial costs as it can be implemented using conventional welding equipment. However, WAAM also has some disadvantages that the arc plasma heat source has a large heat input range compared to a laser or electron beam as the heat source for AM, which leads to deformation and lower resolution of the deposited metal[1)]. Therefore, WAAM is generally considered unsuitable for manufacturing milli-scale products, for which high precision is required, compared to other AM methods that use lasers or electron beams as heat sources[2)]. Nevertheless, if WAAM can be used to manufacture milli-scale products, it is expected that WAAM, whose initial cost is relatively low, will promote the spread of AM technology and contribute to improving manufacturing productivity.

Oliveira et al.[3)] attempted to establish a GMA-based WAAM process using 0.25-mm-diameter wire to manufacture high-resolution milli-scale products. Consequently, although a single layer was successfully formed, its shape was non-uniform. Therefore, it is difficult to determine whether a stable manufacturing process has been established. They reported that the arc plasma heat source was unstable because the time that the arc plasma was maintained during manufacturing was short at 1 ms[3)].

Based on their findings, it was expected that a concentrated arc heat source, even with a low current, and a fine wire would be necessary to manufacture high-resolution milli-scale products using WAAM. In this study, constricted GTA was selected as a suitable concentrated arc heat source. Figure 1 shows schematic illustrations of the constricted GTA torch. A constricted nozzle with six slits, as shown in Fig. 1(a), is attached between the gas nozzle and tungsten electrode of a conventional GTA torch, as shown in Fig. 1(b)[4)]. This nozzle divides the shielding gas into two layers: inner and outer gas. The inner gas is accelerated as it flows through the narrow slits of the constricted nozzle, cooling the outer edge of the arc plasma and causing a thermal pinch effect. Therefore, constricted GTA is concentrated and the heat input range to the base metal is narrow[4)].

Therefore, this study aimed to develop a WAAM process that uses a fine wire and a concentrated arc heat source, even with a low current, for manufacturing high-resolution milli-scale products, and to demonstrate its usefulness.



(a) Cross-section of the constricted nozzle
(b) Internal structure of the constricted GTA torch
Fig. 1 Schematic illustrations of the constricted GTA torch

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2. EXPERIMENTAL PROCEDURE

2.1 Experimental setup for milli-scale WAAM technology

A wire feeder was developed for fine wire. Figure 2 shows a schematic illustration of the wire feeder. As can be seen in Fig. 2, the wire feeder consisted of a motor, roller, roller with bearing, and hollow tungsten for guiding the wire. The wire is fed from points A to B. Figure 3 shows a schematic illustration of the experimental setup. The setup consisted of a pulsed TIG welding machine (DAIHEN, DA300P), GTA torch, wire feeder, regulated DC power supply (TAKASAGO, GP0110-5R), and voltmeter (HIOKI, DT4282). As can be seen in Fig. 3, the wire feeder was installed in front of the GTA torch's traveling direction, and a single layer was attempted. The GTA torch was positioned vertically relative to the base metal, while the wire feeder was inclined at an angle of 30 degrees. During the deposition, the GTA torch and wire feeder were fixed, and the stage holding the base metal moved at a constant speed.

