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High-power COIL and YAG laser welding

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ABSTRACT

We have constructed a laser welding system, which enabled high-power laser welding by combining three laser beams of 1 μm wavelength. Its wavelength enables optical silica fibers transmission and the flexible system. The heart of this system consists of a 4 kW and a 6 kW Nd:YAG lasers and a 10 kW Chemical Oxygen-Iodine Laser (COIL). The average power of the combined beam is up to over 20 kW. The effects of various welding parameters were investigated, such as the laser power, pulse modulation, and so on. The 10 kW COIL has a very good beam quality which is 64 mm·mrad. The beam spot diameter is 0.48 mm at the focal point. On the contrary the beam quality of Nd:YAG laser is worse, but it has the function of pulse modulation which the COIL does not have. As a result of the welding test with the 6 kW Nd:YAG laser, it was clarified that the pulse wave (PW) has good efficiency of deeper penetration at low welding speed. When the combined beam with CW COIL and PW Nd:YAG laser was used, 20 mm penetration on the stainless steel could be achieved at a welding speed of 1 m/min.

Keywords: Laser welding, thick plate welding, COIL, YAG, combined laser beam

1. INTRODUCTION

Laser welding has come into general use in various manufacturing processes because laser welding has many beneficial features such as deep penetration, low distortion and low thermal damage in material processing due to the small beam spot with high-power density^{1,2}. In addition, the laser, whose wavelength is located in 1 μm region, enables flexible optical silica fiber transmission of the output power. This attribute brings substantial production advantages over the other industrial lasers, especially CO₂ laser. In particular, this flexibility weighs with the heavy industry in which the products are made of thick and large metal parts. The technological innovations of the lamp-pumped Nd:YAG laser had raised the possibility several years ago, but as it was difficult because of the expensive running cost and unreliability. Therefore, the Japanese national R&D project "Advanced Photon Processing and Measurement Technologies" was started in 1997. In this project, the technologies of laser diode (LD) pumped 10 kW Nd:YAG laser and also the advanced processing which will use it are being developed. We secured a contract for the development of the advanced laser processing, namely, "Macroscopic processing technology", and had started the development of highly reliable laser welding technology. The goal of this contract is to establish the technology for laser welding of 30 mm thick steel plates and 20 mm thick aluminum alloy plates at a welding speed of higher than 1 m/min, providing high aspect ratio and equivalent or better strength than the base material. In order to realize it, we developed the laser welding system composed of a beam combining system, in-process monitoring sensors, Nd:YAG lasers and a COIL and many beneficial findings were obtained^{3,4,5}. In this paper, we report the high-power laser welding results with this system.

2. EXPERIMENTAL APPARATUS

The schematic diagram of our laser welding system is shown in Fig. 1. The heart of this system consists of a 4 kW and a 6 kW Nd:YAG lasers and a 10 kW class supersonic COIL. This system is equipped with in-process monitoring sensors, photo diodes and CCD cameras. It makes defect free welding by controlling welding parameters based on monitoring information from the sensors. This series of experiments were conducted by using the 6 kW Nd:YAG laser and the 10 kW COIL mostly. The photographs and specifications of both lasers are shown in Fig. 2. The maximum

output power of COIL is 12 kW. On the other hand, the Nd:YAG laser has a function of pulse modulation which the COIL dose not have. The peak power is 12 kW at a pulse duty of 50 % and the pulse frequency is CW or 40~500 Hz.

Figure 3 shows the welding apparatus of the flat position welding. The COIL beam was delivered by a bending mirror and focused by using a 200 mm focal length lens. The shielding gas, N₂, Ar or He gas, was flowed through a coaxial nozzle whose diameter was 8 mm. A standoff height of the nozzle was set up in 8 mm. When the laser output power were 7.5 kW and 11 kW, the measured beam diameters at the focal point were 0.3 mm and 0.36 mm, respectively.

Figure 4 shows the welding apparatus of the horizontal position welding. The COIL beam and the Nd:YAG laser beam were delivered by bending mirrors into a beam combining system. The beam combining system contained two focal lenses, whose focal lengths were 300 mm for each beam, and one dichroic mirror. The system was assembled on an optical table; this setup gives an easiness to maintain the optical parts. In the beam combining system, laser beams were focused and

