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Flow and Bead Formation Characteristics in High Power Laser Welding at Different Welding Positions (Invited Talk)

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Abstract

The numerical simulations of high power laser keyhole welding at different welding positions are performed by using Volume-Of-Fluid (VOF) method. The main material is SS400. The multi-physics phenomenon is considered using several models, such as the heat flux of Gaussian heat source, the recoil pressure with Clausisus-Clapeyron equation, the Marangoni flow considering temperature gradient, the buoyancy force with Boussinesq approximation, the additional shear stress and heat source due to metallic vapor ejected through keyhole entrance, the bubble formation assumed as adiabatic bubble, and the multiple-reflection by solving proper discriminant, are used. To analyze the fluid flow pattern, the concept of streamline formed by reconstructing the value of the velocity vector is applied.

Partial and full penetration cases at different welding positions are considered. The welding position seems to have only a minor influence on bead formation characteristics in both cases. This is probably due to the fact that the recoil pressure has a major influence when compared to other driving forces. The flow characteristics and fluid velocity in weld pool are analyzed to compare the gravity direction effect at different welding positions. It is observed that the clockwise flow pattern is mainly formed by the recoil pressure on the keyhole surface in the case of partial penetration. The laser energy can't maintain the whole weld pool when the weld pool size becomes too large. And then the solidification starts from the middle part of weld pool and a necked weld pool shape is formed. In the full penetration welding, the weld pool flow patterns are affected by the leakage of laser power through the full penetration keyhole and also by surface tension. Furthermore, the numerical simulation of full penetration welding with AISI316L is also performed to analyze the effect of material properties. The weld bead shapes obtained by simulations were compared with the corresponding experimental results to confirm the validity of the process models adopted and the CFD simulation tool.

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1. Introduction

Laser welding process includes multi-physics phenomenon. Understanding and analyzing the phenomenon is considered important process to predict the bead formation and weld defects. The numerical simulation is considered as an alternative analysis method due to the limitations of experimental analysis method. As the simulation methods have been improved, laser welding simulations of various conditions are also performed to analyze the effect of weld variables and driving forces. In this paper, the numerical simulations of high power laser keyhole welding at different welding positions are performed by using Volume-Of-Fluid (VOF) method. Full and partial penetration cases are considered. To analyze the fluid flow pattern, the concept of streamline formed by reconstructing the value of the velocity vector is applied. The main material is SS400. To analyze the effect of material properties, AISI316L is also used. Mathematical models are validated by comparing the weld bead cross sections between experiment and simulation results.

2. Mathematical models

The molten metal is assumed as incompressible, laminar and Newtonian fluid in this paper. To consider the multi-physics phenomenon, several models, such as the heat flux of Gaussian heat source, the recoil pressure with Clausisus-Clapeyron equation, the Marangoni flow considering temperature gradient, the buoyancy force with Boussinesq approximation, the additional shear stress and heat source due to metallic vapor ejected through keyhole entrance, the bubble formation assumed as adiabatic bubble, and the multiple-reflection by solving proper discriminant, are used. In full penetration cases, modified vapor-induced model, assumed as zero vapor velocity in center of keyhole and linearly increased velocity through the top and bottom of keyhole, is used.

3. Results and discussion

3.1. Partial penetration cases (SS400)

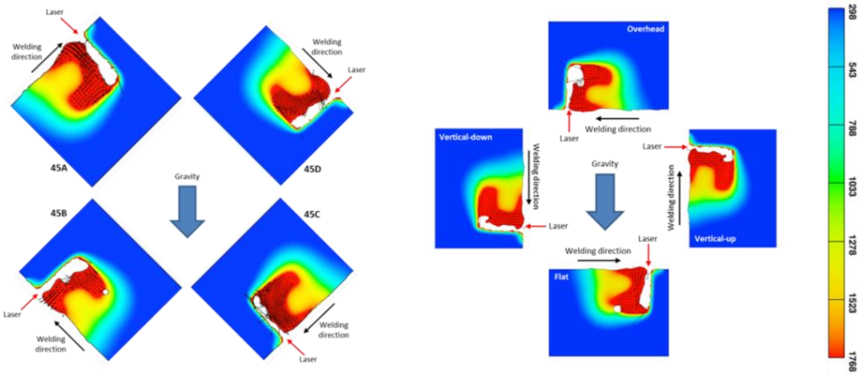


Fig. 1 Temperature profile of longitudinal section in partial penetration

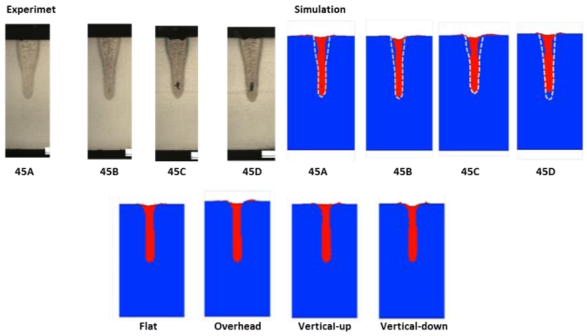


Fig. 2 Cross section bead shapes in partial penetration

Laser power is 9kW, welding speed is 1.5m/min and workpiece thickness is 20mm. Fig. 1 and 2 show the simulation results of partial penetration cases. In partial penetration cases, necked weld pool shape is observed because of weld pool size and solidification. The laser energy can't maintain the whole weld pool when the weld pool size becomes too large. And then the solidification starts from the middle part of weld pool and a necked weld pool shape is formed. The welding position seems to have a minor influence on not only bead formation but also weld pool behavior, and recoil pressure has a major influence. 8 simulation results are almost similar. In partial penetration cases, solid metal around the weld pool is applied as relatively bigger limit and block for interruption of weld pool movement.

