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Deep Penetration Welding with High-Power Laser under Vacuum[†]

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Abstract

The authors have developed a new chamber for laser welding under the low vacuum conditions achieved by using rotary pumps. High-power disk laser bead-on-plate welding was performed on Type 304 stainless steel and A5052 aluminum alloy plate at the powers of 10, 16 and 26 kW at various welding speeds under low vacuum. Sound welds of more than 50 and 70 mm in penetration depth could be produced in Type 304 at the pressure of 0.1 kPa, the speed of 0.3 m/min and the power of 16 kW and 26 kW, respectively. Similar penetration was achieved in A5052 aluminum alloy. Welding phenomena under low vacuum were also examined by observing the behavior of a keyhole inlet, a molten pool, melt flows and a plume ejected from a keyhole using high speed video cameras. Low interaction between a laser beam and a plume under low vacuum was confirmed by using the probe laser beam method.

KEY WORDS: (Laser welding), (High power laser), (Disk laser), (Deep penetration), (Stainless steel), (Aluminum alloy), (Welding phenomena)

1. Introduction

High power and high brightness lasers such as disk and fiber lasers have been developed, and it is demonstrated that a deeper weld bead can be produced with an increase in laser power and/or power density^{1,2)}. It has also been demonstrated that laser welding can produce a sound deep-penetration weld bead comparable to electron beam welding³⁻⁹⁾ although the former process is not so far commercially available. It is moreover expected that sound deep-penetration welds can be produced under vacuum. The reason may be attributed to no proper vacuum chamber although the chamber does not need heavy plates containing lead for shielding X-rays during electron beam welding. Thus, the authors have developed a new chamber for low vacuum conditions achieved by using rotary pumps⁸⁾.

In this study, therefore, bead-on-plate welding was undertaken on Type 304 stainless steel and A5052 aluminum alloy plate under low vacuum of 0.1 to 10 kPa. The observation technique of welding phenomena was utilized to obtain a fundamental knowledge of laser weldability under low vacuum. The weld penetration and phenomena in low vacuum welding and during normal welding at 1 atm. were compared. Interaction between the laser beam and the plume during welding was evaluated using the probe laser method.

2. Experimental

The materials used in this research are commercially available Type 304 austenitic stainless steel and A5052 aluminum alloy of 80 mm in plate thickness. The schematic representation of the experimental setup is shown in **Fig. 1**. Continuous wave (CW) disk lasers (TRUMPF Truism 10003 and 16002, wavelength: 1030 nm) were used. The maximum laser powers are 10 and 16 kW, and the beam parameter products (BPP) are 12 and 8 mm*mrad, respectively. The maximum power of the combined laser beam is 26 kW. A focusing optic with the focal distance of about 1000 mm was employed. A spot diameter at the focus position was about 400 to 500 μ m.

The specimen was fixed on the stage in the vacuum chamber made of acrylic. The vacuum chamber was sealed, and the pressure was lowered by three rotary pumps. The pumping speed of one rotary pump is 500 L/min and that of the other pumps is each 162 L/min. When the ambient pressure in the vacuum chamber decreases to about 30 Pa, N₂ gas is supplied into the chamber as a shielding gas. The ambient pressure in the chamber is adjusted with the flow rate of N₂. Under this given pressure, bead-on-plate welding was performed.

In laser welding of A5052 plate, the laser welding head was declined at the angle of 10° in order to protect from the reflected light. Under the atmospheric pressure, the shielding gas flowed through a 16 mm-diameter side nozzle. The nozzle was declined at the angle of 45°.

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Moreover, in order to observe laser-induced plume and molten pool behavior from the specimen surface, high-speed video cameras were used at the framing rate of 100 or 5,000 frames/s. A diode laser of 980 nm in wavelength was used at the power of 30 W for illumination, and an interference filter of 974.5 nm was utilized to observe the molten pool and the keyhole behavior clearly.

The probe laser method was used to evaluate the interaction level between the laser beam and the plume during high power welding, as shown in **Fig. 2**¹⁰⁾. A probe laser behavior was observed by high speed video camera, and the shift of beam center was measured.