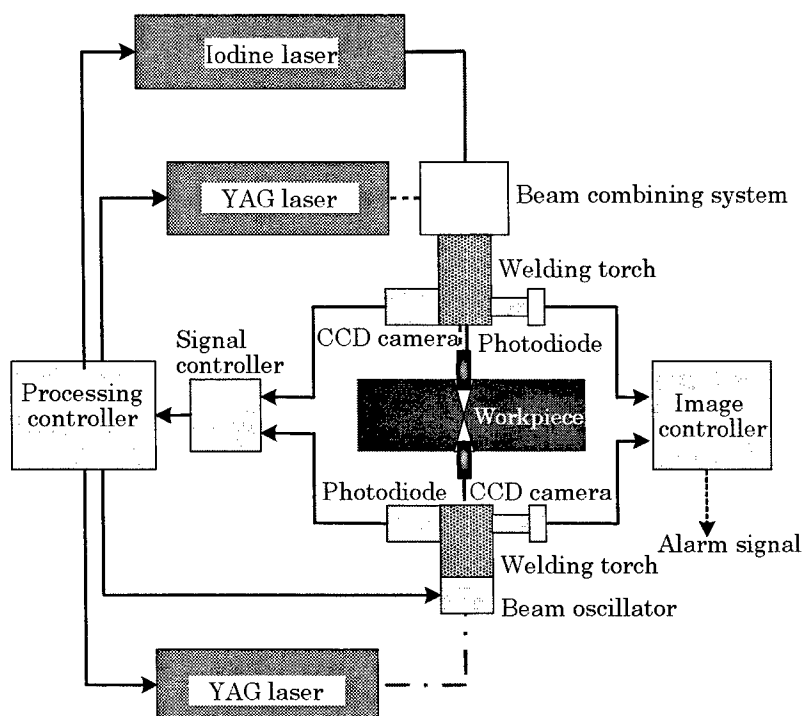


Fig. 1: Schematic diagram of the developed laser welding system

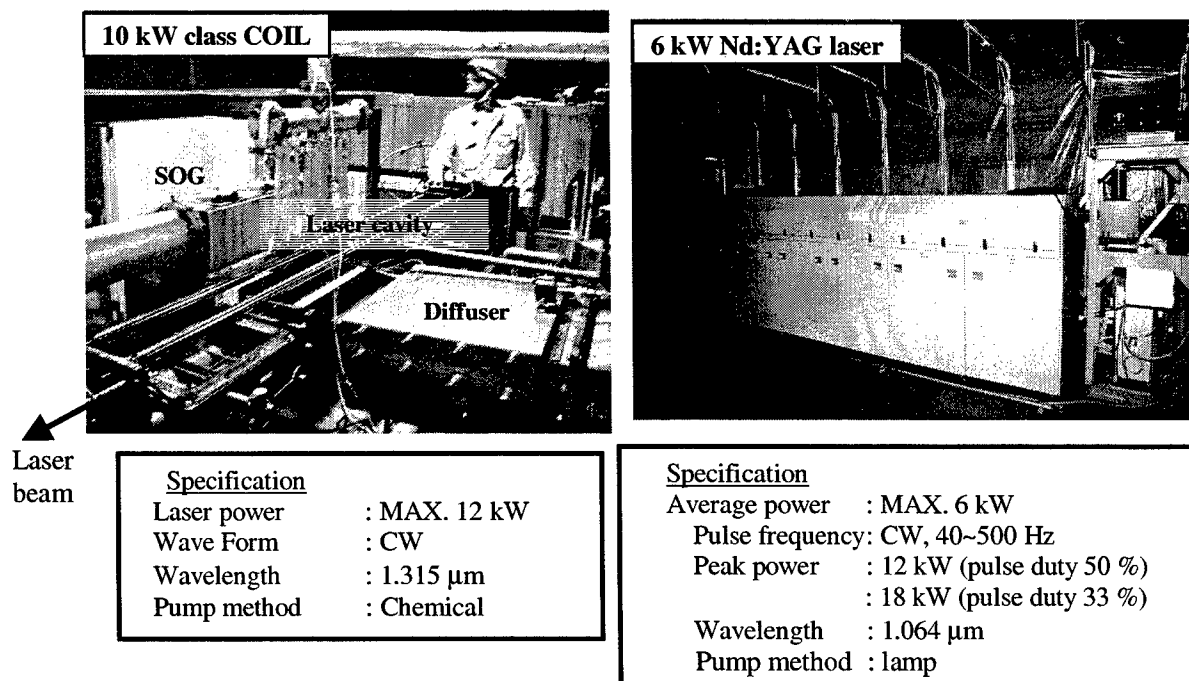


Fig. 2: Photographs and specifications of the 6 kW Nd:YAG laser and the 10 kW class COIL

