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Three-dimensional X-ray transmission in-situ observation of spatter formation and reduction in laser welding of stainless steel

Yosuka Kawahito[a,*], Kouji Nishimoto[b], Hiroshi Kawakami[c], Seiji Katayama[a]

[a]*Joining and Welding Research Institute(JWRI), Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka, 567-0047, Japan*
[b]*National Institute of Technology, Anan College, 265 Aoki Minobayashi, Anan, Tokushima, 774-0017, Japan*
[c]*Graduate School Engineering, Mie University, 1577 Kurimamachiya-Cho, Tsu, Mie, 514-8507, Japan*

Abstract

The objective of this research is to reveal effects of angle of incidence or defocusing distance upon spatter formation and reduction in melt-run welding of a SUS304 stainless steel plate with a 6-kW power laser beam on basis of a high-speed video camera and a three-dimensional X-ray transmission in-situ observation apparatus. The high-speed video images at 150 mm/s in welding speed show the convex molten-pool surface behind a keyhole inlet was elongated and scattered as large spatters over 0.1 mm in size. According to the X-ray images, a melt flew to the elongated part at approximately 2.3 m/s in velocity, which caused the rapid increase of the spatters in size. A 2-mm inner defocusing distance or a 20-degrees angle of advance for an incident laser beam decreased number of spatter by half or one third owing to circulating melt flow behind the keyhole inlet. It was revealed that the large spatter reduction was effective to deceleration or change in direction of the melt flows behind the keyhole inlet, which led to not only suppressing formation of the elongated surface but also improving the frequency that the spatters went back to the molten pool.

Keywords: melt flow, keyhole, spatter, angle of incidence, defocusing distance, laser welding ;

1. Introduction

Welding is a fundamental metal-joining technology, and better understanding of the melt behavior in molten pool is required to realize high-quality, defect-free joints. Typical defects encountered in laser

* Corresponding author. Tel.: +81-6-6879-8652; fax: +81-6-6879-8662.
E-mail address: kawahito@jwri.osaka-u.ac.jp.

welding include porosity (cavities formed upon solidification of molten metal), underfill (dents in the nugget surface), and spatter (expulsion of molten metal). The movement of molten metal is deeply related to all of them, and thus it is particularly important to deeply understand how the melt flows within the pool. For example, in partial penetration welding of stainless steel at a welding speed of 17 mm/s with a 6-kW high-power beam, sporadic formation of bubbles is observed at the leading edge of the keyhole. The bubbles are transported by melt flow swirl around the leading edge of the keyhole and become trapped by the solidification front. The mechanism of porosity defect generation has been clarified through two-dimensional X-ray transmission observation by K. Kinoshita et al., 2007 or Y. kawahito and S. Katayama, 2009. On the other hand, the melt flow at a welding speed of 100 mm/s differs from that at a low welding speed. It is reported that the melt flow from the inlet of the keyhole to the rear is observed clearly, and the generation of bubbles which cause porosity is not observed. A numerical analysis of three-dimensional melt flow has been reported by A. Otto, et al., 2011. But no three-dimensional measurement has been reported. Thus, the relationship between melt flow and welding defects has not been elucidated sufficiently.

In this study, we focused on the relationship between melt flows and spatter formation in melt-run welding of a SUS304 stainless steel plate with a 6-kW power laser beam and investigated effects of angle of incidence and focal position upon spatter reduction with a high-speed video camera and a three-dimensional X-ray transmission in-situ observation apparatus.

2. Materials and experimental procedures

The test material was a SUS304 (austenitic) stainless steel plate as base material and a disk laser oscillator (consecutive oscillation type, max. power: 16 kW) was used as the welding device. **Fig. 1** is a schematic illustration of the experimental setup.

The beam was transmitted from the oscillator through a fiber having a core diameter ϕ of 0.2 mm. It was then focused by a lens (focal distance: 280 mm). The beam spot diameter, ϕ was 0.3 mm, and peak power density was 200 kW/mm^2. The focal position was fixed. In this arrangement, melt-run welding was performed at welding speeds of 50, 100, 150, and 250 mm/s at a 6-kW power setting. Subsequently, focal position of -4, -2, 0, 2 mm or angle of incidence of -20, -10 ,0 10, 10 degrees were changed.

A real-time X-ray transmission imaging system was used to observe three-dimensional melt flow within molten pool. The system consists of a micro-focused X-ray beam (max. resolution: 4 μm, resolution at time of experiment: 70 μm, max. voltage: 230 kV, max. current: 1 mA, max. stainless steel plate thickness photographable at 1,000 fps: 5 mm) and a mini-focused X-ray beam (resolution: 0.4 mm, maximum voltage: 225 kV, maximum electric current: 3.5 mA, max. stainless steel plate thickness photographable at 1,000 fps: 10 mm). The X-rays can be observed by means of a fluorescent image intensifier (afterglow time: 0.1 ms) and a high-speed camera (10,000 fps). From the image data measured at two different angles simultaneously, the three-dimensional velocity of the melt flow can be measured by using parallax. In addition, the test metals used for X-ray transmission observation are T-shaped to prevent omission. The X-ray penetration was 5 mm at a welding speed of 25 mm/s, 3 mm at 50 mm/s, and 1.5 mm at 100 mm/s or above. Small (diameter: 0.5 mm) tungsten carbide balls were embedded into the test materials before welding as tracers for the visualization of melt flow.

