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Pulsed Nd:YAG laser drilling of alumina ceramics and silicon wafers

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Abstract

This paper reports about drilling of alumina ceramics samples and silicon slabs with thickness about 2.3 mm, 7.5 mm and 8 mm using a stable and two types of non-stable resonator setups in pulsed Nd:YAG laser KLS 246-102 with different theoretical focus diameter and beam quality. Pulse energy and peak power were increased by setting of charging voltage from 280 V to 370 V with 10 V step for each type of resonator, their maximal values always depend on resonator power limits.
Constant burst of pulses is applied on thinner samples to find holes dimensions dependence on peak power, than number of pulses needed to drill complete holes in thicker samples was investigated. Effect of the laser energy input and laser beam diameter on the holes depth and diameters was evaluated for all samples using both laser scanning confocal and optical stereo microscopes. It was observed, that achieved holes depth has tendency to increase with increasing value of the energy in case of blind holes, just as entrance/exit diameter of complete holes. Exit diameter of cone-shaped holes is always smaller than that of the entrance. Maximal material removal was achieved with the most efficient stable resonator, but the best holes quality was obtain with non-stable resonator for drilling. Numerical model of the vaporized and melted area in the holes cross section was made using finite differences method to display temperature distribution dependence on increasing pulse energy.

Keywords: Laser drilling; alumina; silicon; beam quality; numerical model

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1. Introduction

Alumina ceramics and polycrystalline silicon are non-metal materials with different chemical composition, method of production and physical properties, but machining both of them by conventional contact method is rather difficult due its hardness and lower order fracture toughness.

Laser drilling, scribing and fine cutting has been studying in research centers equipped with various types of the industrial laser sources to develop method for creating through holes, resizing of the semi products etc. Nedialkov et al., 2003 has studied laser ablation of alumina and other ceramics by 6 ns Nd:YAG laser at fundamental, the second and the third harmonic wavelengths. Samant and Dahotre, 2008 have described process of alumina ceramics drilling by JK 701 pulsed Nd:YAG laser with maximal pulse energy 55 J. Kacar et al., 2009 reported about Nd:YAG laser JK 760 drilling of 10 mm thick alumina ceramics samples. Hanon et al., 2012 has followed previous work with mathematical model. New possibility of the more precious and high speed drilling is brought by new fiber ytterbium lasers (Mendes et al., 2015). Patwa et al., 2013 investigated drilling of thin silicon wafers by pulsed disc laser Jenopik IR 70.

Our experiments with pulsed Nd:YAG laser KLS 246-102 (Lasag AG) were realized with objective to find dependence of the hole both entrance and exit diameters, so as a maximal depth of the blind holes dependence on the laser beam diameter and a pulse energy. Obtained knowledge will be useful for trepanation drilling of the different prototype device parts developed in our facility.

Numerical model of the vaporized and melted area in the holes cross section was created using finite differences method with equidistant mesh to illustrate temperature distribution dependence on increasing power in alumina ceramics bulk material.

1.1. Experimental set-up

Pulsed Nd:YAG laser KLS 246-102 resonator can be set by rear mirror (HR) distance from crystal, diaphragm diameter and curvature of the rear mirror. Standard resonator for welding and fiber applications has the shortest mirror distance (L_2) 190 mm, a diaphragm diameter (D_{dph}) 5.8 mm and a plane rear mirror. It can be used in the whole power range up to 160 W. Its beam parameter product (*BPP*) has maximal value 22 mm.mrad. All special resonators for cutting and drilling have the longer rear mirror distances 300 mm or 390 mm, diaphragm diameter 4.2 mm or 5.8 mm and a plane or spherical rear mirror. To avoid a damage of the optical elements, special resonators have restricted average power range up to 40 W or 80 W. Their *BPP* strongly dependents of the thermal lensing effect of Nd:YAG crystal and its value changes from 2.5 mm.rad to 11 mm.rad for half divergence and beam radius (Table 1). Different laser spot diameters on the material surface can be created with focus lens 100 mm in fixed processing head, that determined surface energy density (fluency) and intensity.

Alumina ceramic samples (aluminum oxide, 99.6 % Al_2O_3, CeramTec, CR) with thickness 2.3 mm and 8 mm were used as received from producer. Polycrystalline silicon slabs were provided from firm Themis, CR), where big original rods were cut by wire saw to thin wafers or thick slabs. Our samples used in experiment have thickness 2.5 mm and 7.5 mm.

