Numerical simulation of laser welding processes with CIP finite volume method†

YAMASHITA Susumu*, YONEMOTO Yukihiro*, YAMADA Tomonori*, KUNUGI Tomoakiand MURAMATSU Toshiharu***

KEY WORDS: (Laser welding simulation) (CIP finite volume method) (Multiphase flow) (One fluid model) (Marangoni convection)

1. Introduction

Quantitative evaluation and controlling the residual stress which is induced by laser welding is one of the important subjects for a plant life extension of FBRs (Fast Breeder Reactors) and the guarantee of the reliability of the repair domain. Numerical simulation is an effective tool for deep understanding of their phenomena and it needs to have high accuracy, robustness and reliability. Recently, in order to satisfy those requirements, we have developed the laser welding simulation model using some advanced numerical models; surface capturing scheme, THINC[1] and spatial discretization scheme, VSIAM3[2]. We have conducted three-dimensional simulations of the laser welding processes using physical properties of the pure aluminum and the stress jump across the interface[3], [4]. The behavior of the welding pool is qualitatively the same as the experimental one. It is concluded that the present numerical model can be expected as a practical tool to simulate laser welding processes.

2. 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

$$\frac{\partial u_i}{\partial x_i} = 0,$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(2\mu D_{ij}\right) + F_i, \quad (1)$$

$$\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} = \frac{1}{\rho C_v}\frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + \frac{1}{\rho C_v} Q,$$

where u_i, F_i, T, ρ, μ, C_v, λ, Q and ϕ represent the velocity vector, external force (gravity, surface tension force, etc.) temperature, density, viscosity, specific heat, thermal conductivity and heat source.

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

$$\frac{\partial \phi_k}{\partial t} + \frac{\partial (u_i \phi_k)}{\partial x_i} = \phi_k \frac{\partial u_i}{\partial x_i}. \quad (2)$$

Based on the local values of ϕ, 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

$$Y(\phi) = Y_s \phi_s + Y_\ell \phi_\ell + Y_g (1 - \phi_s - \phi_\ell), \quad (3)$$

where subscripts s, ℓ and g represent solid, liquid and gas phase, respectively and ϕ takes 0 to 1.

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

$$F_i = \sigma \kappa n_i - \frac{\mathrm{d}\sigma}{\mathrm{d}T}\left(I_{ij} - n_i n_j\right) \cdot \nabla T_i \quad (4)$$

where n_i is the unit vector perpendicular to the fluid/fluid interface, κ is the curvature, σ is the surface tension coefficient and I_{ij} is the identity matrix,

$$n_i = \frac{\partial \phi / \partial x_i}{|\partial \phi / \partial x_i|}, \quad \kappa = -\frac{\partial n_i}{\partial x_i}. \quad (5)$$

The second term of the right hand side in the Eq.(4) is the contribution related to surface tension gradients along the interface (Marangoni stress).

3. Numerical configuration

Figure 1 represents the computational domain of the laser welding simulation. The length of x, y and z are 2 cm (the thickness of the aluminum solid plate 1 cm). In this study, $80 \times 80 \times 80$ grid points for each direction are used. The laser heating starts from far left of the plate and is scanning on the aluminum plate with constant velocity, 2 cm/s. The diameter of the laser spot and the total laser power are 2 mm and 300W, respectively. The energy input from the laser light was modeled as a surface heat flux.

† Received on 30 September 2010
* Japan Atomic Energy Agency, Fukui, Japan
** Kyoto University, Kyoto, Japan

Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

Currently, spatial intensity of the heat flux on the plate was distributed as a Gaussian laser-beam distribution and the profile for the depth direction, Bouguer-Lambert-Beer law[5-7] was used.

We used a FAVOR (Fractional Area/Volume Obstacle Representative) method[8] as the expression of the solid phase and the temperature recovering method is used as the phase change model. Boundary conditions of the velocity, pressure and temperature are no-slip, Neumann and constant temperature conditions, respectively.

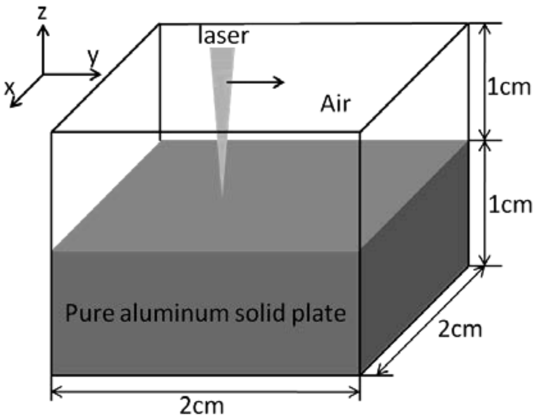


Fig.1 Schematic diagram of the laser welding simulation.

