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Defects inhibition and process optimization for thick plates laser welding with filler wire

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ABSTRACT

One of the challenges in laser welding of thick plates is the formation of lack of fusion defects. In this paper, it is found that the formation of such defects has relations with the surface profile of the weld joint. Experiment results indicate that the weld joints can form perfect fusion when the surface of solidified filling metals is concave. Then the author studied the relations between input welding parameters and single bead geometry, which can affect the surface shape of solidified metals, filling passes and defects formations during the multi-pass laser welding process. Further investigations and analysis show that P/V_f (the radio of laser power to wire feed rate) and V_f/Vw (the radio of wire feed rate to welding speed) can be used to quantify the input variables and impede the formation of lack of fusion defects. Verification results show that the optimized parameters for perfect fusion are: $P/V_f > 1.5$ and $V_{f/}Vw < 6$.

1. Introduction

High strength steel with a thickness over 15 mm are widely applied in shipping hulls, nuclear power plant, and natural gas pipeline [1,2]. One of the methods to join these thick plates is laser welding. When compare with the traditional arc welding, laser welding has specific advantages, such as little deformation, focused heat input and flexibility [1–3]. At the same time, laser welding has much more strict demands on the process parameters. The welding parameters including laser power, welding speed, laser spot diameter, defocused length, incident laser angle, shielding gas and position accuracy all can directly affect the quality of the weld bead [4]. In order to increase the compatibility of input parameters, filler wire is introduced in this process [5].

During the process of thick plate laser welding with filler wire, a narrow gap with a root face is prepared on the bulk plates. The filling metals which are melted by laser beam are used to connect the separated pieces together. Usually, at least two passes are required to fill the gap efficiently. However, defects like lack of fusion, undercut, porosity and pore are often produced during the welding process. Among all of these defects, lack of fusion is one of the most common defects in laser welding with filler wire [6,7]. Usually, inadequate energy input and insufficient filling metals are considered as the main reasons for this kind defect formation [8,9]. Zhang et al. [7] investigated the possibility of laser welding of thick stainless steel plates up to 50 mm. Lack of fusions which appeared in build-up welding can be divided into the lack of fusion A and lack of fusion B. The formation of lack of fusion A is due to the fact that the bead formed in the initial root pass welding was not re-melted during the following build-up welding. The reason of lack of fusion B formation is that the fusion zone is narrower than that of the groove.

For the welding of steel, when the laser power intensity reaches to 0.5×10^4 W mm^{-2}, it will transform from conduction mode to keyhole mode [10]. The so called keyhole is a thin capillary with high temperature and deep penetration. Power density (P/S) is widely used to calculate the threshold of keyhole welding [11]. But, recent researches show that P/d (the radio of laser power to laser spot diameter) is more accurate than P/S to calculate the threshold transition value [12,13]. Zou et al. [13] investigated the theoretical characterization of deep penetration welding threshold induced by 1-μm laser. P/d value is elaborated in mathematical model in order to indicate its usability in calculating the threshold value. Based on the balance between surface tension and vaporization recoil pressure, the deep penetration-welding threshold P/d can be expressed by Eq. (1) [13]. The right hand of the equation indicates that the threshold is related to the physical nature of the welded materials.

$$\frac{P}{d} \approx \frac{\sigma L_v}{A_l}\sqrt{\frac{\pi m_v}{kT_s}} + \frac{2\sqrt{2\pi}(T_v - T_m)\bar{\lambda}_l}{\bar{A}_l \exp(-\frac{P_l C_l v d}{4\bar{\lambda}_l})} + \frac{2\sqrt{2\pi}(T_m - T_o)\bar{\lambda}_s}{\bar{A}_s \exp(-\frac{P_s C_s v d}{4\bar{\lambda}_s})} \quad (1)$$

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where P is the laser power; d diameter of the light spot; b the structure coefficient (ranging from 0.5 to 1); σ surface tension coefficient of the molten pool; L_v latent heat of evaporation; A_l the absorptivity of the incident laser by the liquid material; $\bar{A}_l$ and $\bar{A}_s$ mean absorptivity of the liquid material and solid material, respectively; m_v quality of metal atoms; k Boltzmann constant (1.38×10^{-23} J/K); T_s the surface temperature of the molten pool; T_m melting temperature of welded material; T_v evaporating temperature of welded material; T_0 room temperature; $\bar{\lambda}_l$ and $\bar{\lambda}_s$ mean thermal conductivity of liquid metal and solid metal respectively; $\bar{\rho}_l$ and $\bar{\rho}_s$ mean density of liquid metal and solid metal respectively; $\bar{c}_l$ and $\bar{c}_s$ mean heat capacity of liquid metal and solid metal respectively; v velocity of molecules departing from the molten pool surface;

Usually, the laser works on keyhole mode for thick plates welding [14–17]. Wu et al. [8] proposed to impede the lack of fusion defects by adjusting the laser working mode to conduction mode. This can be achieved by changing the laser spot diameter. As the laser spot diameter d increases, P/d value decreases and the fusion zone will be extended accordingly. When the laser welding is performed in conduction mode, the input P/d of fiber laser ranges from 0.35 to 1.2 kW/mm. However, the disadvantage of this approach is the low energy efficiency. It is reported that the laser energy absorption during conduction mode is less than 20% [18–20]. Besides, the shallow penetration of conduction mode welding can cause the formation of lack of fusion A defects at the interface between adjacent layers [7]. Therefore, the investigation of valuable parameters for deep penetration welding mode is necessary.