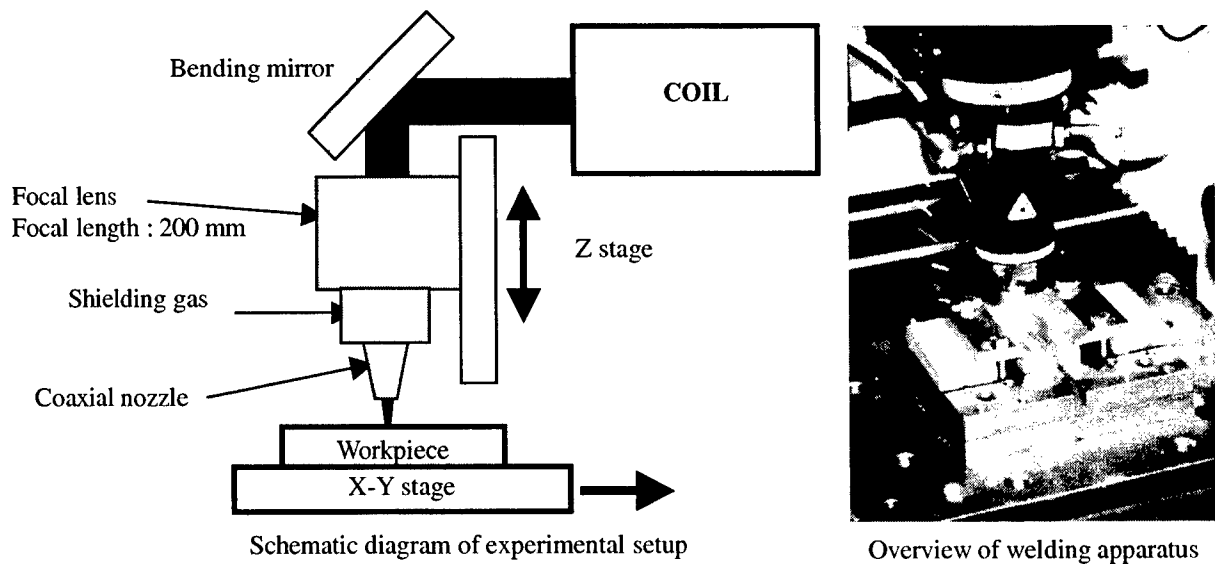


Fig. 3: Welding apparatus of the flat position welding

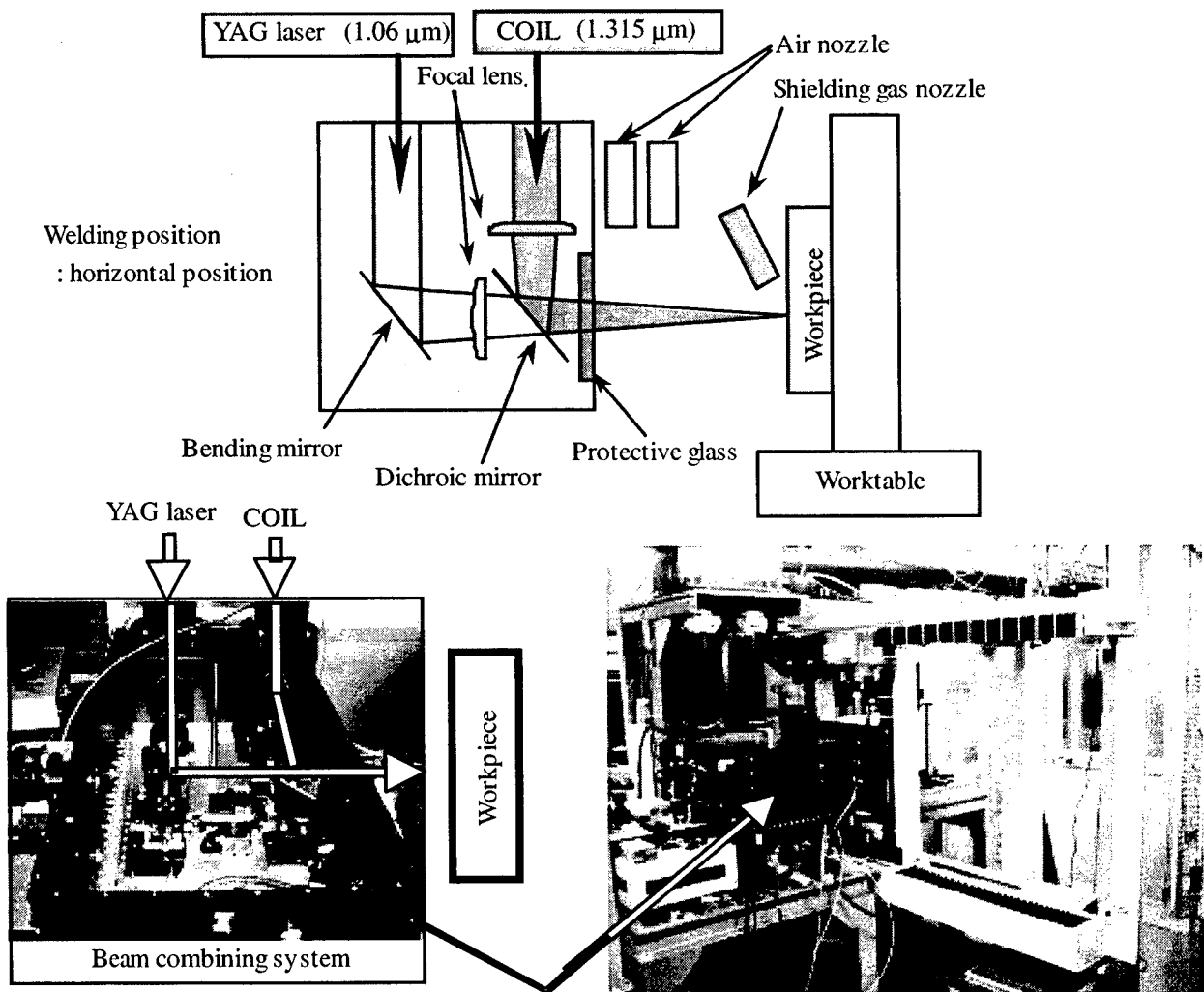


Fig. 4: Welding apparatus of the horizontal position welding

then combined to the same optical axis. The combined laser beam was irradiated to a workpiece horizontally. The shielding gas, N_2 or Ar gas, was flowed through a side nozzle whose diameter was 10 mm. A standoff height and an angle of the nozzle were set up in 10 mm and 45 degrees, respectively. Two air nozzles were set before the protective glass in order to remove spatter. The beam profiles near the focal point were measured by PROMETEC laser scope UFF100. Figure 5 shows the beam profiles of COIL and Nd:YAG laser. The measured diameters of each beam at the focal point were 0.48 and 0.88 mm respectively, at the COIL power of 12 kW and the Nd:YAG laser power of 6 kW. The COIL beam had smaller spot size than the Nd:YAG laser beam because the beam quality of COIL was very good.

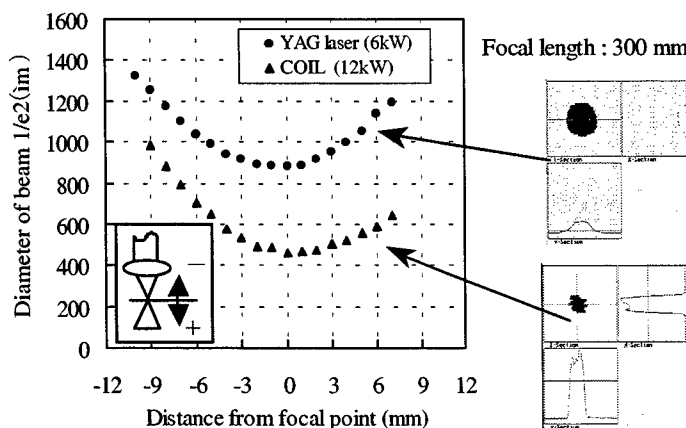


Fig. 5: Beam profiles of COIL and Nd:YAG laser

3. RESULTS AND DISCUSSION

3.1 WELDING CHARACTERISTICS WITH HIGH-POWER COIL

