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# An octree-based adaptive mesh refinement method for three-dimensional modeling of keyhole mode laser welding

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ABSTRACT

Numerical simulations of laser welding could provide unprecedented insight into the physical details of the welding process; however, it remains a central challenge to understand laser welding with a high-efficiency and high-resolution method. This paper reports an octree-based adaptive mesh refinement method for efficient process modeling of laser welding in three dimensions. Based on multiresolution analysis algorithm, we also propose a hybrid adaptive mesh refinement strategy depending on local temperature, fluid velocity, and volume of fluid (VOF) value of weld pool of laser welding. Using the proposed method, the predicted heat transfer, and fluid flow behaviors of weld pool are consistent with experimental and previous theoretical results. Spatter formation at the beginning stage of laser welding is observed with a grid resolution in tens of microns. Under certain circumstances, the liquid jet can be produced when the fluid speed near the top surface of the weld pool is 1 m/s. The time for breakup of a liquid jet into spatters is about 0.065 ms. Furthermore, using the method, we just need 7 hours to complete a simulation of a 40-ms real laser welding process on a small workstation (2.60 GHz CPU, 16 cores), comparing with 120 hours needed using uniform grids. In a word, this method shows great potential for efficient computer simulation-based process optimization of laser material processing.

## 1. Introduction

Numerical simulations have been believed to be an important way for investigating heat and mass transfer phenomena during laser welding. However, the formidable computational cost for solving the complicate physical problem often severely hampers their practical applications in engineering. More efforts should be devoted to develop high efficient and high resolution adaptive mesh refinement method for modeling laser welding process.

The past few years have seen significant advances in modeling of laser welding. Kaplan [1] proposed a model by calculating the keyhole profile using a point-to-point determination of energy balance on the keyhole wall. Lee [2] suggested a two-dimensional transient model based on the volume of fluid (VOF) method for the static keyhole welding process. Zhou [3] proposed a similar two-dimensional transient-free surface model using VOF method, considering the vapor plume/plasma inside the keyhole. Recently, Pang [4] developed an improved three dimensional sharp interface model for self-consistent keyhole and weld pool dynamics for laser welding. Also the influence of metal vapor had been considered in their subsequent work [5]. Lu [6] investigated the porosity formation mechanism in laser welding.

However, as plenty factors are considered and most of these numerical simulations are based on uniform grids, large consumption of computational time is unbearable. To overcome this problem, Cho [7] carried the research by using non-uniform mesh technique. Dasgupta [8] took the adaptive mesh refinement method to simulate the laser welding process, which is based on the block structure. While the numerical research using the octree-based adaptive mesh refinement method is still very rare. Due to the simple Cartesian structure and embedded hierarchy, octree grids make mesh adaptation, reconstruction and data access fast and easy [9]. It has been well applied in computational fluid dynamics, plasma physics and other fields [10–13]. Although, there are still no details about the octree-based adaptive grid technique for modeling keyhole dynamics in laser welding. The mesh refinement strategy for efficient laser welding simulation is still unknown. The aim of our work is to carry out a study that contributes to fill this void.

In this paper, we implement an octree-based adaptive mesh refinement method for better understanding heat and mass

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transfer phenomena in laser welding. For reducing human intervention, we propose a multiresolution analysis based hybrid adaptive mesh refinement strategy according to the local temperature, fluid velocity, and VOF value of weld pool. The accuracy and efficiency of the method is verified. Moreover, by using this method, the laser welding process is simulated efficiently, and a splash phenomenon is studied deeply. In welding, spatter will lead to irregular weld surface. Irregular weld surface features such as undercut, craters, and blowouts, act as stress raisers, which can severely reduce the mechanical properties of a weld [14]. For this reason the investigation of spatter is of enormous importance. The results of this study should not only provide a more efficient method for understanding of the heat and mass transfer process in laser welding but should have practical applications for efficient computer simulation-based process optimization of laser material processing.

## 2. Mathematical model and numerical method

### 2.1. Mathematical model

This paper is concerned about the mesoscale free surface evolutions of keyhole, heat transfer and fluid flow in weld pool. Like the previous studies [4], we neglect the hydrodynamic effect of the vapor plume toward the keyhole, the effect of the shielding gas and the condensation of metallic vapor. Then the melt liquid in the weld pool during the welding process could be assumed to be incompressible fluid. Therefore, the mass, momentum, and energy conservation equations can be expressed as follows:

$$\nabla \cdot \vec{U} = 0, \tag{1}$$

$$\rho\left(\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U}\right) = \nabla \cdot (\mu \nabla \vec{U}) - \nabla p - \frac{\mu}{K}\vec{U} + \rho \vec{g}\,\beta(T - T_{ref}), \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\vec{U} \cdot \nabla)T\right) = \nabla \cdot (k\nabla T), \tag{3}$$

where $\mu$ is the viscosity of the fluid, $\rho$ is the density, $p$ is the pressure, $\vec{g}$ is the gravitational vector, $\beta$ is the thermal expansion coefficient, $C_p$ is the thermal capacity, $\lambda$ is the thermal conductivity, and $T_{ref}$ is the reference temperature, $K$ is the Kozeny–Carman coefficient [4].

