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Study of Role of Enhancement Factor on Melt Pool Characteristics in Conduction Mode Laser Welding using OpenFOAM

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Abstract

It has been well established in the literature of laser welding that computationally predicted melt pool dimensions differ with the experimentally measured melt pool dimensions. Therefore, in order to validate with the experimental results, researchers in the past performed numerical simulations by using enhanced values for viscosity and thermal conductivity of the liquid metal. The justification is that the enhanced values can take care of the flow instabilities present in the melt pool which were not accounted by the model. This indirect approach using enhanced values gave reasonable agreement with the predictions. It should be noted that in the past researchers have used randomly enhanced values for viscosity and thermal conductivity of the liquid metal without any explanation for using that particular values. In this work, a 2-D axisymmetric model is developed in-house in OpenFOAM for investigating the effect of the enhancement factor on the heat transfer and melt pool flow dynamics during the conduction mode laser spot welding process of 304 stainless steel. The melt pool characteristics, such as melt pool width and melt pool depth obtained with different enhancement factors are compared with the experimental results. The results suggest that there is an optimum enhancement factor for a particular metal for which simulations results compare well with the experimental results.

Keywords: Laser welding, OpenFOAM, Melt pool, Flow dynamics.

1. INTRODUCTION

Laser welding involves joining of two or more pieces of metals or alloys using the intense heat of laser beam. Laser welding is widely used in telecommunications, defense, aerospace, medical and automobile industries due to its advantages, such as high precision and high controllability [1]. The process involves interaction of the workpiece with a very high energy beam involving high temperature gradients. The process is accompanied by various physical phenomena that are quite complicated and challenging to model numerically. It includes melting, vaporization, solidification, surface tension driven free surface flow and natural convection in the melt pool. Temperature gradients within the melt pool leads to surface tension driven flow from regions with low surface tension to regions with high surface tension, known as Marangoni convection. Laser welding is generally characterized by shape and size of the weld pool, cooling rate and process duration. These characteristics play important role in thermal cycle, fluid flow and properties of the weld pool, such as weld pool convection patterns, geometry, composition and microstructure [2, 3]. The fluid flow in the melt pool is mainly due to the buoyancy force and the surface tension. The liquid metal flow affects the heat transfer in melt pool near the liquid-solid interface. Heat transfer by conduction also plays a significant role, when the magnitude of velocity is very small either during melting or solidification [4].

It is very challenging to study the process experimentally as it involves interaction with high energy beam along with high melting and solidification rates [5]. Therefore, alternative strategies, such as computational modelling and simulations are an emerging area to study this process. Numerical modeling becomes an effective tool to understand deeper insights of the process, effect of the process parameters, and to obtain optimized process conditions. Several computational works have been reported in the literature to investigate the conduction mode laser spot welding process [8-10].

To keep the computational complexity and cost tractable, various simplifying assumptions have been made in the past, such as laminar flow of the molten liquid, the flat surface consideration of the melt pool, 2-D axisymmetric reduction of the domain, usage of constant thermo physical properties etc. These assumptions induces free surface and fluid flow instability, which leads to strong momentum and heat and mass transfer. Therefore, enhancement of thermal and momentum diffusivity in the molten pool is required to compensate for these instabilities and to obtain a good agreement between experimental and simulation results.

In this study, a 2D axisymmetric computational model of conduction mode laser spot welding of 304 stainless steel has been developed using OpenFOAM in order to understand the effect of enhancement factor on the melt pool characteristics. The objective is to find an optimum enhancement factor for 304 stainless steel for which simulations results show good comparison with the experimental results.

2. NUMERICAL MODELLING

A two-dimensional heat transfer and fluid flow model is developed to study the transport phenomena in the conduction mode laser welding process. The model was implemented using open source C++ code OpenFOAM. Due to the axisymmetric nature of spot welding, the governing transport phenomena equations can be solved in a two-dimensional axisymmetric plane. Fig. 1 shows the computational domain and meshing structure considered. The laser beam is stationary focusing on a spot of the 304 stainless steel plate. The material properties are taken from reference [4] and are given in Table 1. The thermal conductivity and dynamic viscosity of liquid metal are modified according to enhancement factor. Parameters considered in the simulations are listed in Table 2.

