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A three-dimensional numerical simulation model for weld characteristics analysis in fiber laser keyhole welding

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ABSTRACT

The weld geometry characteristics are highly related to the mechanical properties and performance of the joints. The top surface of the weld is often assumed as the flat surface during calculating the fluid flow in the molten pool and hence weld reinforcement is ignored among the geometric parameters. In this paper, a three-dimensional numerical simulation model is developed to investigate the characteristics of the weld generated in the fiber laser keyhole welding. The gas layer above the molten pool has been considered to simulate the top surface of the weld in the simulation model and the free surface shape of the keyhole is calculated by the volume of fluid method. The hybrid heat source model is determined by the analysis of weld bead characteristics. Based on the numerical simulation results, the evolution of the weld profile characteristics have been demonstrated and the results are adopted to estimate the shape and sizes of the generated weld bead. From the comparison, the simulated results of the weld bead agree well with that of experiments. Furthermore, weld beads formed under different process conditions are calculated and the errors between the simulated and experimental results are analyzed in details.

1. Introduction

Laser welding is an as an advanced manufacturing technique increasingly being used for joining materials due to high welding speed, high aspect ratio, and narrow heat affected zone. The laser beam with high energy density is loaded on the surface of the metal plate and the evaporated materials in the region result in the formation and evolution of the keyhole rapidly. The weld bead is formed under the condition of instable keyhole behaviors and complex multiphase flows involved in the welding process. The weld geometry characteristics play a major role in the mechanical properties and performance of the joints. The welding quality is often evaluated on the weld bead geometry, mechanical properties, and distortion [1]. Consequently, investigating the geometry characteristics of the weld bead to improve the welding quality is of great significance in the practical production.

The process parameters optimization methods have been introduced into the welding field to acquire the desired weld bead. Casalino et al. [2] investigated the effects of welding parameters on the shape of the welded area, hardness variation and the defects level by the statistical and Taguchi approaches. Based on the analysis, the optimization process could be performed empirically. Olabi et al. [3] employed the back-propagation artificial neural network and Taguchi approach to find out the optimum levels of the welding process parameters for laser welding of medium carbon steel butt weld. They observed that the obtained optimal solution was valid for weld improvement. Park and Rhee [4] reported that the laser power, welding speed and wire feed rate were optimized based on the process modeling and parameter optimization using back-propagation neural network and genetic algorithm in aluminum laser welding. The optimal results illustrated good agreement with the experimental results. Sathiya et al. [5] introduced that input parameters, laser power, welding speed, focal position and shield gas had great effects on the weld geometry characteristics in the laser welding. In their study, the artificial neural network was used to correlate the weld shape with the process parameters and the depth penetration and bead width were optimized by the relationship model. Katherasan et al. [6] optimized the weld bead geometry in flux cored arc welding based on artificial neural network and particle swarm optimization. The maximization of depth of penetration and minimization of bead width and reinforcement were achieved through the optimization

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method. Ai et al. [7] proposed the particle swarm optimization and back propagation neural network integrated method which considered the evaluation indexes of the geometric imperfections of the weld bead. The optimal process parameters for the desired weld geometry were identified. Owing to large amount of experiments in advance is required to achieve the optimal results, these mathematic methods are costly and time consuming and the formation process of weld geometry characteristics is difficult to be demonstrated by the experimental method.

The popular numerical simulation method like: finite element method (FEM) and finite volume method (FVM) [8–10], is as a valid method and widely used to calculate the weld geometry, microstructure and other weld properties. To some extent, numerical analysis of the lase welding process involved thermal phenomena, including heat and mass transfer and fluid flow in the weld pool, can be as an alternative way to replace the expensive and time consuming experiments to obtain the high quality welded joints with desired shape and appropriate mechanical properties. Kaplan [11] developed a moving line source of heat to describe the process of deep-penetration laser welding. The keyhole profile and molten pool have been calculated. Casalino et al. [12,13] predicted the thermal behavior and weld pool shape in the fiber laser welding of titanium and titanium to aluminum with the 2D FEM model. The temperature distribution was calculated for different welding conditions and numerical results approached the experimental data with good accuracy. It is clearly seen that the 2D welding simulation can reduce the computation time substantially. While, the actual heat and mass transfer phenomena involved in the welding process is difficult to be expressed accurately and the deviation between the experimental and calculated results is generated. To improve the validity of the model and the accuracy of described physical phenomena, adopting the three-dimensional (3D) model is focused on the description of numerical simulation of welding process. Shanmugam et al. [14] employed the FEM to analyze the temperature distribution by using a 3D conical Gaussian heat source in the T-joint laser welding process. The effect of process parameters like laser beam power, welding speed and beam incident angle on the weld profile (depth of penetration and bead width) were investigated. Zhang and Zhang [15] proposed a 3D laser deep penetration welding model with the FVM to simulate the dynamic coupling between keyhole and molten pool. The simulation results showed that the calculated weld cross-section morphology and molten pool length on both upper side and lower side agreed well with experimental results. Pang et al. [16] developed a novel 3D transient multiphase model which took the self-consistent keyhole, metallic vapor plume and weld pool dynamics into consideration in the deep penetration fiber laser welding. The obtained weld bead dimensions, transient keyhole instability, weld pool dynamics, and vapor plume dynamics were kept consistent with the results from experiments. However, the calculation of evolution of the weld pool and keyhole and the prediction for weld penetration and width are mainly focused by these methods. They may not be efficient for the geometry characteristics analysis of the weld profile, especially for the significant parameters in the weld bead like reinforcement and waist.

