DEVELOPMENT OF UNDERWATER WELDING WITH A HIGH POWER YAG LASER

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ABSTRACT

Underwater YAG laser welding technology has been developed by IHI. Use of optical fiber for the YAG laser welding system provides accessibility to distant or confined repair work sites. The welding system is also applicable to repair welding of reactor pressure vessels (RPV) and the internal structures of these vessels. Stable underwater welding was successfully performed using the center gas shielding method at a water pressure up to 0.4 MPa. No defects were found in welds by radiographic testing. Bead width and penetration depth became wider and shallower with increasing water pressure, respectively. The cooling rate of YAG laser welding was measured and proved to be higher than that of TIG welding.

INTRODUCTION

Recently, demand has been increasing for high quality underwater welding technology not only for repairing/modifying marine structures, etc. but also in many other fields. One application for which much is expected of this technology is repair welding of RPV (Reactor Pressure Vessel) and vessel internal structures of nuclear power plants. Much research has been conducted on the underwater welding, focused mainly on arc welding [(1)(2)]. In underwater arc welding, the arc phenomenon changes due to the increase in ambient pressure, making a stable welding difficult.

The authors, therefore, focused on another welding method that does not use the arc phenomenon or the laser welding, which is considered to be applicable in RPV. In laser welding, a CO_2 laser and YAG laser are normally used, but we have promoted the development focusing on YAG laser welding in consideration of the remote control and application to a confined place. In underwater welding, a YAG laser was used for the heat source, and the welded zone was shielded by the shielding gas. A YAG laser beam was induced through optical fiber and irradiated to the welded portion. Important features of YAG laser welding are less welding distortion and a small Heat Affected Zone (HAZ) because of the smaller heat input and high cooling rate than with other welding methods. Also, the welding head can be made smaller than that for local water shielding types, and the shielding box is not needed. This simplifies the welding system, making it applicable to a wide range of places in the RPV.

FEATURES OF UNDERWATER YAG LASER WELDING

Underwater welding using the YAG laser has the following four advantages:

(1) Since the heat input is small and the cooling rate is high, the HAZ on the materials is small.
(2) Since the welding system can be simplified and made compact, it can be applied to a wide range of portions.
(3) Since direct welding can be done without draining water from around the portion to be welded, the welding process can be shortened.
(4) Since it can be combined with surface treatment of material through laser irradiation, a total maintenance system that includes not only repair but also preventive integrity can be developed.

As an example of the application, repair of the bottom area of the RPV, shown in Figure 1, can be considered. As in this example, the underwater YAG laser welding having the above features is considered best for remote, confined, and underwater places. Figure 2 shows the general idea of the underwater welding. The laser beam and shielding gas are coaxially supplied into the welding head, and the welded portion is partially placed in a gaseous atmosphere by this shielding gas. The water shielding method is very simple, but we are able to secure sufficient shielding in this method. As well as the welded portion, the welding wire is also protected by the shielding gas to prevent its direct contact with the surrounding water.

EXPERIMENTAL EQUIPMENT

IHI developed the world's first high power YAG laser oscillator of 4 kW as shown in Figure 3, making it possible to perform underwater laser welding. Figure 4 shows the experimental equipment for underwater YAG laser welding. The laser beam from the laser oscillator is introduced to the welding head through an optical fiber of 1.0 mm in diameter and 70 m in length and is irradiated to the welded portion through the focused lens. The welding head is designed to withstand water pressure up to 1.0MPa and can be used for both welding in the atmosphere and underwater. Figure 5 shows the welding head. The pressure chamber is designed to withstand water pressure up to 0.4 MPa in consideration of the environment at the bottom of the RPV (water depth of about 30 m and pressure of 0.3 MPa).