Table 1. Parameters of KLS 246-102 pulsed Nd:YAG laser three different resonator setups

Type of the resonator	HR distance L_2 (mm)	Diaphragm D_{dph} (mm)	*BPP* (mm.mrad)	Spot *D* (mm)
Welding	190	5.8	14 – 22	0.4 – 0.7
Drilling	390	5.8	5 – 11	0.15 – 0.35
Cutting	390	3.5	2.5 – 6	0.08 – 0.18

2. Experimental Procedure

Samples were fixed on the XY positioning table, focus plane was positioned approximately 0.5 mm under sample surface and a filtered compressed air with pressure 5 bar was guided coaxially with laser beam. Constant pulse frequency 10 Hz and pulse length 0.8 ms were chosen to satisfy power limit for all types of resonators. CNC program was edit to create row of 10 separate holes with burst of 10 pulses. Alumina ceramic samples were painted by a black permanent marker to increase initial absorption.

Pulse energy and appropriate peak power were increased by setting of the charging voltage from 280 V to 370 V with 10 V step. At first, alumina ceramics and silicon samples with thickness 2.3 mm were drilled with one burst, then thicker samples of alumina (8 mm) and silicon slabs (7.5 mm) were drilled with six bursts, after each two bursts the focus plane was shifted down of distance 1 mm.

This procedure has been repeated for each type of above mentioned resonators. Pulse energy displayed on the laser terminal was recorded for each charging voltage, it is clear from Table 2, that energy values for special resonators are lower due to restricted beam diameter and power limit.

Table 2. Energy values and summary of the experiments results for each type of resonator and 2.3 mm thick samples

Resonator / Voltage (V)		280	290	300	310	320	330	340	350	360	370
Welding	Energy (J)	2.32	2.53	2.78	3.05	3.28	3.56	3.78	4.02	4.45	4.79
Alumina	Entrance (μm)	345	350	390	395	425	470	485	480	475	535
2.3 mm	Exit (μm)	220	250	235	253	275	315	265	290	310	320
Silicon	Entrance (μm)	370	390	395	410	430	420	450	455	490	505
2.3 mm	Exit (μm)	260	265	275	285	305	310	305	340	305	335
Drilling	Energy (J)	2.09	2.29	2.6	2.89	3.16	3.39	3.62	3.92	4.15	4.46
Alumina	Entrance (μm)	305	318	295	365	366	355	380	410	405	421
2.3 mm	Exit (μm)	210	215	260	265	265	260	275	270	273	270
Silicon	Entrance (μm)	330	325	375	410	410	428	380	420	450	445
2.3 mm	Exit (μm)	245	260	255	290	270	255	275	275	267	295
Cutting	Energy (J)	1.02	1.11	1.24	1.32	1.41	1.53	1.65	1.76	1.88	2.01
Alumina	Entrance (μm)	164	172	185	198	205	215	197	235	280	278
2.3 mm	Exit (μm)	85	92	88	121	142	135	133	151	127	142
Silicon	Entrance (μm)	165	205	215	190	240	260	266	282	300	310
2.3 mm	Exit (μm)	-	-	-	-	140	146	141	170	185	190

3. Results and discussion

Diameter both of the entrance and exit holes were measured by means of the laser scanning confocal microscope LEXT and the color images were saved with magnification 480x or 120x. Thick silicon sample was broken along holes row to measure a maximal depth of blind holes and display complete cross section by means of stereomicroscope with magnification 4X to illustrate hole's depth dependence on pulse energy and type of resonator. Results for samples of 2.3 mm are summarized in Table 2 and set of graphs was created to compare entrance and exit hole diameters for thin and thick samples of both materials, so as display blind hole progress with increasing energy. All measured data were stored for additional processing.

3.1. Welding resonator

Only with welding resonator maximal peak power can be reached and laser output can be switched to optical fibers. Pulse energy values increase from 2.32 J to 4.79 J, adequate peak power is computed as ratio of energy and pulse length and changed from 2.9 kW to 6 kW that corresponds with laser intensity (1.03 up to 2.12) MW.cm^{-2}. Samples of both materials with thickness 2.3 mm were drilled completely by one burst, ejection of molten material was visible under the samples after the first three – four shots. Level of noise was the biggest in comparison with two other resonators. Average entrance diameter of alumina ceramics was measured in interval from 345 μm for the lowest energy to 535 μm for the highest energy, in silicon sample from 370 μm to 505 μm. Average exit diameters reached about 60 % of the entrance ones, from 220 μm to 320 μm for alumina ceramics and from 260 μm to 335 μm for silicon. Only alumina ceramics sample 8 mm thick was drilled completely, but silicon sample of thickness 7.5 mm was drilled to the maximal depth 6.2 mm. Probably due to the wider laser beam, considerable amount of ejected spatters is visible on the hole entrance of both materials, mainly in case of the highest energy 4.79 J (see Fig .1 a, 1 b).