To understand the basic welding performance of the 10 kW class COIL, bead-on plate welding tests were carried out at laser power of 8.5 kW and 11 kW in flat position. The welding speed was varied from 0.5 to 1.5 m/min. A focal lens whose focal length was 200 mm was used and the beam focal point was set at the workpiece surface. N_2 gas was used as the shielding gas and the flow rate of it was set at 20 liter/min. Figure 6 shows cross sections of the welded bead at a constant laser power of 11 kW. Figure 7 shows the relationship between welding speed and penetration depth. Full penetration welding with the high aspect ratio in type 304 stainless steel of plate thickness 15 mm was achieved at a laser power of 11 kW and a welding speed of 0.5 m/min.

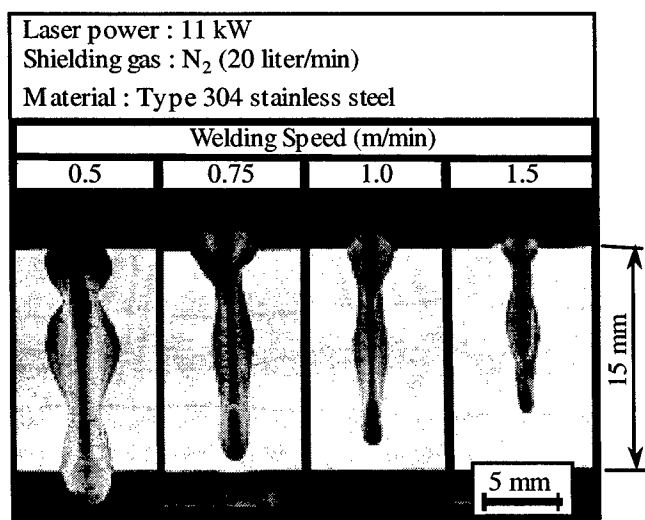


Fig. 6: Cross sections of laser welded beads

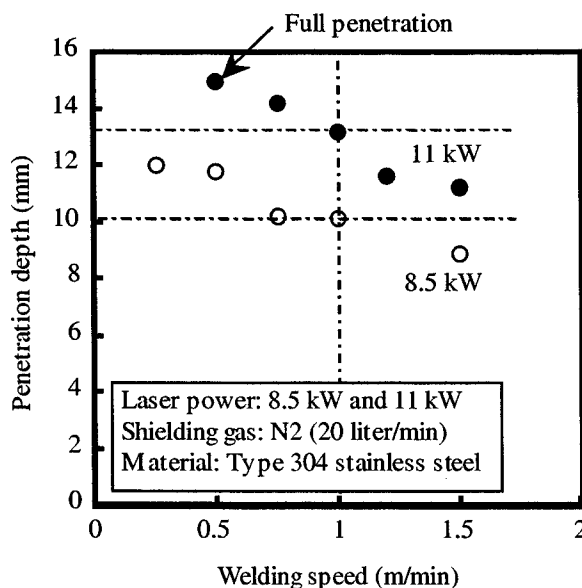


Fig. 7: Penetration depth as a function of the laser power

To confirm the effect of defocus distance of COIL, welding tests were carried out with a constant laser power of 10.8 kW and a constant welding speed of 1 m/min. As a result, the deepest penetration was obtained at a defocus distance of -3 mm as shown in Fig. 8.

