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NUMERICAL STUDY OF SOLIDIFICATION AND HEAT TRANSFER IN THE CAVITY WELD POOL

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ABSTRACT

Fusion welding technology is widely applied in manufacturing industries. To achieve high quality welding is a challenging task in the fusion welding, as the quality of the weld depends on the fluid dynamics, electrodynamics, heat and mass transfer processes that occur inside a weld pool. These processes are non-linearly dependent on each other and, therefore, demand a robust model for the study of various parameters that affect the weld-pool quality. In this work, we use a commercial software, ANSYS-FLUENT, to model the problem of solidification of tin inside a rectangular cavity. A validation of the developed model shows a reasonable match with existing data. It is shown that the convection is a dominant in deciding the solidification rate of tin inside the weld pool.

Keywords: Cavity weld pool, Computational fluid Dynamics, Solidification and melting, welding technology, Numerical simulations

I. INTRODUCTION

Welding technology, for example, fusion welding is widely used in the manufacturing industries. Traditionally, welding was used to be performed manually and its quality was monitored by the operator only. With the advent of automation, for the judgment of the quality of the weld, it is necessary to understand the important operating parameters that affect the quality of the weld beforehand. The quality of the weld depends on the fluid dynamics, electrodynamics, heat and mass transfer processes that occurs inside a weld pool. These processes are non-linearly dependent on each other, and, therefore, demand a robust model for the study the importance of various parameters that affect the weld-pool quality.

In recent years, it is believed that the weld efficiency is dependent on the micro-structure of weld pool and heat affected zone (HAZ). The mechanical properties of the weld, depending on the weld pool subjected to a particular type of fusion welding, are seems to be affected by the relative contribution of: (a) buoyancy effect inside the pool (b) body forces inside the pool (c) shear force on the free surface of the pool. These mechanisms' affecting the convection is a topic of current active research. The experimental work of [1] studied the motion in the weld pool of liquid mercury. In general, the weld pool dimensions are very small and the changes in the magnitude of the flow parameters, for example, temperature, is rapid. This makes the experimental study of these parameters very difficult. This paves the way for analytical and numerical studies. The first mathematical attempt to model the fusion welding is due to Rosenthal [2] without considering the fluid

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motions in his model. On the other hand, numerical simulations of [3, 4] have specifically performed laminar flow study and noted the effect of motion induced by buoyancy, body and shear force on the interface with time. Since then lot of research work is actively going-on. An account of numerical work on weld pool, till 1987, can be found in [5], and in [6] for work till 1998 and theoretical framework of fusion welding. Since 1999, some notable work due to [7, 8, 9, 10, 11, 12, etc.] is available in the literature. However, the sufficient work is still required due to the non-linear nature of processes involved during solidification and melting of the weld-pool.

In this work, a preliminary numerical analysis is performed using ANSYS-FLUENT to study the effect of convection on the weld quality. It can be seen during the welding processes that, a rapid heating and cooling may set very high thermal gradients in the molten region and HAZs. Near the interface, steep temperature gradient due to strong convection may lead to the microscopic mixing of the molten liquid. Therefore, the present study is aimed at the understanding the effect of convection parameters on the quality of the weld-pool of tin in a rectangular cavity.

II. METHODOLOGY

2.1. Problem definition

For numerical simulations, the weld-pool of tin in a rectangular cavity is considered. A diagram of the computational domain along with the boundary condition and the mesh is as shown in Fig. 1. The hot and cold wall temperatures are taken from [13], which respectively are 506.15 K and 502.15 K. Since the temperature difference is very small i.e. 4, the physical properties are assumed to be constant. The physical properties are taken from [13] are as shown in Table 1. The Prandtl number for liquid tin is 0.013, the Stefan number is 0.0132 and the Rayleigh number is 1.59×10^5 in the present simulations.

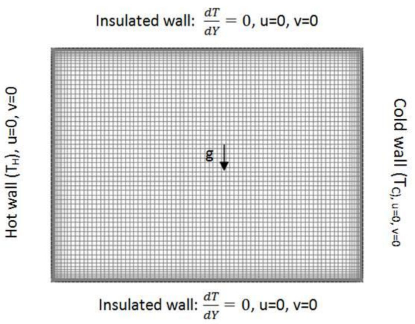

Figure 1: Computational domain, grid and boundary conditions.

Table 1: Thermo-physical properties of tin at 502.15 K used in the present study.