The purpose of this paper is to study the formation of lack of fusion during thick plate laser welding with filler wire. In order to impede the lack of fusion defects, efficient methods will be proposed and two parameters P/V_f and V_f/Vw will be used to quantify the input variables. Based on the results of this paper, the welding joints with perfect fusion can be achieved by optimized process parameters.

2. Material and methods

2.1. Material and equipments

The plates used in this paper is AH32 high strength ship steel. Due to the high strength, low temperature toughness, excellent weld-ability and corrosion resistance, AH32 high strength low-alloy steel is widely used in ship hulls construction [21–23]. The size of each piece is 150 mm × 50 mm × 20 mm. The filler wire is carbon steel wire AWSA5.18 ER70S-6(American standard) with the diameter of 1.2 mm. The detailed compositions have been shown in Table 1. In this paper, all the grooves were milled to the "V" shape with a root face, shown in Fig. 1. The bevel angle θ varies from 5–10°. Laser welding was performed by the YLS-10kw fiber laser with a wavelength of 1070 nm and KUKA KR60HA industrial robot. The diameter of the laser spot used in this experiment is 0.72 mm. The incident angle of the filler wire and the laser beam is 51.28° and 80.76° respectively. In general, the best weld joints can be acquired when the wire feed angle is between 45°–60° [24]. The maximum length of the wire out of the nozzle is 14 mm in order to keep it straight. An extended protective gas nozzle which can deliver into the narrow groove protects the welding process with argon shielding gas. The inner and outer diameter of the extended gas nozzle is 2 mm and 4 mm respectively, shown in Fig. 2.

The laser welding process is shown in Fig. 3. The high accuracy 2D laser displacement sensor (model number: LJ-2000) is applied to measure the geometric parameters of the bead and groove. The precision of the measurement is 0.1%. The cross-section micrographs of the welding joints were acquired by the Stereomicroscope (stem 2000).

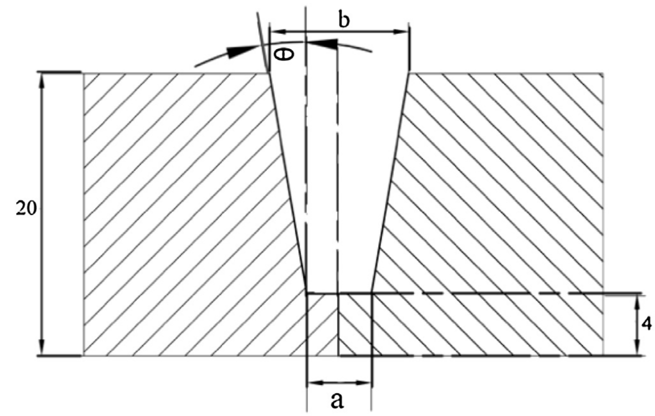

Fig. 1. Schematic diagram of the groove (θ:5–10°).

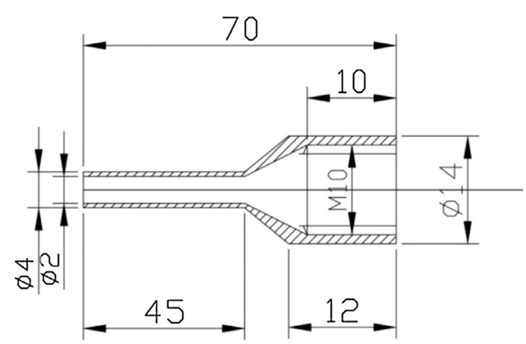

Fig. 2. Schematic diagram of extended shielding gas nozzle.

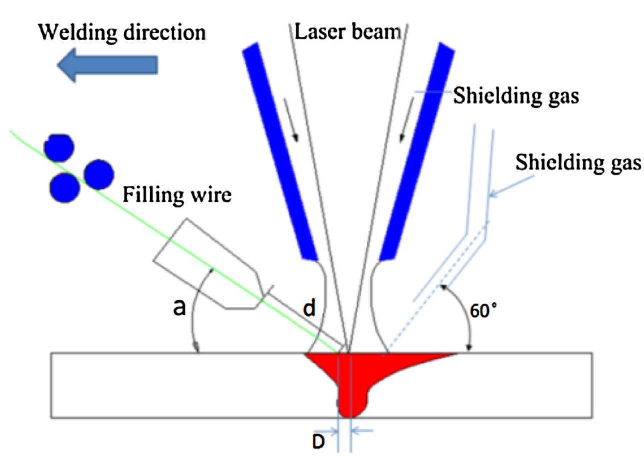

Fig. 3. Schematic diagram of laser welding with filler wire process.

A lot of researches have indicated that parameters including incident laser angle, wire feeding direction, wire and laser beam overlap factor, shielding gas, laser power, welding speed and wire feed rate have direct influences on the surface quality of the filling metals [5,24]. The shape of single build-up weld joint on a flat surface is approaching half circle, shown in Fig. 4. It depends on the radio of bead height (W_H) to bead width (Ww). In the narrow gap laser welding, the bead width, filling volume as well as the bead height of deposited metals should be understood to optimize the multi-pass welding process. The filling volume of the deposited metals can be replaced by the cross-section area of the bead. Previous results have indicated that the interactions among laser power, welding speed and wire feed rate have obvious influ-