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Weld formation mechanism of fiber laser oscillating welding of austenitic stainless steel

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ABSTRACT

The effects of beam oscillating parameters on weld morphologies are investigated. Weld geometrical sizes were counted statistically. The results showed that the difference in cross-section width from the top to the lower gradually reduced to disappear with the increase of oscillating frequency. Weld cross-section was featured by slender nail when the frequency was 10 Hz or so, which was similar with conventional laser keyhole weld. It changed to dumpy nail, V-shape and U-shape in sequence with the increase of the frequency within the range from 20 Hz to 1000 Hz. The welding speed thresholds transforming the welding from keyhole mode to unstable mode and from unstable mode to heat conduction mode were confirmed as 24 m/min and 48 m/min, respectively. Weld formation mechanisms were summarized by weld overlapping ratio and the transformation of welding mode.

1. Introduction

It is well known that laser welding has the advantages of deep penetration, high aspect ratio, narrow heat-affected zone (HAZ), fine grains and excellent mechanical properties due to high energy density. However, critical edge preparation and resultant clamping accuracy are indispensable for laser welding since laser beam is focused on a very small spot. Moreover, the defects of crack and porosity easily occur in laser welds. Lehner et al. (1999) found that the gap width should be controlled below 10% of workpiece thickness in disk laser welding of AZ91D magnesium alloy because larger gap may cause the defect of weld sag. Katayama (2013) demonstrated that fast solidification rate was one of the main reasons to increase crack within laser welds of aluminum alloy and austenitic stainless steel. Meng et al. (2014) found that the porosity easily formed in CO_2 laser lap welding of 4 mm-thick low alloy steel because of the rapid solidification of molten pool.

In order to improve gap tolerance and weld quality of laser welding, Rubben et al. (1997) developed laser welding with beam oscillating along the weld, which is called laser oscillating welding for brief. By using beam oscillating with maximum frequency of 200 Hz, the gap tolerance of tailed blanks was increased to 0.3 mm, 25% of sheet thickness. With rapid development of galvanometer scanner recently, laser oscillating welding has attracted more and more attentions. Schedewy et al. (2008) found that when using high beam oscillating frequency of 100–200 Hz, fiber laser oscillating welding of carbon steel becomes unstable because the liquid metal is thrown out of molten pool by fast moving laser beam. Choi et al. (2010) found that crack susceptibility of 5J32-T4 aluminum alloy welds can be minimized by laser oscillating welding with the frequency of 5 Hz. Kim et al. (2011) showed that the shear-tensile strength of 6k21 aluminum alloy joint made by disk laser oscillating welding is 29% higher than that of conventional laser welding. Vanska and Salminen (2012) claimed that laser oscillating welding could increase the safety factor of industrial applications by widening the weld. Yamazaki et al. (2013) found that increasing beam oscillating frequency widens but shallows the weld. Schweier et al. (2013) demonstrated that either increasing welding speed or decreasing laser power helps reduce the spatter number during laser oscillating welding.

Above-mentioned researches indicates that laser oscillating welding is potential to improve industrial adaptability of laser welding by improving gap tolerance, and has its own features in weld morphologies. Relevant studies, especially weld formation mechanisms are few. To deepen the understanding of this new technique, laser oscillating welding of AISI304 stainless steel is studied, and the effects of beam oscillating parameters on weld morphologies are discussed.

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Table 2
Welding parameters used in this study.

Welding parameters	Value(s)
Laser power, P (kW)	2.0
Feeding speed of welding head, v_x (m/min)	3.0
Flow rate of argon shielding gas, (L/min)	18
Oscillating amplitude of laser beam, a (mm)	0.5, 1.0, 1.5, 2.5
Oscillating frequency of laser beam, f (Hz)	10, 20, 50, 100, 200, 500, 1000

2. Experimental

Base metal used is 3 mm-thick AISI304 austenitic stainless steel with chemical compositions in Table 1. The welding system is composed of a fiber laser source, a galvanometer scanner and a six-axis robot, as shown in Fig. 1. The fiber laser is IPG YLS-6000 with the maximum power of 6 kW. The galvanometer scanner is SCANLAB hurrySCAN30. The six-axis robot is KUKA KR60HA. During welding, the welding head is driven by the robot. The laser beam with the wavelength of 1070 nm is transmitted by a fiber to a collimator with focal length of 200 mm, reflected by a copper mirror to the mirrors within galvanometer scanner, and focused by a lens with focal length of 250 mm to irradiate base metal with a 0.4 mm-diameter beam spot.

