

Ablation of ceramics with ultraviolet, visible and infrared nanosecond laser pulses

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ABSTRACT

Laser ablation of alumina (Al_2O_3), aluminum nitride (AlN) and silicon nitride (Si_3N_4) ceramics by 6 ns Nd:YAG laser operating at wavelengths of 1064 nm, 532 nm and 355 nm is studied. For all materials the maximum ablation rate is observed at wavelength of 1064 nm, and the smallest one for irradiation at 532 nm in the case of Si_3N_4 and AlN. The numerical model, based on the heat-transfer equation describes the temperature distribution in the material and the evaporation process. The calculated depths of the drilled holes are in agreement with experiment.

Keywords: nanosecond laser ablation, ceramics, heat transfer equation

1. INTRODUCTION

The ceramics have attracted a great deal of interest in recent years^{1,2}. Because of their useful properties, typically observed for good insulators i.e., excellent chemical and thermal stability, high hardness, and good electric insulation, they are widely used in optoelectronics, high-power electronics, microelectronics, car industry, medicine, etc.^{2,3}. However, they belong to materials that are most difficult to machine by conventional methods due to their hardness and fragility.

The application of lasers in micromachining and microstructuring of ceramics enabled to produce sharp and well-defined holes and cuts^{4,6}. However, the physical phenomena involved in many laser applications are not fully understood. The difficulties are related to the facts that in most of these materials, the phase transition from solid to vapour occurs without melting of the material^{7,8}. Another feature is a strong dependence of the thermo-physical parameters on the grain size and material composition^{9,10}. These specific properties require more careful examination of the interaction between the laser light and the ceramics.

In this work, nanosecond laser ablation of Al_2O_3 , AlN, and Si_3N_4 ceramics with Nd:YAG laser at different wavelengths is studied. The drilling efficiency is estimated for the IR, VIS and UV laser radiation. One-dimensional numerical model based on the heat transfer equation is used to describe the drilling process. Moreover, the absorption of the plasma plume formed on the surface of the ceramics is taken into account, which results in a good agreement between the experimental and theoretical results.

2. EXPERIMENTAL

A TEM₀₀ mode Nd:YAG laser of 6 ns pulse width at FWHM, and working in a single pulse mode (Quantel) is used for ablation and drilling holes in the ceramics targets. The experiments are performed at the fundamental, second, and third harmonic of the laser corresponding to wavelengths of 1064, 532 and 355 nm, respectively. The optical system consists of the beam expander and focusing lens of $f=50$ mm. This system enables to focus laser radiation at a

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spot size of 70 μm . The ablation rate is estimated as an average value from the total depth, drilled by 10 consecutive laser pulses and measured by using an optical microscope. The scanning electron microscope is used to investigate the hole shape and the ablated area. The experiments are performed in air environment.

3. NUMERICAL MODEL

The drilling arrangement considered in the numerical model is based on the following assumptions:

1. The material evaporation occurs in a single step, i. e. the phase transition from solid to vapor occurs without melting in the case of Si_3N_4 or AlN ceramics;
2. The ablation of the material surface takes place in a layer-by-layer way. When a particular layer reaches the evaporation temperature and the incoming energy exceeds the latent energy of evaporation for this layer, the material of this layer is being removed and no longer considered;
3. The plasma plume absorption is taken into account;
4. A change of the type of the equivalent heat source from a volumetric to a surface one is considered during the laser pulse irradiation. Si_3N_4 and AlN ceramics decompose at temperature 2151 K⁷ and 2790 K¹, respectively. In these processes a thin layer from liquid silicon or aluminum, is formed on the surface of the material, which lead to rise of the absorption of the laser radiation. (Al_2O_3 is melted at temperatures higher than 2300 K that also results in increase of its absorption¹¹);
5. The material density does not vary with the temperature;
6. The thermal properties of the ceramics change with the temperature. The respective dependencies are taken from Ref. 12;
7. The reflectivity of the surface of the material also changes; once the above-mentioned temperatures are reached, the reflectivity of the liquid silicon or aluminum (in the cases of Si_3N_4 or AlN, respectively) are taken into account.

The laser drilling is modelled using the following one-dimensional heat-transfer equation:

$$C\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} K \frac{\partial T}{\partial z} + A(z, t), \quad (1)$$

where C is the heat capacity of the material, ρ - the density of the material, K - the heat conductivity, t is the temporal variable, and A represents the heat source defined as:

$$A(z, t) = I(t)(1 - R)\alpha \exp(-\alpha z). \quad (2)$$

Here α is the absorption coefficient, R - the reflectivity of the material, and I stands for the laser power density, which is assumed to have the Gaussian temporal shape with laser pulse duration τ_0 (half width at 1/e of maximum intensity level):

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau_0^2}\right). \quad (3)$$

Eq.(1) is solved together with the boundary conditions using the common forward time centered space (FTCS) finite difference scheme¹³. More detailed description of the numerical model can be found in Ref. 8.

