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High-power fiber laser welding and its application to metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$

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Abstract

Fiber laser has been receiving attention due to its advantages of high-power and high-beam quality to produce narrow and deep penetration welds at high-welding speeds. Therefore, fiber laser welding is expected to apply to the joining of metallic glass which has unique properties such as high-mechanical strength or small solidification shrinkage, because extremely rapid quenching for the laser weldment or heat-affected zone (HAZ) is possible to remain amorphous. In this research, fiber laser welding was first performed with the objective of obtaining a fundamental knowledge of weld property produced in bead-on-plate welding for common marital such as Type 304 stainless steel with 6 kW fiber laser beams of several peak power densities. Deeply penetrated weld beads with narrow widths were produced with small spots of tightly focused laser beams and full-penetration welds in 8 mm thick plate could be obtained at the high-welding speed of 4.5 m/min. Subsequently, the tightly focused 2.5 kW fiber laser beam was applied to 72 m/min ultra-high-speed welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ in order to keep amorphous metals. Consequently, the weldment and HAZ remained desirably amorphous at ultra-high-welding speed with a tightly focused fiber laser beam.

Keywords: Laser welding; Metallic glass; Fiber laser; $Zr_{55}Al_{10}Ni_5Cu_{30}$

1. Introduction

Various lasers such as CO_2 laser, Nd:YAG laser, diode laser, disk laser and fiber laser have been developed as a high-power laser heat source for welding. Recently, the fiber laser has been receiving attention due to its advantages of high-power, high-beam quality and high-efficiency to produce deep penetration welds at high-welding speeds [1–4]. Metallic glass has also been receiving attention due to the possible production of thicker sheets as well as unique properties such as high-mechanical strength, small solidification shrinkage, small elastic modulus and fluidity in the supercooled liquid state. It is important for metallic glass joining to generate extremely rapid thermal quench and solidification in order to keep the characteristic features of the metallic glass. Several articles have recently been devoted to the study of metallic glass joining with pulsed lasers [5,6]. However, only few attempts have so far been made at high-speed welding of metallic glass with a high-power and tightly focused fiber laser beam.

In the research, therefore, fiber laser welding was exploited under several conditions such as four kinds of peak power densities or several laser powers in bead-on-plate welding of Type 304 stainless steel with a 6 kW-high-power fiber laser beam. The effects of power density or laser power on the weld bead penetration and geometry were investigated in order to understand high-power fiber laser weldability. Moreover, the tightly focused fiber laser beam was applied to 72 m/min ultra-high-speed welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ in order to keep amorphous in the welded joint.

2. Experimental set-up and materials used

The materials used are Type 304 austenitic stainless steel of 8 mm thickness and metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ of 1 mm thickness. A continuous wave (CW) fiber laser (IPG YLR-10000) was used for bead-on-plate welding. The maximum laser power is 10 kW and a beam parameter product (BPP) is

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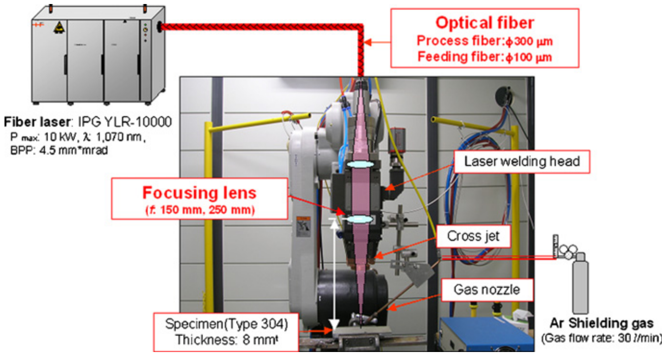

Fig. 1. Schematic experimental set-up in high-power fiber laser welding.

4.5 mm mrad. The schematic drawing of experimental set-up for fiber laser welding is shown in Fig. 1. A 6 kW-power fiber laser beam was transmitted through two kinds of optical fibers and focused on the specimen surface by two kinds of focusing lens. The spot diameters at the focused position were from 130 to 560 μm as demonstrated in Fig. 2. The 130 μm tightly focused fiber laser beam can produce an ultra-high-peak power density of 0.9 MW/mm^2 corresponding to a focused electron beam. The shielding gas was 30 l/min argon gas through an 8 mm-diameter side nozzle. The effect of four kinds of the power densities on the weld penetration was investigated as a function of welding speed. Moreover, fiber laser welding was exploited at the laser power of 2–10 kW with 130 μm-tightly focused beams in order to understand the relationship between the penetration depth and the laser power. At last, the 130 μm-tightly focused fiber laser beam was applied to 72 m/min ultra-high-speed welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$. Here, argon gas chamber was used for the prevention of oxidation. As for evaluation of the welding parts, micro-focused X-ray diffraction (XRD) method using Cu K radiation with spot size of 20 μm in diameter was used to identify the amorphous state of the metallic glass.

