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Porosity formation mechanism and its prevention in laser lap welding for T-joints

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ABSTRACT

A high-speed camera and X-ray transmission observation system were used to observe the keyhole and molten pool dynamic behavior in laser lap welding T-joints. The oscillation frequency of the molten pool and the keyhole increases with increasing gap. The lower keyhole becomes slant with the large gap and large quantities of bubbles are formed at the bottom tip of the keyhole. The molten pool is divided into three different zones by the large gap and a small eddy is formed at the lower molten pool. The bubbles are difficult to escape from the lower molten pool and the gap when the gap is large, resulting in the formation of porosity at the gap and root of weld seam. The distribution characteristics of porosity in different gap have an excellent agreement with the keyhole and the molten pool dynamic behavior. Porosity can be suppressed by maintaining a small gap or adopting high welding speed. The paper provides fundamental insights into the mechanism of porosity formation during laser lap welding T-joints and guidance to aid in its elimination.

1. Introduction

Katayama et al. (2010) showed that the formation of porosity during pulsed laser welding was closely linked to the instability of the keyhole. In pulsed laser welding, once the laser irradiation is terminated, the melt surrounding the upper part of the keyhole flows downward to fill the keyhole. At the same time, the upper part of the melt rapidly solidifies which prevents the melt from flowing to fill the keyhole, leading to the formation of porosity. In continuous laser welding, Seto et al. (2000) found many bubbles formed mainly from the bottom tip of the keyhole by X-ray transmission real-time imaging apparatus. Some bubbles can escape from the molten pool, while the majority of bubbles are trapped at the solidifying front in the rear part of the molten pool and results in the formation of porosity distributed at the bottom of the weld seam.

Laser lap welding can be divided into two kinds of types: laminated lap welding and stake overlap welding. Stake welded T-joint is the basic unit of all metal sandwich structures as shown in Fig. 1a, in which the core and cover plates are joined by laser welding. In order to eliminate the gap between the core and cover sections, Romanoff et al. (2007) reported the core plates must be fabricated to maintain linearity along the length and proper height, while the gap induced by the fixing force and welding distortion was unavoidable during laser welding (Fig. 1b). If the defects (porosity) are formed at the joint between the core and cover sections, it will greatly impair the mechanical property of T-joints. Unfortunately, at the present time, an unequivocal explanation for porosity formation during laser lap welding T-joints is unavailable, particularly the influence of gap on porosity formation. Matsunawa et al. (2000) observed keyhole and weld pool dynamics by optical method and X-ray transmission imaging system. A hole drilled in a liquid pool is primarily unstable by its nature and the instability of keyhole also causes the formation of porosity. However, Tsukamoto (2011) reported keyhole instability was the main cause of bubble initiation, especially in deep penetration laser welding. It is agreed that porosity results from bubbles trapped when the front wall of molten pool solidifies. Katayama et al. (2001) showed that the keyhole-induced porosity could be eliminated by optimizing welding parameters and the use of vacuum conditions. Kawahito et al. (2007) also recently reported that porosity formation greatly depends upon processing parameters and surface condition in laser welding.

The effect of gap on the keyhole and molten pool dynamics and porosity formation during laser lap welding is seldom reported.

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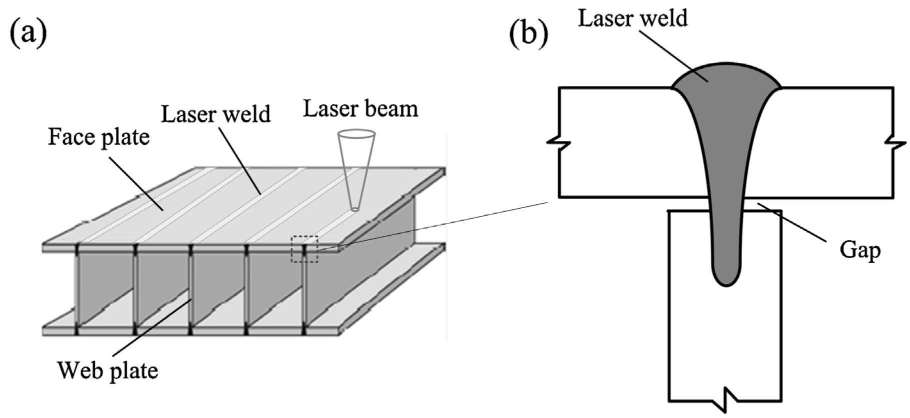

Fig. 1. (a) Laser-welded all-metal sandwich panel and (b) laser welded overlap T-joint.