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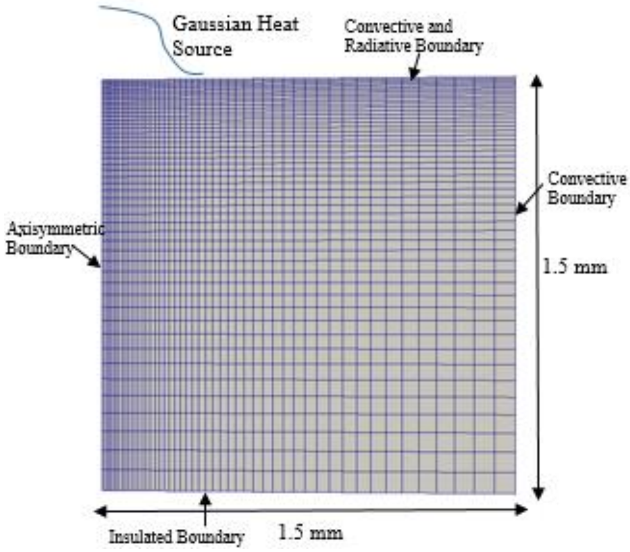


Fig.1. Schematic of computational domain and mesh structure

The whole domain is meshed with Cartesian rectangular mesh. To obtain accurate results of melt pool evolution, top left part near the heat source is meshed finely and in order to save the computational cost, the remaining domain is meshed with spatially non-uniform coarse elements.

Table 1
Thermo-physical properties of 304 Stainless steel

Liquidus Temperature (K)	1697
Solidus Temperature (K)	1727
Solid specific heat (J kg^{-1} K^{-1})	711.8
Liquid specific heat (J kg^{-1} K^{-1})	837.4
Solid Thermal conductivity (W m^{-1} K^{-1})	19.63
Liquid Thermal conductivity (W m^{-1} K^{-1})	28.99 × Enhancement factor
Density (kg m^{-3})	7200
Latent heat of fusion (kJ K^{-1})	246
Dynamic viscosity (N m^{-1} s^{-1})	0.008 × Enhancement factor
Thermal expansion coefficient (K^{-1})	1.96 × 10^{-5}
Surface tension coefficient (N m^{-1} K^{-1})	-0.43 × 10^{-3}

Table 2
Parameters for simulation

Parameter	*Value*
Laser spot size (mm)	0.428
Ambient temperature (K)	298
Laser power (W)	1967
Pulse duration (ms)	3
Absorptivity	0.27

2.1 Governing Transport Equations

2.1.1Mass Conservation

The continuity equation during the phase change is given by

$$\nabla \cdot (\rho\vec{u}) = 0 \quad (1)$$

where ρ denotes the density and$\vec{u}$ is the velocity vector.

2.1.2Energy Conservation

The governing heat transfer equation is given by

$$\frac{\partial(\rho C_P T)}{\partial t} + \vec{u}\cdot\nabla(\rho C_p T) = \nabla\cdot(K\nabla T) + S_{latent} \quad (2)$$

where C_p denotes the heat capacity, K denotes the thermal conductivity of the material and $S_{latent}$is the latent heat source term.

2.1.3Momentum Conservation

The governing momentum conservation equation is given by

$$\frac{\partial(\rho\vec{u})}{\partial t} + \vec{u}\cdot\nabla(\rho\vec{u}) = -\nabla p + \nabla\cdot(\mu(\nabla\vec{u} + (\nabla\vec{u})^T) + \vec{F} \quad (3)$$

$$\vec{F} = \overrightarrow{F_S} + \overrightarrow{F_N} \quad (4)$$

The source term $\overrightarrow{F_S}$ in Eq. (4) is defined in Eq. (5). It aids to bring down the velocity of the fluid at the liquid-solid interface and makes the fluid motion in the unmelted solid zone as zero.

$$\overrightarrow{F_S} = \frac{(1-\beta)^2}{\beta^3 + b} C\vec{u} \quad (5)$$

The constant C in Eq. (5) represents mushy zone constant and a value of 100,000 kg m^{-3} s^{-1} is considered in the current model. The term b is a constant with small value to prevent division by zero when βbecomes zero. β represents the liquid fraction given by

$$\beta = \begin{pmatrix} 0 & T < T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & T_{solidus} \le T < T_{liquidus} \\ 1 & T \ge T_{liquidus} \end{pmatrix} (6)$$

where $T_{solidus}$ and $T_{liquidus}$ represent solidus and liquidus temperature, respectively.

Natural Convection

The buoyant flow is included in this model with the help of Boussinesq approximation [10]. The source term$\overrightarrow{F_N}$ in Eq. (4) is given as

$$\overrightarrow{F_N} = \rho_{liquid}\vec{g}\beta_T(T - T_{ref})(7)$$

where ρ_{liquid} , β_T and T_{ref} aredensity of liquid, coefficient of thermal expansion and reference temperature, respectively.

