Lasers in Manufacturing Conference 2017

Laser scribing of alumina ceramics by Nd:YAG and ytterbium fiber laser

Lenka Rihakova[a,*], Hana Chmelickova[b]

[a]*Regional Centre of Advanced Technologies and Materials, Joint Laboratory of Optics of Palacký University and Institute of Physics CAS, Faculty of Science, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic*
[b]*Institute of Physics of the Czech Academy of Sciences, Joint Laboratory of Optics of Palacký University and Institute of Physics CAS, 17. listopadu 50a, 772 07 Olomouc, Czech Republic*

Abstract

This paper focuses on laser scribing of alumina ceramics as they are hard to machine by conventional methods due to their high hardness and brittleness. Scribing is very promising method of separation based on making a groove, either fully penetrated or not. The scribed line creates a stress concentration and weakens the structure thus enabling easy breakage of the material along the line using mechanical force. Scribing process and the depth of penetration depend on laser parameters, laser beam diameter and its quality. The quality of the process is ensured by the less amount of debris and heat affected zone and no evidence of cracking. In this paper laser scribing of alumina ceramics using Nd:YAG and quasi-continuous-wave fiber laser was investigated in dependence on pulse length, pulse energy, pulse frequency, peak power and number of crossings. Optimum combinations of process parameters to ensure good results and easy breakage of samples using mechanical force were found for both lasers.

Keywords: alumina ceramics; laser scribing; groove characteristics

1. Introduction

Ceramics are widely used in automobile engines, heat exchangers, microelectronics, electronic packaging and as orthopedic implants, seals, valves and pump impellers (Preusch et al., 2014, Chang and Kuo, 2007). They are considered as difficult-to-machine for the conventional machining techniques due to high hardness and brittleness.

* Corresponding author. Tel.: +420-585-631-677.
E-mail address: lenka.rihakova@upol.cz.

Lasers bring various approaches for cutting ceramics such as evaporative laser cutting and controlled fracture technique. Evaporative cutting with pulsed lasers is predominantly used for through cutting as it ensures achieving finer cuts and minimum damage to the surrounding materials. However, the ceramics are very often cut also by scribing a line along the cutting path followed by controlled breaking by applying the mechanical stress. This method was applied for example by Tsai and Chen, 2003 who discussed the machining parameters, such as processing speed and specimen size. They also performed temperature and stress distribution analyses using appropriate software. Due to the brittleness of ceramics, the fracture can be fast enabling cutting speeds up to 250 mm/s (Dahotre and Harimkar, 2008). Scribing by quasi-continuous-wave (QCW) ytterbium fiber lasers operating in the near-infrared at wavelength of 1 070 nm is very promising technique as they provide unique properties like high pulse energy, high peak power and very good beam quality and can bring an improvement and remarkable results (Mendes et al., 2015).

In this paper, laser scribing of 2mm thick alumina ceramics was carried out using two different lasers, Nd:YAG and QCW fiber laser. First, optimum combination of frequency and pulse energy at constant power was found using Nd:YAG laser. Then, these parameters were selected for scribing in dependence on number of crossings (2-12). Limit value of peak power sufficient for radiation absorption and creating complete groove was also established. Using QCW fiber laser, the process of alumina ceramics scribing was investigated in dependence on pulse length, peak power and number of crossings. Both processes were compared and the effect of laser parameters on the groove depth, width and quality was examined and optimum parameters were determined.

2. Materials and methods

First laser source used for alumina ceramics scribing was flash lamp pumped Nd:YAG laser LASAG KLS 246 - 102 emitting at wavelength of 1 064 nm. The laser offers pulse duration in the range from 0.1 ms to 20 ms, pulse frequency from 0.1 Hz to 1 000 Hz, pulse energy can be varied between 0.1 J and 30 J and it provides average power up to 150 W. Setting of the process parameters is controlled by computer or remote unit. Theoretical beam diameter in the focal plane for laser scribing was 0.16 mm. Relative movement of sample and laser beam was assured by positioning table, guided by servomotors in axis X and Y, value of the Z coordinate is set by independent linear axis. The CNC program was edited to move samples in particular way.