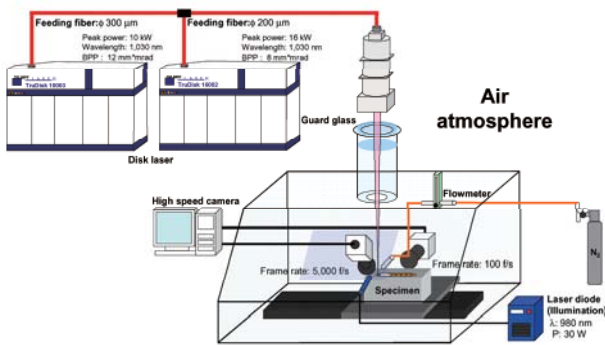


Fig. 1 Schematic experimental setup for laser welding under low vacuum.

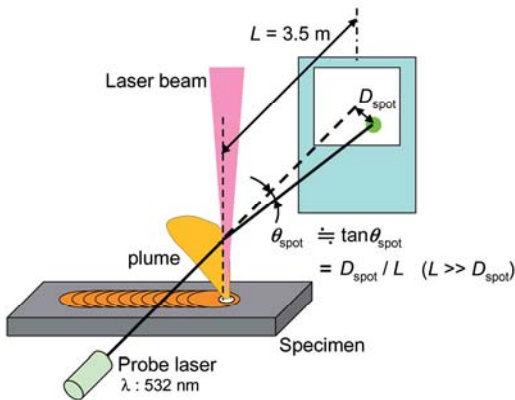
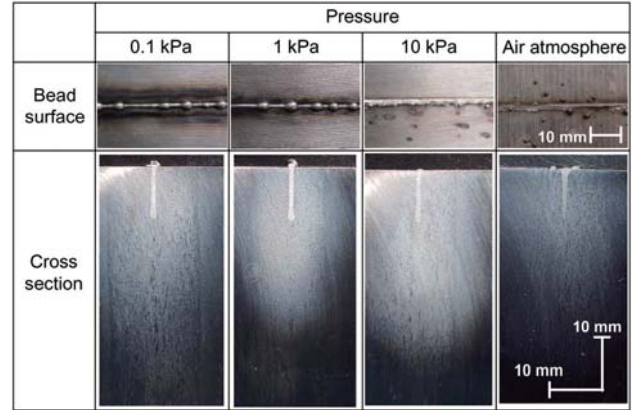


Fig. 2 Schematic experimental setup of high-speed observation and measurement system for interaction between probe laser beam and laser-induced plume during welding.

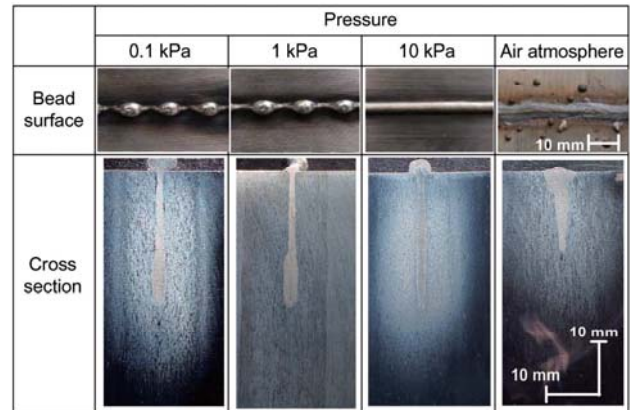
3. Results and Discussion

Bead-on-plate welding was performed with a disk laser at 10 and 16 kW in normal gas shielding and under low vacuum. Examples of welding results of Type 304 with 16 kW disk laser at 0.3, 1 and 6 m/min are shown in **Fig. 3**, indicating cross sections of weld beads. At 6 m/min, narrow weld beads were formed, and the weld penetration increases slightly with a decrease in the pressure. At 1 m/min, the penetration increases

