

Application of High Power YAG Laser Welding to Stainless Steel Tanks

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Laser beam welding of high quality and high efficiency has been applied to precision parts such as core internal parts in nuclear power plants. In order to apply laser beam welding to thick plate and large scale products, high power laser beam need to be transferred and deep penetration welding procedure must be developed. In this paper the optical fiber transmission system for 7 kW-class high power YAG laser and pulsed laser welding techniques to obtain deep penetration were developed. Furthermore this procedure has been applied to the welding of stainless steel tanks for nuclear fuel reprocessing plants.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) has so far paid due attention to the high quality (low distortion and low heat input) and high efficiency of laser welding and has applied CO₂ laser welding to the products of the nuclear power plant with strict accuracy and quality requirements. However, because of the limited oscillator output power (5 kW) of the CO₂ laser, its application is confined to the thickness under 6 mm. Hence, the high power laser welding is an indispensable technology to our field.

In the case of high power CO₂ laser welding, on the other hand, it is difficult to secure the welding quality during the welding of thick plate because of the change in beam quality and the effect of laser induced plasma. And its application is confined to limited size and shape of products because of the beam transmission using a mirror. In the case of high power YAG laser welding, however, it is possible to transmit the laser beam through optical fiber and the procedure has less effect of laser induced plasma, so that study has been made on putting the high-power YAG laser welding into practical use.

In this paper the authors used a 7 kW-class high power YAG laser oscillator which can output the highest power in actual production line. In order to establish the welding techniques, optimization of pulse welding conditions to get deep penetration and to reduce welding defect was carried out. Further, the high power YAG laser welding was applied to the stainless steel tanks for nuclear fuel reprocessing plant after the welded joint performance was confirmed on the basis of the obtained conditions. Described below is the report on the result.

2. Test method

A 7 kW-class YAG laser oscillator capable of generating the pulse wave modulated (hereafter

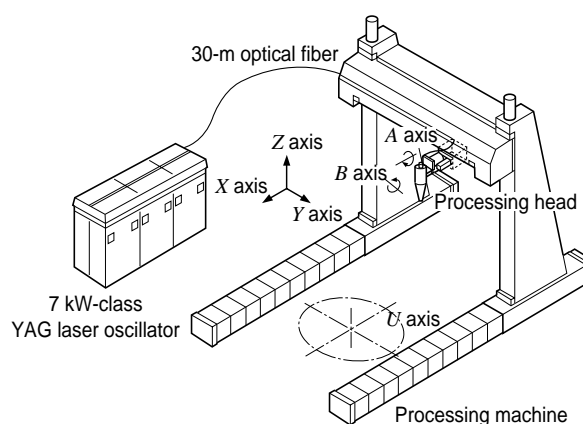


Fig. 1 Constitution of equipment

“PW”) beam with peak power 21 kW is used in the test.

The laser beam is transferred through a distance of 30 m by means of the SI-type optical fiber with core diameter 0.7 mm and NA 0.2 before being converged by an optical system with back focal length 200 mm and magnification rate 1.69. Further, the converging optical system is driven by a simultaneous 6-axis control CNC processing unit with X-axis 5 m, Y-axis 2.5 m and Z-axis 4 m applicable to large-scale products. **Fig. 1** shows the constitution of the equipment.

The welding phenomenon is observed by using a high-speed video camera (2 000 frame/s).

The material under test is the stainless steel SUS304L used in the actual product for application.

