Study on the weld bead formation on square-groove butt joint using plasma-MIG hybrid welding process*

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The welding with hybrid heat sources combined a plasma arc and a metal inert gas (MIG) arc was performed on the I-groove joint of 9 mm thick high-strength steel plates. The plasma torch is set up in the leading position, while the MIG torch is set up in the trailing position. As a result of observing hybrid welding with a high-speed camera, the plasma arc and the MIG arc are repelled each other. The influence of the root gap on the cross section and the bead formation was investigated. As a result, defect-free beads were formed at the root gap of 1.5 mm.

Key Words: Plasma welding, MIG welding, Hybrid welding, High strength steels, Penetration

1. Introduction

In welding of high-strength steel thick plate, the formation of a full penetration weld bead by single pass process is great effective in manufacturing cost point of view. Especially welding at the I-groove as it is cut with a laser can reduce the cost of groove processing. To solve the contradiction between quality and efficiency in the welding of high-strength steel plate, some new welding methods such as laser-arc hybrid welding 1-3), have been used. However, the equipment cost of the laser-arc hybrid welding is high. The plasma arc hybrid process is expected to be a process that can weld thick plates in one pass4), because plasma welding equipment is much cheaper than laser welding equipment and is easier to be installed. Plasma arc welding has the advantages such as high concentration heat input and deep penetration. Whereas Metal Inert Gas (MIG) welding enables to fill a gap and has wide processing parameter ranges. The plasma-MIG hybrid welding combining these two processes can improve welding efficiency and reduce weld defects. According to the different configuration of heat sources, the plasma-MIG hybrid welding can be divided into coaxial plasma-MIG hybrid welding and paraxial plasma-MIG hybrid welding. The coaxial plasma-MIG hybrid welding creates a stable metal transfer5), however it is difficult to make a keyhole. For achieving the keyhole welding, the paraxial plasma-MIG hybrid is superior to the coaxial plasma-MIG hybrid. There are many reports applied it to aluminum alloys6,7), however there are still few reports about steel8). Anh et al. performed paraxial plasma-MIG hybrid welding to SS400 using pilot gas of Ar + 10% H₂ 4). Since the mechanical property of high strength steel decreases dramatically in a hydrogen environment, this method is difficult to be performed to high-strength steel. The influence of geometric parameters, such as root gap, two torch distance was not discussed.

In this study, paraxial plasma-MIG hybrid welding was performed on the I-groove joint of 9 mm thick high-strength steel plates. The influence of the root gap on the cross section and the bead formation was investigated. To understand the arc interaction between plasma arc and MIG arc, high-speed videos were used.

2. Materials and experimental procedures

The base material used in this study is 780 MPa high-strength steel of 9 mm in plate thickness. The chemical compositions of the steel are given in Table 1. C (carbon), P (phosphorus), and S (sulfur) contents are on the lower levels than normal carbon steels. The specimen size is 300 mm in length, 50 mm in width and 9 mm in thickness. The root gap was varied from 0.5 mm to 2 mm. The welding parameters used in the present study are shown in Table 2. The used filler wire, named MG-S80, is 780 MPa class filler wire of 1.2 mm in diameter. The wire contains about 2.7%Ni for high toughness. In order to fill the gap, MIG current was optimally adjusted depending on the root gap width. As the hybrid weld heat sources, a transfer-type plasma arc welding torch, a MIG inverter pulse welding power source, a wire feeder were used. The MIG power source has constant voltage characteristics and operated in electrode positive (EP) mode. Meanwhile, the plasma power source has constant current characteristics and was used in electrode negative (EN) mode. Fig.1 shows the experimental setup of the hybrid welding system and high-speed camera arrangement. The plasma torch was set up in the leading position, while the MIG torch was set up in the trailing position.

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Table 1 Chemical compositions of 780 MPa high-tensile strength steel.

|          | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  | V   | Ti  | Cu  | Al  | Nb  | B   | N   | Fe      |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Chemical compositions (wt.%) |     |     |     |     |     |     |     |     |     |     |     |     |     |     | Bal.   |
|          | 0.14| 0.30| 1.15| 0.011| 0.001| 0.30| 0.07| 0.167| 0.011| 0.009| 0.1 | 0.037| 0.001| 0.001| 0.002Bal.|

The distance between the plasma electrode and the MIG electrode tip was 25 mm on the specimen surface. The standoff of plasma torch was set up at 3 mm.

Contact tip to work distance (CTWD) for the MIG torch was set up at 20 mm. In order to observe the welding phenomena such as plasma arc and droplet, high-speed video cameras were employed at the frame rate of 2000 frames/s. The microstructure of beads made was evaluated using an optical microscope. Microhardness profile was defined using micro Vickers hardness tester with load of 1.961 N and holding times of 5 seconds.