The resulting system of pressure equations was solved by means of a Krylov-Subspace solver. For this purpose the AMG-BiCGSTAB library was chosen.

We carried out the simulation of the laser welding in air (combustion and evaporation were not considered). The physical properties are shown in **Table.1**.

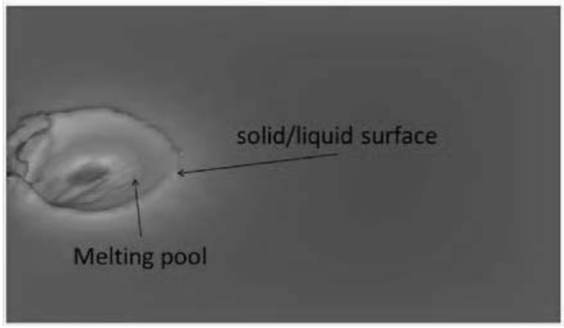
4. Results and Discussion

Figure 2(a)-(d) shows the snap shots of the simulation of the laser welding on the aluminum plate. At the irradiation 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 melt pool. Thus, as shown in Fig.2(a) and (b), in the vicinity of the solid/liquid surface swells and the irradiation point sinks in. After some time proceeding, in Fig. 2(c) and (d), the bead was formed at the back of the melting pool. These results indicate that the present numerical model can be applied to practical laser welding processes.

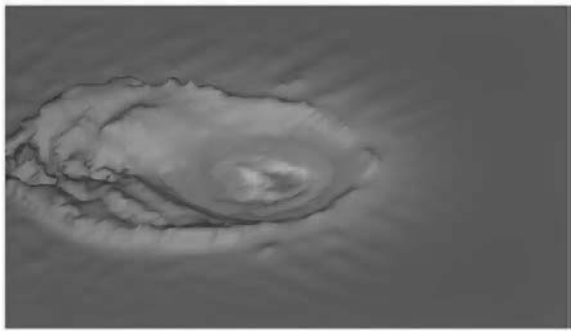
Table 1 Physical properties of the molten aluminum.

Density [kg/m^3]	2357
Viscosity [Pa s]	1.178e-3
Thermal conductivity [W/m/K]	93
Specific ratio [J/kg/K]	1090
Surface tension coefficient [N/m]	0.9
Melting point [K]	933
dσ/dT [N/m/K]	-3.5e-4

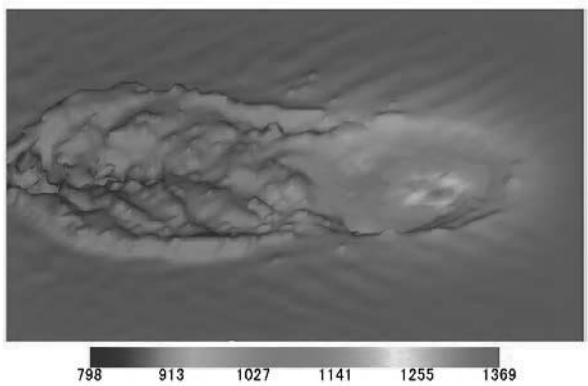
(a) t = 0.125 s.



(b) t = 0.33 s.



(c) t = 1.0 s.



(d) t = 1.51 s.

Fig.2 The three-dimensional views of the surface of the laser welding. The blue and red are indicating the low and high temperature regions.

5. Conclusions

We carried out the laser welding simulation using a one fluid model by CIP finite volume method. Although the model considered only thermocapillary and surface tension force as a surface force models, the representative behavior of the laser welding was obtained. Therefore, it is concluded that the model can be applied to practical laser welding problems. In order to investigate the details of the flow of the inside the molten pool, the high resolution simulation is indispensable. So we parallelized the model by means of 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 will be revealed and it will contribute to controlling the residual stress on laser welding processes.

References

[1] K. Yokoi: J. Comput. Phys. 226 (2007), pp.1985-2002.
[2] F. Xiao: J. Comput. Phys. 195 (2004), pp.629-654.
[3] M. S. Gross, I. Black and W. H. Muller: J. Phys. D: Appl. Phys.36(2003), pp.929-938.
[4] M. Lappa: CMC, vol.2, no.1 (2005), pp.51-64.
[5] M. Von Allmen: Springer-Verlag, Berlin (1987).
[6] J. F. Ready: Academic Press, New York (1971).
[7] S. I. Anisimov, Ya. A. Imas, G. S. Romanov and Yu. V. Khodyko: National Technical Information Services (1971).
[8] W. Hirt et al: 4th Int. Conf. Washington DC (1985).