3. Study of pulse welding techniques to obtain deep penetration

The 3–5 kW-class oscillators, currently gaining popularity, are mainly the continuous wave oscillation (hereafter “CW”) type applied to the high speed welding in automobile industry, with few examples

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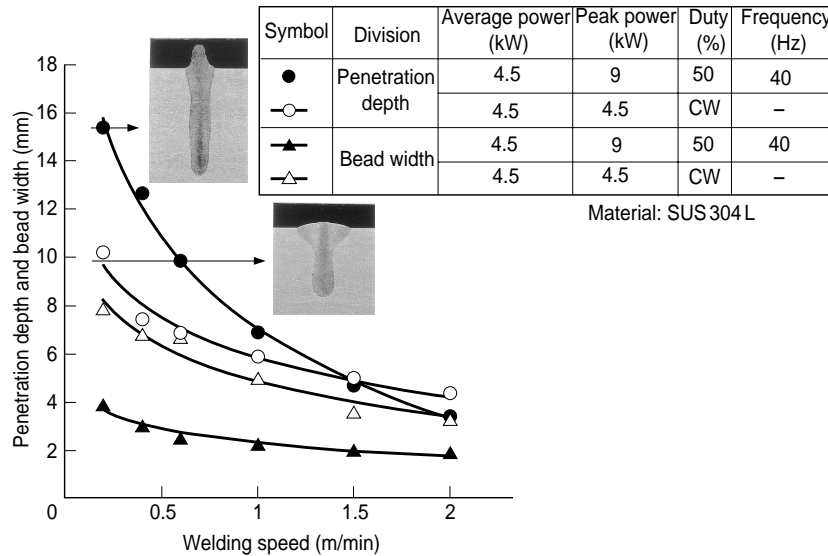


Fig. 2 Comparison of oscillation mode for penetration shape
Maximum 1.5 times deeper penetration is obtained through the pulsed oscillating wave.

of the penetration ability examined in high power PW welding. Hence, the effect of pulse frequency and pulse duty (the rate of beam ON time during 1 cycle of pulse, with the peak power calculated by dividing the average power by duty) on penetration will be investigated.

3.1 Comparison between CW and PW

Fig. 2 shows the effect of CW and PW (pulse frequency 40 Hz and pulse duty 50%) at average power 4.5 kW on penetration shape against the welding speed. At welding speed region below 1 m/min, PW provides maximum 1.5 times deeper penetration than CW, with smaller bead surface width. Study will be made on the pulse condition to obtain still deeper penetration.

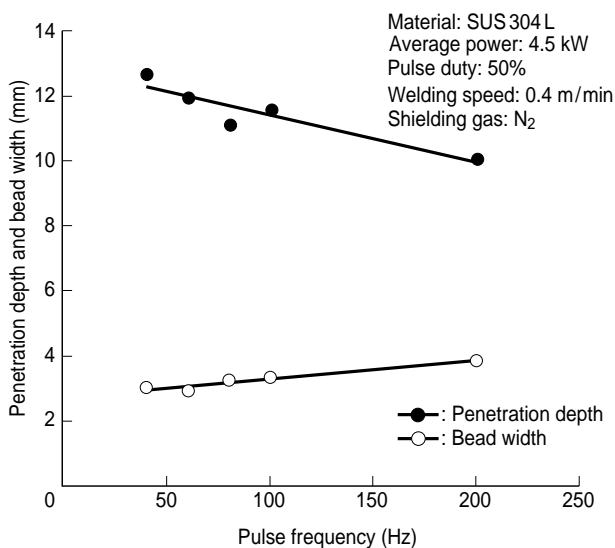


Fig. 3 Relationship between pulse frequency and penetration shape

At constant pulse duty, the penetration depth can be increased by reducing the pulse frequency in order to enlarge the pulse width of 1 pulse.

3.2 Effect of pulse frequency

Fig. 3 shows the penetration shape when the pulse frequency is changed from 40 Hz to 200 Hz at average power 4.5 kW and welding speed 0.4 m/min. It has been confirmed through the Fig. 3 that the penetration tends to increase and the bead width decrease as the pulse frequency is lowered down. This is probably attributed to the pulse ON time getting longer when the pulse frequency is lowered down, causing the 1-pulse penetration to get increased.