Table 2 Welding conditions of plasma-MIG hybrid welding.

|                             | Plasma welding | MIG welding |
|-----------------------------|----------------|-------------|
| Current                     | 280 A          | 110-230 A   |
| Arc length                  | 3 mm           | CTWD 20 mm  |
| Shielding gas               | Pure Ar/ 15 l/min | CTWD 20 mm |
| Pilot gas                   | Pure Ar/ 2.0 l/min | Shielding gas Pure Ar/ 15 l/min |
| Welding speed               | 30 cm/min      |             |

3. Results and discussion

Figure 2 shows high speed images of plasma-MIG hybrid welding plasma at root gap of 1.5 mm and MIG current of 160 A. The period of the MIG pulse current was 6.0 ms, and metal transfers with one pulse and one drop were observed periodically. At $t_1$ and $t_1 + 6$ ms, the MIG current was in pulse peak duration. On the other hand, the MIG current from $t_1 + 3.0$ ms to $t_1 + 4.5$ ms was in transition period. At $t_1$ and $t_1 + 6$ ms, the plasma arc was tilted forward in the welding direction. Further, at $t_1 + 3.0$ ms and $t_1 + 4.5$ ms, the plasma arc penetrated perpendicularly to the base material, while the MIG arc was inclined backward in the welding direction. Kanamura et al. simulated the TIG-MIG hybrid welding arc phenomena and reported that both arcs were repelled due to the electromagnetic field produced by the self-magnetic field of two arcs. From the above, it is considered that the plasma arc and the MIG arc were also repelled each other, and the plasma arc was deflected greatly when the MIG current was the peak current, and the MIG arc was deflected greatly when the MIG current was the base current. Also, at $t_1 + 1.5$ ms, the plasma arc could not be observed below the base metal, so the keyhole was closed depending on the MIG current cycle.

Figure 3 shows the top and back side bead appearances and the cross sections at root gaps of 0.5, 1.0, 1.5 and 2.0 mm. It also shows the MIG current used for each root gap. Only when the root gap was 1.5 mm, a sound bead without any defects was formed on the top and bottom surfaces and the cross section. At the root gap of 0.5 mm, the weld bead had a blowhole and the penetration was not complete. In the case of a root gap of 0.5 mm, the plasma arc didn’t seem to reach the bottom because the groove was too narrow. At root gap of 1.0 mm, the top surface had a defect at the weld toe.
At the gap width of 1.0 mm, 1.5 mm and 2.0 mm in which the back bead was formed, a poor penetration was seen at the weld toe only at 1.0 mm with the smallest welding current. This defect at the weld toe was thought to be caused by fluctuations of the MIG arc due to the interference with the plasma arc. At root gap of 2.0 mm, the bottom surface was humping and sagging. Also, the crack was caused in the bottom side of the weld bead. In other words, heat input was insufficient at bottom side for a root gap of 2.0 mm. There are two possible causes for this. The first one is that the root gap was too wide for the plasma heat source, so enough heat was not transferred to the base metal. The second one is that the plasma arc became unstable due to the large MIG current. From the above results, it was clarified that the plasma welding arc was difficult to penetrate deeply under a narrow gap condition such as a root gap of 0.5 mm, and the bottom surface was difficult to be melted sufficiently under a wide gap condition such as a root gap of 2.0 mm. Under the welding conditions in this study, 1.5 mm was the optimum condition for the root gap. Furthermore, the prevention of the interference between two arcs is predicted to stabilize not only the arcs but also the keyhole formation process. The stable plasma arc obtained by preventing the arc interference enables to continuously impose the strong arc pressure to weld pool to maintain the open keyhole. This can be realized by controlling the current waveform of both arcs optimally.

| Root gap and MIG Current | Bead appearance | Cross section |
|---------------------------|-----------------|--------------|
| 0.5 mm 110 A              | Top side        | Blow hole    |
|                           | Bottom side     |              |
| 1.0 mm 130 A              | Top side        | Void         |
|                           | Bottom side     |              |
| 1.5 mm 160 A              | Top side        |              |
|                           | Bottom side     |              |
| 2.0 mm 230 A              | Top side        | Crack        |
|                           | Bottom side     | Humping      |

Fig. 3 The bead appearance and the cross sections of plasma-MIG hybrid weld beads at root gap of 0.5, 1.0, 1.5 and 2.0 mm.
Figure 4 shows the hardness profiles on the cross section at root gap 1.5 mm. The center parts scanned in the horizontal direction. The hardness of the base metal (BZ) was about 264 HV. The highest hardness of HAZ is 311 HV, while Heat affected zone (HAZ) hardness of annealing zone is reduced to about 235 HV. On the other hand, the highest hardness of fusion zone (FZ) was 284 HV. In the research that applied the laser-arc hybrid to the high strength steel of 780 MPa class at welding speed of 1.5 m/min, the FZ was hardened up to 370-380 HV\(^9\). Plasma-MIG hybrid are less likely to be harder than laser-arc hybrid joints, so it is considered that the risk of cold cracking is low.

The effect root gap was investigated. The results are summarized as follows;

1. The plasma arc is deflected greatly when the MIG current is the peak current, and the MIG arc is deflected greatly when the MIG current is the base current.
2. The defect at the weld toe were caused by fluctuations in MIG arc plasma due to interference with the plasma arc under the condition such as MIG current of 130 A.
3. The plasma welding arc difficult to penetrate under a narrow condition such as a root gap of 0.5 mm, and the bottom surface difficult to be melted sufficiently under a wide condition such as a root gap of 2.0 mm.
4. The prevention of the interference between two arcs is predicted to stabilize not only the arcs but also the keyhole formation process.

4. Conclusions

In this study, a plasma-MIG hybrid welding was performed on the I-groove joint of 9 mm thick high-strength steel plates.

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