Only a few methods for the analysis of weld bead characteristics with full dimensions have been studied in the literatures. Kong et al. [17] achieved the geometry characteristics of full weld bead by using the double-ellipsoidal and cylindrical volume heat source model in the hybrid laser-gas metal arc welding process. In the characteristic geometry parameters of the weld bead, the reinforcement was taken into consideration together with the width and penetration which agree well with experimental results. Joshi et al. [18] employed the welding simulation of two overlapping beads on the plate. The simulated geometry parameters including the reinforcement were kept consistent with the macrographs of cross-sections from the experiments. However, the height of the reinforcement of the weld bead was constructed in the grid model in advance of simulation. The assumed reinforcement is determined by the experience and error and trial method, which is difficult to reveal the evolution process of the weld characteristics. Hence, this paper proposes a 3D numerical simulation model to investigate the characteristics of the weld generated in the fiber laser keyhole welding. To reveal the evolution of the top surface of the weld, the gas layer above the molten pool is considered in the simulation model. The weld geometry characteristics are analyzed to determine the hybrid heat source model adopted in the simulation process. The evolution of weld profile characteristics is illustrated based on the simulation results and found to be good agreement with the experimental results. To further verify the validity of the model, the weld beads formed under different process conditions are also calculated by the numerical simulation and the corresponding errors are analyzed in details.

The rest of the paper is summarized as follows: In Section 2, the experiments are designed and the weld bead characteristics are analyzed. The introduction of the numerical simulation modeling including the determination of the heat source model and boundary conditions is provided in Section 3. The Section 4 describes the evolution process of the weld bead characteristics, the model validation and comparison of the simulated and experimental results. Finally, the conclusions of the current research are offered.

2. Experiments and weld characteristics analysis

2.1. Design of experiments

The weld geometry is affected greatly by the welding process parameters and selecting appropriate process parameters are often used to obtain a desired shape as well as excellent properties of welded joints [19]. In current research of the fiber laser welding, the welding process parameters, laser power (LP), welding speed (WS) and focal position (FP), are mainly considered as the independent input variables. The schematic of weld bead is shown in Fig. 1. The front width (WF), weld reinforcement (WR), waist depth (WD) and weld penetration (WP) are the geometry parameters to describe the weld characteristics and selected as the corresponding responses. To identify the main effects on the weld characteristics, the three factors and three levels Box-Behnken statistical design

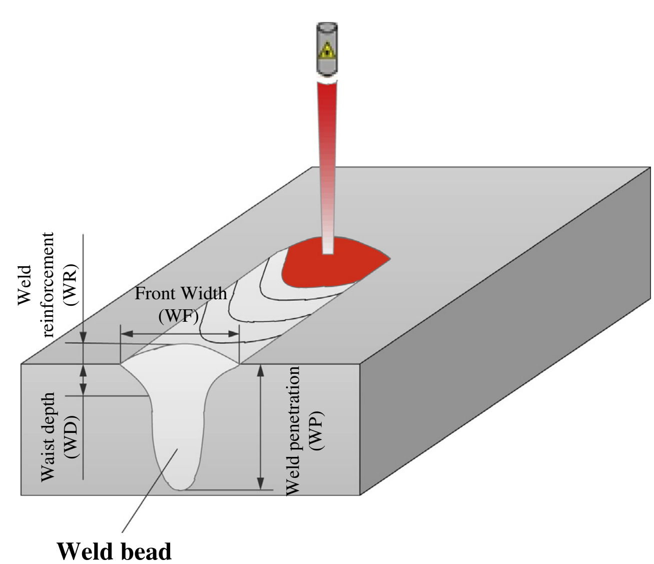

Fig. 1. The schematic of weld bead in the fiber laser keyhole welding.