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Experimental and numerical analysis of molten pool and keyhole profile during high-power deep-penetration laser welding

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ABSTRACT

High power laser welding is as an ideal advanced technology for joining the thick steel plates with high efficiency in the industries. This paper proposes a 3D numerical simulation modeling method to investigate keyhole profile characteristics and the effect of keyhole evolution on the molten pool, and understand weld formation process and defect generation, including the welding phenomena such as swelling, column and spatter in the weld pool during high-power deep-penetration laser welding. To reveal the weld formation process, the gas layer, keyhole free surface, molten pool surface, and solid-liquid-vapor three-phase transformation are considered in the model. Based on the proposed model, the keyhole periodic variation profiles and molten pool evolution are calculated. The interaction between the keyhole and molten pool dynamic behavior and weld defects are also identified and discussed in details. The numerical simulation results are compared with the experimental and literature results and good agreements are achieved. It is found that the constriction and bulge formed on the rear keyhole wall is the key factor causing periodical change of keyhole inlet. The oscillating interface between the keyhole and molten pool is often accompanied by swellings and columns, which is the main factor for spatter formation.

1. Introduction

High power laser welding has been as an ideal advanced technology for joining the thick steel plates with high efficiency and widely used in the industries. The ultrahigh peak power density from a 10 kW fiber laser can reach MW mm^{-2} levels [1], which enables the thick plates to be joined with single-pass welding and hence greatly improves the welding efficiency. The maximum weld depth with high power fiber laser welding has been over than 12 mm [2]. In the conventional method, the pre-processing for specimen and multi-pass welding are often required during the thick steel plates joining [3]. Since the high power laser welding process is affected by the complex heat and mass transfer behavior, the weld defects like undercut [4], spattering [1] and humping [5,6] are easily generated. Especially, the keyhole and molten pool dynamic behavior are becoming more and more instable as the increase in welding speed. The defects will emerge in the weld much more frequently. Improving the welding efficiency without sacrificing weld quality is severely limited by the weld defects. Therefore, understanding the formation process of instable keyhole profile and the dynamic characteristics of interface between the keyhole and surrounding molten pool in the high power welding is of great significance for improving the productivity and weld appearance quality.

To study the dynamic behavior of the keyhole and molten pool in the high power laser deep penetration welding, experimental efforts have been made to observe the welding process. Fabbro [7] defined the characteristic regimes of laser welding in a large welding speed range. The humping weld seam with strong undercuts was observed at above 20 m/min high speed welding in their study. Kawahito et al. [1] investigated the effects of laser power, power density and welding speed on the formation of sound weld in the bead-on-plate welding of type 304 stainless steel plates with 6 kW and 10 kW high power fiber laser. The welding phenomena recorded by high-speed video cameras and X-ray transmission real-time imaging system were clarified. They recognized that the humping formation was dependent upon the volume of molten metal above the surface, strong melt flow and other dynamic or static factors. Zhang et al. [8] presented a modified sandwich specimen with a 10 kW fiber laser used for observing the keyhole profile during the deep penetration laser welding. In their experiments, the distinct keyhole wall, moving liquid shelf on the front

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keyhole wall and accompanying hydrodynamic and vapor phenomena are directly observed. Li et al. [9] studied the dynamic behavior of keyhole based on a butt-joint configuration of transparent glass and stainless steel during the high-power deep-penetration welding. Their results showed that the gauffers and vapor whirlpool were the main factors causing the vapor-generated wave on the rear keyhole wall and fluctuation of keyhole profile, which resulted in the changes of keyhole inlet and molten pool accompanied by swellings, columns and spatter. They also investigated the relationship between spatter formation and molten pool dynamic behavior using the high-speed camera and X-ray transmission imaging system during the high power laser welding under different welding parameters [10]. Zhang et al. [11] observed the dynamic behavior of the keyhole, vapor plume, and weld pool with the spatters formation and analyzed the formation mechanisms of spatter in both top and bottom surfaces in high power fiber laser welding of thick plate. The spatter ejected from the keyhole inlet was mainly affected by the upward molten metal flow above the keyhole and strong shear stream of the directed vapor plume force at partial penetration. For the full penetration of the keyhole situation, the viscous friction drag associated with high-speed motion of vapor plume was the crucial driving force for spatter generation. Nakamura et al. [12] clarified the relationship among the laser-induced plume, molten metal flowing and spatters formation mechanisms during the 10 kW high power laser welding of pure titanium plate. Luo et al. [13] performed the welding experiments to investigate the coupling interaction mechanism between the molten pool and metallic vapor by analyzing their behavior from high-speed camera. The results showed that the fluctuation of molten pool surface was greatly affected by the metallic vapor, which plays major role in the weld bead formation. However, the application of experimental methods is limited due to the fact that the equipment is often costing and bulky and observing process is time and labor consuming. Moreover, the interfacial interaction between the molten weld pool and keyhole has been not understood well.