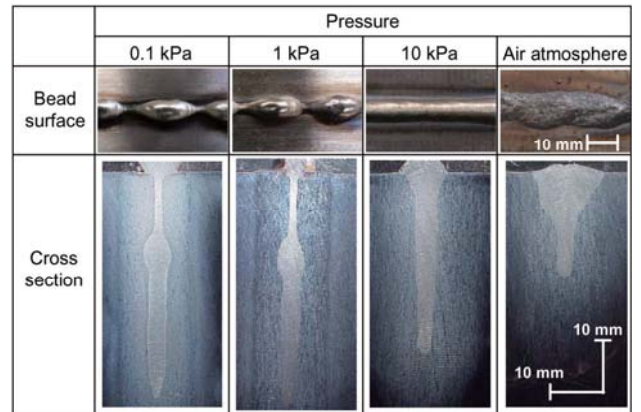
apparently with a decrease in the pressure. At 0.3 m/min the welds became deeper drastically with a decrease in the ambient pressure. The penetration depth of 43 mm was obtained at 0.1 kPa. The shapes of cross sections also changed significantly under various ambient pressures. The decrease in pressure from 101.3 to 10 kPa rendered the weld bead deeper and narrower. At 0.1 kPa, it was found that the cross sectional weld bead was in the vase-form whose middle depth part was inflated. At 0.1 and 1 kPa, humping beads were formed.



(a) Welding speed of 6 m/min



(b) Welding speed of 0.1 m/min



(c) Welding speed of 0.3 m/min

Fig. 3 Bead surfaces and cross sections of disk laser welds in SUS304 stainless steel plate at different speeds under various pressures.

The effect of ambient pressure and welding speed on weld penetration depths are summarized in **Fig. 4**. The penetration depth increases with a reduction in the pressure, especially at low welding speed.

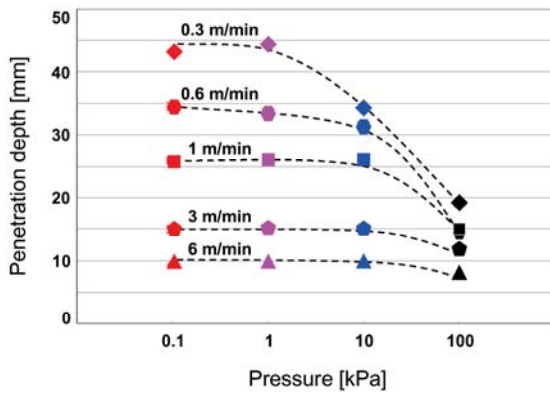
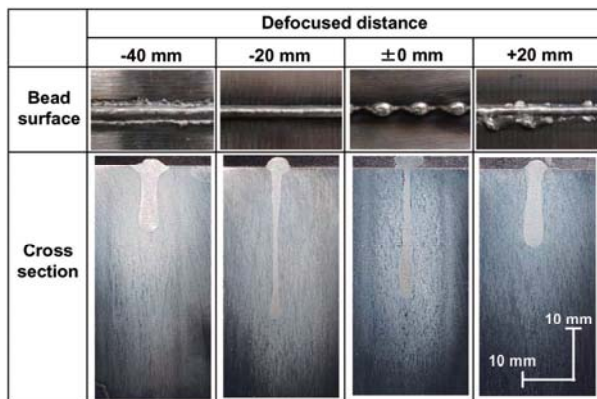
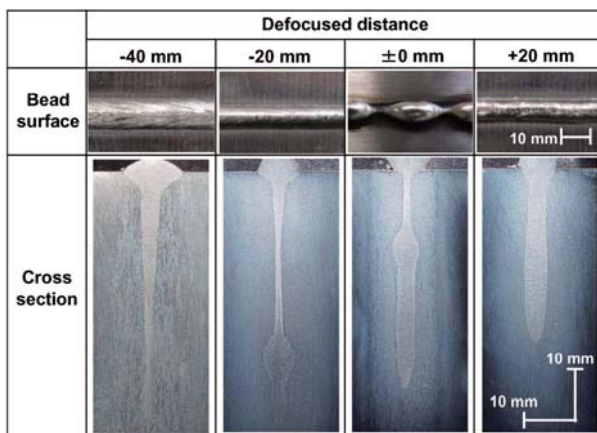


Fig. 4 Effect of pressure on penetration depths of Type 304 laser welds produced at various welding speeds. (Laser power: 16 kW, defocused distance: 0 mm, incident angle: 0°)

The effect of defocused distance on penetration was also investigated. The results of cross-sectional welds and penetration depths are shown in **Fig. 5** and **Fig. 6**,



(a) Welding speed of 1 m/min



(b) Welding speed of 0.3 m/min

Fig. 5 Bead surfaces and cross sections of 16 kW disk laser welds in SUS 304 at various defocused distances and welding speeds of 0.3 and 1 m/min.