Tests were performed at ambient temperature in air with the aid of compressed air supplied at pressure of 5 bars. At first pulse length 0.2 ms and average power 32 W were fixed during Nd:YAG laser scribing. High frequencies and low energies were selected while frequency was continuously decreased and energy increased in order to keep average power constant. With decreasing frequency (from 300 Hz to 100 Hz) the processing speed had to be also lowered to preserve pulse overlap 90 %. To get complete cut, ceramic surfaces were irradiated and crossed 12 times, after each two crossings the focal position was moved 0.2 mm into the material by positioning the focal lens. Then the pulse frequency 125 Hz was adjusted as the best choice and the process of scribing was investigated in dependence on number of crossings (2 – 12, with a step 2) by keeping other parameters constant. During the second experiment, the process of laser scribing was studied in dependence on pulse length that was raised from 0.2 ms to 0.4 ms whereas pulse frequency 175 Hz and pulse energy 0.18 J were invariable which resulted in decrease of peak power. The aim of this experiment was to find the limit of peak power that ensured the formation of grooves. Processing parameters are shown in Table 1.

Second laser used for drilling was QCW ytterbium fiber laser YLR-150/1500-QCW (IPG) with a multi - mode core that can operate with variable pulse length in pulsed mode at high peak power and high repetition rate, as well as in continuous-wave (CW) mode at high average power. QCW mode was chosen providing a maximum peak power of 1.5 kW. High beam quality and small spot size enable achieving high power densities for precise process. During scribing the pulse frequency was 500 Hz and processing speed 5 mm/s. The value of processing speed was calculated in order to ensure the pulse overlap of 80 %. The influence of pulse length (0.1 ms, 0.2 ms), peak power (0.3 kW - 0.75 kW) and thus pulse energy (0.03 J - 0.075 J) was analyzed. The effect of number of crossings (6, 12) was also investigated.

For experimental studies alumina ceramic (Al_2O_3, purity 96 %) plates with dimensions 10 mm x 10 mm x 2 mm were used. Before starting experiments, the sample surface was cleaned by acetone to remove any oil and dust residues. Groove characteristics were measured with the help of scanning confocal microscope OLYMPUS LEXT3100. Measurements of dimensions and 3D reconstructions of the irradiated surfaces were provided by attached software.

Table 1. Process parameters of the selected experiments during scribing using Nd:YAG laser

Focal diameter (mm)	Pulse length (ms)	Pulse frequency (Hz)	Pulse energy (J)	Average power (W)	Peak power (W)	Processing speed (mm/s)	Pulse overlap (%)
0.16	0.20	300	0.106	31.8	530	4.8	90
0.16	0.20	275	0.117	32.2	585	4.4	90
0.16	0.20	250	0.128	32.0	640	4.0	90
0.16	0.20	225	0.145	32.6	725	3.6	90
0.16	0.20	200	0.158	31.6	790	3.2	90
0.16	0.20	175	0.183	32.0	915	2.8	90
0.16	0.20	150	0.200	30.0	1 000	2.4	90
0.16	**0.20**	**125**	**0.250**	**31.3**	**1 250**	**2.0**	**90**
0.16	0.20	100	0.306	30.6	1 530	1.6	90
0.16	0.20	175	0.183	32.0	900	2.8	90
0.16	0.25	175	0.183	32.0	720	2.8	90
0.16	0.30	175	0.183	32.0	600	2.8	90
0.16	**0.35**	**175**	**0.183**	**32.0**	**514**	**2.8**	**90**
0.16	0.40	175	0.183	32.0	450	2.8	90

3. Results

3.1. Scribing using Nd:YAG laser

3.1.1. Optimization of frequency and pulse energy

Fig. 1 shows the dependence of groove width on pulse energy. It can be seen that there is slight rise of the top groove width with increasing pulse energy followed by values fluctuation around 200 µm. Heat affected zone around the groove as well as the depth of melted area on side walls of cut (Fig. 2) increase with increasing pulse energy. Energies and peak powers higher than 0.183 J and 1 kW ensure the presence of groove visible from the bottom sample surface after 12 crossings. The best results were obtained by application laser radiation with parameters of pulse energy 0.25 J and frequency 125 Hz as the parameters guaranteed good quality of the grooves without large amount of debris or cracking and the radiation penetration was deep enough to provide easy breakage of the sample across the scribed line. Therefore these parameters were used for next experiment.