Since it is difficult to obtain the pulse frequency below the 40 Hz-level because of the characteristic of laser oscillator, the 40 Hz pulse frequency that provides the deepest penetration is regarded as the pulse frequency in the hereafter welding test. The

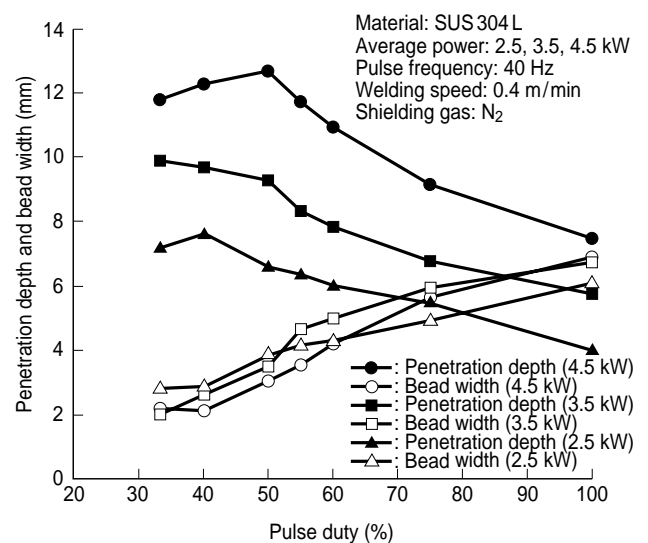


Fig. 4 Relationship between pulse duty and penetration shape

Lowering down the pulse duty (in this case the peak power gets increased) causes the penetration depth to increase, leading to the reduction of surface bead width.

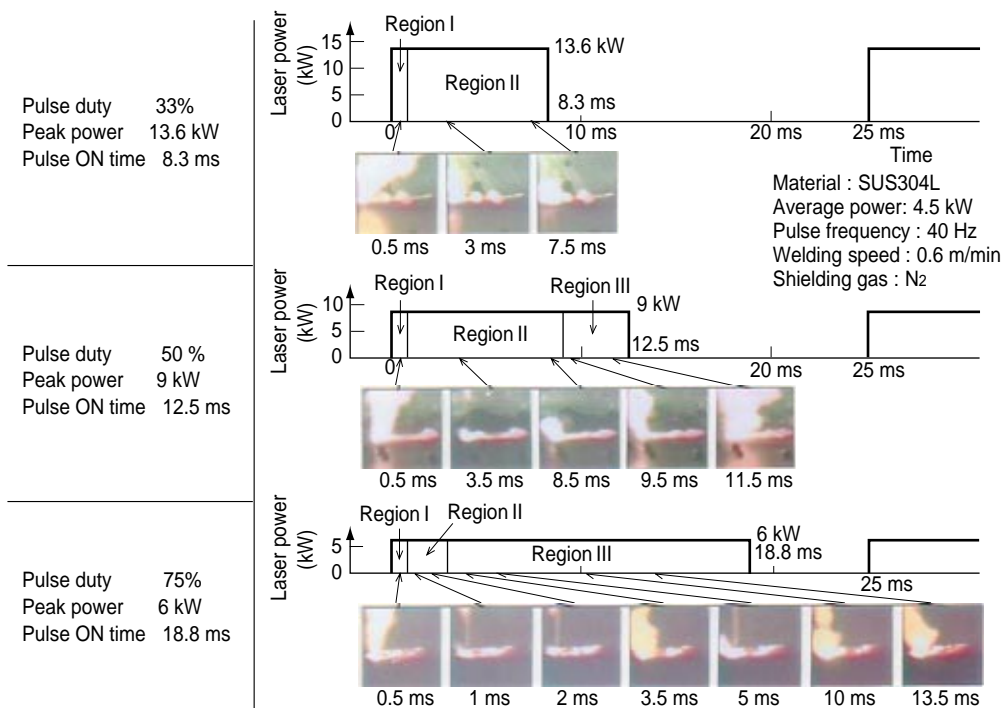


Fig. 5 Laser plume situation during one pulse irradiation

The induced plume behavior in 1 pulse can be largely divided into three types.

observation of the longitudinal section of the weld shows smooth and steady depth line of penetration at the pulse frequency 40 Hz and at the welding speed used in the test.