Marangoni Convection

The following equation describes the forces that the Marangoni convection induces on the interface at the free surface

$$\mu\left(\frac{\partial u}{\partial y}\right) = -\left(\frac{\partial\gamma}{\partial T}\right)\left(\frac{\partial T}{\partial x}\right) \quad (8)$$

where $\mu$and γ are viscosity and surface tension, respectively.

2.2 Boundary Conditions

The heat energy from the laser beam can be approximated by a Gaussian distribution and the heat flux (W m^{-2}) is given by the following expression

$$q = \frac{2AP}{\pi R^2} \, exp\left(-\frac{2r^2}{R^2}\right) \quad (9)$$

where q is the input heat flux, A is the absorptivity, P is the power of laser beam and R is the radial distance in which energy density equals to e^{-2} times that at the centre of the laser spot.

Energy balance at the top surface leads to the following boundary equation

$$k\frac{\partial T}{\partial n} = q - h_c(T - T_\infty) - \varepsilon\sigma\left(T^4 - {T_\infty}^4\right)(10)$$

Terms on the right-hand side are heat energy from the laser beam, convective heat loss and radiation heat loss to the surrounding, respectively. In Eq. (10) h_c is the convective heat transfer coefficient, ε is the emissivity and $\sigma$is the Stefan-Boltzmann constant.

3. RESULTS

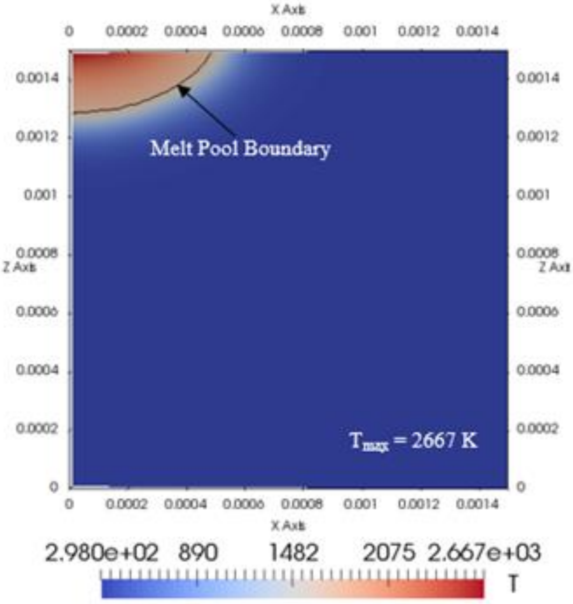
In simulations, a laser power of 1967 W was applied for a period of 3 ms to the top surface of the 304 stainless steel plate. The Gaussian beam spot radius was taken to be 0.428 mm. During heating by the laser, the formation of the melt pool and the effect of enhancement factor on its characteristics dimensions is analyzed.

3.1 Melt Pool Transport Phenomena

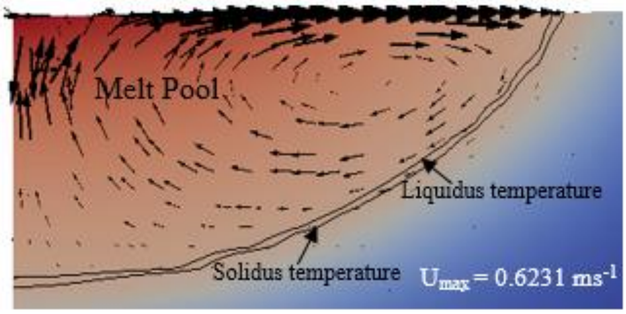
Figure 2(a) shows the temperature distribution at 3 ms with enhancement factor taken as8. The melt pool is confined by the melt pool boundary as shown in the figure. It can be observed that there is not much temperature rise in the portion of the domain which are away from the melt pool boundary. This is due to the low thermal conductivity of 304 stainless steel and shorter heat source interaction time (3 ms).Figure 2(b) shows the velocity vectors superimposed on the temperature map. It can be observed that the maximum velocity occurs along the free surface and the molten liquid tends to flow outward from the centre of melt pool. This is because of the nature of temperature gradient within the melt pool that causes a surface tension driven flow, often called thermo capillary fluid flow (or Marangoni convection), from a region with low surface tension to regions with high surface tension. Due to this Marangoni convection, there is a recirculating fluid flow. The magnitude of the velocity in the melt pool is in the range of 0.5–3.0m s^{-1} which is quite substantial. The high velocity in the melt pool makes the molten liquid to flow away from the centre resulting in a shallow melt pool as shown in the Fig 2(b). It was observed that the magnitude of velocity in the recirculating flow increases with progress in time.