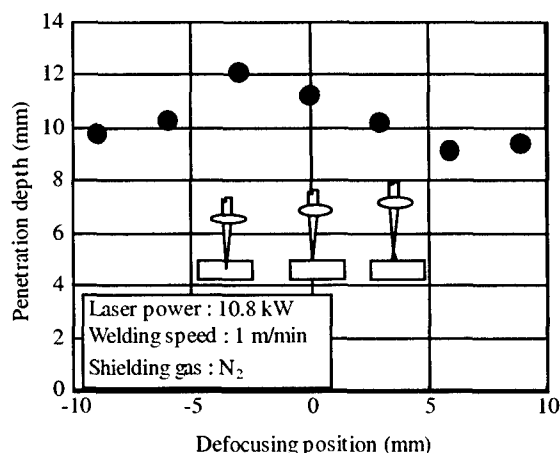


Fig. 8: Penetration depth as a function of the defocusing position

3.2 WELDING CHARACTERISTICS WITH PULSE WAVE OF YAG LASER

Bead-on-plate welding tests were carried out on stainless steel plates with thickness of 15 mm to examine the welding characteristics of the 6 kW Nd:YAG laser. The pulse duty was varied from 33 to 100 % at a constant average power of 6 kW. In these tests, the welding speed and the pulse frequency were kept to 1 m/min and 40 Hz respectively. Figure 9 shows the relationship between the pulse duty and the penetration depth. The deepest penetration was obtained at a pulse duty of 50 %. As the pulse duty increased, the bead shape became shallower and wider, and the bead appearance became better. In the range of pulse duty lower than 40 %, many spatters were generated and the penetration depth became shallower. This is attributable to the insufficient optimization of welding parameters for welding speed and pulse frequency.

The pulse frequency was varied from continuous wave to 500 Hz at a constant average power of 6 kW. This series of tests was conducted with a constant pulse duty of 50 % and a welding speed of

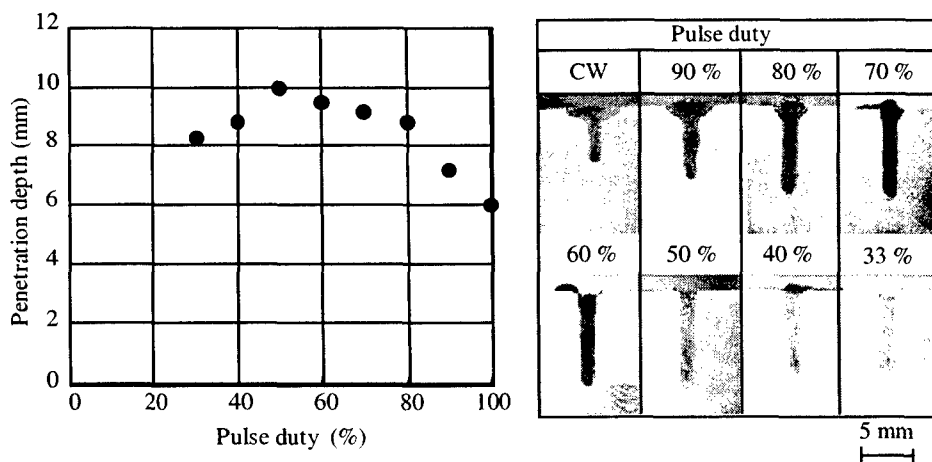


Fig. 9: Relationship between pulse duty and penetration depth

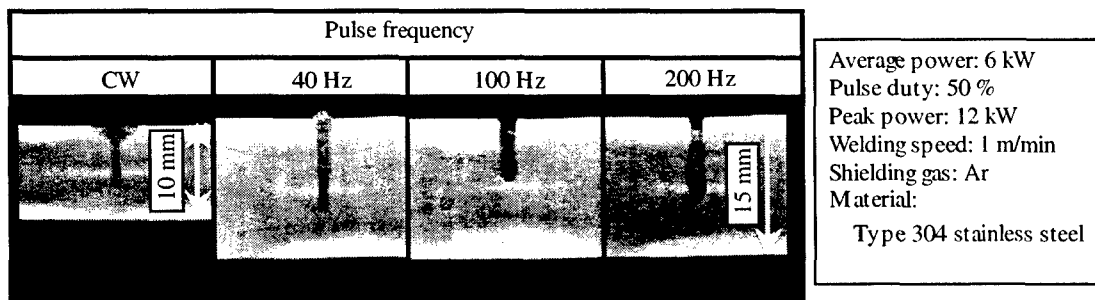


Fig. 10: Cross section of welded bead as a function of pulse duty

1 m/min. Figure 10 shows the cross section of welded bead. The bead shapes of pulse wave conditions were deeper and narrower than of a continuous wave condition. The spatters of molten metal increased as the pulse frequency increased. In the range of higher pulse frequency, underfills appeared in the weld bead surface and penetration depth fluctuated on one bead. As a result, the best frequency condition was 40 Hz.