3.3 Effect of pulse duty

Fig. 4 shows the effect of pulse duty on penetration shape at average power 2.5, 3.5 and 4.5 kW. Since the penetration depth gets increased and the surface bead width is narrowed as the pulse duty becomes smaller (i.e. peak power is increased), it is indicated that a deep-penetration welding close to a welding by ideal linear heat source can be obtained by increasing the peak power through pulse irradiation.

However, at duty less than 50% each penetration depth tends to show saturation, and the penetration was getting reduced particularly at average power 4.5 kW.

Fig. 5 shows the generated laser plume at the time of welding for each duty, observed through high speed video, to investigate the cause of the aforesaid phenomenon. The figure shows laser oscillation waveforms and the plume behavior for respective times, with 3 types of plume behavior observed during the time period of 1 pulse. Supposing the regions in the order of elapsed time to be I, II and III, they can be classified as follows.

Region I: The time region where the leading portion of pulse oscillation waveform is seen and where the laser plume generation is remarkable

Region II: The time region where the laser plume generation is hardly seen.

Region III: The time region where the plume generates again, with fluctuation

In region I the rapid increase in penetration with the large laser plume generation, while in region II, the penetration does increase but not as much as in region I.

In region III the keyhole becomes unsteady and the beam is irradiated onto the molten metal flowing into the keyhole, which is considered to cause a large plume to generate again.

It can, therefore, be deduced from the above that at pulse duty 33%, the penetration gets reduced because the keyhole depth is not saturated due to the short pulse ON time. On the other hand, when the pulse duty is increased, the peak power gets decreased and the region III gets expanded. This suggests that although the average power is the same, the laser beam energy fails to contribute sufficiently to increasing the penetration depth.

The aforesaid results indicate that there exists a pulse duty capable of deep penetration at various welding speed and welding power levels.

In our tests hereafter we adopted the pulse duty that provided maximum penetration for each welding power and welding speed zones used in the test at pulse frequency 40 Hz.

4. Study on welding conditions

The welding test was carried out in flat position with the focal point of processing head adjusted to the surface of the base metal so far. However, in application to actual products, the welding with

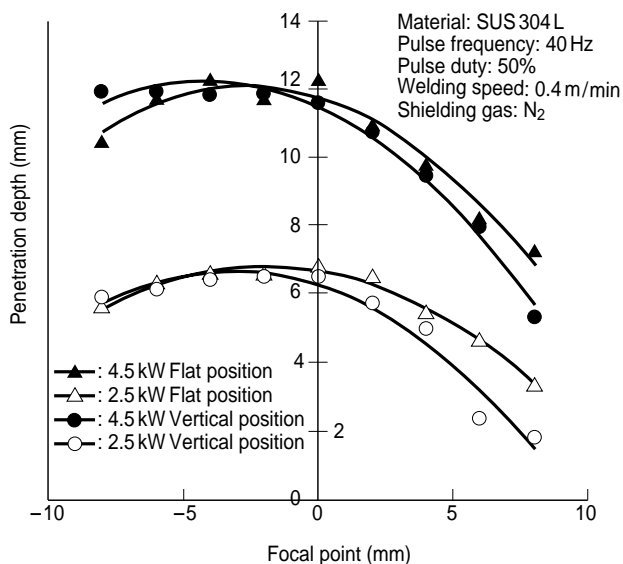


Fig. 6 Relationship between focal point and penetration at flat and vertical welding position

