2D Multiphysics Modeling Framework for Laser Ablation of Al_2O_3 Ceramic Coating

Nazim Khan [a], Abinesh K [a], Rajdip Mukherji [b], Somnath Bhowmick [b], and Pritam Chakraborty [c*]

[a] Postdoctoral Fellow, Department of Aerospace Engineering, IIT Kanpur-208016, India.

[a] Project Associate, Department of Aerospace Engineering, IIT Kanpur-208016, India.

[b] Associate Professor, Department of Materials Science and Engineering, IIT Kanpur-208016, India.

[c*] Associate Professor, Department of Aerospace Engineering, IIT Kanpur-208016, India.

ABSTRACT

This work presents the development of a two-dimensional multiphysics model for laser ablation of Al_2O_3 ceramic coatings to elucidate the ablation dynamics. The model integrates thermophysical effects through the governing equations of continuity, momentum, and energy, coupled with a level-set equation to dynamically track the interface during the ablation process. The model is implemented in COMSOL Multiphysics through the weak form of the heat and fluid flow models and level set equation, ensuring numerical stability with strong nonlinear couplings. The results highlight the transition from melting to vaporization and the subsequent interface recession with damage morphology, providing insights into the thermo-fluid mechanisms of the ablation process. The proposed framework provides a robust computational method for understanding laser–ceramic interactions and supports the optimization of material parameters to minimize the ablation-induced damage.

1. INTRODUCTION

Solid-state lasers are widely used to emulate high-energy laser threats, owing to their ability to produce highly focused beams that facilitate precise and controlled energy deposition on the target surface [1]. The rapid development of high-energy laser technologies poses increasing threats to aerospace applications. When the laser beam incident on the ceramic coating applied on the substrate, a fraction of energy is absorbed by the ablative material and the remaining energy is reflected to the ambient. This leads to a rapid increase in temperature of the material, ultimately causing ablation damage once the material's thermal tolerance is exceeded. The interaction of laser energy with the material can lead to melting, vaporizing, ionizing or spattering of ablative layer, depending on the intensity of the laser energy and exposure time. Direct observation of laser–material interaction in experiments can be challenging and expensive, particularly when involving high-power lasers and specialized materials. Thus, numerical simulation has become an essential tool for studying and predicting the complex physical processes associated with laser-induced ablation. The proposed multiphysics framework integrates the heat transfer and fluid flow model with a level-set method to predict the laser ablation behavior of ceramic coating.

2. MATHEMATICAL MODEL

The mathematical framework integrates thermo-physical phenomena such as conduction, convection, radiation, and material phase changes, utilizing a combination of heat and fluid flow models and level set function to capture interface dynamics. The mathematical framework of these processes includes as follows:

$$\nabla \cdot \mathbf{u} = \dot{m}\,\frac{\delta(\phi)}{\mathrm{d}_m}\left(\frac{(\rho_l - \rho)}{\rho^2}\right) \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = \nabla\cdot\left[-p\mathrm{I} + \mu(\nabla\mathbf{u} + \nabla(\mathbf{u})^{\mathrm{T}})\right] + \frac{F_\delta}{\mathrm{d}_\delta} \tag{2}$$

$$\rho\,\mathrm{Cp}(\mathrm{T})\left(\frac{\partial \mathbf{T}}{\partial t} + \nabla.(\mathbf{u}\,\mathrm{T})\right) = \nabla\cdot(\mathrm{k}(\mathrm{T})\nabla\mathrm{T}) + \left(\frac{\mathrm{A}Q_L}{\mathrm{d}_q} + \frac{Q_v}{\mathrm{d}_v} - \frac{\mathrm{h}(\mathrm{T}-\mathrm{T}^0)}{\mathrm{d}_c} - \frac{\varepsilon K_B(\mathrm{T}^4 - \mathrm{T}_0^{\,4})}{\mathrm{d}_r}\right)\delta(\phi) \tag{3}$$

$$\frac{\partial \phi}{\partial t} + \mathbf{u}\cdot\nabla\phi + \frac{\dot{m}\delta(\phi)}{\rho\,\mathrm{d}_\phi} = \gamma_{ls}\nabla\cdot\left(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{4}$$

where **u,** ρ, p and T denotes velocity, density, pressure, and temperature. C_p is the material's specific heat capacity, ϵ is the emissivity, $\dot{m}$ is the mass flux rate, A is the absorptivity, k is the thermal conductivity, κ_b is Boltzmann constant. F_δ is the surface tension due to Marangoni effect and di is the length scale representing the absorption depth used to convert surface force (energy) into volumetric. $\delta(\phi)$ represents the Dirac delta function of the level set (ϕ), defined as $\delta(\phi)=16\phi^3(1-\phi)^2$, γ_{ls} is the level set interface re-initialization velocity, ε_{ls} is the transition thickness, and Q_L is the Gaussian distribution of laser heat flux.