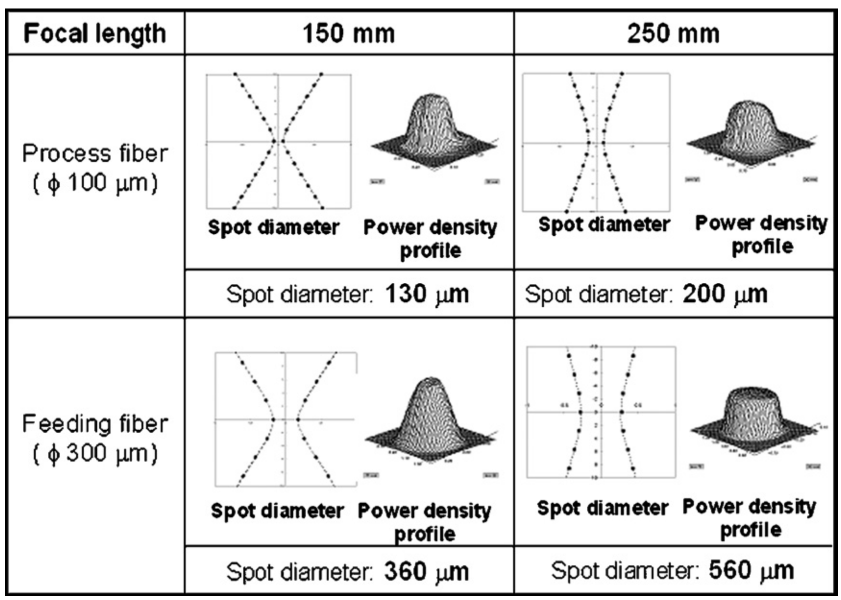

Fig. 2. Fiber laser beam diameters, profiles measured with respective fibers or focusing lens.

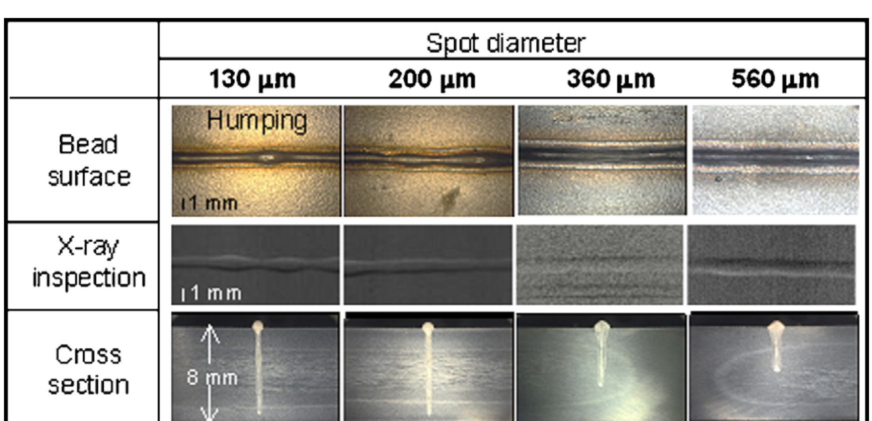

Fig. 3. Surface appearances, X-ray inspection results and cross sections of weld beads produced at various power densities at 6 m/min welding speed and 6 kW laser power in bead-on-plate welding of 8 mm-thick SUS304 plate.

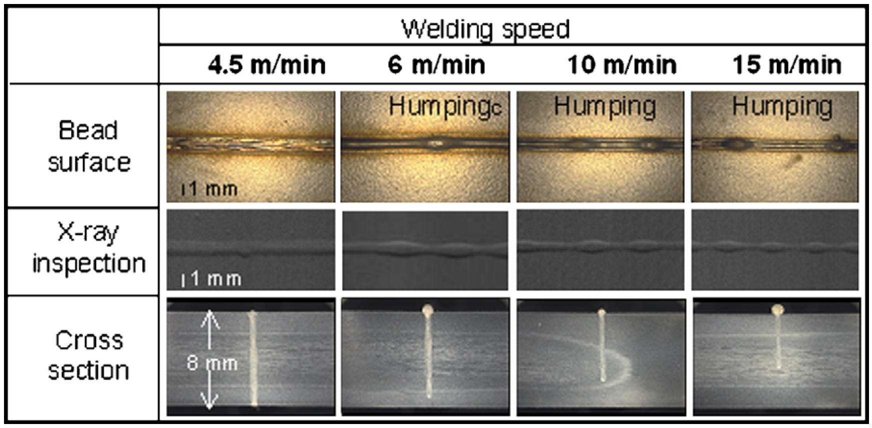

Fig. 4. Surface appearances, X-ray inspection results and cross sections of weld beads produced at various welding speeds with a 130 μm-tightly focused fiber laser beam.