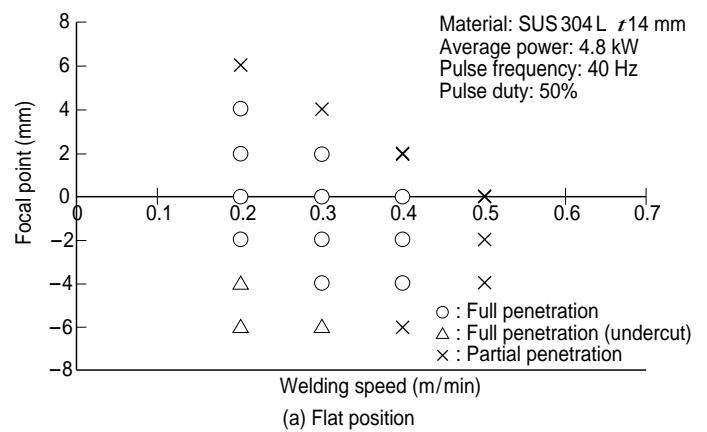
The deep penetration can be maintained within the range of 0 to -4 mm from the focal point at flat and vertical welding positions.

another position is also required. Further, since the distance between optical system and welded object, i.e., the tolerance of focal point position becomes an important factor in application, it is necessary to investigate the effect of these parameters. **Fig. 6** shows the results of welding carried out in flat position and vertical position, with the welding conditions being: average power 2.5 and 4.5 kW, and welding speed 0.4 m/min. The results indicate that there exists a region where the deep penetration can be obtained over a wide range of focal point position from the surface of base metal: 0 to -4 mm (with the focal point located inside the base metal), irrespective of the welding position.

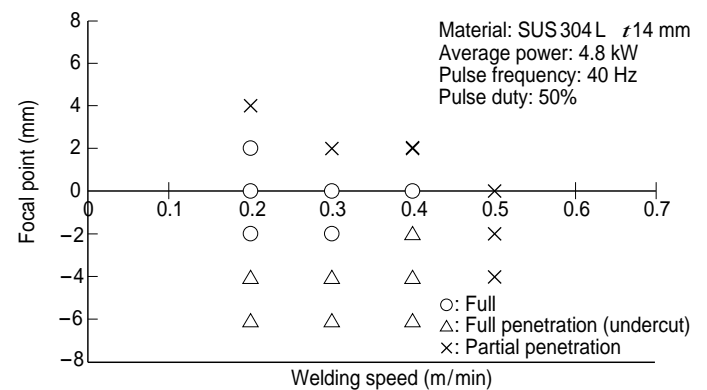
Further, the full penetration welding is required in the case of the stainless steel tank to which the YAG laser welding is to be applied. Hence, the appropriate conditions range of full-penetration welding for flat position and vertical position of SUS304L product with thickness 14 mm were investigated. The result taking into consideration the penetration bead and surface bead shapes is given in **Fig. 7**. The appropriate condition range for vertical position welding was slightly narrow because of the defective appearance of the bead due to the effect of gravity, but welded joint with good penetration bead shapes were obtained in both welding positions.

5. Performance of welded joint

An investigation of laser welded joint property was carried out on the butt welding of SUS304L ($t = 14$ mm) using the welding conditions described so far. Moreover, the tests were conducted in compliance with the welding procedure qualification test for the



(a) Flat position



(b) Vertical position

Fig. 7 Proper full-penetration-welding conditions

The appropriate condition region regarding the welding speed and focal point position for 1-pulse full penetration welding of SUS304 product ($t = 14$ mm) are shown.

nuclear fuel reprocessing plant.

(1) Nondestructive inspection

Both the liquid penetrant test and radiographic examination showed no defect and the result was satisfactorily.

(2) Microscopic and macroscopic test

No abnormal structure or defect was found on the weld, and the weld metal was found to have wholesome structure of austenite + ferrite. The hardness of both the weld metal and HAZ was found to be within the range of HV 170–200, equivalent to the hardness of the base metal, through Vickers hardness test and no hardened or softened area was observed.

