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In-situ observation of gap filling in laser butt welding

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A B S T R A C T

The process of melting the metal and filling the gap in laser butt welding of aluminum was firstly in-situ observed with the X-ray phase contrast method. Because the molten metal dropped down through the gap firstly, keyhole and molten pool were initially observed in the middle of the samples, then grew up towards both the upper surface and the bottom. The typical two-dimensional evolution routes of bubbles in the molten pool of laser butt welding were captured, which acted as an indicator for metal flow to fill the gap.

Laser has been widely used as a heat source to melt and join the separate parts [1–3], where the butted joint is a typical style [4]. Metal can be evaporated when irradiated by high power density laser, and keyhole is formed [5]. Multiple reflections of light happen in the keyhole, which contributes to light absorption [6]. Laser energy is mainly absorbed by the keyhole wall [7], then transfers to the metal surrounding the keyhole. Revealing the dynamic characteristics of keyhole and molten pool could contribute to better understanding of joint formation, and prevent defects (e.g. porosity and spatter).

Because the keyhole and molten pool are surrounded by the solid metal, the inner characteristics couldn't be captured by camera directly. Several researchers have tried various methods to explore the inner characteristics during welding process. Matsunawa and his colleagues in Osaka University [5,8,9] developed the X-ray transmission method to in-situ observe the keyhole in the molten pool of laser welding, where the dynamic characteristics of keyhole during the welding process could be directly captured. By implanting tiny W (Tungsten) particles into the base metal in advance, this X-ray transmission method was also used to track the movement routes of particles during the welding process, which indicated the flow routes of metal in the molten pool [5,10]. However, the X-ray transmission method couldn't identify the interface between liquid metal and solid metal due to the tiny difference in mass density between these two phases. Some researchers observed the inner characteristics of keyhole and molten pool with a specially designed structure [11–13], where the metal was laminated with a transparent glass plate so that the inner characteristics could be observed by high speed camera through the plate. With this method, the clear characteristics of dynamic keyhole, metal flows and temperature distribution in the molten pool, and the origin of porosity were captured [13], which promoted the understanding of phenomenon in laser welding. However, the welding condition in this situation was not totally the same with the actual welding situation, for example, the observed keyhole diameter was obviously larger [13]. Recently, the X-ray phase contrast method was used to capture the characteristics of keyhole, molten pool and porosity in laser bead on plate welding of aluminum, which provided a clear image of the inner characteristics during welding [14]. Besides the application in laser welding, the X-ray imaging technology has also been used in exploring the melting characteristics in laser powder bed fusion [15–18] and the solidification characteristics in casting [19,20], which validated the function of the X-ray system in observing the inner characteristics.

Porosity is one of the most severe defects in high energy beam welding [21–23], especially for light metal, e.g. titanium and aluminum [8,24,25]. Several researchers developed the numerical model to estimate the origin of porosity and analyze the key factors that leading to the porosity formation in laser bead on plate welding [21,22,26]. These simulation results show that the porosity is mainly produced at the interface between keyhole and molten pool due to the violent keyhole collapse. In our previous research, the origin of porosity in laser welding of steel was observed by high speed camera through transparent glass plate with a specially designed structure [9]. The experimental results show that the porosities are mainly produced with two modes. The porosity starts from the tip of the keyhole in the first mode, while from the middle of the keyhole in the second mode. In both situations, the produced porosities flow into the molten pool in the rear of the keyhole. These researches contributed to the understanding of porosity formation mechanism in laser welding.

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However, most of current researches about the dynamic characteristics in the molten pool were conducted in the laser bead on plate welding situation. Characteristics of molten pool and the origin of the porosity in the real situation of laser butt welding, where there is a gap at the butted interface, have rarely been investigated. In present work, X-ray phase contrast method was used to in-situ observe the dynamic characteristics of keyhole and molten pool in laser butt welding of a representative aluminum alloy A1050. The gap filling phenomena at both the initial stage and the stable stage were observed, and the metal flows to produce these unique phenomena were analyzed. This paper firstly revealed the mechanism of gap filling and joint formation in laser butt welding.

The X-ray phase contrast method [14] was used to observe the characteristics of keyhole and molten pool during the laser butt welding process. When an X-ray irradiates to the interface of different phases, interference occurs. With X-ray phase contrast method, a clear image of molten pool characteristics is obtained from a contrasting stripe pattern on the basis of the differences in refractive indices of the gas, liquid, and solid phases. Because X-ray phase contrast method requires a highly coherent and monochromatic X-ray beam, the X-ray beam of the BL22XU beam line at SPring-8 (Super Photon ring-8 GeV, Hyogo, Japan) was used for this experiment.