3. Results and discussion

3.1. Laser weld penetration with high-power fiber laser

Bead-on-plate welding with a fiber laser was performed on Type 304 steel under various laser conditions. The photos of bead surfaces, X-ray inspection results and cross sections of welds produced at 6 kW laser power and 6 m/min welding speed are shown with laser beam spot diameters of 130, 200, 360 and 560 μm in Fig. 3. Narrow and deep partial-penetration weld beads could be produced in the 8 mm-thick plates. The penetration became deeper and narrower with the decrease in the laser beam diameter and the consequent increase in the power density. X-ray inspection results revealed that no pores were generated with all spot diameters. The surface appearances show that humping was formed the most easily with the smallest spot diameter of ϕ 130 μm.

The surface appearances, X-ray inspection results and cross sections of fiber laser welds made with the beam of about 130 μm focused spot diameter are shown at the welding speed of 4.5, 6, 10 and 15 m/min in Fig. 4. At 4.5 m/min welding speed, fully penetrated weld beads could be obtained in the plates of 8 mm in thickness and no porosity was generated according to the X-ray inspection results. The penetration shapes were desirable keyhole type and the penetration depth reached 4.6 mm at 15 m/min. However, humping weld beads were obtained under the partially penetrated weld beads at the welding speed of more than 6 m/min. The humping is considered to be suppressed by formation of full penetration.

The effects of beam diameter and welding speed on the weld penetration are investigated. The welding results are shown in Fig. 5. The penetration was shallower with the increase in the welding speed. It was confirmed that the laser power density exert a remarkable effect on the increase in weld penetration at high-welding speeds.

Furthermore, the typical effects of laser power on the weld penetration is plotted as a function of laser power of 2–10 kW in Fig. 6. The weld beads were made with the 130 μm-focused beam at 3 m/min welding speed. The samples were 20 mm thick for comparison of penetrations at the laser power of 2–10 kW. It was found that the penetration depth increased in proportion to the laser power. This means that the adequate

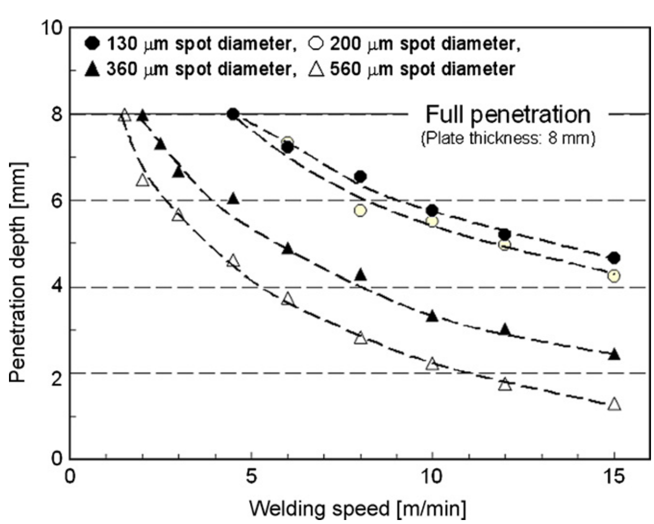

Fig. 5. Fiber laser welding results of penetration depth as function of welding speed for four laser power densities.

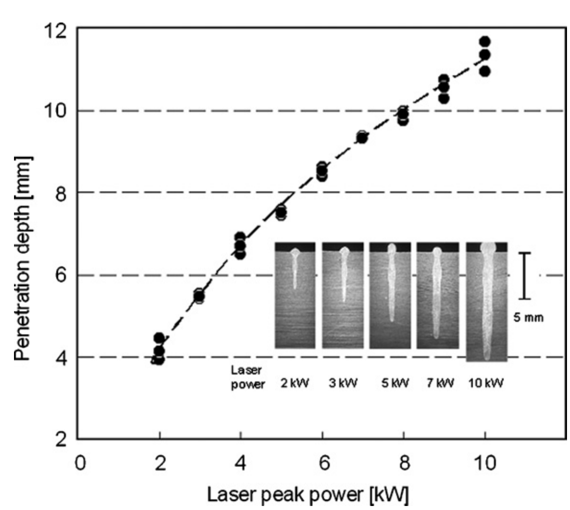

Fig. 6. Penetration depth produced by various laser powers at 130 μm laser beam spot diameter and 3 m/min welding speed.