EXPERIMENTAL RESULTS

Welding Characteristics Underwater

At first we performed bead-on-plate welding at a water depth of 10 mm without removing the water around the weld zone to determine if the YAG laser could be transmitted through water for underwater welding. The welding conditions were laser power 3.0 to 4.0 kW and the welding speed of 8.3 mm/s. Since the molten pool is immediately brought into contact with water, the oxidized bead surface with many defects such as pits, was observed, and the penetration depth was shallow. This result confirmed that it was necessary to remove the water from around the molten pool for underwater welding. Considering that the shielding gas flow rate would mostly affect the shielding ability in the water, we investigated the effect of the shielding gas flow rate on the penetration of the deposit metal. We did the bead-on-plate welding with the shielding gas flow rate in the range of 60 to 100 l/min. As the shielding gas flow rate increased, the bead width increased but the penetration became shallower. We consider this is because the shielded condition of the weld zone changes as the shielding gas flow rate changes.

To investigate welding characteristics in the water, we conducted the bead-on-plate tests in 300 mm water depth in the range of laser power 3.0 to 4.0 kW and welding speed 4.2 to 33.3 mm/s. The bead surface was not oxidized and a metallic gloss was observed. Observation of the bead cross-section showed that the welds without defects such as blowhole was obtained. Figure 6 shows the relationship between the welding speed and the penetration depth. In the underwater welding as well as welding in the atmosphere, the penetration depth increased as the welding speed decreased. The penetration depth of about 4 mm was obtained at the welding speed of 4.2 mm/s.

The bead formation in the water is affected by the shielding gas flow rate, welding speed, work distance, nozzle diameter, etc. By selecting these parameters adequately stable welding can even be done in water by the simple shielding method using only the shielding gas discharged from the nozzle.

Welding Characteristics in Pressurized Water

In underwater welding, the ambient pressure increases as the water depth increases. To investigate the effect of these pressure increases on the YAG laser welding, we conducted bead-on-plate welding tests in pressurized water up to 0.4 MPa using the pressure chamber. Using Ar for the shielding gas, we conducted the welding tests under the same welding conditions as the underwater welding of laser at a power of 3.0 to 4.0 kW and a welding speed of 8.3 mm/s. Figure 7 shows the penetration shapes and Figure 8 the relationship between ambient pressure, bead width, and penetration depth. As the pressure increases, the penetration depth decrease and bead width tends to increase a little, and at 0.4 MPa, the penetration depth of 3.5 mm is obtained.

With Filler Welding in Pressurized Water

In RPV repair welding it is necessary to remove the defective portion first, then to groove the relevant portion, and to weld within the groove. We conducted these welding tests to obtain basic welding conditions when the welding wire was added, considering the repair welding in actual plants. These welding tests were conducted with the flat position using flat plate samples in three types of environments: atmosphere, underwater, and pressurized water (the test in the atmosphere was conducted for comparison). Figures 9 and Figure 10 show the weld bead shapes of SUS304 stainless steel plate in the underwater and pressurized water welding, respectively. These figures show the bead appearances, cross-sections, and radiographic test (RT) results of a single pass bead and multi pass beads. In both cases, no defect is detected as a result of RT. No significant difference in the bead shape was observed between the atmospheric welding and underwater welding, probably because the ambient pressure was almost equal. In the welding under pressurized water, however, both penetration depth and excess metal height were small. The bead shape looked like that of clad welding. Similar tests were also conducted on Inconel 600, and a tendency similar to that of SUS304 was observed.

The underwater laser welding involves many parameters of not only optical values but also laser power, welding speed, and wire feed rate. Figure 11 shows the relationship between wire feed rate and bead appearance quantitatively. This figure shows that the bead width is almost constant regardless of the wire feed rate. It is also known that as the wire feed rate increases, the bead penetration depth decreases, and the excess metal height increases accordingly.

