Effect of focal position on laser-MAG arc hybrid weld bead of thick high-strength steel plate*

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The welding with hybrid heat sources combined a high-power disk laser and a metal active gas (MAG) arc was performed on the I-groove joint of 12 mm thick high-strength steel plates. To investigate the effect of laser focal position on joint formation, the combination effect of laser power and focal position on the cross section and the backing bead shape was investigated. The results showed that a good welded joint was obtained at the minimum laser power of 8 kW when focal position is 6 mm below the surface of the base material. At the minimum laser power, it was clarified that the welding penetration depth was deeper at focal position of the below the surface than at focal position of the above the surface.

Key Words: Laser welding, MAG welding, Hybrid welding, High strength steels, Penetration, Thick plate

1. Introduction

High-strength steel plates are widely used in ships, bridge and crane to better product performance in terms of higher payload, higher crashworthiness and longer service life. There is thus much interest in methods of producing high quality welded joints between high-strength thick plates. Recently, laser arc hybrid welding that combines deep penetration of laser welding and simple installation of arc welding has been studied for practical application1). Pan et al. performed laser-MAG hybrid welding to high-strength steel with a thickness of 12 mm, and investigated the effects of welding conditions on penetration, geometry and welding defects2). One of the most important topics to be studied is indeed the stability and repeatability of whole process. Many researchers concentrated on the influence either of geometric parameters, such as the distance of the laser beam to the arc3,4), root gap2,5) and the laser beam focal position2,5,6). Many researches on defocused distance evaluate penetration depth by hybrid welding on bead on plate2,6,7). However, these studies did not consider the effects of square-groove gaps, so the effects of defocused distance on backside bead formation were not reported. The influence of the defocused distance on welding of the stainless steel with 8 mm thickness and I-groove was investigated, and it was reported that the optimum defocused distance was 4 to 8 mm on the material surface side, depending on the droplet transfer form8). But the defocused distance in the experiment was limited to the material surface side, so the discussion was not made systematically.

In this study, a high-power disk laser-MAG hybrid welding was performed on 12 mm thick high-strength steel plates. The combined influence of laser power and defocused distance on the cross section and the backing bead shape was investigated. To understand the back bead formation, the root surface was observed using a high-speed videos camera.

2. Materials and experimental procedures

The base material used in this study is 590 MPa high strength steel of 12 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 12 mm in thickness. The welding parameters used in the present study are shown in Table 2. A schematic representation of the Laser-MAG hybrid welding system and high-speed camera arrangement for the bottom observation of a molten pool is shown in Fig. 1. The laser apparatus employed is a continuous wave disk laser of 16 kW maximum power, 1030 nm wavelength, and 8 mm*m rad beam parameter product (BPP). The laser beam is transmitted through an optical fiber of 200 μm in core diameter and focused by a lens of 280 mm in focal length. Fig 2 shows beam diameter of laser at each defocused distance. The beam diameter was measured by a beam profiler. Table 3 show the power density at each defocused distance and each laser power. The arc welding machine consisting of a MIG/MAG inverter pulse welding power source and the wire feeder is used. The maximum arc current is 350 A. A mixed active shielding gas, containing 80 % argon and 20 % carbon dioxide, is supplied from the arc nozzle at a flow rate of 30 l/min. The used filler wire, named MG-50, is 550 MPa class filler wire of 1.2 mm in diameter. The distance between the laser beam central axis and the MAG electrode tip is 5 mm on the specimen surface. The length...
of a filler wire from a MAG nozzle to a workpiece is 15 mm. Defocused distance is zero when the focal point is set on the specimen surface. When the focal point is set below or above the surface, the defocused distance is defined to be negative or positive, respectively. In order to observe the bead formation at bottom side, high-speed video cameras were employed at the framing rate of 2000 frames/s. Interference filters were mounted for the observation without influence of a bright laser-induced plume.

Table 1 Chemical compositions of 590 MPa high tensile strength steel.

| Chemical compositions (wt.%) | C  | Si  | Mn  | P   | S   | Cu  | Ni  | Others | Fe  |
|-----------------------------|----|-----|-----|-----|-----|-----|-----|--------|-----|
|                             | 0.10 | 0.26 | 1.57 | 0.016 | 0.004 | 0.01 | 0.02 | 0.10 | Bal. |

Table 2 Parameters for hybrid welding

| Parameter       | Value                  |
|-----------------|------------------------|
| Laser Power     | 8-14 kW                |
| Welding Speed   | 2.0 m/min              |
| Root gap        | 0.5 mm                 |
| Welding current | 260 A                  |
| Welding voltage | 34 V                   |
| Defocused distance | -12,-9,-6,-3,0,6 mm |

Table 3 The power density at each defocused distance and each laser power.