The evaporation of the target leads to the formation of a plasma plume. In this case the attenuation of the light intensity is modeled by using the exponential form of the Lambert's law with plasma absorption coefficient α_{pl} . The data for the value of α_{pl} and its dependence on the laser energy density are taken from Ref. 14.

4. RESULTS AND DISCUSSIONS

The dependencies of the hole depth per pulse drilled in the materials on the laser energy density E for three wavelengths, respectively are presented in Fig.1 a), b), and c). As one can see, the highest drilling efficiency is obtained at 1064 nm for all the materials. The smallest ablation rate is observed for VIS radiation (532 nm) in the case of Si_3N_4 and AlN. The reason for that can be the different nature of the absorption and scattering of the laser beam by the vapour particles and droplets being ejected during laser-material interaction. There are two dominant mechanisms for plasma absorption: 1) inverse bremsstrahlung (IB), where photons are absorbed by free electrons during collisions with neutral

and ionized atoms, 2) – photoionization (PI)¹⁵. Generally, IB process is more efficient in the visible and infrared spectral region than UV, although its effectiveness depends on several factors, which involve the target thermo-physical properties, degree of ionization and the temperature of the plasma. The direct PI of excited atoms in the vapour can be significant in VIS and UV laser ablation processes. Moreover, the increase of the electron and ion number densities by PI, enhances also the probability of

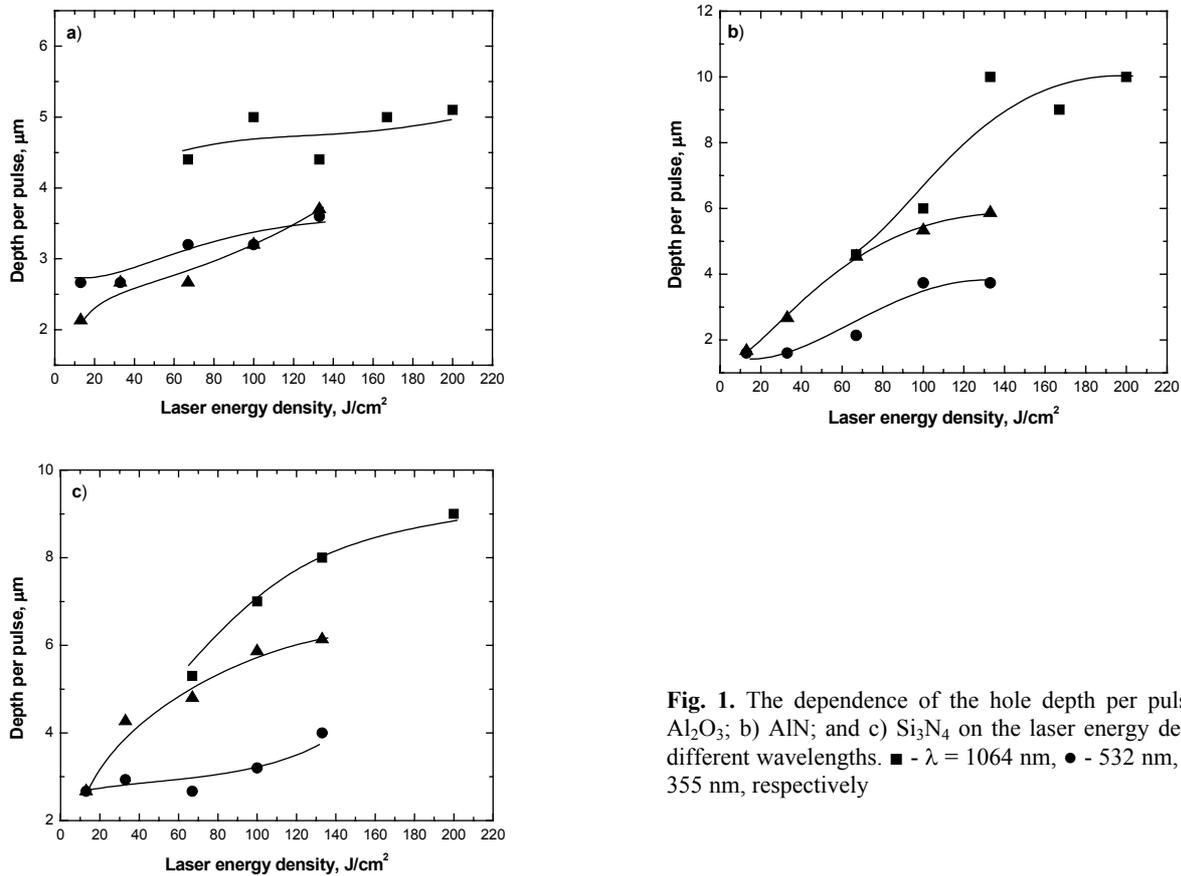


Fig. 1. The dependence of the hole depth per pulse in: a) Al₂O₃; b) AlN; and c) Si₃N₄ on the laser energy density for different wavelengths. ■ - λ = 1064 nm, ● - 532 nm, and ▲ - 355 nm, respectively

absorption by IB. The combination of these two mechanisms of absorption and their wavelength–dependence results in the different behaviour of the plasma in the ablation process.

