Development of laser welding simulation code with advanced numerical models*

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Toward a standardization of laser welding repair processes and controlling a residual stress which is induced by laser welding, we constructed the fully parallelized laser welding simulation model using one-fluid model (in the simulation, solid, liquid and gas phase are simultaneously calculated by one set of governing equations) and some advanced numerical models. In the simulation, the base material is a pure aluminum which was included to the code as a physical parameter and we considered the surface tension force and its effect of a temperature gradient named Marangoni stress. As a result, reasonable results were obtained that is welding bead which is one of the representative behavior of a low power density laser welding and the appropriate shape of inside the molten pool. Therefore, the model can be applied to be practical laser welding problems.

Key Words: Laser welding, One-fluid model, Multiphase flow, Marangoni stress, CIP finite volume method

1. Introduction

In a practical use of sodium-cooled FBRs (Fast Breeder Reactors), the standardization of a repair process by a laser welding is of great importance for various reactor components. Since the power density of a laser welding is higher than that of an arc welding, there are many advantages in the laser welding in comparison to the arc welding. Thus, the repairing of the laser welding has been implemented to the R&D of practical use of the FBRs cycle. However, mechanisms of the laser welding processes are not completely understood. Toward a standardization of laser welding repair processes and controlling a residual stress which is induced by a welding, the elucidation of its mechanisms is indispensable research issue. For that issue, numerical simulation is to be expected the powerful tool for understanding the phenomena.

There are two types of the study of the laser welding by numerical simulations. One is assuming the flat surface of the base material and the other one is considering surface deformations. So far, however, there are a few studies which are taken into account the solidification process and the interaction between gas and the surface of a molten pool. It is obvious that the solidification processes is very important for controlling the residual stress with considering such processes. And the interaction between gas and the surface is assumed to be affecting the solidification processes. In order to construct the numerical model which treats the solidification and the welding processes, we have to consider accurate, robust and efficient numerical aspects because the phenomenon has a lot of complex physical processes and wide range of the scale and time of phenomena. To satisfy such numerical aspects, recently, we have constructed the fully parallelized numerical model for the laser welding processes using some advanced numerical models. The model consists of VSIAM3 (Volume and Surface Integrated Average based Multi Moment Method) numerical model and the accurate surface capturing scheme, THINC/WLIC scheme. In the present study, we employed those models from following reasons:

- To avoid time-consuming calculation, the mesh stencil of VSIAM3 is simple compared with other multi moment discretization.
- Since the model is based on finite volume method, physical variables, e.g. mass, momentum, etc., are completely conserved.
- THINC/WLIC method does not emanate numerical diffusion of the free surface so that the surface re-initialization does not need like a Level-Set method.
- In the case of each surface of the gas and liquid phase significantly deform, since surfaces are expressed by orthogonal coordinate, we do not need grid reconstruction due to deformed free surfaces. Therefore, a numerical error and instability can be reduced.

Toward the standardization of the repairing technology and reducing the residual stress using a laser welding simulations, the purpose of this study is that the constructing of the numerical model of laser welding and evaluating the efficiency of the model. In section 2, we show governing equations for the one-fluid model and numerical configurations. In section 3, we show the preliminary results of the laser welding on the pure aluminum solid plate. In section 4, we conclude the present work.

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2. Numerical procedures

2.1 Governing equations

A welding pool which is induced by a laser irradiation can be treated as a fluid so that the governing equations can be described by equation of continuity, Navier-Stokes equation and energy equation. Assuming the incompressible fluid, those equations can be expressed as

\[
\begin{align*}
\frac{\partial u_i}{\partial x_i} &= 0, \\
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} &= -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \left(2\mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + g_j + F_i, \\
\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} &= \frac{1}{\rho C_v} \left(\frac{\partial T}{\partial x_i}ight) + \frac{1}{\rho C_v} Q_i,
\end{align*}
\]

where \( u, p, \rho, \mu, g \) = \((0, 0, -g)\), \( F_i, T, C_v, \lambda \) and \( Q \) represent the velocity vector, density, pressure, viscosity, acceleration due to gravity, external force, temperature, specific heat, thermal conductivity and heat source, respectively.