3.2. Full penetration cases (SS400)

Laser power is 8kW, welding speed is 1m/min and workpiece thickness is 10mm. Fig. 3 and 4 show the simulation results of full penetration cases. The necked weld pool shape is also observed. The welding position seems to have a minor influence on bead formation. However, there are differences in weld pool shapes probably due to the gravity effect caused by the welding position. In full penetration cases, the effect of solid metal limit around the weld pool becomes relatively smaller. The flat and vertical-up positions have relatively longer length of lower part of weld pool indicated by black and blue circle in Fig. 3 when compared to overhead and vertical-down positions. Generally, the behavior of fluid flow in weld pool has clockwise rotation by recoil pressure in lower part, and intermittently rising flow by strong recoil pressure in lower part or descending flow by gravity in upper part as shown in Fig. 5. Fig. 5 indicates streamline and flow velocity with color, and bright color means fast flow velocity.

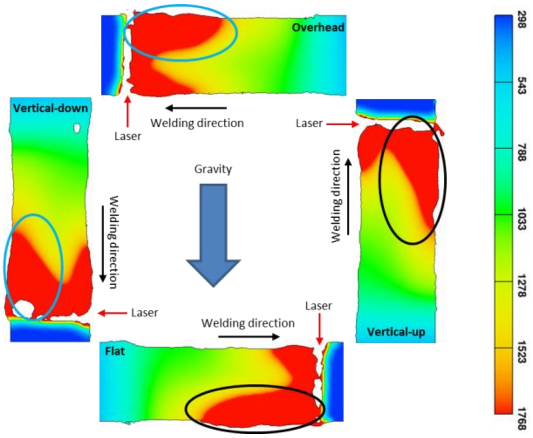
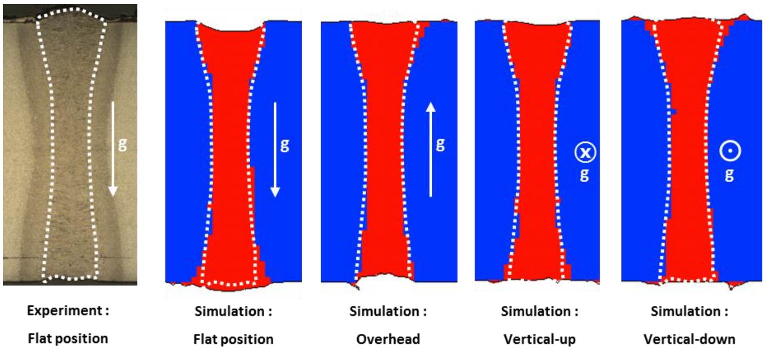
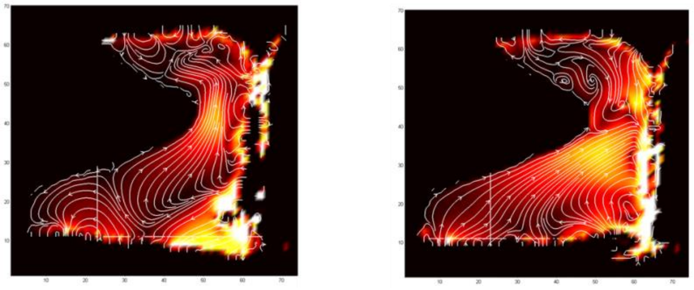


Fig. 3 Temperature profile of longitudinal section in full penetration



Experiment : Flat position **Simulation : Flat position** **Simulation : Overhead** **Simulation : Vertical-up** **Simulation : Vertical-down**

Fig. 4 Cross section bead shapes in full penetration



(a) Rising flow (b) Descending flow

Fig. 5 Streamline of weld pool; (a) Rising flow; (b) Descending flow

Overhead position has stronger rising molten metal movement by fluid flow and weaker descending behavior than flat position due to the opposite gravity effect. Therefore overhead position has relatively shorter length of lower part of weld pool, because more molten metal exists in upper part of weld pool in overhead position than flat position. Weld pool of vertical-up position is tensioned and weld pool of vertical-down position is compressed by gravity. In both cases, the size of lower part of weld pool is bigger. So stronger tensile force has influence on the lower part of weld pool in vertical-up position, and stronger compression force has influence on the lower part of weld pool in vertical-down positions. Therefore, vertical-down position has relatively shorter length of lower part of weld pool, because more molten metal is moved from lower part to upper part in vertical-down position than vertical-up position.