The absorption in the plasma plume is clearly pronounced in the case of Al₂O₃ where the ablation rate rises slowly regardless of the variations of laser energy density by about an order of magnitude. Similar saturation can be observed in the other investigated ceramics at higher laser energy density, too.

The mechanism of ablation is different depending on the kind of ceramic. Si₃N₄ and AlN decompose into gaseous nitrogen and liquid silicon or aluminum, respectively. The ablation process of Al₂O₃ includes melting at temperature 2323 K and vaporization at 3773 K¹⁶. Fig. 2 represents the SEM images of the holes drilled by 1064 nm laser radiation in AlN – a) and in Al₂O₃ – b). Holes as small as 40 μm are produced in both cases. The ejected gaseous products in the decomposition reaction in AlN cannot redeposit on the surface and additionally help to move larger fragments away from the surface. This is the reason that almost no ablated material is found re-deposited around the

hole. In the case of Al_2O_3 the presence of melting phase in the ablation process is evident. The recast layer formed by re-solidification of melt material surrounds the hole. The melting phase results also in smoother hole walls compared to these in AlN . Furthermore a part of melt material fills the drilled hole and causes shallower and narrower crater compared to the other investigated ceramics. Moreover, some cracks in the re-solidified material surrounding the hole are observed.

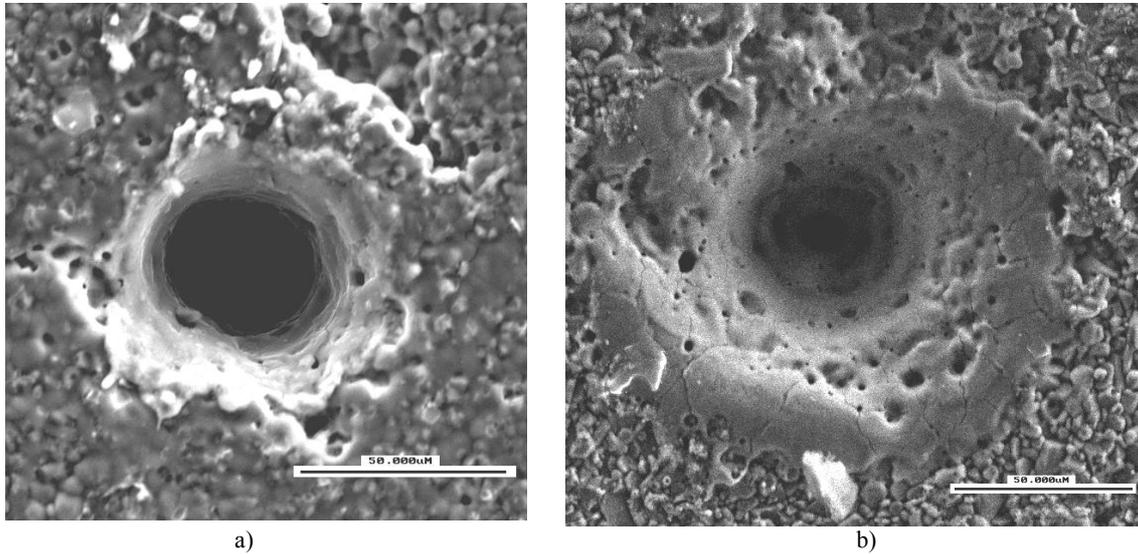


Fig. 2. SEM images of the holes in: a) AlN and b) Al_2O_3 , drilled by 1064 nm laser radiation. The laser energy density is 133 J/cm^2 .

The increasing of the laser energy density does not affect significantly on the hole diameter and the amount of the recast material. However, the change of the laser wavelength results in significant change of the hole diameter. Fig. 3 represents the SEM images of the holes drilled by $\lambda = 1064 \text{ nm}$ – a), 532 nm – b), and 355 nm – c), respectively, in Si_3N_4 . The laser energy density in each case is constant - 133 J/cm^2 .