In order to express the multiphase flows, e.g. solid, liquid and gas phase, we employ the one-fluid model. In the model, effective fluxes on each surface is evaluated by the advection equation of VOF (volume of fluid) function, \( \phi \).

\[
\frac{\partial \phi_i}{\partial t} + \frac{\partial (u_i \phi_i)}{\partial x_i} = \phi_k \frac{\partial u_i}{\partial x_i}. 
\]

Based on the local values of \( \phi \), the appropriate properties and variables are assigned to each control volume within the computational domain. If \( Y \) denotes the generic fluid property (e.g. density, viscosity, specific heat, etc.) the corresponding value in each cell is given by

\[
Y(\phi) = Y_s \phi_s + Y_l \phi_l + Y_g (1 - \phi_s - \phi_l),
\]

where subscripts \( S, L, G \) represent solid, liquid and gas phase, respectively and \( \phi \) takes 0 to 1.

It is known in fact that the expression for the stress jump \( F_i \) across the interface is given by

\[
F_i = \sigma \kappa n_i = \frac{\partial \sigma}{\partial T} \left[I_{ij} - n_i n_j\right] \frac{\partial T}{\partial x_j}.
\]

2.2 Phase change model

The solidus and liquidus are determined by the temperature recovering method\(^{16}\). The time change of the amount of the phase change can be estimated by this method. In the present study, we directly treat it as a change of the VOF function. The latent heat releases of solid phase to liquid phase is defined as

\[
Q_i = \rho \Delta V \Delta g L.
\]

2.3 Expression of a solid phase

For the solid phase expression, we employed the FAVOR (Fractional Area/Volume Obstacle Representation) method\(^{15}\). The volume-fraction and open area fraction are defined as, respectively and \( \phi \) takes 0 to 1.

It is known in fact that the expression for the stress jump \( F_i \) across the interface is given by

\[
F_i = \sigma \kappa n_i = \frac{\partial \sigma}{\partial T} \left[I_{ij} - n_i n_j\right] \frac{\partial T}{\partial x_j}.
\]

where \( n_i \) is the unit vector perpendicular to the fluid/fluid interface, \( \kappa \) is the curvature, \( \sigma \) is the surface tension coefficient and \( I_{ij} \) is the identity matrix.

\[
n_i = \frac{\partial \phi}{\partial x_i}, \quad \kappa = -\frac{\partial n}{\partial x_i}.
\]

The second term of the right hand side in the e.q.(4) is the contribution related to surface tension gradients along the interface (Marangoni stress)\(^{12}, \(13\)).

2.4 Laser irradiation model

The energy input from the laser light was modeled as a surface heat flux. Currently, Bouguer-Lambert-Beer law\(^{16}\),

\[
q(x, y, z, t) = (1 - R)q_s(x, y, z, t) \exp(-\alpha z),
\]

was used. Thus the second term of right hand side in e.q.(1) is given by

\[
Q = -\frac{\partial q}{\partial z} = -(1 - R)q_s(x, y, z, t) \exp(-\alpha z),
\]

where \( R \) and \( \alpha \) represent the reflection rate and the absorptivity...
which depend on the wave length. The irradiation intensity is described by the product of spatial function \( f(x, y) \) (the profile of heat input on the base material) and the time function \( g(t) : q_0 = q_m f(x, y) g(t) \). In the present study, we assume \( g(t) = 1 \) and \( f(x, y) \) are defined as a Gaussian laser-beam distribution,

\[
f(x, y) = \exp \left( -\frac{x^2 + y^2}{r_0^2} \right), \tag{10}\]

where \( r_0 \) and \( q_m \) represent the radius of the laser irradiation and laser power density [W/m²].