3. RESULTS

A 2D FEM model consisting of air and ceramic coating is shown in Figure 1. The size of the model is 4 mm (in the x-direction) and 1.3 mm (in the y-direction), with the laser irradiating the top surface of the ceramic coating. The domain consists of 0.3 mm ceramic coating and 1 mm thick layer of air. Multiphysics simulations integrating heat transfer, fluid flow, and the level-set method were performed to investigate the ablation behavior of Al_2O_3 ceramic coatings subjected to a laser power of 500 watts with r_{spot} of 0.8 mm. The contours of the level set function and temperature distribution are shown in Figure 2, highlighting the localized heating and progression of the ablation interface.

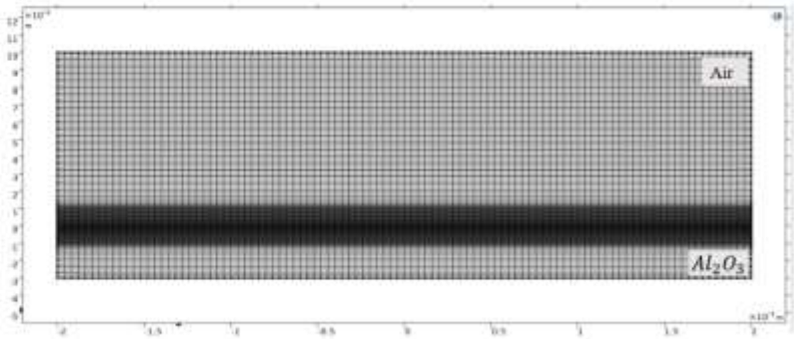
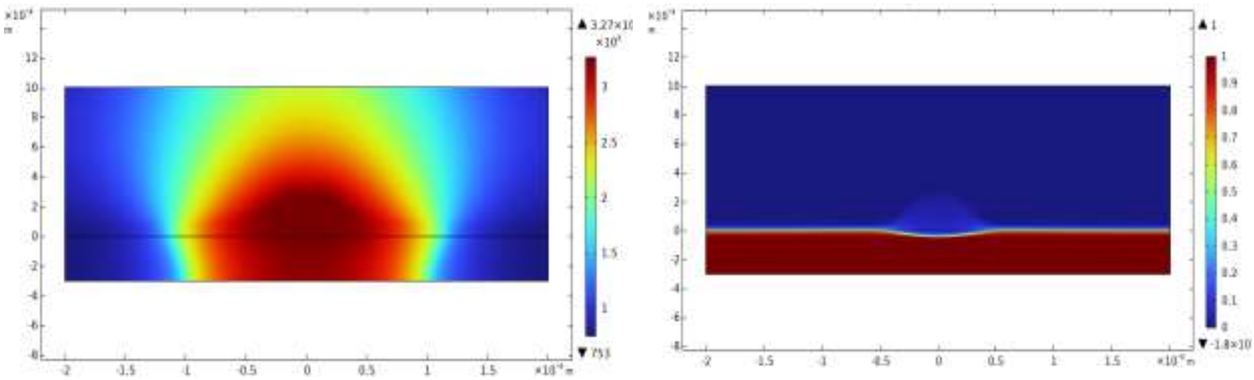


Figure 1. 2D FEM model for air and ceramic domains.



(a) (b)

Figure 2. Contours of (a) temperature and (b) level set function after the onset of vaporization.

4. CONCLUSIONS

This study presents a multiphysics simulation of laser ablation in Al_2O_3 ceramic coatings, capturing the coupled interaction between heat transfer, fluid flow, and phase change using a level set function. The model highlights the strong coupling between temperature, velocity, and interface motion, providing a valuable framework for understanding laser–material interactions in the ablation process.

5. REFERENCES

[1] S. Liu, Z. Tian, L. Shen, and M. Qiu, "Numerical simulation and experimental investigation of laser ablation of Al2_22O3_33 ceramic coating," *Materials*, vol. 13, no. 23, p. 5502, 2020, doi: 10.3390/ma13235502

* Communicating Author: Pritam Chakraborty and email: cpritam@iitk.ac.in