Fourier number (F_o)	4.31	Thermal conductivity (K)	56.5 $W/m-K$
Thermal diffusivity (α)	1.78 × $10^{-5} m^2/s$	Fluid dynamic viscosity (μ)	0.002314 $kg/m-s$
Fluid kinematic viscosity (ν)	3.419 × $10^{-7} m^2/s$	Latent heat of melting (h_f)	70456.67 J/kg
Density (ρ)	7273.3 – 0.5981T kg/m^3	Thermal expansion coefficient (β)	1.31× 10^{-4} $^1/_K$
Specific heat (Cp)	317.415 $J/kg\,K$	Solidus and liquidus temperature	505.08 K

2.2. Governing equations

The conservation equations governing the two-dimensional laminar flow with constant flow properties along with the boundary and initial conditions (u =0, v =0, T =502.15K) are solved using the enthalpy-porosity formulation (partially solidified region, called as mushy region, is treated as porous medium). The governing equations applicable to rectangular domain are:

1. Continuity equation: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$
2. Momentum equation:

   Momentum in x-direction: $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + S_u(u)$

   Momentum in y-direction: $\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + g\beta\left(T_l - T_f\right) + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + S_u(v)$

   where $S_u = A_{mush}\,(1-\alpha)^2/(\alpha^3 + \epsilon)$, $A_{mush} = 10^4 to\ 10^7$, ϵ is a small number (0.001), $\rho = \rho_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right]$, liquid fraction $\alpha = 0$, if $T < T_{solidus}$, $\alpha = 1$, if $T > T_{liquidus}$ and $\alpha = (T - T_{solidus})/\left(T_{liquidus} - T_{solidus}\right)$.
3. Energy equation: $\frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x} + v\frac{\partial H}{\partial y} = \frac{k}{\rho c_p}\left(\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2}\right)$ where, $H = h + \Delta H$, and

   $h = h_{ref} + \int_{T_{ref}}^{T} C_p T$.

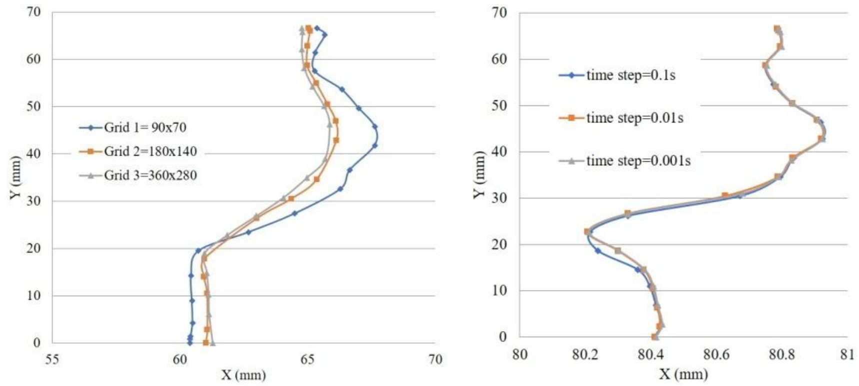

Figure 2: Grid-size independence and time-step independence test.

The equations are solved by the SIMPLE method. The discretization scheme used to discretize momentum and energy conservation equations is the second-order upwind, and for the pressure PRESTO! is used. The convergence criterion for the energy, momentum and continuity, respectively, is 10^{-6}, 10^{-4} and 10^{-4}. The thermo- physical properties of tin used in the numerical simulation are presented in Table 1.

III. RESULTS AND DISCUSSIONS

3.1. Grid size and time-step independence:

To study the flow in the weld-pool, a strategy is used: problem of solidification of tin is modeled using an ANSYS-Fluent solver in this work. Grids are generated using ICEM-CFD (90×70, 180×140 and 360×280 cells). Grid-size and time-step independence (time-steps taken are: 0.1, 0.01 and 0.001) is performed. Fig. 2 shows the results of the test. It can be seen from the figure that the grid-size of 180×140 and time-step of 0.01 are found optimal, similar to [13], and the further simulations are performed with the optimum grid-size and time-step.

3.2 Comparison of numerical data:

Figure 3 shows the comparison of predicted solidification fronts at various times. It can be seen from the figure that the present data shows reasonable validation with the analytical data of [13]. The discrepancy in the results, between present data and data of [13] may be due to the three-dimensional nature of the problem.