To track the keyhole free surface, a piecewise-linear geometrical volume-of-fluid method (VOF) method [10] is adopted. The governing equation is as follow,

$$\frac{\partial F}{\partial t} + \vec{U} \cdot \nabla F = 0. \tag{4}$$

The deformation of the keyhole free surface is mainly affected by surface tension force, thermal-capillary force, recoil pressure, viscous force, and so on. Considering the coupling effect, we adopt a CSF algorithm [10] to treat those forces near the free surface of weld pool given by

$$F_s = (\sigma\kappa\vec{n} + \sigma_T \nabla_{\parallel} T + p_s)\delta_s, \tag{5}$$

where $\vec{n}$ is the normal vector of free surface, $\delta_s$ is a Dirac delta function, and $p_s$ is the recoil pressure [5].

For the thermal boundary of the weld pool free surface, the heat fluxes that result from heating by laser irradiation and cooling by convection, thermal radiation, and evaporation are applied according to the following expression:

$$\lambda \frac{\partial T}{\partial \vec{n}} = \eta q - h_A(T - T_\infty) - \varepsilon_r \sigma_s (T^4 - T_\infty^4) - \rho V_{\exp} T_v, \tag{6}$$

where $\lambda$ is the thermal conductivity, $h_A$ is the air convection coefficient, $V_{\exp}$ is the keyhole interface recession speed due to evaporation, $\sigma_s$ is the Stephen-Boltzmann constant, $T_\infty$ is the ambient temperature, $\varepsilon_r$ is the black body radiation coefficient, $T_v$ is the vapor temperature, and the laser absorptivity $\eta$ is related to the material. The heat fluxes $q$ due to laser energy absorption is determined as follows [15]:

$$q = f(I_0(r,z)) \cdot \delta_s \tag{7}$$

where $f(I_0(r,z))$ represents laser energy distribution calculated by ray tracing method. The laser beam irradiance $I_0$ was modeled as a Gaussian function:

$$I_0(r,z) = 3Q/(\pi R^2)\exp(-3(r^2)/R^2), \tag{8}$$

where $R$ is the effective beam radius and $Q$ is the laser power.

### 2.2. Discretization and solution

With octree, we discrete the spatial domain in a hierarchy of grids. Every grid is represented by one node on the tree [10]. Generally, non-uniform grids will bring some difficulties to the spatial discretization of the laser welding model. The key point about the discretization is to construct local uniform stencil by introducing ghost values from interpolation or weighted average. Here, we take the temperature gradient calculation at grid 1 (Fig. 1a) as an example. Firstly, we need to construct a locally uniform template for simple discretization (Fig. 1b). It means we need to construct a ghost value $T_8$ to compute $\frac{\partial T}{\partial x}\big|_1$. With bilinear interpolation method, $T_8$ can be calculated based on the four points' value (5, 6, 7 and the red[1] point)

$$T_8 = \frac{9}{16}T_5 + \frac{3}{16}T_6 + \frac{3}{16}T_{parent} + \frac{1}{16}T_7, \tag{9}$$

where the red point value represent the parent node value $T_{parent}$. It is easily gotten by weighted average, namely $T_{parent} = \frac{T_1+T_2+T_3+T_4}{4}$. Then we can calculate the central difference $\frac{\partial T}{\partial x}\big|_1 = \frac{T_2 - T_8}{\Delta x}$.

In this way, we can deal with the discretization in other cases. This method takes full advantage of the multi-layer structure of octree without considering the complex topological relation of the leaf grid [10]. Complicated discretization method is avoided. The extension to three dimensions is straightforward.

For reducing the parasite currents resulting from using CSF method, we need adopt the balanced-force algorithm [10] to calculate the surface tension force. To solve the Poisson equation efficiently, we use a geometrical multigrid method.

### 2.3. Adaptive mesh refinement

The heat and mass transfer phenomena during the laser welding process are mainly concerned. Also the free surface profile of the weld pool and keyhole is important. Thus, it is necessary to choose a mesh refinement strategy depending on local temperature, fluid velocity, and VOF value of weld pool of laser welding. For reducing human intervention, we take a multiresolution analysis scheme to control the mesh dynamical refinement, which is robust and applicable to non-equidistant data sets or tree structures [13].

To illustrate the multiresolution analysis based mesh refinement process, an example of the mesh refinement according to the temperature criterion is given. In Fig. 1a, whether the grid 1 (red grid) is refined or coarse depends on the difference between

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[1] For interpretation of color in Figs. 1 and 2, the reader is referred to the web version of this article.