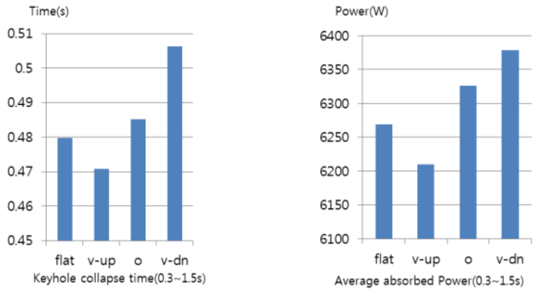


Fig. 6 Comparison of keyhole collapse time and average absorbed power

Because more molten metal exists in upper part in overhead and vertical-down position, keyhole collapse occurs more frequently than the other positions. This phenomenon means that there is more leakage of laser power through the full penetration keyhole as shown in Fig. 6. The leakage of laser power can cause the decreasing of recoil pressure. This reduction in the recoil pressure decreases the rising movement of molten metal. When full penetration keyhole occurs, vapor-induced heat source is applied in bottom parts of workpiece. And this heat source enhances the temperature and decreases the surface tension of workpiece bottom. The decrease in surface tension can reduce return movement to weld pool at the bottom part. As a result, the length of lower part of weld pool can become longer.

3.3. AISI316L cases

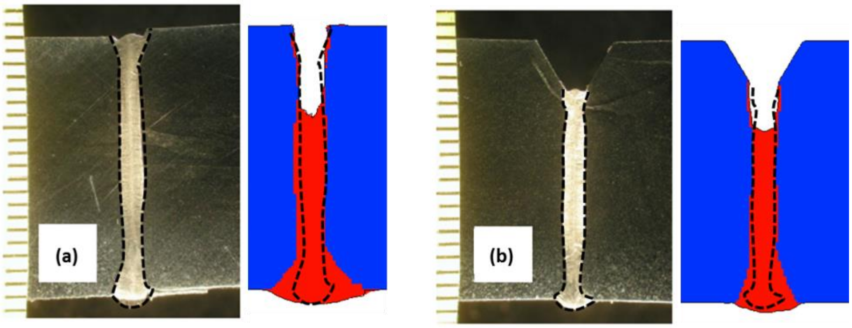


Fig. 7 Cross section bead shapes in AISI316L cases; (a) 19kW case; (b) 16kW case with V-groove

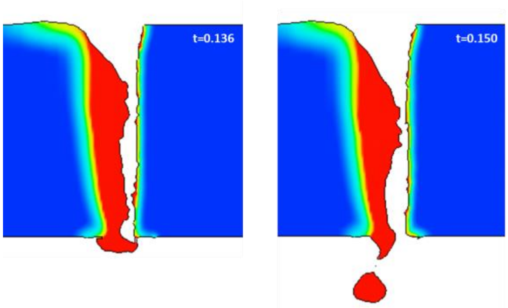


Fig. 8 Separation of molten metal

19kW in case (a) and 16kW in case (b) laser power are applied, welding speed is 1.5m/min and workpiece thickness is 20mm. In case (b), 5mm groove depth and 3mm groove width are applied. There is difference between the simulation results of SS400 and AISI316L cases as shown in Fig. 7. In AISI316L cases, there is undercut in upper part of bead and lower part of bead is large. It is caused by the concentration of molten metal in lower part of weld pool and separation of molten metal through the full penetration keyhole as shown in Fig. 8. There can be two reasons. One is about surface tension and the other is about size of weld pool. AISI316L has smaller surface tension coefficient than SS400 (AISI316L: 1.15kg/s^2, SS400: 1.87kg/s^2). Therefore, the molten metal of AISI316L can be separated easily compared to SS400. And this separation of molten pool can cause the undercut in upper part. In 19kW laser power case, the undercut is larger because high power laser welding has large size of molten pool. When molten pool size becomes larger, recoil pressure caused by laser power can't maintain the whole weld pool and the gravity effect becomes bigger. As a result, some molten metal is separated from weld pool or concentrated in lower part of weld pool.

Therefore, molten metal separation and surface tension can also be the reason for large bead in lower part. However, there is small undercut of bead in experiment. So, additional models and/or modification of the current models will be considered in the future study.

4. Conclusions

In partial penetration cases, necked weld pool shape is observed. The welding position seems to have a minor influence on not only bead formation but also weld pool behavior due to the effect of solid metal limit around the weld pool.

In full penetration cases, necked weld pool shape is also observed and the welding position seems to have a minor influence on bead formation. However, the welding position has an influence on weld pool shapes. Flat and vertical-up positions have relatively longer length weld pool bottom part due to the movement of molten metal, leakage of laser power through the full penetration keyhole and the reduced surface tension by vapor-induced heat source.

In AISI316L cases, there is the undercut by molten metal separation and the concentration of molten metal in lower part. Molten metal separation and concentration are caused by smaller surface tension coefficient and size of weld pool. In 19kW laser power case, the undercut is larger due to large size of weld pool.

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