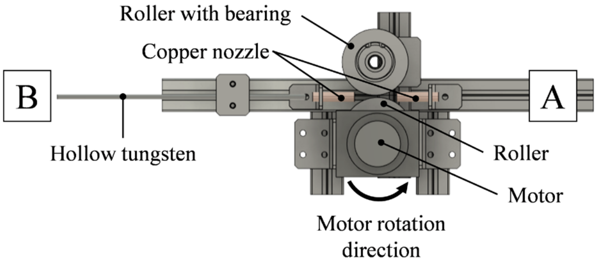


Fig. 2 Schematic illustration of the wire feeder

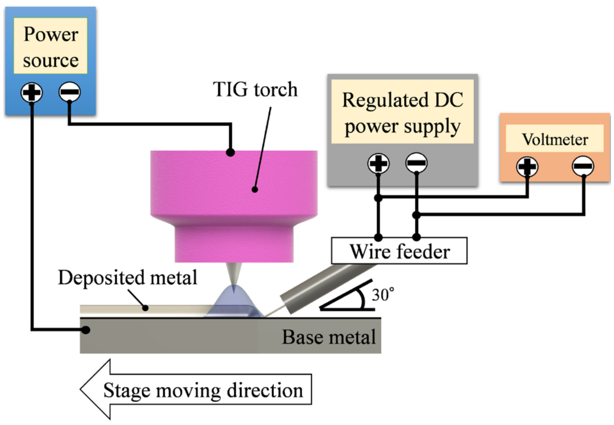


Fig. 3 Schematic illustration of the experimental setup for milli-scale WAAM

2.2 Experimental setup for measuring the differences in arc heat source characteristics

To investigate the effect of differences in heat source characteristics between conventional and constricted GTA on the deposited metal, the current and heat input density distributions were measured using the split anode method[5, 6]. Under the assumption that the GTA is axisymmetric, Abel inversion[7] was applied to the collected data, and radial distributions were obtained.

2.3 Experimental conditions

In this study, conventional and constricted GTA were used as heat sources, and a 99.5 wt.% Fe wire with a diameter of 0.3 mm was used as the deposition material and SS400 was used as the base metal. The arc current was set to 70, 75, 80, 85, and 90 A; the traveling speed was set to 1, 3, 5, 7, and 9 mm/s; the arc length was set to 2 mm; and the wire feed rate was fixed at 5 m/min. Pure argon gas was used as the shielding gas for both arc heat sources. For conventional GTA, the shielding gas flow rate was set to 17 L/min. For constricted GTA, the inner and outer gas flow rates were set to 2 and 15 L/min, respectively, indicating that the total shielding gas flow rate for both heat sources was the same. When the arc current was varied, the traveling speed was fixed at 5 mm/s; when the traveling speed was varied, the arc current was fixed at 80 A.

3. RESULTS AND DISCUSSION

3.1 Effects of different heat sources on the forming deposit metal conditions

First, the effects of the arc current, traveling speed, and differences in heat sources on the deposited metals were investigated. Table 1 lists the appearance of the deposited metal for each arc current and heat source. Table 2 presents the appearance of the deposited metal at each traveling speed and heat source. In both tables, red arrows indicate the traveling direction. As can be seen in Table 1, when the arc current was set to 75–90 A, continuous beads were successfully formed using both heat sources. However, when the arc current was set to 70 A, a discontinuous bead was formed using conventional GTA, whereas a continuous bead was formed using constricted GTA. This indicates that using constricted GTA enabled the formation of continuous beads even at a lower arc current compared to using conventional GTA. As can be seen in Table 2, when the traveling speed was set to 1–5 mm/s, continuous beads were successfully formed using both heat sources. However, when the traveling speed was set to 7 and 9 mm/s, a discontinuous bead was formed using conventional GTA, whereas a continuous bead was formed using constricted GTA. This indicates that the use of constricted GTA enabled the formation of continuous beads at a faster traveling speed than when using conventional GTA. Furthermore, it was observed that the width of deposited metal using constricted GTA was more uniform.

Figure 4 shows the measurement results for the deposited metal height for each arc current and heat source; Fig. 5 shows the results for each traveling speed and heat source. In both figures, the color bars show the average measurement values and the error bars show the maximum and minimum values. From Figs. 4 and 5, the error bars tended to be smaller when using constricted GTA than when using conventional GTA. Therefore, it was indicated that more uniform deposited metal height was obtained using constricted GTA.

These results suggest that compared with using conventional GTA, using constricted GTA enables the formation of continuous beads with uniform height and width, even at lower arc currents or faster traveling speeds.