Cooling Rate in YAG Laser Welding

Generally, the width of HAZ decreases in the laser welding because the cooling rate is higher than with the TIG welding. Since the HAZ causes an increase in the sensitivity of Stress Corrosion Cracking (SCC), the width of HAZ is preferably smaller. Because there are almost no reports on the measurement of cooling rate related to laser welding, we measured the cooling rate in the YAG laser welding (in the atmosphere and in water) and TIG welding (in the atmosphere) to confirm it. The heat input was 9kj/cm (300A) and the welding speed was 5 mm/s in the TIG welding. The heat input was 1.2kj/cm (3.5 kW) and the welding speed was 16.6 mm/s in the YAG laser welding. The temperature measuring points, which were not HAZ but the penetration portions, were at a depth of 1mm from the specimen surface (laser irradiated side) on the weld line. The measurement was conducted by making a hole of 1mm diameter in the back of the specimen and inserting a W-Re thermocouple of 0.25 mm diameter. Figure 12 shows the measurement results. This figure shows that the YAG laser welding is higher in cooling rate, while the maximum temperature is higher than with the TIG welding. We confirmed that the underwater welding has a higher cooling rate due to the cooling effect of the surrounding water, in comparison with welding in the air.

TEST OF UNDERWATER WELDING TO CRD STUB TUBE MOCKUP TEST PIECE

The final target of this technology is repair welding in the RPV and vessel internal structures. Among these applications, the repair welding at the bottom of the RPV is considered to be the most difficult. The RPV bottom area includes many penetrations called Control Rod Drives (CRD) stub tubes, which are about 200 mm in outside diameter and made of Inconel 600 to guide the control rods. The weld zone between the CRD stub tubes and bottom head is considered to be very difficult for repair welding because of the following points.

(1) The welding robot must pass through obstacles such as the top guide and core plate located along the way.
(2) The welded portion has a complicated three-dimensional shape, so it is difficult to control the welding head.

To solve these problems, the authors are promoting development of technology aimed at repair welding of the weld zone. In repair welding of welded portions between the CRD stub tubes and the bottom head, underwater welding is desired. If this repair welding is done in the atmosphere, the shielding effect of the reactor water against radiation is lost and the repair welding work itself becomes large in scale.

We conducted the welding test with a CRD stub tube mock-up test piece in pressurized water, which simulates the center position of the CRD stub tube with a simulated defect removal groove. The welding robot was fixed at the upper part of the CRD stub tube and only the welding head was adjusted to move about 120 in the circumferential direction against the weld zone. We are now conducting bending tests, tension tests, measurements of residual stress, etc. using the flat plates of Inconel 600 to confirm the joint performance of the weld bead. Figure 13 shows the shape of the test piece simulating the CRD stub tube center portion, used in this test, and Figure 14 shows the welding test.

CONCLUSION

The underwater YAG laser welding test was successfully performed using the center gas shielding method at a water pressure up to 0.4 MPa, and the following results were obtained.

(1) In welding in pressurized water, we can use the simple method of just feeding the shielding gas coaxially with the laser beam, and the shielding gas flow rate can be the same as that in the atmosphere.
(2) The weld metal penetration depth becomes shallow and the bead width tends to increase in welding in pressurized water.
(3) With filler welding it is possible, and as good a weld bead could be obtained, in pressurized water as in the atmosphere.
(4) We welded to the CRD simulating test piece in pressurized water and obtained good results.

Future subjects are considered to be as follows.

(1) Further quality improvement of weld joint performance
(2) Development of a repair welding robot
(3) Mock-up test simulating the actual plants

REFERENCES

(1) M. Perman, A. W. Pence and R. D. Staout “Ambient Pressure Effect on Gas-Arc Welding of Mild Steel “. Welding journal Vol.48 No.6 (1969) pp.231-238.
(2) J. C. Amson and G. R. Salter ”Analysis of the Gas-Shield Consumable Metal-Arc Welding system - Effect of Ambient Gas Pressure -.” British Welding Journal Vol.12 No.11 (1963) pp.472-483.

