Ultrashort Laser Interaction with Dielectric Materials
--A Numerical Approach Based on a Plasma-Temperature Combined Model

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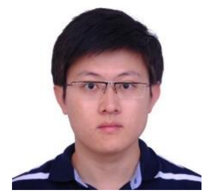
Biography

Xiao Jia graduated from Nanjing University of Aeronautics and Astronautics (NUAA) with B.S. degree in 2012, and Tongji University with M.S. degree in 2015, majoring in Automotive Engineering. He is now a second year PhD student in the Department of Mechanical Engineering at Clemson University. His current research focuses on ultrashort laser-matter interaction, micro/nano-machining. He is a student member of APS.



Overview:

Ultrashort laser-matter interaction is investigated to understand the mechanisms of laser-induced ablation (LIA). A numerical approach is employed based on a plasma-temperature combined model, considering the behavior of electronic and thermal processes during ablation. Material decomposition is captured based on the material temperature evaluation, and the dynamic material removal is considered during the ablation process. With the vaporization temperature as the ablation criterion, phase explosion and boiling are considered as the dominating channels for ablation. LIA threshold, ablation depth, ablation efficiency, transient optical properties, and laser beam propagation are predicted, and good agreements with the experimental measurements are obtained. The proposed model helps to enhance the understanding of the primary ablation mechanisms in LIA, and provides an efficient tool to predict LIA for micromachining applications.

Motivation

Ultrashort laser has great potential in direct micromachining of dielectric materials, such as microchannel fabrication of glass for micro-fluidic applications. With ultrashort pulse duration, less thermal damage and higher precision in the microstructure can be obtained. Though numerous experimental and numerical studies have been done, there are still debates regarding the fundamental mechanisms of laser-matter interaction and laser-induced ablation. The ablation criterion is one of the key parameters during the study of laser-induced ablation and it faces inconsistence in different investigations. For dielectric materials, a critical electron number density is usually employed for the prediction of ablation threshold and ablation depth, while other temperature-based criteria have also been proposed. These inconsistences make it less clear for the understanding of ablation mechanisms, and motivate further investigation through an improved numerical approach.

State of the Art

Various numerical approaches have been proposed for the description of ultrashort laser-induced ablation of dielectric materials. Due to the lack of conduction-band electrons (CBEs), valence-band electron excitation is needed before metallic behavior is shown. Several mechanisms including multiphoton ionization (MPI), impact ionization (II), and tunneling ionization (TI) are involved in either single rate equation (SRE) [1] or multiple rate equation (MRE) [2] to describe the evolution of CBE number density. A critical electron density has been widely employed as the ablation criterion for the determination of ablation threshold [1,3] and ablation depth [4,5]. However, other criteria were also adopted in different studies, such as temperature-based criteria. Both melting temperature [5] and cohesion temperature [6] have been proposed for the prediction of ablation threshold and ablation depth. So far, the proper ablation criterion for ultrashort LIA is still not clear, and better understanding of ablation mechanisms is necessary.

Intellectual Merit

In this study, a numerical approach based on a continuum model has been developed to understand the underlying mechanisms of laser-induced ablation for dielectric materials. An improved two-temperature model (TTM) [7] and a single rate equation (SRE) [1] are combined to describe the thermal and electronic behaviors of dielectric materials during ultrashort laser-induced ablation process. High computational efficiency and accurate prediction of ablation behaviors can be obtained through this numerical approach. Thermal energy loss from ablated materials has been considered through a dynamic description of material removal. Electronic diffusion has been considered by the drift-diffusion model [8]. Temperature-dependent heat capacity of lattice has been employed for better prediction of final crater depth. Vaporization temperature has been selected as the proper criterion for the prediction of ablation threshold and crater depth. Good agreements have been achieved between the simulation results and the experimental observations in the literature.

Broader Impact

Ultrashort laser machining is able to create high-precision microstructures in dielectric materials, which is not easily achievable with traditional methods. With the increasing requirement of size and precision in direct fabrication, ultrashort laser will play a more important role in the manufacturing industry. In this study, the underlying mechanisms of ultrashort laser-matter interaction have been investigated further with a plasma-temperature combined model. Both electronic and thermal behaviors can be observed through this numerical approach and a proper ablation criterion as vaporization point has been proposed. Good prediction of ablation threshold and crater depth can be obtained compared with experiments. Combination of numerical and experimental approaches will help to save costs in time and efforts for investigations on more complicated processes, including ablation enhancement with shaped pulses, and direct fabrication of microchannel with ultrahigh aspect ratio.

Research Approach

A one-dimensional continuum model has been developed to describe the dynamic process of ultrashort laser-induced ablation for dielectric materials. Electronic and thermal behaviors have been described through the combination of the plasma model and the two-temperature model. Electron excitation mechanisms, transient optical properties, ablation threshold, crater depth and Gaussian-shaped beam propagation have been investigated for better understanding the underlying mechanisms of ultrashort laser interaction with dielectric materials. Good agreements with experiments can be obtained through this numerical approach with a temperature-based ablation criterion.

Findings to Date

Based on the numerical model, the transient ablation process can be monitored within the bulk material. Ablation threshold, crater depth, ablation efficiency have been predicted, with good agreements to the experiments. With the increase of incident laser fluence, contribution of free electron excitation from multiphoton ionization decreases, indicating a more important role of its counterpart, impact ionization. Surface reflection and absorption of laser energy both increase with incident fluence and saturate at high fluence region.

Ablation depth experiences fast increase above the threshold fluence and saturates at high fluence region. Higher ablation efficiency and reduced thermal damage can be obtained through low fluence ablation, which is suggested for direct fabrication in experimental and industrial applications. The Gaussian-shaped beam divergence has been observed to be more influential on the ablation depth of dielectric than non-transparent materials.

Conclusions

Ultrashort laser-induced ablation of dielectric materials has been investigated based on a one-dimensional plasma-temperature combined model. Through a temperature-based criterion, material is considered to be ablated when the lattice temperature is higher than the vaporization point. Ablation threshold and crater depth have been studied. The scaling law of threshold fluence obtains good agreements to experimental observations. Good agreement can be achieved as well for ablation depth compared with experimental measurements. The ablation depth experiences significant increase with fluence just above the threshold, and tends to saturate with further increased fluence. Two mechanisms of electron excitation have been compared for their relative contributions. With the increase of incident fluence, impact ionization tends to dominate, because the observed contribution from multiphoton ionization decreases and saturates in high fluence region. As for the ablation efficiency, defined as the ablated volume per unit pulse energy, continuous decrease with fluence can be observed after reaching the peak value at around double of the threshold. Low fluence fabrication is suggested for the overall consideration of ablation efficiency and microstructure quality with pulse duration in femtoseconds range. The divergence in Gaussian-shaped beam plays a more important role in the ablation of dielectric than metals and semiconductors, due to the much shorter optical penetration depth in opaque materials.

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