For brief, as shown in Fig. 1, the feeding direction of welding head is defined as X-axis, and the oscillating direction of laser beam is defined as Y-axis,. The moving speed of welding head is named as feeding speed, v_x, and the moving speed of laser beam driven by galvanometer scanner is named as oscillating speed, v_y. The v_y can be computed as follows.

$$v_y = 4a/T = 4af \tag{1}$$

where, T is the time of one cycle, f is beam oscillating frequency, a is beam oscillating amplitude. The real speed of laser beam resulted by v_x and v_y is denoted as welding speed, v, and the real moving direction of laser beam is named as welding direction. The v can be computed as follows.

$$v = \sqrt{v_x^2 + v_y^2} \tag{2}$$

The welding parameters used are listed in Table 2. The experiments were carried out in bead-on-plate configuration. After welding, the welds were cut down to prepare the metallurgical samples. The samples were etched by a solution of 8 g $CuCl_2$, 100 mL HCl and 100 mL C_2H_5OH. Both surface and cross-section morphologies were examined and measured by optical microscope.

3. Results

3.1. Weld surface morphology

As shown in Fig. 2, the welds begin to overlap from the edge to the center with the increase of oscillating frequency. Under each oscillating amplitude, weld surface is characterized by zigzag line, sawtooth line and smooth line in sequence with the increase of the frequency, indicating the fraction of overlapping zone is increasing. Taking the welds with amplitude of 0.5 mm as example, the weld surface is presented as zigzag line when the frequency is 10 Hz, and then changes to be sawtooth line when the frequency reaches 50 Hz, and finally changes to be smooth line after the frequency is larger than 200 Hz.

3.2. Weld cross-section morphology

As shown in Fig. 3, increasing either beam oscillating frequency or amplitude decreases weld penetration depth, and reduces the difference between the cross-section width at the surface, cw_s and the cross-section width at half depth, cw_m. Four types of weld cross-section morphologies appear in sequence with the increase of oscillating frequency, which are slender nail, dumpy nail, V-shape and U-shape. According to the shape characteristics of conventional laser welds, the nail shape, V-shape and U-shape are corresponding to keyhole mode, unstable mode between keyhole mode and heat conduction mode, and heat conduction mode, respectively. Along the transverse width, moreover, the penetration depth at the edge of V-shape and U-shape welds is bigger than that at the center since the edges are heated repeatedly by reversed laser beam.

3.3. Weld geometrical characteristics

The geometrical characteristics of weld surface are illustrated in Fig. 4. For brief, the widths of overlapping and non-overlapping zones along Y-axis are named as w_o and w_{no}, respectively. The whole width of weld surface is named as w. The w is larger than theoretical value, double amplitudes since the molten pool itself has a width. The extra increment caused by molten pool is named as e. Thus, the w can be expressed as follows.

$$w = 2(w_o + w_{no}) = 2(a + e) \tag{3}$$

The fraction of overlapping zone to whole width of weld surface is defined as overlapping ratio, δ, which can be expressed by Eq. (4).

$$\delta = 2w_o/w \tag{4}$$

In Fig. 5, the w decreases gradually to equal to or even smaller than double amplitudes with the increase of oscillating frequency. Schweier et al. (2011) claimed that galvanometer scanner has a frequency limit related to given amplitude. Once the frequency exceeds the limit, the scanner inertia will prevent the laser beam reaching reversal points, which reduces the real amplitude to be smaller than setting value. Meanwhile, the molten pool at this time is too narrow to compensate the reduction because high oscillating frequency causes a too fast welding speed. As a result, the w is even narrower than double amplitudes when the frequency is large enough. Since this frequency limit increases with the decrease of oscillating amplitude, the frequency threshold reducing the w to be smaller than double amplitudes varies with the amplitude. For given amplitudes of 1.0 mm, 1.5 mm and 2.5 mm, the frequency thresholds are found as 800 Hz, 500 Hz and 100 Hz, respectively. However, this phenomenon disappears when the amplitude is 0.5 mm because its frequency limit is higher than 1000 Hz.

In addition, a strong relationship between the δ and cross-section widths is found in Fig. 5. Firstly, both the difference between cw_s and cw_m and the difference between w and cw_s decrease with the increase of the δ. It implies that the weld is more homogeneous in cross-section width. Secondly, the cw_s is nearly equal to the w when the weld overlaps completely. The welds with the amplitude of 0.5 mm overlap completely when the frequency is higher than 200 Hz, while the welds with the amplitude equal to or larger than 1.0 mm overlap completely when the frequency is larger than 500 Hz.

In Fig. 6a, weld penetration depth decreases sharply as the frequency increases from 10 Hz to 100 Hz or so, and then drops slowly, but nearly keeps stable after the frequency reaches 200 Hz. It would be caused by the variation of welding mode. When the frequency is smaller than 100 Hz, the heat input is sufficient to maintain keyhole mode. Thus, the penetration depth is inversely proportional to the frequency since the welding speed is proportional to the frequency. When the frequency increases to be larger than 200 Hz, the welding is characterized by heat conduction mode because the heat input becomes too small to keep keyhole mode. As a result, the penetration at this stage is shallow and nearly without fluctuations.