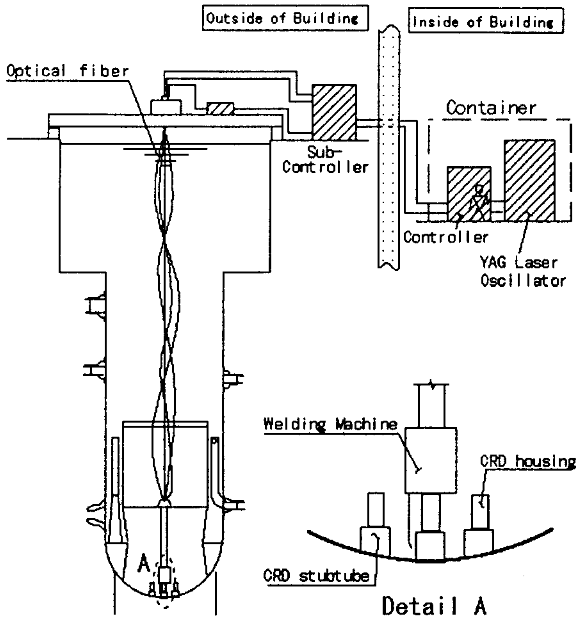

Figure 1 Application plan for RPV bottom area

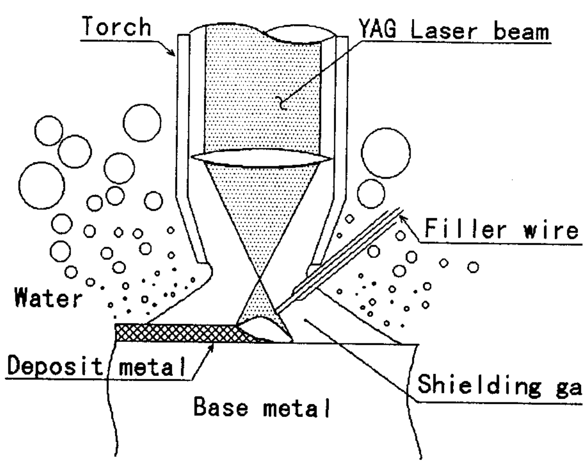

Figure 2 Schematic of underwater welding with a YAG laser

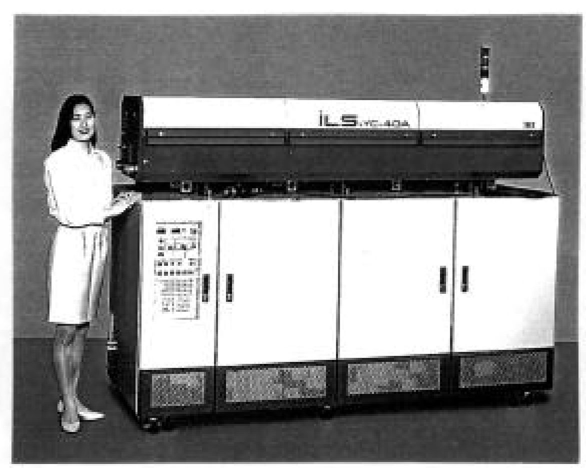

Figure 3 4kW YAG laser oscillator

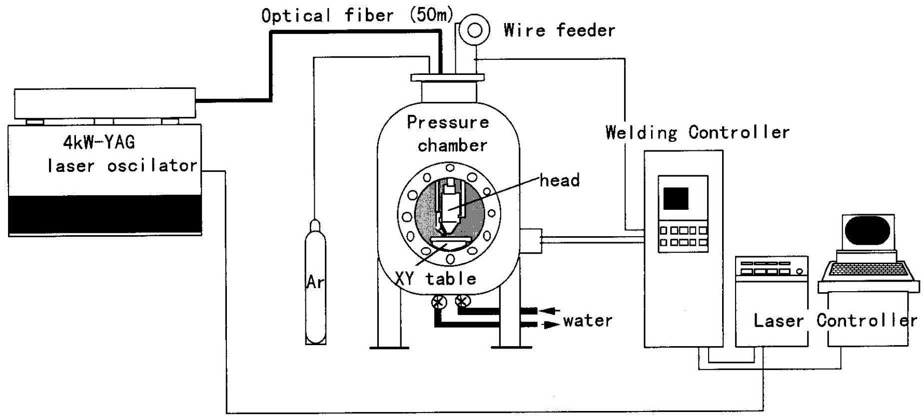

Figure 4 Schematic illustration of underwater welding equipment

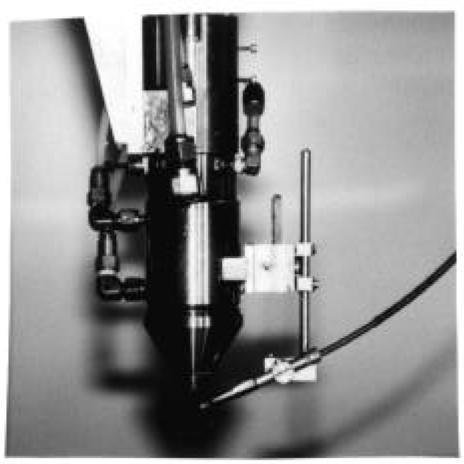

Figure 5 Underwater YAG laser welding head