Therefore, it is necessary to understand the porosity formation mechanism and to find methods to reduce or eliminate porosity defects. This paper provides overall insights into the mechanism of porosity formation in laser lap welding T-joints and guidance to aid in its elimination. The effect of gap on dynamic behavior of the keyhole and the molten pool is also discussed.

2. Experimental procedure

High-strength low alloy (HSLA) steel with 4 mm in thickness was used as a specimen in this experiment. The geometry and size of welded samples were given in Fig. 2a. The experimental setup was shown in Fig. 2b. Laser lap welding was carried out with the 15 kW CO_2 laser system. The laser beam was focused on the upper plate surface with a parabolic mirror of 357 mm focal length. The M^2 value of the laser beam was about 3.6 and the spot diameter was 0.86 mm. Helium shielding gas was blown forward through a nozzle of a 6 mm internal diameter at a flow rate of 30 L/min.

The dynamic behavior of keyhole, molten pool and plasma plume was simultaneously observed by the methods described in Fig. 2b in laser lap welding T-joints. High speed camera system including high speed camera, Marco lens, dimmer glass, interference filter and UV Lens was used. Camera that produced in Switzerland was MV-D1024-TrackCam of Photonfocus Company. Laser induced plume and molten pool were observed by using high speed camera placed in the horizontal plane and in the 75° dip angle, respectively. The framing rate of the camera was set as 1000 frames per second for the plume and 750 frames per second for molten pool. The molten pool was illuminated with a diode laser (2 W at a wave length 808 nm) from horizontal plane with a 30° dip angle.

The keyhole dynamics, bubble formation and molten pool flow were observed through X-ray transmission real-time imaging apparatus. The system was schematically represented in Fig. 2b. The system consisted of a micro-focused X-ray tube (150 kV, 900 mA), a fluorescent image converter and an image intensifier of visible light. The X-rays emitted from the X-ray tube with a focal spot size of 4 μm irradiated the specimen from the side during laser welding. The side view of the keyhole was imaged by a high-speed video camera at a frame rate of 1 kHz. This system could take the high speed camera image up to 5000 frames per second (f/s).

After welding, the samples for cross-sectional and longitudinal section were cut and then mounted for a standard polishing procedure. Then samples were etched with a 4% Nital solution. The longitudinal section was observed by using digital Single Lens Reflex. Macrostructure and porosity of the etched samples were observed, measured and photographed by optical microscope.

3. Results

3.1. *Optical observation of molten pool*

The dynamics of molten pool and keyhole opening were observed by high-speed cameras during CO_2 laser lap welding T-joints. Fig. 3 represents the images of keyhole opening and molten pool with 8 kW laser power and 1 m/min welding speed in different gap size. As shown in Fig. 3, the white round zone at the front of molten pool was keyhole opening and it periodically fluctuated together with the liquid surface of molten metal. The fluctuation cycle was about 6.2 ms when the gap was zero. The above observations were consistent with Matsunawa et al. (2000)'s reports. As the gap increased, keyhole opening fluctuated violently

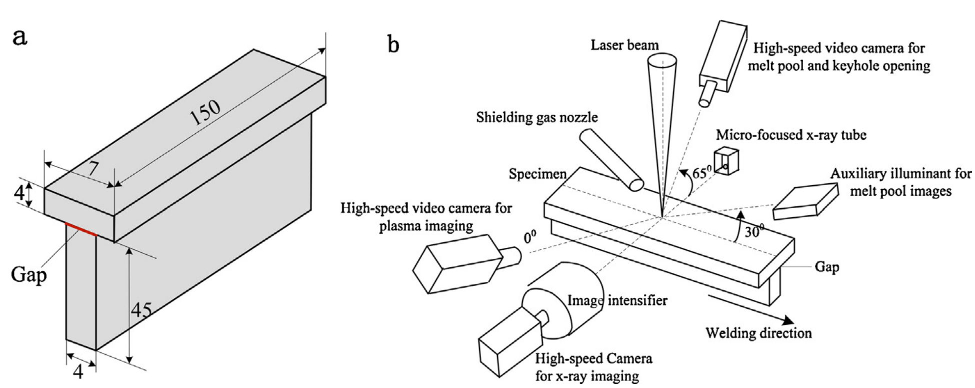

Fig. 2. Specimens and the experimental setup (a) geometry and dimensions of the specimens used in the present study (in mm) and (b) schematic illustration of the experimental setup.