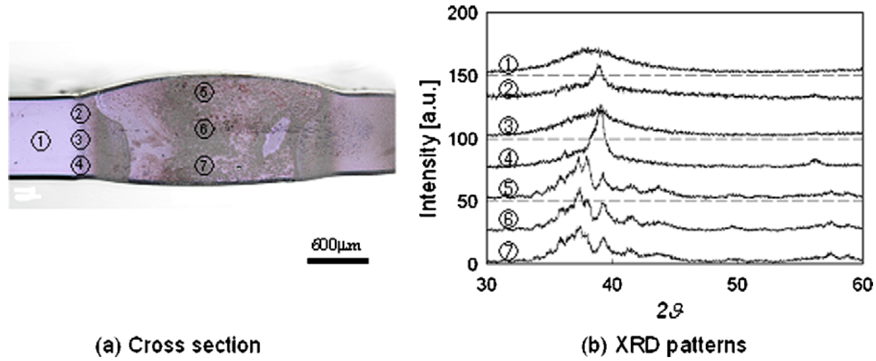

Fig. 7. Cross sections and XRD results of weld bead produced in bead-on-plate welding of 1 mm-thick metric glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ at 48 m/min welding speed.

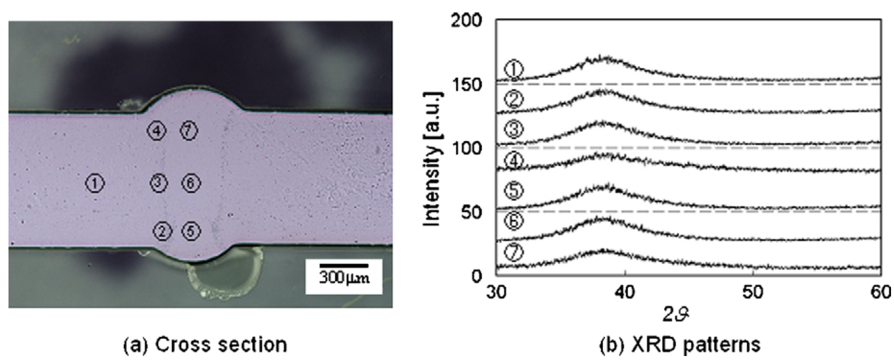

Fig. 8. Cross sections and XRD results of weld bead produced at 72 m/min welding speed.

laser welding conditions for designed penetrations were roughly determined according to change of the laser power.

Consequently, narrow and deep weld beads were obtained with a tightly focused 6 kW fiber laser beam. At 4.5 m/min welding speed, fully penetrated weld beads could be obtained in bead-on-plate welding for the SUS 304 plates of 8 mm in thickness with 130 μm focused spot diameter. Moreover, it was confirmed that the laser power density exert a remarkable effect on the increase in weld penetration at high-welding speeds.

3.2. Application of high-power fiber laser welding to metallic glass

Metallic glass can be easily changed from amorphous state to crystal by slow cooling rate. Therefore, the 130 μm-tightly focused fiber laser beam was applied to 48 and 72 m/min ultra-high-speed welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ of 1 mm thickness. 2.5 kW laser power was selected for full-penetration welding according to the above-mentioned welding results of the SUS304 plate. Fully penetrated welds were obtained at both welding speeds. The cross sections and XRD patterns of the weld beads obtained at 48 and 72 m/min ultra-high-welding speed are shown in Figs. 7 and 8, respectively. The weld bead was wide, and crystalline peaks were measured in the weldment and HAZ made at 48 m/min welding speed. On the other hand, the penetration geometry are desirable keyhole type, and no crystalline peaks were found in the XRD patterns at 72 m/min.

Consequently, the 130 μm-focused fiber laser beam was applied to 72 m/min ultra-high-speed welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ to remain amorphous. Narrow and deep full penetrations of weld beads were obtained, and no crystalline peaks were found in the XRD patterns.

4. Conclusions

Narrow and deep penetrations of weld beads were obtained with a tightly focused 6 kW fiber laser beams. Fully penetrated weld beads could be obtained in bead-on-plate welding for 8 mm-thick SUS304 plates with 130 μm-small spot diameter at 4.5 m/min welding speed. It was revealed that the laser power density exert a remarkable effect on the increase in weld penetration at high-welding speeds. The application of the tightly focused fiber laser beam to welding for metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$ was successful. Desirable deep and full penetrations of weld beads were obtained at 72 m/min ultra-high-welding speed and 2.5 kW laser power. No crystalline peaks were found in the XRD patterns. Therefore, it was found that the weldment and HAZ remained a desirable amorphous state in ultra-high-speed welding with a tightly focused fiber laser beam.

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