Table 1 Deposited metal appearance for each current and heat source

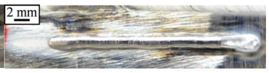
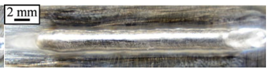
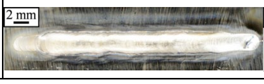
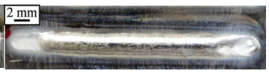
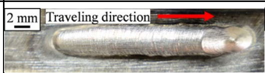
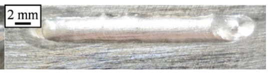
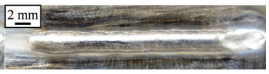
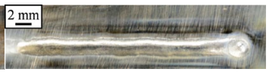
Arc current	Conventional GTA	Constricted GTA
70 A		
75 A		
80 A		
85 A		
90 A		

Table 2 Deposited metal appearance for each traveling speed and heat source

Traveling speed	Conventional GTA	Constricted GTA
1 mm/s		
3 mm/s		
5 mm/s		
7 mm/s		
9 mm/s		

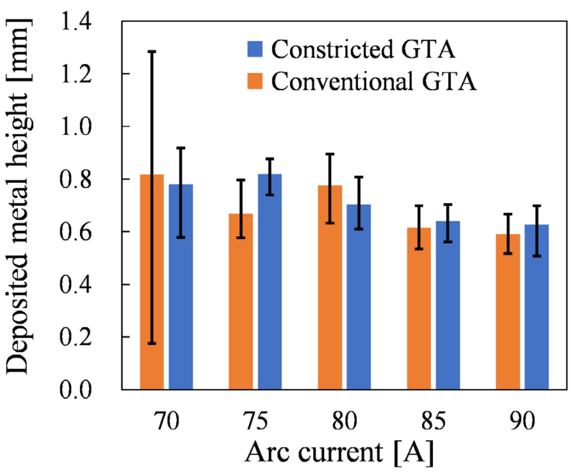


Fig. 4 Measurement results for deposited metal height for each current and heat source

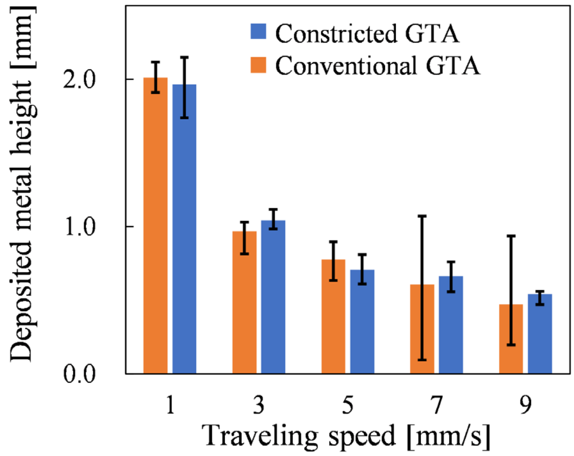


Fig. 5 Measurement results for deposited metal height for each traveling speed and heat source

3.2 Effects of heat source characteristics on the continuous formation conditions

The reason for the difference in the range of conditions under which continuous beads are formed depending on the heat source was investigated. Figure 6 shows the current density distribution on the anode surface for each heat source at an arc current of 70 A, where a discontinuous bead was formed using conventional GTA. Figure 7 shows the heat input density distribution on the anode surface under the same conditions as in Fig. 6. In both figures, the radial position at 0 mm represents the central axis of the electrode. As can be seen in Fig. 6, the current density of the constricted GTA is higher at the center of the arc and lower at the edge of the arc than that of the conventional GTA, confirming that the current path was concentrated at the center of the arc. Additionally, as can be seen in Fig. 7, the heat input density of the constricted GTA is higher at the center of the arc and lower at edge of the arc. These results mean that under the experimental conditions of this study, the energy density of the constricted GTA was concentrated at the arc center. Based on these results, it was considered that, compared to the conventional GTA, the constricted GTA, whose heat input density at the center of the arc was high, increased the wire melting rate, which was fed to the center of the arc, enabling the formation of continuous beads.