The layout of the laser welding system and X-ray phase contrast in-situ observation system in the experiment is shown in Fig. 1. During the experiment, two aluminum alloy samples with dimensions of 70 mm × 30 mm × 1.5 mm were laminated, and penetrated horizontally through 70 mm × 30 mm surface by X-ray. The laser beam irradiated to the top surface, and the center of the beam was set at the interface of two samples. Keyhole and weld pool induced by the laser beam were visualized by the X-ray radiation, and images were captured using a high-speed video camera at a frame rate of 1 kHz. A single-mode-fiber laser with a maximum output power of 500 W was used, and the focal length was 190 mm. The laser head was inclined with an angle of 10° to avoid the damage of the reflected light to the lens. The laser power, welding speed, and defocus distance were fixed at 500 W, 16.7 mm/s, and −1 mm, respectively. The spot size of laser beam at this defocus distance was around 140 μm. Though the designed size of BL22XU Beam in Spring8 at the energy of 30 keV is with 3 mm × 4 mm, the clear phase contrast image with enough resolution rate to identify the interfaces among solid metal, molten pool and keyhole in laser welding observed by our experimental system only appears in the center zone with the approximate size of 1 mm × 1 mm, which is the reason for choosing this specific welding parameter. The welding experiments were conducted with a fan to remove the laser-induced plume, achieving a stable keyhole [14]. The representative aluminum alloy A1050 with the mass fraction of Al larger than 99.5% was used in the experiment. The measured surface roughness of the sample was 0.1 μm.

Fig. 2 shows the dynamic characteristics of keyhole and molten pool in laser welding of A1050 at the initial stage observed by the X-ray phase contrast system. At the time of 1 ms, the molten pool was formed at the middle of the longitudinal section firstly. During the whole initial stage, the section area of the molten pool increased with time. The molten pool reached the maximum depth at 5 ms, and reached the upper surface of the sample at 10 ms. Two boundaries appeared in the molten pool since 5 ms, which were named b1 for the external boundary, and b2 for the inner one as shown in Fig. 2. Keyhole was observed to be in the center of the molten pool. Before the time of 5 ms, the keyhole grew both upward and downward, and the length increased. At 5 ms, the keyhole reached the maximum depth, just as the molten pool. After that, the keyhole grew upward until the upper surface of the sample at 10 ms.

These observed characteristics of molten pool and keyhole in laser butt welding update current knowledge. Generally, laser penetrates from the upper surface into the sample during the welding process. The keyhole and molten pool will be formed at the upper part of the sample firstly, then grow downward [13]. Besides, there is only one continuum boundary in the molten pool of laser bead on plate welding [14]. The actual surface of the aluminum sample was not ideally smooth, and there was small gap at the butted interface. At 1 ms, metal in the upper

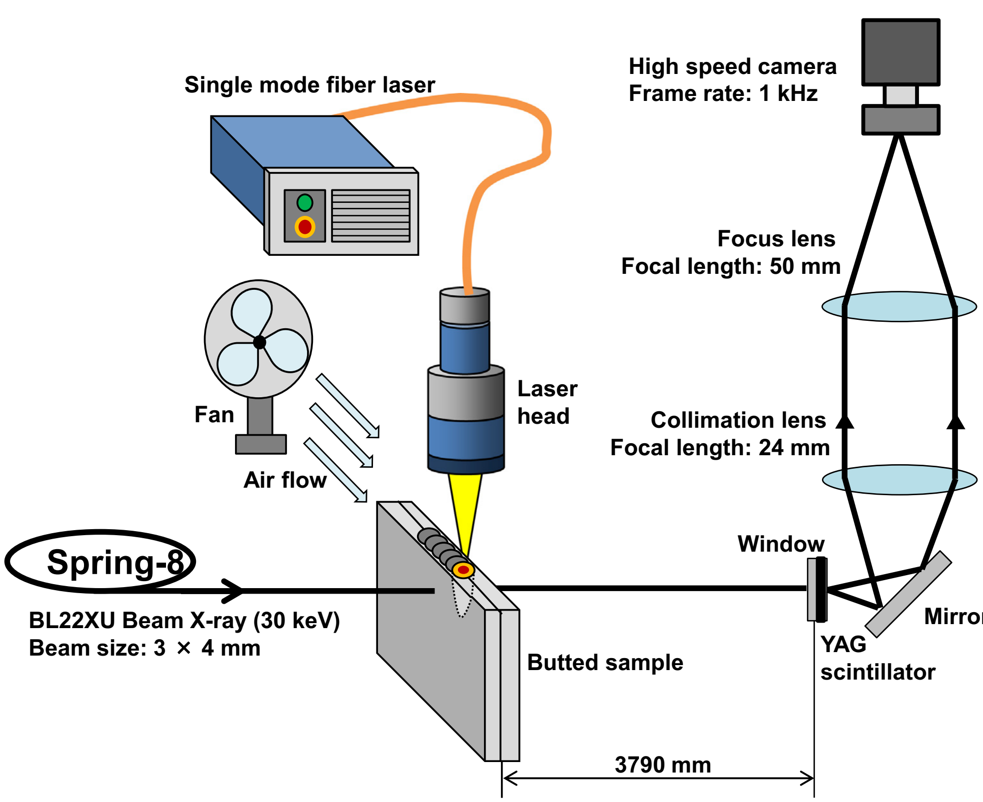

Fig. 1. X-ray phase contrast in-situ observation system for laser welding of aluminum alloy.