



Full length article

Analysis of mechanisms of underfill in full penetration laser welding of thick stainless steel with a 10 kW fiber laser

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ARTICLE INFO

Article history:

Received 2 June 2017

Received in revised form 24 July 2017

Accepted 26 July 2017

Keywords:

Laser welding

Keyhole

Thick plate

Underfill

High-speed imaging

ABSTRACT

With the aim to explore the formation mechanisms of surface underfill, full penetration laser welding of thick stainless steel was conducted, with the use of a 10 kW fiber laser. A modified “sandwich” specimen was used, so as to directly observe the dynamic behaviors of the keyhole, vapor plume, and melt pool with the formation of underfills. On the basis of the experimental investigations, the formation mechanisms of the underfills at the top surface and bottom surface were analyzed. The results show that the downward flow of the molten metal caused by the recoil momentum is a crucial driver for formation of the underfill on the top surface. At full penetration of the melt, a deep underfill with a periodic wide–narrow–wide serrated pattern is formed on the top surface of the weld owing to the periodic fluctuation of the rear keyhole wall. At full penetration of the keyhole, the formation of a deep underfill on the top surface of the weld and undercut on the bottom surface of the weld is presented with massive direct melt loss from the weld pool.

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1. Introduction

With the emergence of commercial high-power, high-brightness fiber and disc lasers, the domination of high-power lasers has been strengthened in material processing, heavy industry and pipeline industry [1–4]. Compared with CO₂ laser, the penetration depth and welding speed obtained by the high-power fiber laser are significantly improved with high laser absorptivity of material and negligible plasma shielding effect [5]. Modern high-power fiber and disc laser sources enable a stable single-pass welding process even for thick plates. Sokolov et al. [6] reported an autogenous full penetration laser beam welding of up to 25 mm structural steel in a single pass with a laser power level of 15–30 kW. Avilov et al. [7] and Bachmann et al. [8] described the experimental and numerical investigations of applying an electromagnetic weld pool support system to full penetration laser welding of a 30 mm thick aluminum plate and a 20 mm thick stainless steel plate using a 20 kW fiber laser, respectively. As expected, a smooth weld without surface underfilling, or

even a convex weld was generated by applying the magnetic field at the bottom in single-pass full penetration welding of thick plates. Zhang et al. [9] experimentally investigated the effect of the processing parameters on the weld bead geometry in laser welding of thick-section stainless steel with a 10 kW fiber laser. Sokolov et al. [10] found that the penetration depth increases significantly in partial vacuum atmospheric conditions during autogenous laser keyhole welding of low alloyed steel with a 16 kW disc laser. Guo et al. [11] and Shen et al. [12] compared the characteristics of high power fiber laser welding of 13 mm thick steel in flat and horizontal positions. Sun et al. [13] presented a new welding technique with combination of the autogenous laser welding and laser welding assisted with a cold wire, for welding a thick stainless steel in horizontal position. Atabaki et al. [14] compared the characteristics of autogenous laser welding and laser welding with a cold filler wire for joining thick plate of a 15 mm structural steel in the horizontal position.

However, a series of experiments in the laboratory and factory proved that the weld appearance of full penetration laser welding of thick plate with the use of high-power fiber laser is very difficult to control. Usually, welding defects, namely surface underfill, root sagging and spatters, are prone to be generated [15–19]. Especially, no matter how one changes the welding speed, either partial penetration joint or full penetration joint, underfill and/or root sagging

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can be obtained [9]. Up to now, several different explanations for the formation of underfill defects have been proposed. Li et al. [20] and Pan et al. [21] showed that the underfilled weld bead is usually caused by the expulsion of liquid metal in the form of spattering. Yang et al. [22] demonstrated that narrow welding pool, less molten metal, as well as poor liquid metal backfilling ability, together with high cooling rate result in the formation of underfilling in autogenous laser welding of 3 mm aluminum alloy. Fabbro [23] pointed out that both keyhole elongation and two side flows also induce underfilling defects as the welding speed is greater than 12 m/min. Kawahito et al. [24] presented that underfilling is found at more than 10 m/min welding speed, due to metal ejection or displacement from the weld pool during high-power laser welding. Guo et al. [11] revealed that the surface underfilling is caused by a gravity-induced fluid flow, towards the root of the weld during autogenous fiber laser welding of 13 mm thick S700 high strength low alloy (HSLA) steel plates in flat position. Furthermore, they found that underfill in the weld is generated when the laser power is increased from 6.7 kW to 6.5 kW during autogenous fiber laser welding of 8 mm thick S960 HSLA steel plates in flat position [16]. Matsumoto et al. [25] demonstrated that a full penetration weld with deep underfill defects is generated on the top or bottom surface of the weld beads with a shorter focus depth optics system during the high-power fiber laser welding of a 12-mm-thick high-strength steel plate.

