# THREE-DIMENSIONAL TRANSIENT NUMERICAL SIMULATION OF GAUSSIAN LASER BEAM DRILLING PROCESS

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*Summary* A solid/liquid/gas three-phase numerical model for laser drilling with Gaussian laser beam is presented by considering material evaporation, molten liquid ejection caused by recoil pressure and beam divergence near the focus. Level set method is used to capture the liquid/vapour (L/V) interface as the hole boundary, temperature field and hole profile evolution are investigated with different defocus distance. Simulated result is compared with the experimental ones to verify the model's validity.

## INTRODUCTION

During laser drilling with $10^5 \sim 10^{15} W/cm^2$ energy intensity, material is mainly removed by vaporization and melt ejection. In this process, the laser beam energy distribution characteristic affects the heat input in L/V interface and will change the hole profile. Previously, the most investigation into numerical modelling and theoretical analysis of laser drilling are mainly one dimensional or ignore the vaporization of material, based on the assumption that the effective radius of laser beam is unchangeable. In this paper, beam divergence near the focus is taking into account, and level set method is adopted to describe the drilling process by considering evaporation and melt metal splashing, temperature field and hole surface morphology evolution is simulated.

## ASSUMPTIONS AND MODELLING

Assumptions:
1. The Laser is assumed to be distributed in Gaussian manner.
2. Energy is absorbed by material in L/V interface, ignoring the impact of multiple reflections of laser in the hole.
3. The moving of L/V interface is driven by the mass lost caused by molten liquid ejection and evaporation.

Modelling:
The level set [1] function is defined as a signed distance function $\phi(x, y, z; t) = \pm d$ in the entire compute domain, it satisfies $\phi = 0$ in L/V interface as the hole profile, physical properties of air and metal are assigned in region $\phi > 0$ and $\phi < 0$, respectively. The evolution of L/V interface then can be described as $\phi_t + (F_v + F_l)|\nabla\phi| = 0$, where $F_v$ and $F_l$ are the interface movement rate caused by vaporization and melts ejection, respectively. High density of the laser results in rapid evaporation of material in a Knudsen layer form [2], mass lost rate caused by it can be expressed as:

$$\dot{m}_v = \rho_{l/v}\left(\frac{R_v T_{l/v}}{2\pi}\right)^{1/2} - \rho_v\left(\frac{R_v T_v}{2\pi}\right)^{1/2}\beta F_-(m) = \rho_l F_v$$

Recoil pressure is generated which initiates radial ejection of liquid melt in evaporation, melt metal ejection velocity can be calculated by $p_{recoil} = \overline{p}_{l/v} = 1/2\,\rho_l V_l^2$. The average melt thickness is approximated as $\overline{\delta}_l \approx \alpha/\overline{F}_p$ [3]. Assuming that the surface area of hole bottom is $A$, and the hole diameter is equivalent to the laser spot, since the conservation of mass, the melting rate of the solid metal equals the sum of vaporization and liquid metal ejection in the whole bottom:

$$A\rho_s(\overline{F}_v + \overline{F}_l) = A\rho_l\overline{F}_v + 2\pi r\overline{\delta}_l\rho_l V_l$$

The laser beam is modelled as Gaussian type, the effective radius of laser beam changes due to the defocusing of laser beam. Taking energy lost in the L/V interface due to metal ejection, vaporization, radiation as well as convection into account, the energy boundary condition of L/V interface can be expressed as:

$$q''(r) = \eta \cdot q''(r)_{laser} - [\rho_s C_{ps}(T_{Sol} - T_a) + \rho_l C_{pl}(T_{vap} - T_{Liq})/2 + \rho_l L_m]F_l - \rho_l L_v F_v - \sigma\varepsilon(T_s^{\,4} - T^4_{\infty}) - H(T_s - T_a)$$

The governing equation of heat transfer in the whole solution domain can be uniformly expressed as:

$$\frac{\partial(\rho C_p T)}{\partial t} = K\nabla^2 T + q''\delta(\phi);\quad \delta(\phi) = \begin{cases} 1 & if\phi = 0 \\ 0 & elsewhere \end{cases}$$

## RESULT AND DISCUSSION

Simulation and experiment are carried out on low mild steel with laser beam which has 0.0375 $mm$ focal radius and 0.23 $mm$ Rayleigh range, with 1000 $W$ laser power and 1 $ms$ pulse time. Non-through holes are produced in material by setting focal plane of the laser at 0.7 $mm$ deep from the material surface (-0.7 $mm$ defocus). Fig.1 gives the computed

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evolution of temperature profile and L/V interface in drilling. The impingement of the laser beam on the metal raises the surface temperature as a result of absorption, and subsequently causes heating, melting and vaporization of the metal, a hole of 1.18 $mm$ deep is formed in 1 $ms$. The maximum temperature in the hole bottom during laser drilling is much higher than the boiling point of material due to the highly superheated of L/V interface, which leads to generation of big recoil pressure. The experimentally determined hole cross sections are compared with the corresponding computed one in Fig.2, it is observed that they agree well both in geometry and dimension. The beam divergence near the focus is shown to affect the hole profile strongly, a waist can be found in the depth of focal plane of the laser beam.