3.2 Effect of Enhancement Factor

To obtain an understanding of the role of enhancement factor, the results are presented for different enhancement factors and are compared with experimental results of He et al. [4]. The numerically predicted values along with the experimental results are given in Table 3. Firstly, simulations were performed without enhancing the properties. It can be clearly observed that in this case due to enhanced heat and momentum transfer melt pool is shallow and nowhere close to experimental results as given in Table 3.



(a)



(b)

Fig. 2. (a) Temperature map (in K) in the complete domain at t = 3 ms with enhancement factor = 8, (b) Velocity vectors superimposed on the temperature map

Table 3
Simulation results

Enhancement factor	1	2	4	8
Simulated Half width(mm)	0.66	0.59	0.52	0.48
Experimental melt pool Half width[4] = 0.45 mm				
Simulated Melt pool Depth(mm)	0.075	0.115	0.164	0.205
Experimental melt pool Depth[4] = 0.25 mm				
Simulated T_{max}(K)	4027	3612	3153	2667
Simulated U_{max}(m/s)	2.691	1.855	1.201	0.6231

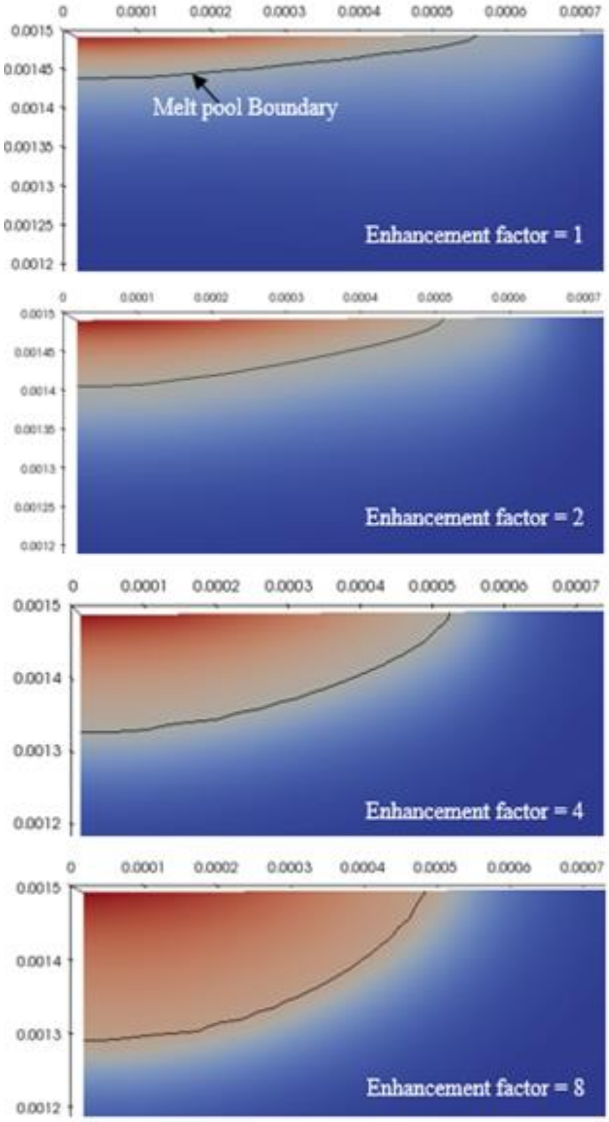


Fig. 3. Temperature map(in K) with different enhancement factors at t = 3 ms

With the introduction of enhancement factor, the compensation of strong momentum and heat transfer occurs leading to shorter and deeper melt pool. Fig. 3 shows the variation of melt pool shape with different enhancement factors. As the enhancement factor increases, the melt pool width decreases and the melt pool depth increases. It is evident from Table 3 and Fig. 3 that with increase in the value of enhancement factor, numerical results show closer comparison with the experimental results. With the choice of enhancement factor as 8, a reasonable match of melt pool width and depth with the experimental data is obtained.

4. CONCLUSIONS

In this study, a two-dimensional axisymmetric model has been developed for simulating the transport phenomena associated with the conduction mode laser spot welding process. It has been found that with the original material properties, there is a huge difference between the numerically predicted and experimentally measured melt pool dimensions. The cause of this difference is the instabilities that cannot be accounted in the laminar flow, 2D axisymmetric simulation. These instabilities leads to strong momentum and heat and mass transfer. To compensate for this instability, the thermal conductivity of liquid metal and the dynamic viscosity are multiplied by a factor called enhancement factor write in line with I told in Intro. It was found that for an optimum enhancement factor simulations results corroborate well with the experimental results. However, the justification of a random value of an enhancement factor is still unanswered. Therefore, for future modelling work, inclusion of parameters inducing instability needs to be avoided, and focus should be on modelling that includes free surface formation, temperature dependent thermo-physical properties and three dimensional formulation.

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