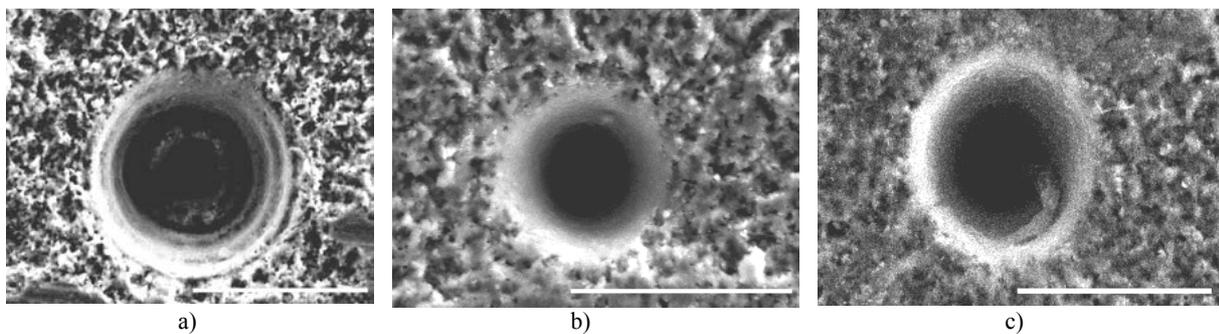


Fig. 3. SEM images of the holes drilled in Si_3N_4 by: a) $\lambda = 1064 \text{ nm}$; b) 532 nm ; and c) 355 nm laser radiation. The laser energy density is 133 J/cm^2 . The white marks represent $50 \mu\text{m}$.

The numerical model is applied to describe the drilling process in AlN . Fig. 4 shows the dependence of the hole depth on the laser energy density at 1064 nm. The line represents data calculated from the heat-transfer equation, the dots are experimental data. As one can see there is an agreement between calculation and experiment. The observed

discrepancy could be referred to the lack of knowledge of reliable value of α_{pl} used for the calculation and its variation with the change of laser energy density.

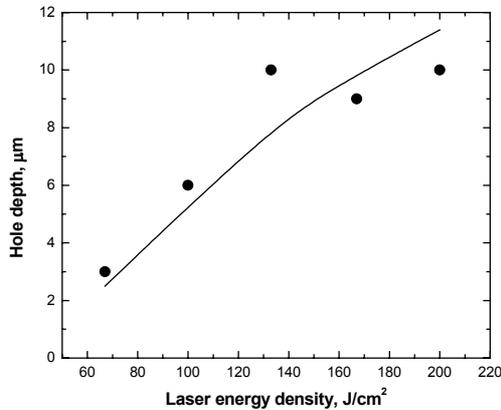


Fig. 4. Hole depth in AlN as a function of laser energy density at 1064 nm. The dots present the experimental data and the solid line – the calculated values.

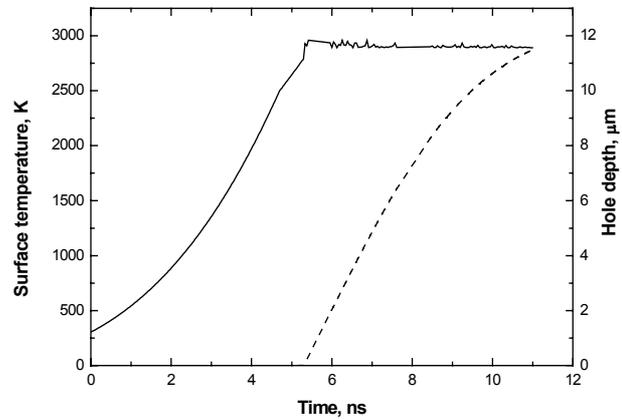


Fig. 5. Temporal behaviour of the temperature (solid curve) on the AlN surface and the evolution of the hole depth (dashed curve) produced at $E = 200 \text{ J/cm}^2$, 1064 nm .

Fig. 5 represents the temporal dependence of the temperature of the AlN surface irradiated at $E=200 \text{ J/cm}^2$, 1064 nm., and also the time evolution of the hole depth (dashed curve). About 5 ns after the laser pulse onset the surface temperature reaches the decomposition point. A thin Al layer, which strongly absorbs the incoming laser radiation, is formed on the surface of the material. The steep rise of the surface temperature at this moment is related to the change of the type of the equivalent heat source from a volumetric to a surface one used in the calculations.

5. CONCLUSION

The process of drilling of ceramics at wavelengths of 1064, 532 and 355nm, of the Nd:YAG laser is investigated experimentally and theoretically. The main results are summarized in the following:

- nanosecond laser pulses can produce holes in ceramics with high quality;
- the laser radiation at 1064 nm produces highest ablation rate;
- the decomposition reactions in AlN and Si_3N_4 help to move larger fragments away from the surface leaving the ablation area without material re-depositing. The melting phase in Al_2O_3 produces recast layer and partially fills the created crater ;
- the holes in Si_3N_4 have best quality in respect to the debris and roundness compared to other ceramics;
- the drilling process can be described by the heat-transfer equation taking plasma absorption and the change of the equivalent heat source into account.

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