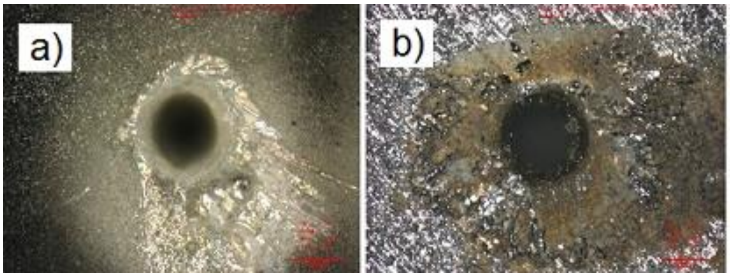

Fig. 1. (a) Entrance hole in alumina ceramics of thickness 8 mm drilled with energy 4.79 J; (b) Entrance hole in silicon slab of thickness 7.5 mm drilled with energy 4.79 J, red rule 320 μm, magnification 120x

3.2. Drilling resonator

Pulse energy values were recorded in range 2.09 J to 4.46 J, adequate peak power increases from 2.61 kW to 5.58 kW that corresponds with laser intensity (2.3 up to 4.92) MW.cm^{-2}. Samples with thickness 2.3 mm were drilled through by one burst, ejection of debris was visible under the samples after the first four - five shots. Average entrance diameter of alumina ceramics started at 310 μm and reached 421 μm for the highest energy, in silicon sample from 330 μm to 445 μm. Average exit diameters are smaller, from 210 μm to 270 μm for alumina and from 245 μm to 295 μm for silicon.

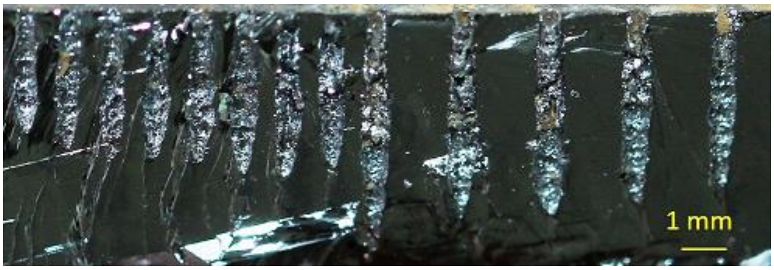

Fig. 2. Side view of the silicon slab of 7.5 mm thickness with holes drilled with single burst of energy 2.6 J to 4.46 J (from left) and with six bursts with increasing energy from 4.46 J to 3.39 J in experiment with drilling resonator.

Drilling of thick samples was completely through only in case of 8 mm alumina ceramics, maximal depth in 7.5 mm silicon slab was reached only 5.8 mm. Typical hole barreling in depth about 2 mm is seen in Fig. 2, that displays a row of the hole profiles for single burst of energy 2.6 J to 4.46 J and for six bursts with decreasing energy from 4.46 J to 3.39 J, respectively. Entrance and exit diameters development with energy of both alumina ceramics samples are displayed in Fig. 3. It is seen, that entrance diameters made by 6 bursts is wider due to higher energy input and shape of the holes in thick sample is more conical in comparison with those of thin alumina ceramics sample, exit holes have mostly irregular shape (Fig. 4).

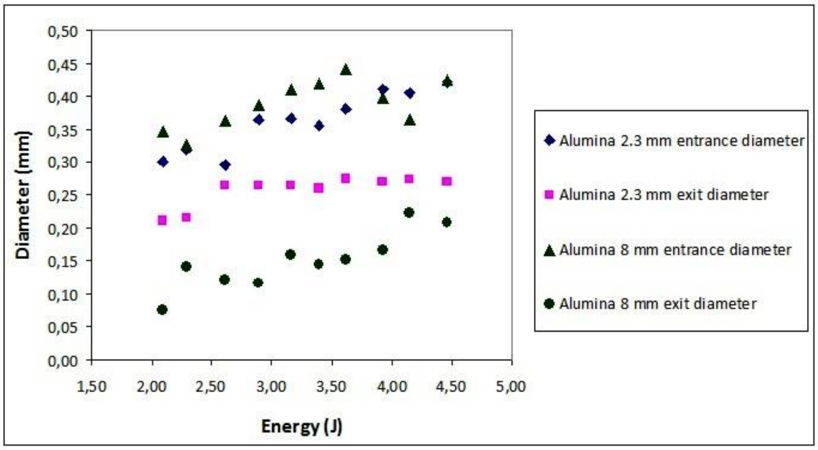

Fig. 3. Average entrance and exit diameters both in 2.3 mm and 8 mm alumina ceramic samples dependence on the pulse energy