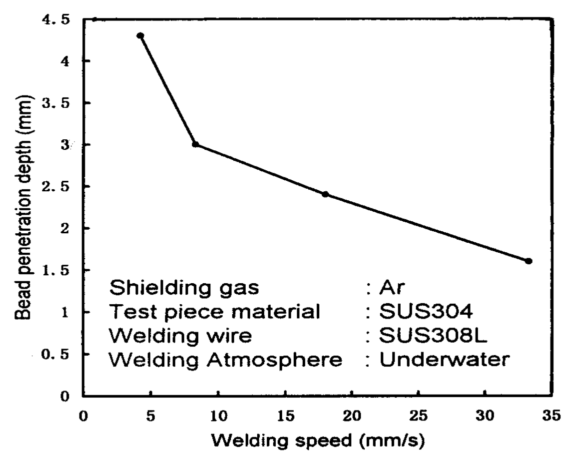

Figure 6 Relationship between welding speed and penetration depth

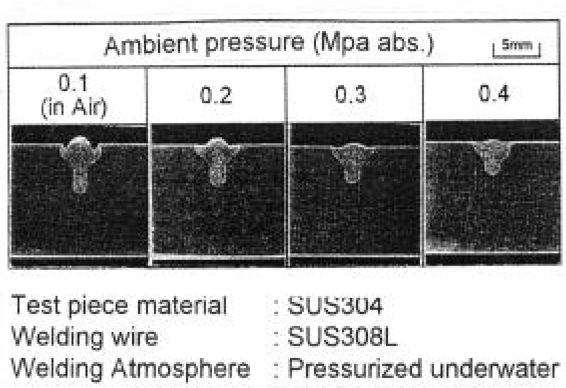

Figure 7 Cross-sections of pressurized underwater welds up to 0.4 Mpa

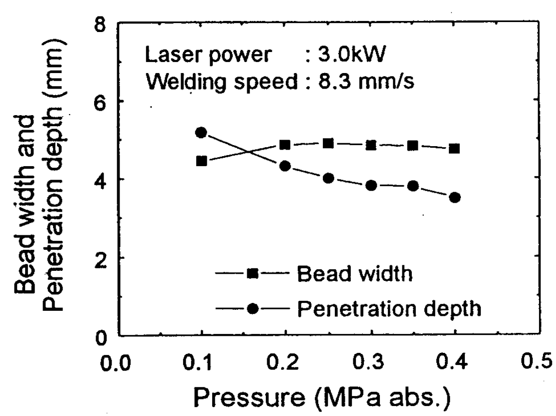

Figure 8 Relationships between ambient pressure and bead width and penetration depth

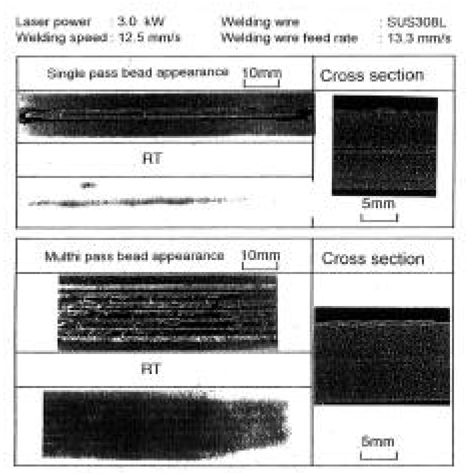

Figure 9 Underwater welding (Type 304 stainless steel)

