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Experiments on formation mechanism of root humping in high-power laser autogenous welding of thick plates with stainless steels

Mingjun Zhang[a,c,*], Yingzhe Zhang[b,c], Cong Mao[a], Yongle Hu[a], Genyu Chen[c], Zhuming Bi[d]

[a] Key Laboratory of Lightweight and Reliability Technology for Engineering Vehicle, Education Department of Hunan Province, Changsha University of Science and Technology, Changsha 410114, PR China
[b] College of Materials and Metallurgical Engineering, Guizhou Institute of Technology, Guiyang 550003, PR China
[c] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, PR China
[d] Department of Civil and Mechanical Engineering, Purdue University Fort Wayne, Fort Wayne, IN 46805, USA

HIGHLIGHTS

- The focal position had a great effect on the formation of root humps.
- Root humps were always generated during full penetration autogenous laser welding at a positive defocus.
- The formation of root humps depends on stability of the keyhole at a negative defocus.
- The welding speed could be optimized to suppress root humps only when a negative defocus was applied.
- Shielding gas played a positive role in suppressing root humps.

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ABSTRACT

Deep penetration laser welding is an efficient and effective way to produce the heavy section structure. Deep penetration can be achieved by high-power autogenous laser welding; however, it poses a significant challenge in obtaining good quality of welds, which are free of imperfects such as root hump, under-fill, and collapse. It is partially attributed to a lacking of understanding on the formation of imperfects. In this paper, we looked into the formation mechanism of root humping experimentally. The laser autogenous welding were implemented using a 10 kW fiber laser on thick stainless steel plates. A high-speed imaging system was applied to observe the metallic vapor and molten pool flow during the welding process. The formation mechanism of root humping with different focal positions were analyzed and discussed. The results showed that the most important welding parameter was the focal position; it had a strong effect on the formation of root hump; it affected the penetration mode of laser keyhole welding. The root hump had a large volume and were generated periodically when a positive defocus was applied. When a negative defocus was applied, the root hump had a small volume and with no obvious periodicity. On the other hand, the welding speed could be optimized to suppress root hump only when a negative defocus was applied. Finally, applying a bottom shielding gases played a positive role in reducing root hump. The results from our study provides the evidences to develop the strategies to suppress root hump during high-power laser autogenous welding on thick metal plates.

1. Introduction

The emergence of commercial 10 kW level high-power lasers makes it possible to join thick metal plates by autogenous welding with single pass. In contrast to conventional welding processes, the welding process with high-power laser possesses a number of significant advantages including lower heat input, higher speed of welding and increased depth of penetration. However, autogenous laser welding brings a significant challenge in maintaining the consistence of weld appearance. Inappropriate welding parameters such as a high aspect ratio or an exceeded depth of penetration may cause some imperfects of laser welding such as root hump, under-fills and spatters [1–6]. In this paper, the imperfects associated with root hump are especially interested. Root hump are also commonly known as *dropping* [7], *root dropouts* [8] and

* Corresponding author at: Key Laboratory of Lightweight and Reliability Technology for Engineering Vehicle, Education Department of Hunan Province, Changsha University of Science and Technology, Changsha 410114, PR China.
E-mail address: mj_zhang@csust.edu.cn (M. Zhang).

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chain of pearls [9]. It is well known that a welding process becomes increasingly challenging when the thicknesses of metal plates to be jointed increase; since root defects are likely formed when the plates are thick. For an autogenous laser welding, Guo et al. [10] found that it was difficult to achieve the satisfactory quality of welds without using a weld pool supporting system [11]; this was due to an obvious downward melt flow, which was formed underneath the wall of the front keyhole. The melt was pressured towards the bottom surface that led to root hump of welds [12,13]. Moreover, it was proven that due to the difference of absorptivity, the laser with a wavelength of 1 μm (i.e., fiber, disc and yttrium aluminum garnet (YAG)) would accelerate the melt downwards at keyhole exits more than conventional CO_2 lasers with a wavelength of 10 μm [14]. Haug et al. [15] also confirmed that the welding by CO2 lasers was more robust and less susceptible for the formation of root hump.

Many workers have investigated of the formation mechanism of root humping in welding processes [1,15–17]. For examples, Powell et al. [16] found that supplying the melt into the weld pool and surface tension formed large humps at the rear of the bottom weld pools. They verified this concluded by numeric simulation and experiments. Kaplan and Wiklund [18] indicated that the weld of metal plates with a thickness of 16 mm was sagged when a high line energy was used and the focusing lens were set as a focal length inappropriately. Ohnishi et al. [19] demonstrated that a sufficient laser power integrated with a hot wire produced a keyhole with a complete penetration and obtained the welds with hump-free butts for thick steel plates with a high strength. Havrilla et al. [7] also found that root defects could be eliminated by increasing laser power when the laser welding on 12 mm-thick steel plates were tested. Ilar et al. [1] looked into the combination of surface tension, melt supply and gravity effort on root humping, a significant difference was observed in comparison to the top surface humping in laser welding. Blecher et al. [20] concluded that root defects were governed by the difference of the gravity force of melt in the weld pool and the surface tension at the bottom surface. Furthermore, welding of the plates with stainless steel was prone more to form a root defect than that of the plates with low-carbon steel since there surface tensions are different. Frostevarg and Haeussermann [8] tried a pulse laser to suppress root defects; the liquid material was ejected as spatters from the exit of welding process. This was equivalent to the effect from an increase of laser power; it eliminated root hump by producing a full penetration [15]. In our previous investigation [21], of the welding parameters were optimized in the laser welding of plates with thick stainless steel, and we found that the root sag defects occurred at a lower welding speed and the focal position was the critical factor to obtain a fully-penetrated weld.