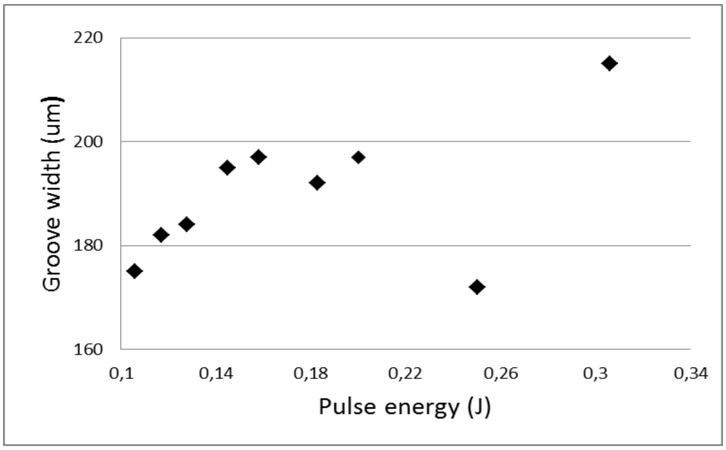

Fig. 1. Dependence of groove width on pulse energy keeping average power constant at 32 W.

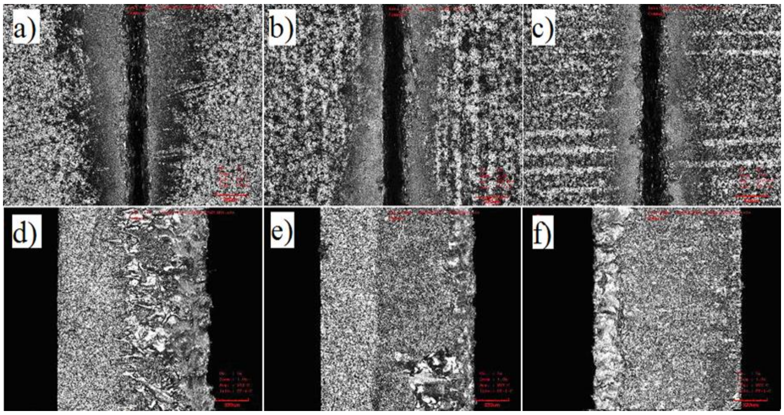

Fig. 2. Grooves on the top sample surfaces using laser parameters: a) 300 Hz, 106 mJ, b) 175 Hz, 183 mJ, c) 125 Hz, 250 mJ. The depth of melted area on the side walls of cut using laser parameters: d) 300 Hz, 106 mJ, e) 175 Hz, 183 mJ, f) 125 Hz, 250 mJ. Magnification 120x, red scale 320 µm.

3.1.2. Dependence on number of crossings

The effect of number of crossings was also investigated and it was found that the groove depth under the sample surface increases with increasing number of crossings. Maximum groove depth reached the value of 440 µm after 12 crossings. The groove width also grows up to 6 crossings, when it reaches its maximum 200 µm, and then the values fluctuate around 180 µm (Fig. 3). Number of crossings also influences the formation of heat affected zone on the top sample surface and penetration of radiation through the sample that are both more extensive after application of higher number of crossings. After 2 crossings the groove on the bottom sample surface is not visible although the sample is melted to the depth of 1 mm and it is easy to break. More crossings (4-6) provide generation of discontinuous groove and 8 crossings is enough to produce consistent groove on the bottom sample surface. Melted and re-solidified mass is presented at the edges of grooves after 8 crossings towering to the high of 80 µm. After the breakage of the sample the melted area on the side walls is proportional to number of crossings.

