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Numerical simulation of metal removal in laser drilling using radial point interpolation method

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ABSTRACT

Prediction of penetration depth in metal laser drilling is done through a simple meshfree numerical model. 2D axisymmetric simplified model of transient metal laser drilling is proposed for continuous laser beam of Gaussian distribution with strong form of Radial Point Interpolation Method (RPIM) used for approximating the temperature field. The commonly used Multi-Quadrics (MQ) and Exponential (EXP) Radial Basis Functions (RBFs) are tested and compared with each other. The model logic is constructed in MATLAB code, while the results are compared with published numerical and experimental work. The simulation results give good agreement with the previous numerical and experimental work, showing the model reliability in predicting the penetration depth in such a physically complex process.

1. Introduction

Mesh-based numerical methods have been extensively used in both fields of computational solid mechanics (CSM) and computational fluid mechanics (CFD). The most widely used mesh-based methods are Finite Volume Method (FVM), Finite Difference Method (FDM) and Finite Element Method (FEM). They were successfully applied in both areas of fluid dynamics and solid mechanics. Despite the heavy and consistent usage of such methods, their mesh-based nature of fixed topological connectivity limits their potential in handling problems of high/severe deformation, crack propagation or free surface without continuous re-meshing and heavy computational load, yet the result may not be reliable.

Consequently, meshfree methods were introduced to compensate the deficiency in grid/mesh-based methods in addressing such problems. Meshfree methods basically rely on discretizing the computational domain of interest into a finite number of particles with physical meaning and properties such as pressure, temperature, velocity, mass, etc. There is no fixed geometrical connectivity between the particles as in the case of nodes in mesh-based methods. The solution for the field variable of interest can be approximated locally or globally based on the meshfree method used. Development of meshfree methods has been rapidly increasing with several introduced methods such as Smoothed Particle Hydrodynamics (SPH), Element-Free Galerkin (EFG), reproducing kernel particle method (RKPM), Moving Least Square (MLS), Radial Basis Function (RBF) methods, Meshless Local Petrov-Galerkin (MLPG) [1–5].

Due to their dimensionality-independence, easy implementation and integration-free properties, RBF collocation methods have proved to be a reliable tool in solving partial differential equations (PDEs), multi-variate scattered data processing, machine learning and neural networks [6,7]. Their applications in solving PDEs have been widely reported in fields of solid mechanics and fluid dynamics [8–15]. On the other hand, due to the solution accuracy and convergence sensitivity to the shape parameters in RBFs, attention and effort have been given to evaluate the optimal shape parameters [16–19].

In order to fulfill the strict industry requirements imposed on the final product size, quality, material and operating conditions, Laser Beam Machining (LBM) has been an indispensable industry process [20–22]. Therefore, this leads to the pursuit of developing numerical and analytical models such that a better understanding of the physical process, in addition to the parameters effect, can be given without the need of extensive experimental work [23–28]. Meanwhile analysis and prediction using Taguchi Artificial Neural Network and Fuzzy logic

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Nomenclature

C_p	Specific heat
h	Support domain radius
h_a	Coefficient of convective heat transfer
k	Coefficient of thermal conductivity
l_r,l_z	Lengths of specimen in radial and axial directions, respectively
$\hat{n}_l$	Unit normal vector outward laser-irradiated surface
n_r,n_z	Direction cosines of the normal vector outward the laser-irradiated surface
N	Total number of particles in the whole domain
P_l	Laser power
r, z	Spatial coordinates in radial and axial directions, respectively
r_b	Laser beam radius at the focal point
t	Laser processing time
T	Particle temperature
T_a	Ambient temperature
T_m	Metal melting temperature
α_l	Laser absorptivity
Γ_a	Convective boundary
Γ_l	Laser-irradiated boundary
Δ	Nodal spacing
Δt	Simulation time step
λ	Thermal diffusivity
ρ	Density
Ω	Whole domain

have also been undertaken [29–31].