As a summary, root hump is most problematic imperfect [20], and a comprehensive understanding of root humping mechanism in high-power laser welding is lacking. Therefore, we are highly motivated to investigate the formation mechanism of root humping during autogenous laser welding, and the welding process on thick stainless steel plates using a 10 kW fiber laser was focused. To examine root hump in details, a high-speed imaging system was applied to observe the melt flow and metallic vapor in high-power fiber laser welding with different focal positions. Finally, the formation mechanism of root humping with different focal positions were discussed.

2. Design of experiments (DoE)

Fig. 1 showed the setup of experiments. The selected laser source was a continuous wave fiber laser (IPG YLS–10000) [22]. The main specifications of the laser source were (1) the options of beam parameter product were 3.8, 5.2, and 7.0 (mm × mrad), (2) maximized average power is 10 kW, and the options of output fiber core diameters were 100, 150, and 200 μm. The laser beam emitted from the end of the optical fiber was collimated by a lens with a focal length of 150 mm; it was then focused on the specimen surface using another lens with a focal length of 300 mm.

Fig. 2 showed the schematic representation of the experimental setup with different camera configurations. The materials to be welded were Type 304 austenitic stainless steel, and the thickness of steel plates was 12 mm. The chemical composition of the plate materials was given in Table 1. The experimental parameters are listed in Table 2.

3. Results and discussion

3.1. Effects of welding parameters on formation of root hump

Three main welding parameters under investigation are focal position, welding speed, and shielding gas at bottom surface. The effects of these welding parameters on the formation of root hump are discussed as below, respectively.

3.1.1. Focal position

Fig. 3 showed the appearances of the welds at different focal positions with the same intensity of laser (i.e., 10 kW), the welding speed was 0.9 m/min, and the top shielding gas flow of 20 L/min (N_2). Defocus distance was measured from the focal position to the top surface of the specimen. The positive defocus meant that a focal position was above the top surface of the specimen; while the negative defocus meant the top surfaces of the specimen was above. As seen in Fig. 3, the weld was not fully penetrated at the beginning of the welding process, then, the weld was penetrated at a spot with the formation of a separate dropout. Where after, the weld was penetrated through the specimen and it came with the formation of a root hump at the defocus of +10 mm. When the defocus was reduced to +5 mm, two large dropouts sagged on the bottom surface along the welding direction. At the beginning of the welding process, two large spatters were formed on the top surface, the weld was then under-filled at the top surface until the welding process was completed. Based on the observation on the weld appearance, one could concluded that the weld failed to penetrate the specimen at the beginning of the welding process, which was shown in Fig. 7 from high-speed imaging. When the focal position was located on the top surface of specimen, the weld penetrated the specimen from the beginning to end; the weld appearance on the bottom surface was satisfactory since only a few of small spatters occurred on the weld bead. However, the weld appearance on the top surface was unsatisfactory since a deep under-fill and several spatters were observed. The full penetration welds were obtained when a negative defocus was applied. As shown in Fig. 3, the material around the weld bead at the bottom surface was scorched by the vapor plume at the exit which was ejected out of the process zone. Two small dropouts and several small spatters were formed on the bottom surface. The weld width was consistent, and the under-filling appearance did not have spatters on the top surface; it showed that the welding process was instable and the liquid metal was flown away at the exit of the processing zone at the bottom surface.

3.1.2. Welding speed

Fig. 4 showed the appearances of welds at different welding speeds when the laser power was 10 kW, the defocus was varied from +10 mm and −10 mm, and the top shielding gas flow was set as 20 L/min (N_2). As shown in Fig. 4, at the defocus of +10 mm and a low welding speed the welds penetrated through the specimen with the formation of the under-fill on the top surface and the root humps on the bottom surface. Once the welding speed was increased to 1.5 m/min, the weld partially penetrated into the specimen. In comparison with the welds at the defocus of −10 mm, bigger dropouts sagged at bottom surface of the welds at the defocus of +10 mm, which was shown in Fig. 4. More interestingly, the dropouts inevitably occurred at the beginning of the welding process at the defocus of +10 mm. For a defocus of −10 mm, the dropouts usually occurred at the middle or end part of the welds. Numerous experiments proved that when a positive defocus was applied and the welding process was executed horizontally, it was