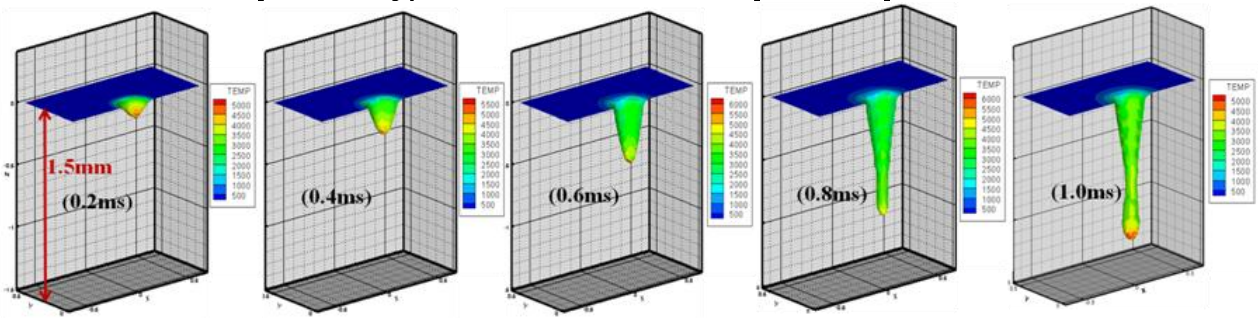

Fig.1.Hole geometry and temperature field evolution in laser drilling process

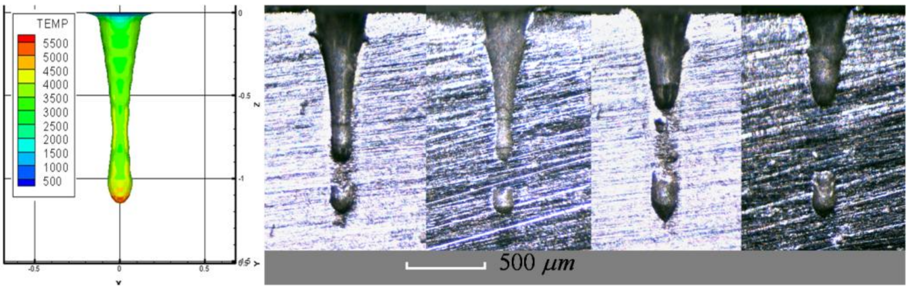

Fig.2. Comparison of the simulated hole geometry to the experimental ones.

Effects of laser defocus distances on hole profile are investigated in Fig.3 with different negative defocus distances from -0.7 $mm$ to -1.0 $mm$. Hole shape is a sensitive function of the position of the beam focal plane relative to the sample surface. The hole inlet diameter decreases with the reduction of the depth of focal plane away from the top surface, this can be attributed to the extension of effective radius on the top of the material, which also decrease in energy density and result in the reduction of drilling speed. At the start, material is removed over a larger area at a slower rate; much of the pulse energy is expended drilling an enlarged entrance leaving less for deepening the hole. Thus, a deeper and smaller hole can be gotten when shorter negative defocus distance is used in the drilling process.

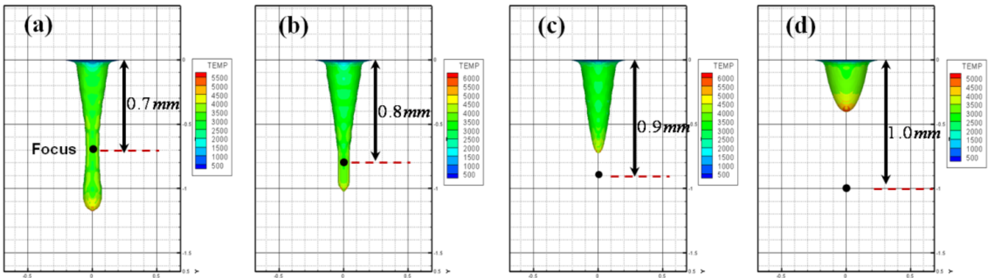

Fig.3. Hole geometries with different defocus distances.

## CONCLUSIONS

A three-phase numerical model for laser drilling with Gaussian laser is presented in this paper, good agreement is obtained between the simulated hole geometry and corresponding experimental ones. Due to the highly superheated of L/V interface under the impingement of the laser beam, temperature in the hole bottom is much higher than the boiling point of material, which results in the generation of recoil pressure. It shows that the defocusing position relative to material surface do have great effect on hole profile, shorter negative defocus distance can reduce the inlet diameter and increase the depth of the hole.

**References**

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