(3) Tensile and bend test

The tensile strength was 581 MPa or above, equivalent to or higher than that of the base metal (575 MPa). Further, the face-bend and root-bend test (with bending radius twice as large as the thickness) showed no crack, ensuring sufficient ductility.

(4) Corrosion test

The corrosion test in 65% nitric acid showed the corrosion rate of 0.11 g/(m²·h), considerably lower than the standard value 0.36 g/(m²·h) of the

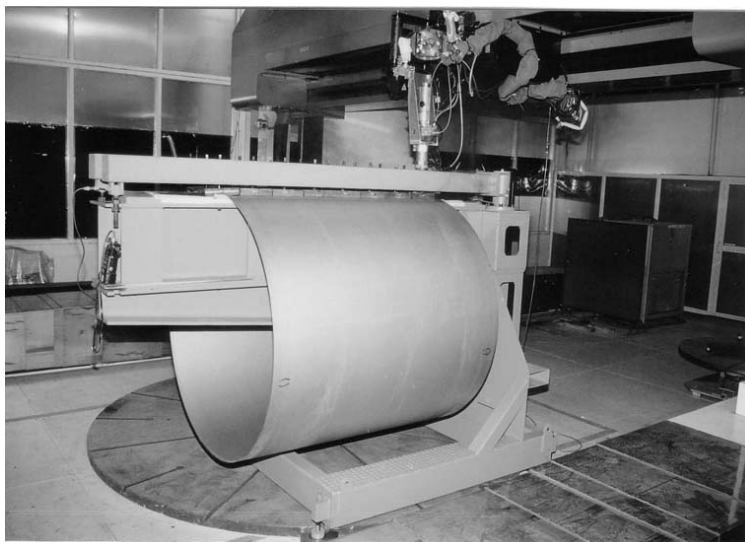


Fig. 8 Over view of YAG laser application for stainless steel tank
The application of YAG laser welding to stainless steel tank (SUS304L, ϕ 1.4 m \times H 1.8 m \times t 6 mm) for nuclear fuel reprocessing plant is shown.

stainless weld material Y308L.

Thus, all of the joint performance tests carried out above showed satisfactory results.

6. Application to actual products

The stainless steel tanks produced by MHI are large with the thickness 3–16 mm, height 0.5–4 m and diameter 0.3–6 m, and require various welding positions, so that transmission through optical fiber is indispensable. Hence, YAG laser welding was applied to such products for longitudinal and circumferential welding.

These welded joints are required to have excellent corrosion resistance and less weld deformation. The deep penetration welding obtained above sufficiently meets these requirements.

Fig. 8 shows the application of YAG laser welding to the stainless steel tank (ϕ 1.4 m \times H 1.8 m \times t 6 mm) for nuclear fuel reprocessing plant. The figure shows the material which is made by roll bending of flat plate and with the square groove, being fixed to the jig for longitudinal welding.

The liquid penetrant test and radiographic examination conducted after welding showed satisfactory results.

7. Conclusion

In this research, PW laser welding techniques were established for deep penetration welding procedure with a view to apply the high power YAG laser

transmitted through optical fiber to the stainless steel tank. The obtained results are summed up below.

- (1) The enhanced peak through the PW laser beam enabled deep-penetration with narrow bead width that could not be obtained by CW.
- (2) Out of the various pulse-welding conditions, pulse frequency and pulse duty were optimized on realize high quality deep penetration welding. The weld bead thus obtained was found little affected by the welding position and was confirmed to be applicable to large-scale products.
- (3) The PW laser welding enabled full penetration of 14 mm thick stainless steel (SUS304L) plate, ensuring good penetration bead. The welded joint was confirmed to have proper mechanical property and corrosion resistance.
- (4) The YAG laser welding was applied to the stainless steel tank for nuclear fuel reprocessing plant.

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