Computational fluid dynamics (CFD) methods have recently been discussed in the literature [14–17] and applied to high energy beam welding including the phenomena observed in experiments such as weld bead formation and defect generation. Panwisawas et al. [14] proposed a physics-based model considering the heat transfer, fluid flow and interfacial interactions to simulate keyhole and porosity formation during laser welding of Ti-6Al-4V titanium alloy. Pang et al. [15] developed a novel 3D transient multiphase model which took the self-consistent keyhole, metallic vapor plume and weld pool dynamic behavior into consideration in the deep penetration fiber laser welding. The obtained weld bead dimensions, transient keyhole instability, weld pool evolution, and vapor plume dynamic behavior were kept consistent with the experimental results. Tan et al. [16] developed a three-dimensional transient model to investigate the dynamic behavior of keyhole, vapor plume and molten pool. The complex surface phenomena on the keyhole wall and molten pool hydrodynamic behavior were calculated and validated against the experiments. Bachmann et al. [17] investigated the effect of alternating current magnetic field on the laser beam keyhole welding based on the three-dimensional turbulent steady state numerical model. Their results indicated that the gravity drop-out caused by the hydrostatic pressure could be prevented by alternating current magnetic field. However, the calculation of evolution of the weld pool and keyhole and the prediction for weld penetration and width in the normal welding are mainly focused by these methods. They may not be efficient for investigating the keyhole profile characteristics and molten pool dynamic behavior in the high power fiber laser welding. In particular, the formation processes of weld appearance defects which are affected by the molten pool dynamic behavior are not involved.

Only a few methods for the analysis of keyhole profile characteristics and the effect on the molten pool and weld defects formation in high power laser welding based on the numerical simulation have been reported in the previous literatures. Zhang et al. [18] simulated the coupling behavior between keyhole and molten pool in laser full penetration welding using 16 kW maximum power thin disk laser. The weld cross-section morphology and molten pool dynamic behavior were identified and the calculated results agreed well with the experimental results. The keyhole wall features and the interaction between the keyhole and molten pool, especially for the influences on the weld defect formation during the high power laser welding were still not revealed. Therefore, this paper proposes a 3D numerical simulation modeling method to investigate keyhole profile characteristics, the effect of keyhole evolution on the molten pool, and understand the weld formation and defect generation, including the welding phenomena such as swelling, column and spatter in the weld pool during high-power deep-penetration welding. The gas layer above the molten pool, keyhole free surface, molten pool free surface, and solid-liquid-vapor three-phase transformation are considered in the model to reveal the weld formation process. The keyhole periodic variation profiles, molten pool dynamic behavior, the interaction between the keyhole and molten pool behavior, and weld defects are analyzed based on the calculation results. The numerical simulation results show good agreements with the experimental and literature results.

The rest of the paper is summarized as follows: In Section 2, the experiments are designed and conducted. The description of the numerical simulation modeling including the boundary conditions and numerical implementations is provided in Section 3. The Section 4 introduces the model validation and comparison of the simulated and experimental results, keyhole profile characteristics, molten pool behavior, interfacial interaction of keyhole and molten pool. Finally, the conclusions of the current research are offered.

2. Experimental set-up

In this paper, the 8 mm thickness SUS316L stainless steel plate is selected as the base material. Table 1 shows the chemical composition. The whole laser welding process is conducted using a fiber laser (IPG YLS-10000) with the continuous wave. The maximum output power is 10 kW. The optical fiber diameter is 0.2 mm and the laser beam wavelength is 1070 nm. The output laser beam is converted into parallel light by the collimation lens with 150 mm focal length and then focused into spot diameter 0.4 mm at the focal point with lens of 300 mm focal length. The beam intensity distribution is approximate Gaussian distribution and the top surface of workpiece is set as the focal plane. The welding head is equipped with coaxial air blowing protection device and installed on a welding robot, KUKA. The laser welding system is shown in Fig. 1 and the corresponding technical parameters are tabulated in Table 2.

To obtain the keyhole and molten pool behavior, the welding process is observed by a high speed CMOS camera. The detailed keyhole and molten pool behavior are captured with 5000 frame per second (fps) from the top view. The 10 W diode laser with 808 nm wavelength is used to illuminate the welding zone. A narrow band-pass (808 ± 3 nm) interference filter is installed in front of the camera lens to improve the contrast between the molten pool and other region. To avoid the oil pollution and oxide film, all of the surfaces of specimens are brushed using fresh wire brush and cleaned by acetone swabbing carefully in advance. The shielding gas, Argon, is supplied laterally with a flow rate of 20 L/min.