Moreover, behaviors of molten pool surface and laser-induced plume were observed at 10,000 fps by using a high-speed video camera.

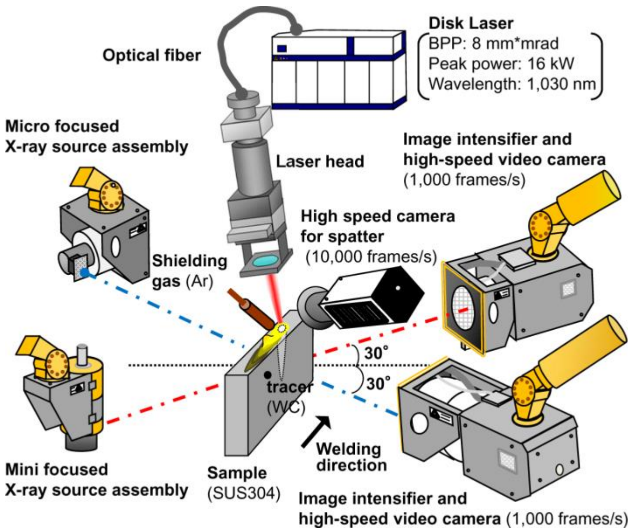

Fig.1. Schematic illustration of experimental set-up of high-speed video camera and three-dimensional X-ray transmission system for observation of welding phenomena with high power laser.

3. Effects of angle of incidence or focal position upon spatter reduction

To investigate the melt flow under the conditions that led to the spatter generation upon deep penetration welding at a welding speed of 150 mm/s, three-dimensional X-ray transmission observation was performed using 17 tungsten carbide balls embedded 1 mm, 2 mm, and 3 mm beneath the plate surface. There were two kinds of melt flows, one being in the upper part and another in the lower part of molten pool at the rear of keyhole. The upper melt flew to the elongated part of the molten pool surface behind a keyhole inlet at approximately 2.3 m/s in velocity, which caused the rapid increase of the spatters in size.

A 2-mm inner defocused position decreased number of spatters by half in comparison with that at focus position and zero angle owing to circulating melt flow behind the keyhole inlet as demonstrated in **Fig. 2**. On the other hand, a 20-degrees angle of advance for an incident laser beam also reduced number of spatters by one third due to circulating melt flow behind the keyhole inlet as indicated in **Fig.3**.

It was revealed that the spatter reduction was effective to deceleration or change in direction of the melt flows behind the keyhole inlet, which led to not only suppressing formation of the elongated surface which became a spatter but also improving the frequency that the elongated surface or spatters went back to the molten pool.

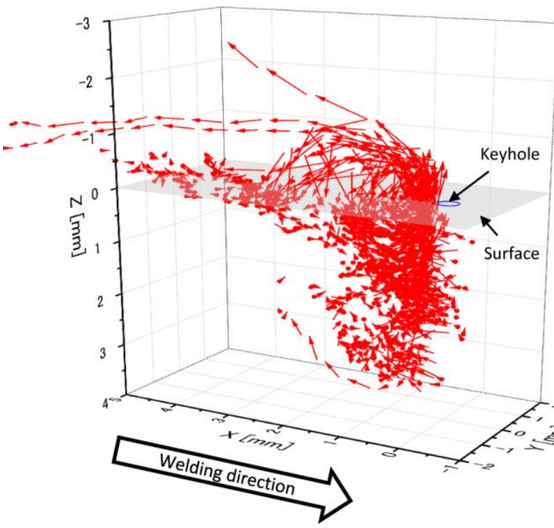

Fig.2. Display of three-dimensional melt flows calculated from 80 tracers during laser welding at -2 mm defocused position.

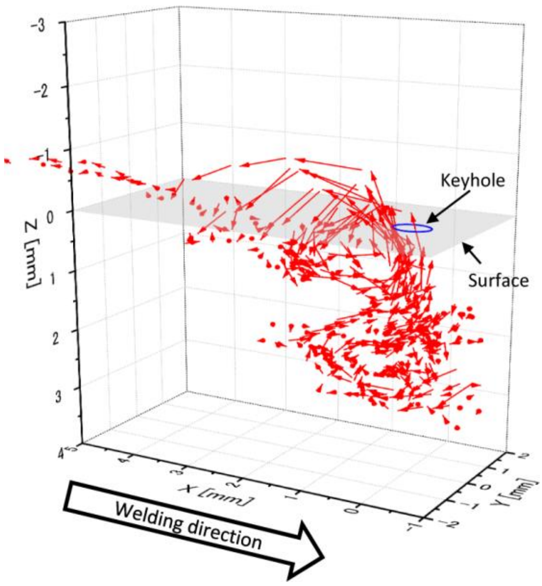

Fig.3. Display of three-dimensional melt flows calculated from 20 tracers during laser melt-run welding at 20 incident degrees.

4. Conclusions

In laser welding, there were two kinds of melt flows, one being in the upper part and another in the lower part of molten pool at the rear of keyhole. The melt flow was fast at the keyhole inlet and keyhole tip, and heat transfer in the melt flow governed energy transfer in molten pool. Furthermore, the speed and the direction of the melt flows were sensitive to welding speed, focal position or angel of incidence. In spatter generation, the melt flow accelerated from the inside of keyhole and flowed straightly into the keyhole inlet. Proper angel of incidence or focal position produced the circulated melt flow in the upper part of the molten pool, which led to spatter reduction.

Acknowledgements

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