### 2.5 Algorithm for the laser welding

Fig.1 shows that the flowchart of the numerical model. We used the fractional step method for time proceeding. Firstly, grid, the laser irradiation profile, etc. are set in the initialization phase. After that, in the time proceeding loop, advection equation is solved by CIP-CSL scheme. After calculating the external forces, e.g. surface tension force, gravity, etc., diffusion equation of the velocity and the space distribution of physical properties are updated as provisional values. And the pressure Poisson equation was solved by Krylov subspace method named AMG-BiCGSTAB solver. The solver can solve the Poisson equation which has a large density difference.

As shown in Fig.2, the laser heating starts from far left of the plate and is scanning on the aluminum plate with constant velocity, \( v_s = 1 \) cm/s. The diameter of the laser spot and the total laser power are 2 mm and 300W, respectively. Thus the laser power density is 9554 kW/m². Boundary conditions of the velocity, pressure and temperature are assumed as no-slip, Neumann and constant temperature boundary, respectively. We carried out the simulation of the laser welding in the air (Combustion and evaporation were not considered). The reflection rate, \( R \) and the absorptivity were supposed zero and \( 1/0.05 \). The physical properties are shown in Table.1.

### 3.2 Results and discussion

Fig.3 (a)-(d) show that the snap shots of the laser welding.
simulation on the aluminum plate. At the irradiation point of the laser beam, the temperature increases and, because the temperature coefficient of the surface tension is negative for most materials, the surface tension increases along a line from the irradiation point to the edge of the molten pool. Thus, as shown in Fig. 3 (a) and (b), in the vicinity of the solid/liquid interface swells and the irradiation point sinks in. This result is also shown in literature 2) so that the model is adequately implemented to our numerical model. After some time proceeding, in Fig. 3 (c) and (d), the bead was formed at the backward of the molten pool.

Fig. 4 shows the top view of the solid/liquid interface and velocity vector distribution on the molten pool. The flow on the molten pool radially spreads to the solid/liquid interface from the irradiation point due to the Marangoni effect and the complicated flow exists in the vicinity of solid/liquid interface.

Fig. 5 represents the y-z cross-section of the molten pool. As shown in Fig.5, since we took into account the gas phase, the temperature in the molten pool was transported to the air phase due to thermal conduction and surface deformation. The shape of the molten pool is almost parabola shape. This is because the thermal conductivity of aluminum is high. These results can also observe in laser welding experiments. Thus our numerical model will be a powerful tool to investigate laser welding processes in near the future.
4. Conclusions

Toward a standardization of laser welding repair processes and controlling a residual stress which is induced by laser welding, we carried out the laser welding simulation using the one fluid model by VSIAM3 based on CIP finite volume method. Although the model was considered only thermocapillary and surface tension force as a surface force models, the representative behavior of the laser welding was obtained. Conclusions are listed as follows,

- We simulated the Marangoni convection on the molten pool and the vicinity of the solid/liquid interface swells and the irradiation point sinks in. This characteristic can be found in previous study.
- Welding bead was obtained at the backward of the molten pool.
- The flow on the molten pool radially spreads to the solid/liquid interface from the irradiation point.
- In the $y$-$z$ cross-section of the molten pool, the representative feature of the aluminum, parabola shape, was obtained by our model.

Therefore, it is concluded that the model can be applied to practical laser welding problem. We will quantitatively evaluate numerical results with laser welding experiments in the future and improve the numerical model, e.g. models for mushy zone and residual stress.

Additionally, in order to investigate the details of the flow of the inside the molten pool, the high resolution simulation is indispensable. Using our fully parallelized numerical model which is parallelized by MPI, after some improvement the numerical model, massively-parallel computers with more than one hundred CPUs will be used. Thus, in near the future, details of the laser welding processes could be revealed and it will contribute to a controlling the residual stress on laser welding processes.

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