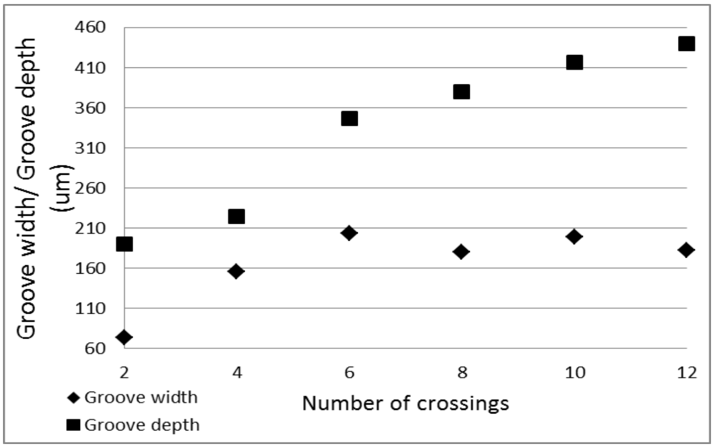

Fig. 3. The dependence of groove width and depth on number of crossings keeping average power constant at 32 W, frequency 125 Hz and pulse energy 250 mJ.

3.1.3. Detecting of the limit of peak power

Detection of the limit of peak power was carried out at constant pulse energy 183 mJ and selected laser parameters were pulse frequency 175 Hz and number of crossings 12. Pulse length was gradually increased from 0.2 ms to 0.4 ms with the step 0.05 ms while the charging voltage was simultaneously decreased to preserve the pulse energy. As a consequence the peak power decreased from 900 W to 450 W. The aim of this experiment was to establish limit value of peak power sufficient for formation of complete groove. Results show that longer pulse length leads to formation of narrower grooves. Moreover, using the longest pulse length 0.4 ms the formation of groove does not occur as the peak power 450 W is too low. As the limit value of the peak power is thus determined value of 514 W. So to obtain favorable results it is necessary to apply together with minimal pulse energy and corresponding energy density (1 kJ/cm^2) also sufficient peak power.

3.2. Scribing by QCW fiber laser

Fig. 4 shows the grooves created on the top and bottom surface of the samples using pulse length 0.2 ms and increasing series of pulse energy. It is evident that huge heat input was delivered to the sample causing the cracking of several samples. The presence of large number of dross and debris is also visible at the edges of the grooves. Due to these imperfections the pulse length has to be lowered to the value of 0.1 ms to achieve decrease of pulse energy and heat input to the material.

Shorter pulse length 0.1 ms provides formation of grooves without cracking although higher values of pulse energy also lead to large heat input to the material and creation of huge amount of dross (Fig. 5). On the other hand, samples treated by low pulse energy were difficult to break. So as the most suitable laser parameters were selected pulse length 0.1 ms, pulse energy 0.045 J and peak power 450 W because samples influenced by these parameters were easy to break by mechanical force and there was no dross at the edges of the grooves. Fig. 6 depicts the dependence of groove depth on pulse energy. Increase in pulse energy results in the rise of grooves depth although the groove at the bottom sample surface was visible only by using maximal pulse energy 0.075 J. Groove depth also increases with number of crossings. Application of 12 crossings and the highest pulse energy caused that the sample was scribed through its entire depth.

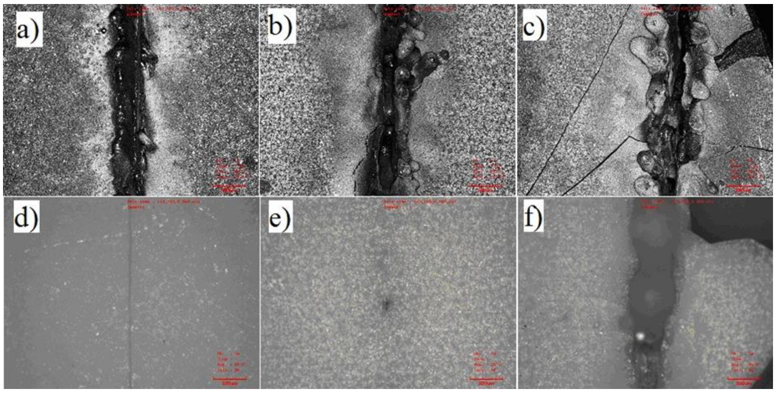

Fig. 4. Grooves on the top and bottom sample surfaces using pulse length 0.2 ms and pulse energy a) 0.06 J, top, b) 0.09 J, top, c) 0.12 J, top, d) 0.06 J, bottom, e) 0.09 J, bottom, f) 0.12 J, bottom. Magnification 120x, red scale 320 µm.