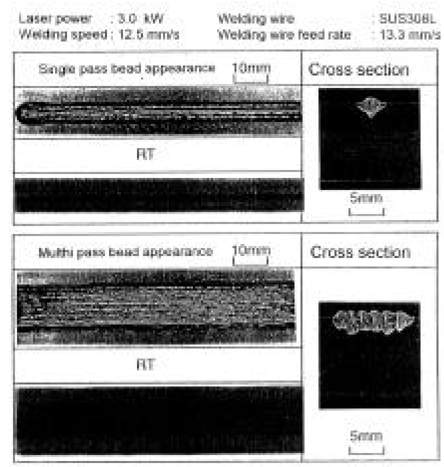

Figure 10 Pressurized underwater welding (Type 304 stainless steel)

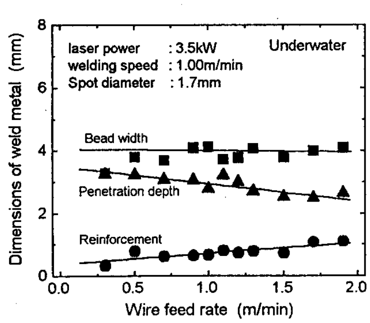

Figure 11 Relationships between wire feed rate and the dimensions of welded material

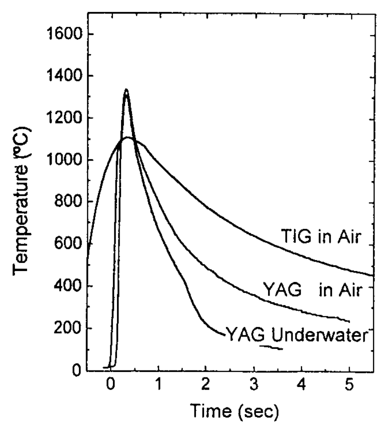

Figure 12 Cooling rate of YAG laser welding

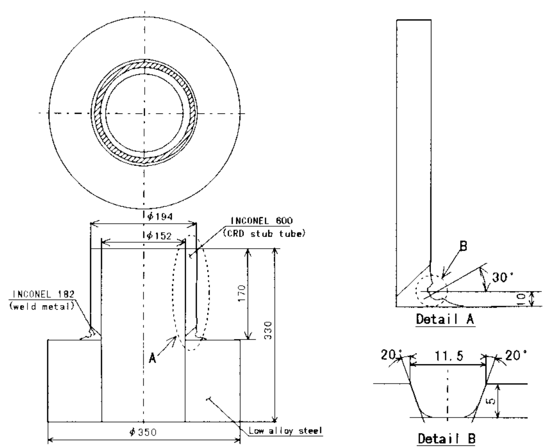

Figure 13 Structure of CRD M/U test piece(unit : mm)

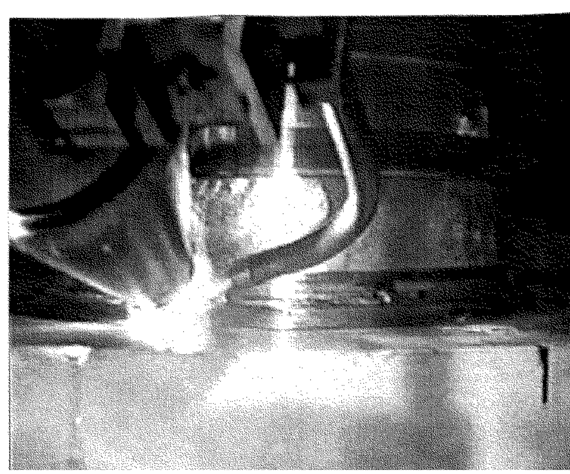

Figure 14 Underwater welding for CRD M/U test piece