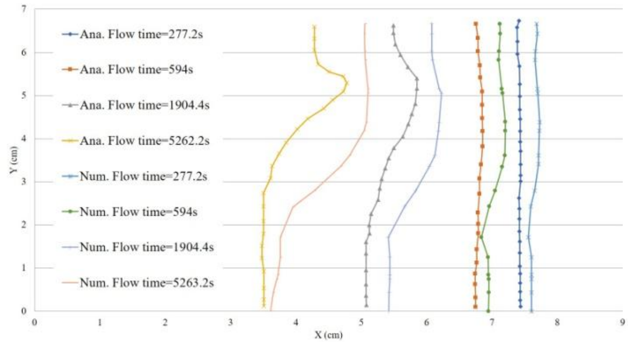

Figure 3: Comparison of predicted (Num.) solidification front, with the analytical (Ana.) data [13], at various times.

3.3. Solidification:

Figure 4 shows the movement of solidification front of tin, inside a computational domain, with respect to time. It can be seen from the presence of nearly vertical-interface, in the figure, that, at smaller times the effect of conduction is dominant. At later times, the interface-front becomes wavy due to the presence of natural convection near the interface.

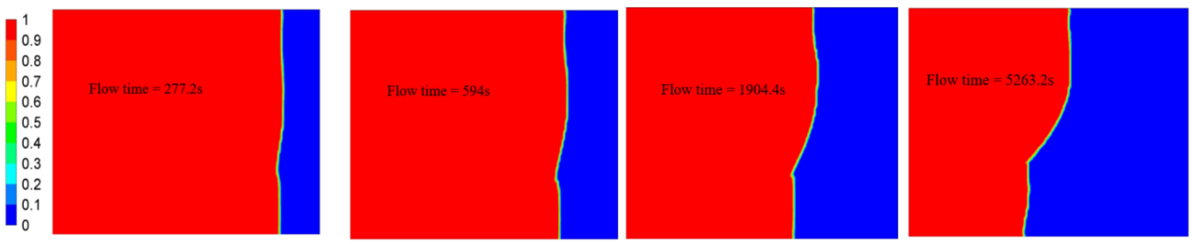

Figure 4: Contour plots showing time-evolution of solidification front of tin

3.4. Heat transfer:

Figure 5 shows the contours of temperature inside a computational domain, with respect to time. It can be seen from the figure that, at smaller times the temperature contours are almost vertical indicating the dominance of conduction mode of heat transfer. At later times, the contours become wavy and the additional change in the direction of temperature gradient occurs indicating the heat transfer due to conduction as well as natural convection near the interface (also in the domain).

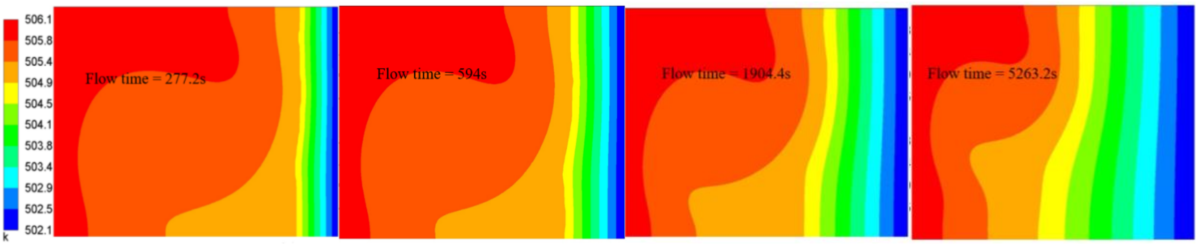

Figure 5: Contour plots of temperature at various time.

IV. CONCLUSION

Preliminary numerical simulation of solidification of tin inside a rectangular cavity of the tin weld pool is performed using commercial software, ANSYS-FLUENT. A validation of the developed model shows a reasonable match with existing data. An effect of fluid flow and heat transfer on the solidification rate of tin is studied. It is observed that the natural convection plays very vital role in the process of solidification (and melting) of the weld pool of tin material. From this preliminary study, it is concluded that the interface between solid and liquid is greatly affected by the effect of buoyancy driven convection. Since the metallurgical structure of the weld depends on how well the mixing was before solidification, strong convection results in good quality welds. In subsequent work, however, surface tension and MHD effect (for various Hartmann number) are intended to be included.

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