3.3. Cutting resonator

Special non-stable resonator with the highest beam quality and the smallest beam diameter started pulse energy values on 1.02 J for charging voltage 280 V and reached 2.01 J at 370 V, peak power raised from 816 kW to 1 608 W, ensured laser intensity (5.01 - 9.88) MW.cm^{-2}. Alumina samples with thickness 2.3 mm were drilled completely by one burst as with two previous resonators, but any exit hole was not observed on the bottom side of the silicon sample below energy 1.4 J. Average entrance diameter of alumina developed from 165 μm to 278 μm, in silicon sample increased from 165 μm to 310 μm. Average exit diameters are smaller again, from 85 μm to 151 μm for alumina and from 140 μm to 190 μm for the last six holes in silicon. Drilling of thick samples was not many effective, complete irregular holes were achieved only in 8 mm alumina ceramics with energy higher than 1.4 J, maximal depth in 7.5 mm silicon was reached about 5.3 mm.

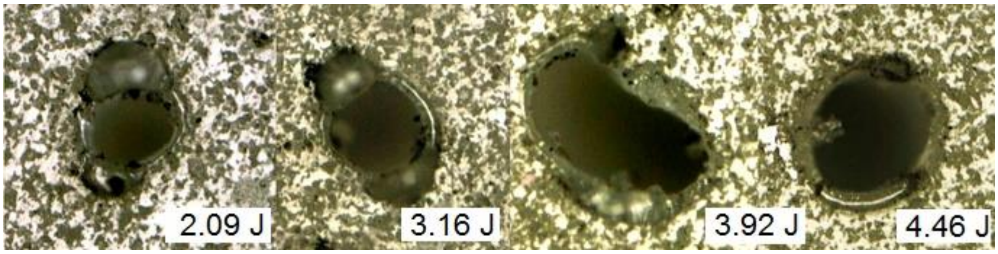

Fig. 4. Irregular shape of the exit holes in 8 mm alumina ceramic sample drilled with pulse energy 2.09 J, 3.16 J, 3.92 J and 4.46 J

4. Numerical model

Various computational tools are used in the material processing to predict optimal parameters of the laser beam and interaction time. For instance Samant and Dahotre, 2018 developed one dimensional model with incorporated effect of multiple reflections with very good agreement with experimental data. Hanon et al., 2012 used ANASYS FLUENT 6.3 package to simulate temperature distribution in alumina ceramics after single pulse (Table 3). Our software IZOTEMPER was compiled in Visual basic to solve partial differential equation of heat conduction by means of finite differences (elementary volumes) method with appropriate boundary and initial condition. Equidistant mesh of 8 640 nodes is created in half space geometry with optimized distance 0.2235 mm. Time step depends on mesh distance, thermal diffusivity of material, beam diameter 0.3 mm and interaction time, that was set to 8 ms as sum of “laser on” time during one burst. Gaussian intensity distribution is defined for laser beam. Laser peak power was changed from 2.62 kW to 4.53 kW, for higher values convergent criterion was not reached. Our model did not involve processing gas force to blow out and multiple reflections in crater, so real maximal depth would be higher (Table 4).

Table 3. Some physical properties of alumina and silicon used in numerical model (Hanon et al., 2012)

Density ($kg.m^{-3}$)	Specific heat ($J.kg^{-1}K^{-1}$)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Thermal diffusivity ($mm^2.s^{-1}$)	Melting temperature (K)	Vaporization temperature (K)	Latent heat of fusion ($kJ.kg^{-1}$)	Latent heat of vaporization ($kJ.kg^{-1}$)	Reflexivity
3 970	775	40	13	2 323	3 253	1 360	1 066	0.2

From file with stored temperature values in all mesh nodes, set of isotherm can be graphically displayed in material cross section for arbitrary selected temperature. To illustrated depth and entrance diameter dependence of the pulse energy, isotherms of alumina melting and vaporization were plotted in Fig. 5.