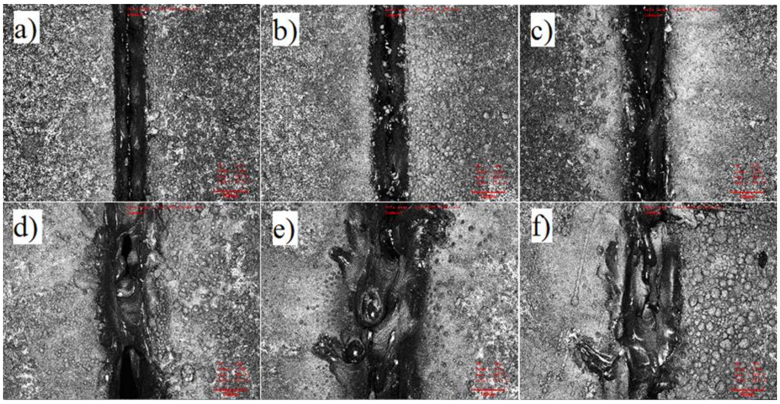

Fig. 5. Grooves on the top sample surfaces using pulse length 0.1 ms and laser parameters a) 0.03 J, 6 crossings, b) 0.03 J, 12 crossings, c) 0.045 J, 6 crossings, d) 0.06 J, 12 crossings, e) 0.075 J, 6 crossings, f) 0.075 J, 12 crossings. Magnification 120x, red scale 320 µm.

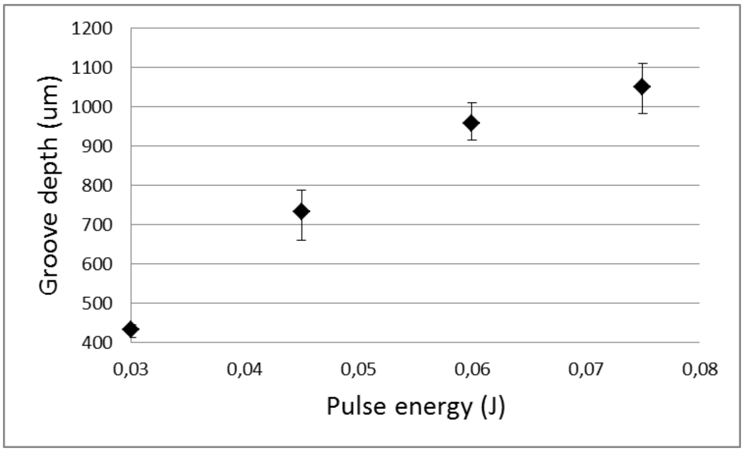

Fig. 6. Dependence of groove depth on pulse energy using pulse length 0.1 ms

4. Conclusion

In this paper the alumina ceramics scribing was performed using two different lasers. The effect of several laser parameters, like pulse energy, peak power, pulse length and number of crossings, was investigated in order to determine optimum parameters for the process. During Nd:YAG laser scribing the right combination of pulse energy and frequency was evaluated. We can conclude that optimum pulse energy 0.25 J and pulse frequency 125 Hz were found as they were required for easy breakage of the sample and high quality of grooves. The number of crossings was mostly important considering the radiation penetration through the sample and it was realized that the 8 crossings are suitable as it is not very time consuming and it provides perfect penetration. Critical parameter is peak power whose limit value is 514 W. Lower values does not cause any influence on the sample surface.

Scribing experiment using QCW laser brings establishment that groove depth increases with increasing pulse energy, peak power and number of crossings which all significantly influence the heat input to the material. As a result shorter pulse lengths and low pulse energies are the best choice for alumina ceramics scribing by QCW fiber laser.

Acknowledgements

The authors gratefully acknowledge the project IGA 2017 – Selected Chapters VIII, IGA_PrF_2017_005.

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