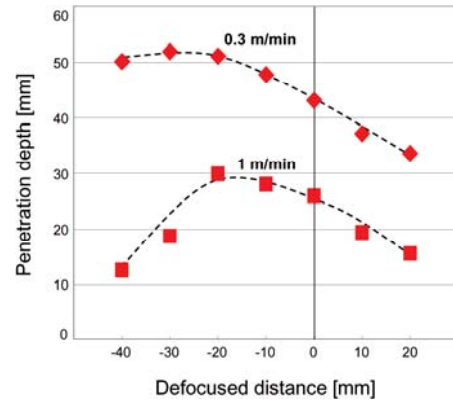
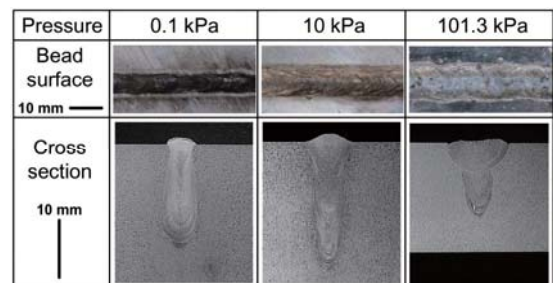


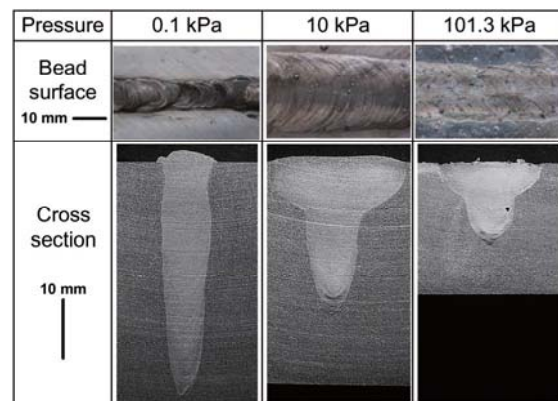
Fig. 6 Effect of defocused distance on weld penetration depth of Type 304 steel plate subjected to 16 kW disk laser at 0.3 and 1 m/min under pressure of 0.1 kPa at incident angle: 0°.

respectively. Under proper defocused conditions of -20 mm for example, the deepest weld was produced. Humping was suppressed by the defocused distances.

Examples of welding results of A5052 with 16 kW disk laser are shown in **Fig. 7**. The weld beads became deep under low vacuum. A deeply penetrated weld of 42 mm was obtained at the welding speed of 0.3 m/min. This tendency is similar to Type 304. But the penetration depth decreased with decreasing the ambient pressure from 10 kPa to 0.1 kPa at 1 m/min. The weld beads were wide under all the ambient pressures and the geometry in A5052 was not the same.



(a) Welding speed of 1 m/min



(b) Welding speed of 0.3 m/min

Fig. 7 Surface appearances and cross sections of laser weld beads in A5052 obtained at 0.3 m/min and 1 m/min.

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According to the observation results of molten pools, as shown in **Fig. 8** (a) and (b) for Type 304 and A5052, respectively, it was attributed to the formation of a wide keyhole due to high vapor pressure of Mg, the high heat conductivity and low surface tension of molten pool.

Moreover, it was confirmed that the plume was becoming weak, spattering was reduced and the trace of interaction between a focused laser beam and a plume became clear with the increase in the vacuum level. The refraction degree was also investigated by using probe laser method indicated in **Fig. 2**.

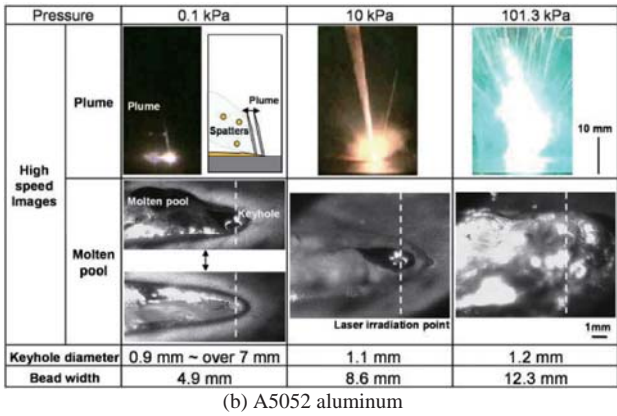
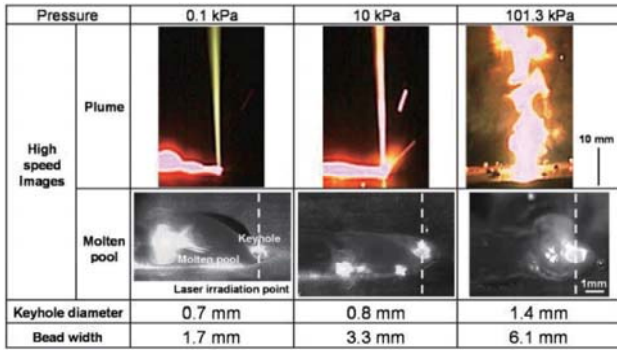