As previously mentioned, mesh-based methods have limitations in handling such severe deformation problems without continuous re-meshing and heavy computational load. Consequently, for metal laser processing, meshfree methods started to be introduced in the numerical simulation like the work in [32] using SPH (as cited in [26]), while a fully developed SPH platform (SPHysics) was used in [26] to simulate the metal laser drilling process considering molten pool hydrodynamics, penetration depth and expelled particles kinetics. In [33,34], the metal laser drilling process was simulated using Isoparametric Finite Point Method (IFPM) through an iterative scheme to find the boundary shape satisfying the energy balance.

In the present work, metal removal in laser drilling is simulated in terms of penetration depth using the Radial Point Interpolation Method (RPIM) with shape functions calculated by two popular different RBFs: Multi-Quadrics (MQ) and Gaussian/Expoential (EXP). Direct Collocation Method (DCM) is used to discretize the governing equation and boundary conditions. Employment of RPIM and DCM boasts a big advantage of computation efficiency in discretizing the governing and boundary equations in addition to assembling the global stiffness matrix in a straightforward manner. In [33,34], the drilling simulation of full-depth penetration was not addressed, however, the present work will simulate the full-depth metal laser drilling process through a simple MATLAB model employing RPIM. Results validation will be done against the numerical and experimental work in [26] to verify the present model accuracy.

2. Formulation of metal laser drilling by RPIM

2.1. Mechanism of metal laser drilling

Metal laser drilling is numerically simulated by RPIM, and Fig. 1 shows the conventional metal laser drilling mechanism. In such a process, the metal is rapidly heated by the laser beam until reaching the melting temperature, while pressurized assist gas expels the molten metal away from he processed work-piece. Moreover, the assist gas protects the metal from the surrounding in addition to reducing the dross and recast.

2.2. Assumptions of numerical model

During model construction, the following assumptions are considered:

1. Laser beam is continuous of Gaussian power distribution and vertically downward.
2. The radius of laser beam is constant and has value of the beam waist.
3. Laser irradiation is considered to be a surface heat flux not volumetric heat source.
4. The processed metal is isotropic with thermos-physical properties independent of temperature.
5. The molten metal does not show hydrodynamic behavior and is removed upon reaching the melting temperature.
6. Removed metal does not absorb the laser energy and is transparent.
7. Heat convection coefficient has single value for both convection and radiation losses.

2.3. Mathematical formulation of laser drilling

According to the previous assumptions, the governing equation is the conventional transient heat conduction equation subjected to natural and Robin boundary conditions. For uniform Gaussian distribution of laser intensity, 2D axisymmetric model in cylindrical coordinates is considered. Following the mathematical formulation in [35,36], while considering the laser irradiation to be a surface heat flux not a volumetric heat source, the transient governing equation of heat conduction for field particles is given by

$$\rho\, C_p \frac{\partial T}{\partial t} = k\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial T^2}{\partial r^2} + \frac{\partial T^2}{\partial z^2}\right) \text{ in } \Omega. \quad (1)$$

subjected to

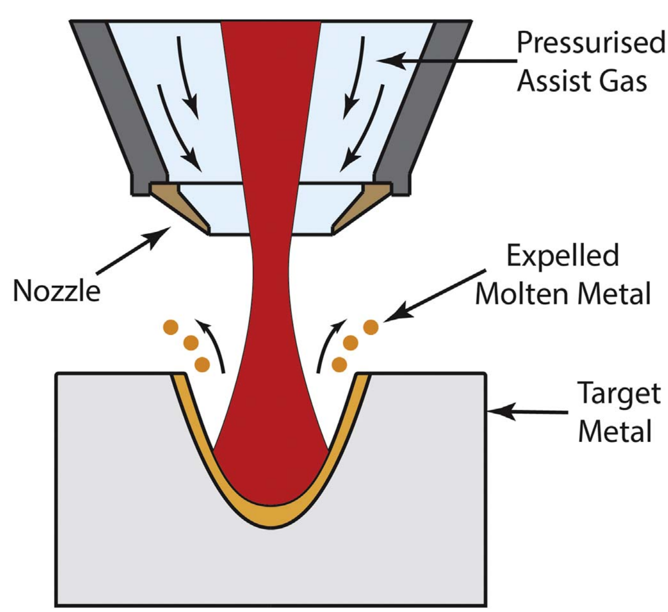

Fig. 1. Fusion Laser Drilling Mechanism.