| Defocused distance | Power density (kW/mm²) |
|--------------------|------------------------|
|                    | -12 mm | -9 mm | -6 mm | -3 mm | 0 mm | 6 mm |
| 8 kW               | 4      | 8     | 16    | 47    | 113  | 14   |
| 10 kW              | 5      | 10    | 20    | 59    | 141  | 18   |
| 12 kW              | 7      | 11    | 24    | 71    | 169  | 22   |
| 14 kW              | 8      | 13    | 28    | 83    | 197  | 25   |

3. Result and discussion

Figure 3 shows the combination effect of laser power and defocused distance on the penetration and bead formation in the butt joint of 12 mm high strength steel with a root gap of 0.5 mm. The white circle indicates joint with full penetration, a smooth joint surface preventing humping, and no defect such as undercut, underfill and crack. The black circle indicates joint with defects, humping bead or no full penetration. The figure also shows the types of welding defects at black circle. Good joints were formed at defocused distance from -9 mm to 0 mm. At the laser output was 8 kW, a good joint was obtained only with a defocused distance of -6 mm. Further, when the defocused distance is -6 mm, root cavity occurs at the laser power of 12 kW. From the above, the combination of laser power and defocused distance is found to affect the bead formation in laser-MIG hybrid welding. Furthermore, the appropriate defocused distance varies depending on the laser output.

Figure 4 shows cross sections of hybrid weld beads at various defocused distances and laser powers. At the defocused distance of 0, the laser diameter is the smallest value of 0.29 mm on the material surface. At defocused distance of -6 mm and laser power of 8 kW, the welding bead has full penetration, no underfill and no undercut. At defocused distance of -6 mm and laser power of 14 kW, root concavity was formed. This is because the heat input by the laser is large, and a large amount of molten metal is scattered as spatter at bottom. Although the welding bead had full penetration at defocused distances of -12 mm, a bead without weld defects was not obtained. At laser power of 12 kW, the welding bead has underfill at surface. This is because at the defocused distance of -12 mm, the laser diameter on the material surface was as large as 1.52 mm and the width of the melted area widened. At laser power of 8 kW, the welding bead has crack. On the other hand, at defocused distance of +6 mm and laser power of 8 kW, the depth of penetration was 9 mm, resulting in incomplete penetration and crack. At a laser power of 8 kW, the spot diameters on the material surface are the same at defocused distances of -6 mm and +6 mm.

However, there was a great difference in the penetration depth. At the defocused distance of -6 mm, the laser diameter at the
bottom surface is 0.84 mm, whereas at the defocused distance of +6, the laser diameter is 2.33 mm. From this result, it is shown that the heat input reaches deeper on the negative side of the defocused distance than on the positive side.

Figure 5 shows surface appearances of hybrid weld bead with focus distances of -9 mm, -6 mm and -3 mm on at a constant laser power of 8 kW. Good bead was formed at a defocused distance of -6 mm. On the other hand, at defocused distances of -9 mm and -3 mm, humps were produced on the bottom surfaces.

Figure 6 shows high-speed video camera observation result during hybrid welding at defocused distance of -9 mm, -6 mm and -3 mm. At the defocused distance of -6 mm, spatter always occurred due to laser penetration. On the other hand, spatter occurred intermittently at defocused distances of -9 mm and -3 mm. Sputtering from the bottom means that the keyhole is formed by the laser. In other words, a completely penetrating keyhole cannot be maintained at the defocused distances of -9 mm and -3 mm. In addition, at defocused distances of -9 mm and -3 mm, it was confirmed that the molten pool became thick and humping occurred.

Jan Frostevarg reported that route humping occurred when the keyhole was unstable and complete penetration was not maintained. The reason why humping occurred in the root area under the conditions of defocused distance of -3 mm and -9 mm is that the keyhole is unstable. It is considered that under the defocused distance of -3 mm, the heat input of laser was low at bottom side. Increasing the defocused distance to the negative side moves the heat input of the laser on bottom side. On the other hand, when the defocused distance is increased, the laser diameter on the surface is increased, and the power density is decreased. The power density of defocused distance of -3 mm, -6 mm and -9 mm are 47, 16 and 8 kW/mm² at top surface under the laser output of 8 kW. It is thought that since the power density at the surface was low and the surface did not melt sufficiently, the heat input of the laser did not reach the inside at the defocused distance of -9 mm. For the above reasons, a good root bead was obtained only when the defocused distance was -6 mm at a laser output of 8 kW.
4. Conclusions

In this study, a laser-MAG hybrid welding was performed on the I-groove joint of 12 mm thick high-strength steel plates. The effect combination laser power and defocused distance on the cross section and the backing bead shape was investigated. The results are summarized as follows;

1. The appropriate defocused distance varies depending on the laser output because the combination of laser power and defocused distance effect the bead formation in laser-MIG hybrid welding.
2. The heat input is deeper on the negative side of the defocused distance than on the positive side.
3. As a result of combining the laser power and the defocused distance, a perfect joint was obtained at the minimum laser power of 8 kW at the defocused distance of -6 mm.

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