The defocusing distance was varied from -15 to +10 mm at a constant average power of 6 kW. The series of tests was conducted with a constant pulse frequency of 40 Hz and a welding speed of 1 m/min; waveform conditions were a pulse duty of 50 % and continuous. Figure 11 shows the relationships between defocusing distance and penetration depth. The deepest penetration was obtained at defocusing distance -6 mm in both cases.

The welding speed was varied from 0.2 to 3 m/min under the best welding condition: the average power of 6 kW, the pulse duty of 50 %, the pulse frequency of 40 Hz, the welding speed of 1 m/min and the defocus distance of -6 mm. To compare the welding characteristics with those of continuous wave, a series of welding tests was also carried out with continuous wave. Figure 12 shows the relationship between welding speed and penetration depth. As welding speed became lower, the penetration depth with pulse wave became deeper than that with continuous wave. The values of penetration depth with pulse wave were 1.5 and 2 times as deep as those of continuous wave at welding speed 1 and 0.2 m/min, respectively. From this result, the deeper penetration with pulse wave at low welding speed can be explained by the high peak power and the high cooling effect of the pulse wave.

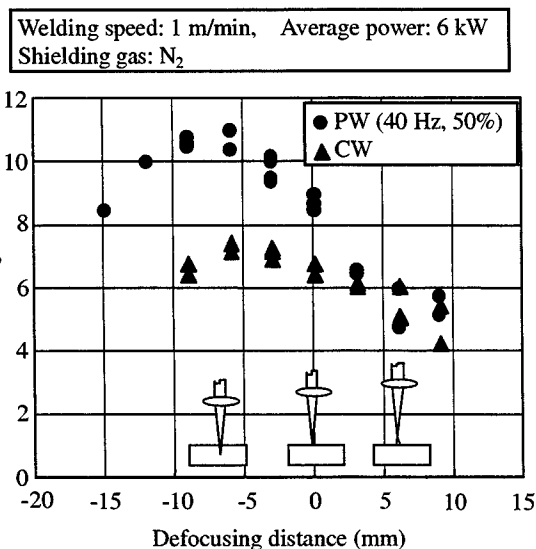


Fig. 11: Penetration depth as a function of the defocusing position

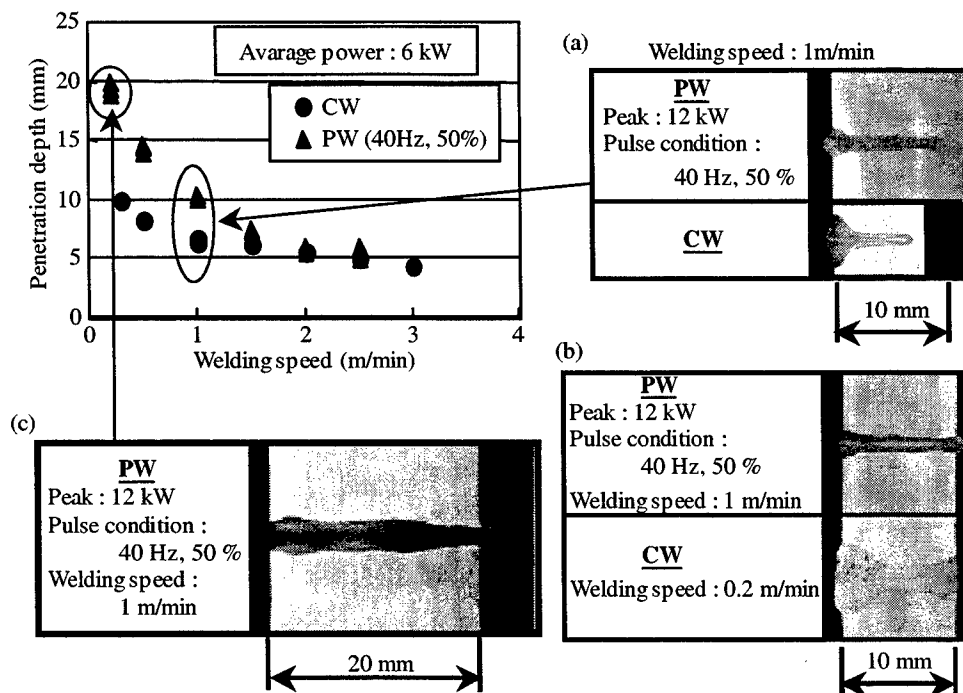


Fig. 12: Relationship between welding speed and penetration depth

3.3 LASER WELDING CHARACTERISTICS WITH HIGH-POWER COMBINED BEAM

Bead-on-plate welding tests were carried out with combining beam. Relationships between penetration depth and welding speed for various laser beam parameters are summarized in Fig. 13. As welding speed was decreased, bead shape was deeper and wider. It is confirmed that the penetration depth at combining beam of continuous wave is nearly equal to additional value of those at each single beam.