Similarly, heat input density distributions were measured using different arc currents and heat sources, and the results are shown in Fig. 8. As can be seen, it was observed that the heat input density at the center of the arc is 30 W/mm² or higher for conditions under which a continuous bead was formed. Therefore, it is suggested that at the wire feed rate of 5 m/min, set in this study, a heat input density of 30 W/mm² or higher at the center of the arc is necessary for continuous bead formation.

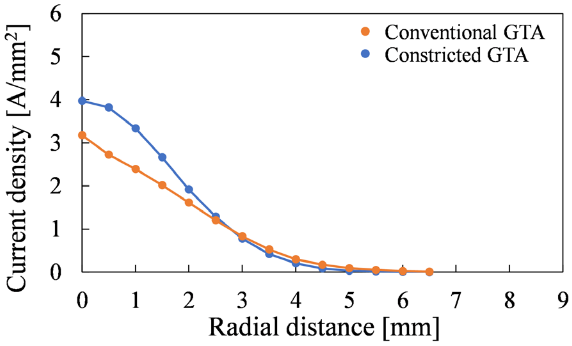


Fig. 6 Current density distribution on the anode surface at an arc current of 70 A for each heat source

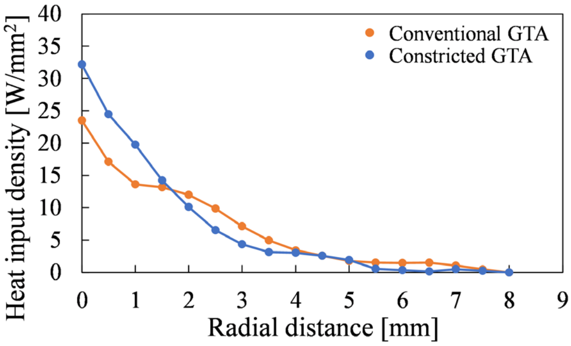


Fig. 7 Heat input density distribution on the anode surface at an arc current of 70 A for each heat source

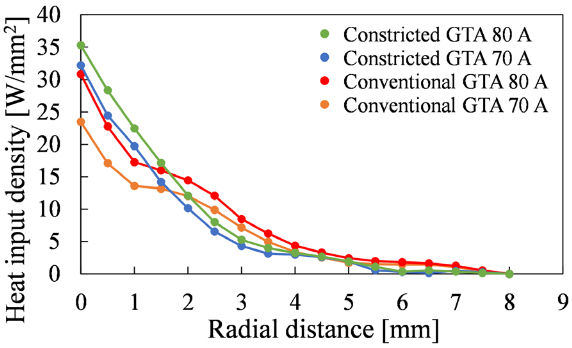


Fig. 8 Heat input density distribution on the anode surface for each arc current and heat source

4. CONCLUSIONS

In this study, a WAAM process using a fine wire and a concentrated arc heat source, even with a low current, for high-resolution milli-scale product manufacturing was developed, and its usefulness was demonstrated. Based on the results, the main conclusions of this study can be summarized as follows:

1. Continuous beads were successfully formed using both conventional and constricted GTA. Using constricted GTA enabled the formation of continuous beads with more uniformity at lower arc currents or higher traveling speeds, demonstrating the usefulness of the fine wire and concentrated arc WAAM process.
2. The measured current and heat input density distributions indicated that the energy density of constricted GTA was concentrated at the center of the arc. This suggests that when using constricted GTA, the melting rate of the wire fed to the center of the arc was faster, enabling continuous bead formation, even at lower arc currents or faster traveling speeds.
3. The heat input density measurement results suggest that at the wire feed rate of 5 m/min set in this study, a heat input density of 30 W/mm² or higher at the center of the arc is necessary for continuous bead formation.

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