Fig. 8 High-speed video observation results, showing effect of ambient pressure on behavior of molten pool surface and laser-induced plume during laser welding of Type 304 (a) and A5052 (b) at 1 m/min.

The observation results of probe laser beam at 5 and 50 mm height are shown in **Fig. 9**. The scattered points were gathering with an decrease in the pressure. It was consequently revealed that the interaction between a laser beam and a plume became smaller with the increase in the vacuum degree.

Examples of weld cross sections produced with 26 kW disk lasers (combined by 10 kW and 16 kW beams) at the defocused distances of +20 and -40 mm is shown in **Fig. 10**. Sound deep welds of about 73 and 46 mm in penetration depth were formed at the defocused distances of -40 and +20 mm, respectively, although porosity was present in the middle part of weld beads at the focused distances between -30 to +10 mm. The penetration

increased with an increase in the defocused distance downwards in the case of the long focusing optic used.

It was confirmed that extremely deep welds could be produced with high power disk lasers.

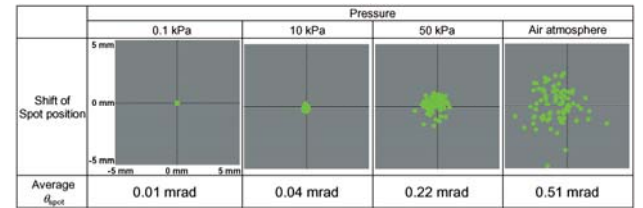
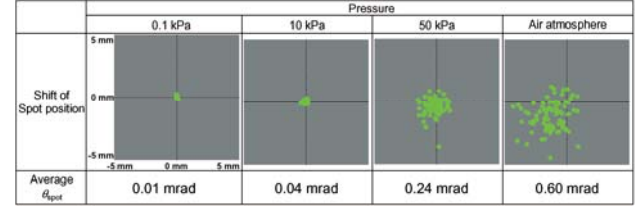


Fig. 9 Shift of spot position and average refraction angle in disk laser welding of Type 304 plate under low vacuum.

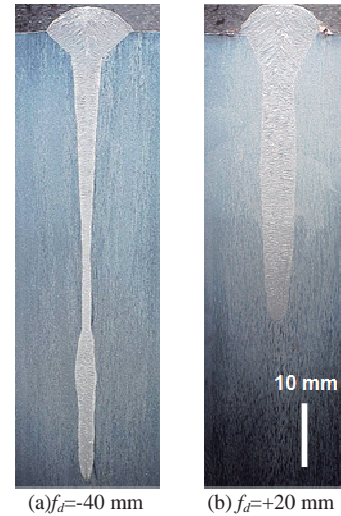


Fig. 10 Cross sections of Type 304 weld beads made with disk laser at 26 kW, 0.3 m/min and 0.1 kPa, showing formation of sound deep-penetration weld.

4. Conclusions

Disk laser welding were performed on Type 304 stainless steel and A5052 aluminum alloy at 16 or 26 kW, and various welding speeds under low vacuum. Weld penetration depth increased with decreases in the ambient pressure (higher vacuum) and low welding speed. Type 304 weld beads of more than 50 and 70 mm in the maximum penetration could be produced with disk laser of 16 and 26 kW power at 0.3 m/min and 0.1 kPa under

the defocused conditions. Observation results showed that spattering was reduced under higher vacuum, and backward melt flows caused narrow weld beads and sometimes humping beads to form at lower pressures. The interaction between a laser beam and a plume became smaller with the decrease in the pressure (higher vacuum).

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