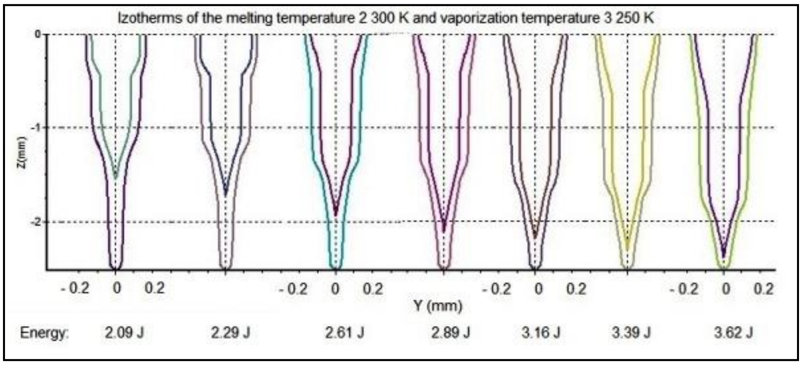

Fig. 5. Plot of the melting and vaporization temperature isotherms of alumina ceramics in dependence on pulse energy

Table 4. Comparison of the measured and simulated values of the entrance holes diameters in alumina ceramics sample made using drilling resonator and maximal depths of vaporization isotherms for energies from 2.09 J to 3.62 J.

Energy *E* (J)	2.09	2.29	2.61	2.89	3.16	3.39	3.62
Measured entrance diameter (μm)	305	318	295	365	366	355	380
Simulated entrance diameter (μm)	328	349	342	349	370	377	390
Maximal depth of vaporization isotherm (mm)	1.54	1.71	1.93	2.11	2.18	2.30	2.39

5. Conclusion

Drilling of alumina ceramic and polycrystalline silicon slabs was realized by 3 different spot diameters, set by a various resonator configuration in one laser head in pulsed Nd:YAG laser KLS 246-102. According critical refraction power of the active crystal, energies in range from 1.02 J to 4.79 J were achieved. Samples of thickness 2.3 mm were completely drilled by one burst of ten pulses with length 0.8 mm in case of all resonators with exception of silicon sample and pulse energy lower than 1.4 J. Entrance and exit diameters strongly depends on the laser spot diameter and energy, so obtained data in experiment can be used for future parameters optimization of the drilling of other nonmetal materials. The best results were of course obtained with drilling resonator that overcame alumina ceramics sample of thickness 8 mm with the good holes quality. More energy would be applied to drill silicon slab of thickness 7.5 mm, where maximal crater depth 6.2 mm was achieved in presented experiments. Although welding resonator beam contained the most energy, there are a lot of spatters visible on the sample surface. Cutting resonator is suitable, if drilling of small holes is required in thinner samples.

Results of numerical model were interpreted in form of set of isotherms which marked out melted and vaporized region in half space geometry. While simulated values of the holes depth increase proportionally with energy, some deviations from increasing trend occur in row both of the simulated and the adequate measured values of entrance diameter. One of the reasons could be that drilling of inhomogeneous nonmetals depends also of initial surface roughness and internal structure.

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References

Hanon, M.M., Akman, E., Genc Oztoprak, B., Gunes, M., Taha, Z.A., Hajim, K.I., Kacar, E., Gundogdu, O., Demir, A., 2012. Experimental and theoretical investigation of the drilling of alumina ceramics using Nd:YAG pulsed laser. Optics c Laser Technology 44, p. 913.

Kacar, E., Mutlu, M., Akman, E., Demir, A., Candan, L., Canel, T., Gunay, V., Sinmazcelik, T., 2009. Characterization of the drilling alumina using Nd:YAG pulsed laser. Journal of material processing technology 209, p. 2008.

Mendes, M., Sarrafi, R., Schoenly, J., Vangement, R., 2015. Fiber laser micromachining in high –volume manufacturing. Industrial laser solution for manufacturing, Special report, p. 12.

Nedialkov, N. N., Atanasov, P. A., Sawczak, M., Sliwinski, G., 2003. "Ablation of ceramics with ultraviolet, visible and infrared nansecond laser pulses", Proc. SPIE 5120, 14th International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers. Wroclaw, Poland, paper #703.

Patwa, R., Herfurth, H., Mueller, G., Bui, K., 2013. "Laser drilling up to 15.000 holes/sec in silicon wafer for PV solar cells", Proc. SPIE 8826, Laser Material Processing for Solar Energy devices II. San Diego, CA, United States, paper #88260G.

Samant, A. N., Dahotre, N.B., 2008. Computational prediction in single-dimensional laser machining of alumina. International Journal of Machime tools & manufacture 48, p. 1345.