Figure 14 shows the comparison of bead shape between pulse modulation and continuous wave. At combining beam of continuous and welding speed 0.5 m/min, 20 mm penetration depth was obtained, but the heat effect was so large that welded metal was dropped. On the other hand, by using combined beam with the pulse modulation of Nd:YAG laser, 20mm penetration depth was achieved in high aspect ratio at a welding speed of 1m/min. It was confirmed that pulse modulation was effective for deeper penetration.

In addition, welding tests for square groove butt joint were conducted with the combined beam. Figure 15 shows the results of butt joint welding in type 304 stainless steel of plate thickness 20 mm. One-side and double-side welding was conducted, then defect-free and full-penetration welding was obtained in the both cases, as shown in Fig. 15. Butt joint welding tests for 30 mm thickness stainless steel plates were also carried out. Defect-free and full-penetration welding was also obtained in the cases of both side welding at a welding speed of 1 m/min. The cross section of welded plate is shown in Fig. 16.

We also conducted various welding experiments in aluminum alloy to realize the defect-free welding in aluminum alloy of plate thickness 20 mm. It was difficult

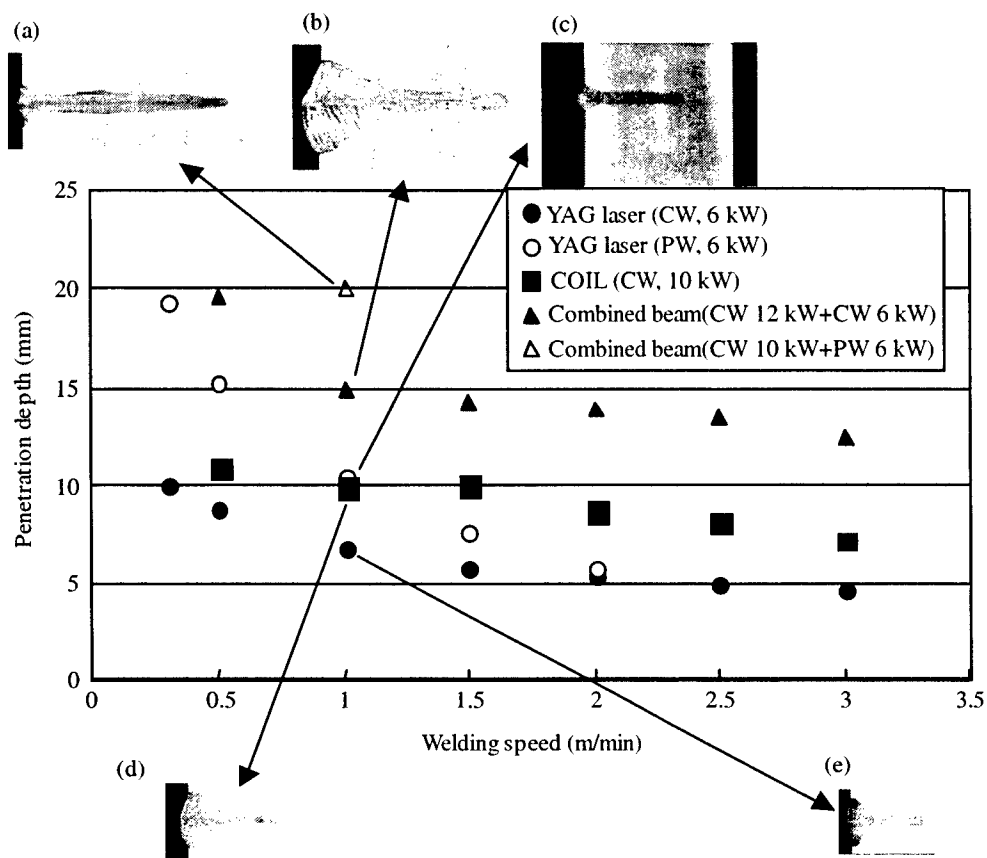


Fig. 13: Relationship between welding speed and penetration depth

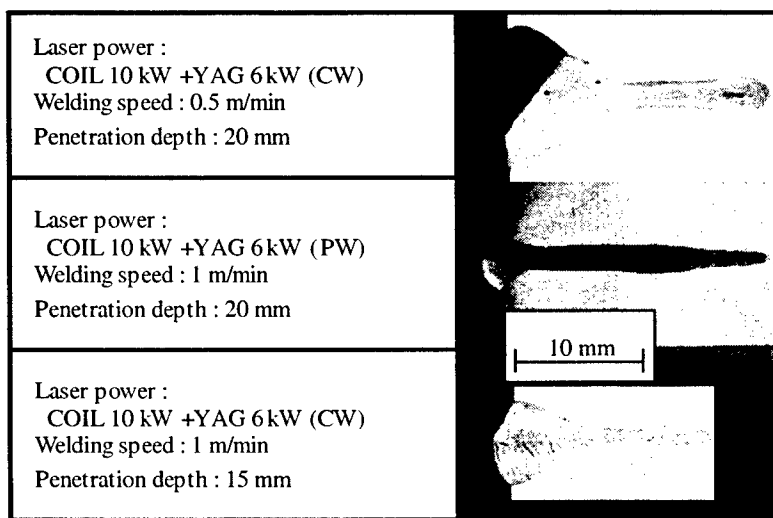


Fig. 14: Welded beads with combined beams (type 304 stainless steel)