In the reported literatures, there have been few attempts to study the surface underfilling in the full penetration laser welding of thick plates at low welding speeds with the use of a high-power fiber laser. They fail to fully illustrate the underfilling phenomena in the high-power fiber laser welding of thick plates at low welding speeds. Moreover, the relationship between underfill defects and the penetration regimes has not been discussed. In the present study, direct observations of the keyhole and molten pool flow during a high-power fiber laser welding process were implemented on a modified “sandwich” specimen [26–28] using high-speed

photography. With the use of a high-speed camera, the bead-on-plate welding process was under observation as well, so as to work out the formation mechanisms of surface underfilling in the high-power fiber laser welding of a 12 mm thick stainless steel plate. The formation mechanisms of the surface underfill were also investigated.

2. Experimental procedures

The experimental setups are illustrated in Fig. 1. With a maximum power of 10 kW and beam parameter product of 7.5 mm·mrad and a processing fiber of 200 μ m in diameter, a continuous wave fiber laser (IPG YLS-10000) was used as the laser source. The laser beam emitted from the end of the optical fiber was collimated by a lens with focal length of 150 mm and afterwards it was focused on the specimen surface using a lens with focal length of 300 mm.

The Type 304 austenitic stainless steel was used as the base material, whose chemical composition is presented in Table 1. A 12 mm stainless steel sheet was used for the bead-on-plate welding, as illustrated in Fig. 2(a). One sheet of stainless steel with the size of $40 \times 12 \times 5$ mm³ and one sheet of GG17 glass with the same size were aligned and clamped by a jig, to form a modified “sandwich” sample, as shown in Fig. 2(b). The experimental parameters are listed in Table 2. The shielding gas was nitrogen supplied from the side during bead-on-plate welding.

During high-speed imaging experiments, a high-speed camera was used with the frame rate ranging from 5000 fps (frames per second) to 20,000 fps. As can be seen from Fig. 2, the high-speed camera was positioned laterally and mounted horizontally to observe the surface melt pool, the longitudinal keyhole and melt pool, respectively. For the sake of observing the molten pool, a 30 W diode laser with a wavelength of 808 nm was used to irradiate the welding zone. Correspondingly, a filter with a passband of 808 ± 3 nm was mounted in front of the camera lens.

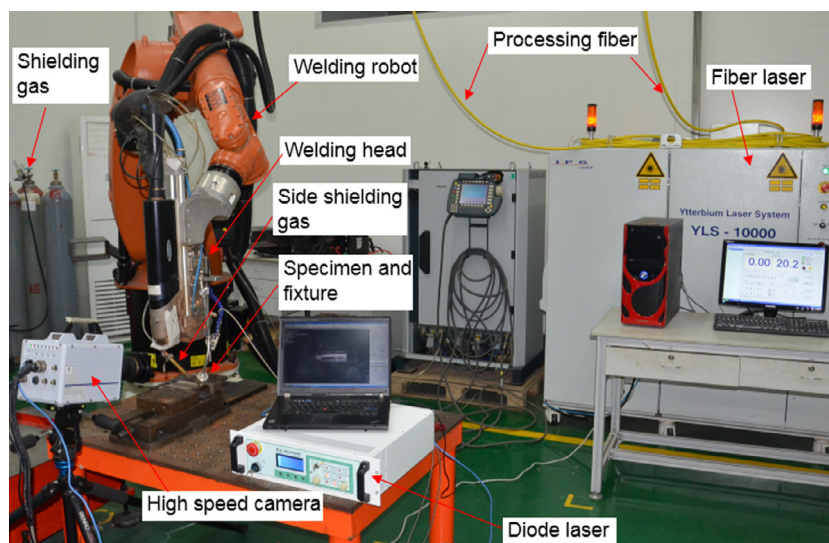


Fig. 1. Experimental setup.

Table 1
Chemical composition of the base material.

Element	C	Mn	P	S	Si	Cr	Ni	N	Fe
(Wt.%)	0.07	2.00	0.045	0.03	0.075	18.28	8.15	0.1	Balance

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