to obtain the defect-free welding in aluminum alloy compared to steel because of the vaporization of volatile alloying additions such as magnesium. To clarify the optimum welding conditions in aluminum alloy, bead-on-plate welding tests were conducted with combined beam and single COIL beam. The defocusing distances of both beams were varied individually. The typical cross sections of welded aluminum alloy (A5083) plates are shown in Fig. 17. A penetration depth of 11.6 mm was attained with the combined beam, whose total laser power was 10 kW (COIL) + 6 kW (CW, Nd:YAG), at a welding speed of 1 m/min. In the COIL single beam welding, a penetration depth of 9.1 mm was obtained with the laser power of 10 kW at same welding speed. Now we are trying to achieve the full penetration welding with good welding quality in aluminum alloy (A5083) of plate thickness 20 mm.

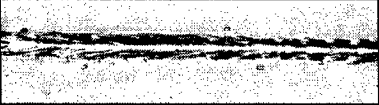
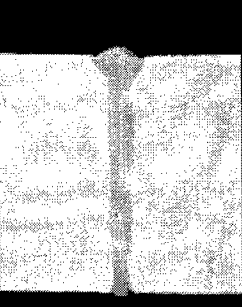
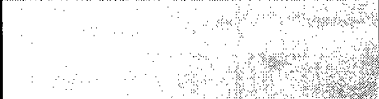
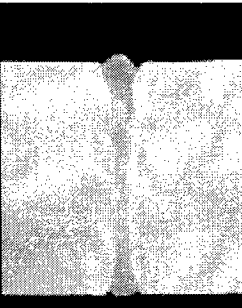
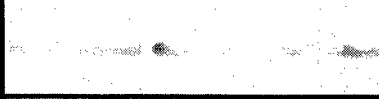
<u>One-side welding</u> Power : 10 kW COIL + 6 kW YAG YAG Pulse condition : 40 Hz, 50 % Welding speed : 0.8 m/min	Front side		
	Reverse side		
	Radiograph		
<u>Double-side welding</u> <u>Front side</u> Power : 10 kW COIL + 6 kW YAG YAG Pulse condition : 40 Hz, 50 % <u>Reverse side</u> Power : 6 kW YAG YAG Pulse condition : 40 Hz, 80 % Welding speed : 1.5 m/min	Front side		
	Reverse side		
	Radiograph		
		10 mm 	5 mm 

Fig. 15: Welding results in type 304 stainless steel butt joints of plates thickness 20 mm

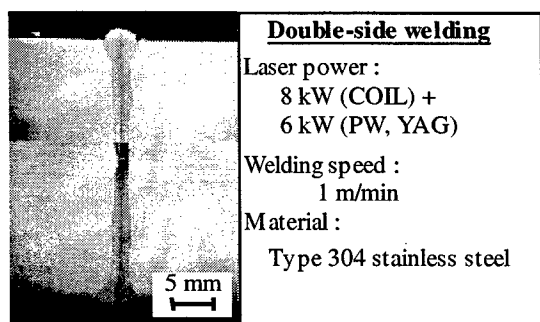


Fig. 16: Welding results in type 304 stainless steel butt joints of plates thickness 30 mm

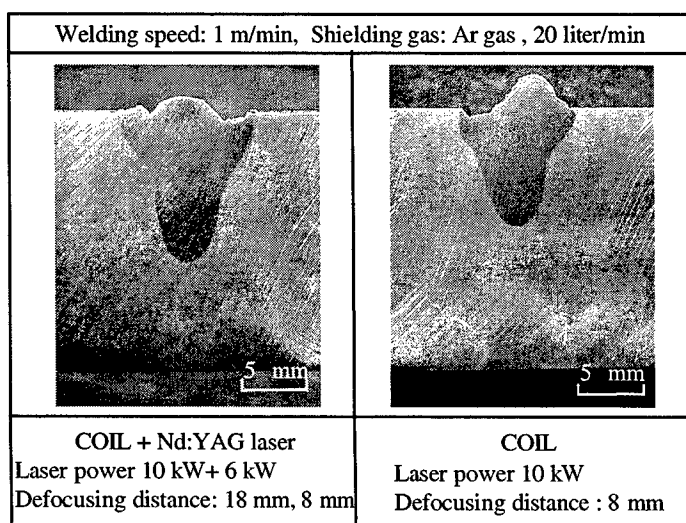


Fig. 17: Welding results in A5083 of plates thickness 20 mm

CONCLUSION

We are developing the highly reliable laser welding technology with high-power lasers whose wavelengths are located in 1 μm region. To establish the technologies for the thick plate laser welding, we carried out various welding experiments and obtained following results.

The beam combining system with beams of 6 kW Nd:YAG laser and 10 kW-class COIL was developed. By using this system, abundance of valuable results about high-power laser welding were obtained. Full penetration welding with good welding quality in type 304 stainless steel of plates thickness 20 mm (one-side welding) and 30 mm (double-side welding) was achieved at a welding speed of 1 m/min.

ACKNOWLEDGMENTS

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