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Laser drilling of alumina ceramics using solid state Nd:YAG laser and QCW fiber laser: Effect of process parameters on the hole geometry

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ABSTRACT

Nowadays a lot of lasers working at different parameters could be used for machining of a wide spectrum of materials. One of these materials is alumina ceramic as it is hard to machine using conventional methods due to high hardness and brittleness. In this paper the percussion drilling of alumina ceramics was performed by Nd:YAG laser and quasi-continuous-wave fiber laser. Effects of laser wavelength, pulse energy, pulse length and number of pulses were examined and the comparison of produced holes geometry was reported. The results show that it is possible to control the holes dimensions by changing lasers and parameters. Fiber laser provides generation of narrower holes due to its small spot and better beam quality together with high power densities. Shorter pulses 0.5 ms, high peak power 1 kW and energy density around 10 kJ/cm² are satisfactory for drilling, as they assured good holes circularity and less amount of melt. For Nd:YAG laser it was found that both entrance and exit holes diameters go up proportionally with the pulse length and pulse energy. The optimum parameters for this laser were pulse length 1 ms as good circularity and less amount of dross was obtained, and energy densities around 1 kJ/cm² leading to formation of hole with better quality. Moreover, higher number of pulses improves holes circularity.

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1. Introduction

Technical ceramic such as Al_2O_3 can be found in many fields of human activity. It is used for example in microelectronics as thin film substrate in circuit boards, in automobile engines, telecommunication or mechanical engineering for producing valves, seals and pump impellers. Significant exploitation of ceramic is also in medicine as orthopedic implants are made from it. Due to its characteristic properties, like high hardness and brittleness, high thermal conductivity and wear, and chemical resistance, it is hard to machine it by conventional methods. Fortunately, laser machining brings several advantages including high precision and process control together with reduction of mechanical stress. Moreover, laser treatment ensures low heat input to the material thus the heat affected zone around the interaction area is limited [1-4].

Laser machining ceramics is the actual issue for many applications including cutting, drilling and scribing. Lots of laser parameters, mainly pulse length, peak power, pulse energy, pulse frequency and focus position are involved in laser drilling [5-7]. The previous papers are mostly devoted to the study of the effect of the laser parameters on the drilled holes and their characteristics involving taper, recast, spatter and micro-cracks. For every specific application, it is important to find the optimum parameters to achieve required holes geometry and quality. For example, Sibalija *et al*. 2011 studied the process of Nd:YAG laser drilling of Ni-based superalloy Nimonic 263 sheets and developed a hybrid strategy that is able to find optimum process parameters and fulfill the specific demands for seven characteristics of the drilled holes including holes diameter, circularity, aspect ratio, tapper and spatter [8].

In literature there are reports that concern experimental and theoretical investigation of the laser drilling process of alumina ceramics. Kacar *et al*. 2009 [9] inspected the dependence of the hole diameter on the laser peak power using Nd:YAG laser. They ascertained that the holes diameter increases with increasing peak power. Nedialkov *et al*. 2003 [10] compared the process of ceramic drilling using fundamental, second and third harmonics of Nd:YAG laser experimentally and theoretically. Another theoretical model for predicting the holes circularity was presented in Bharatish *et al*. 2013 [11]. Hanon *et al*. 2012 [6] examined and simulated the influence of laser parameters on geometrical and microstructural hole properties. They also compared the experimental and simulation results to assess the differences in the holes dimensions. Although many researches have been held, several problems concerning laser drilling, such as sample cracking or melt deposition need to be figured out.

Thermal effects can be strongly reduced using short pulses, but processing speeds have to be lowered [12]. A new generation of quasi-continuous-wave (QCW) ytterbium fiber lasers emitting at wavelength of 1070 nm, with unique properties including high pulse energy and high average and peak power together with excellent beam quality can bring an improvement. Extreme high-power densities allow high quality and rapid machining of ceramic materials. Fiber lasers also offer the possibility to machine structures with dimensions smaller than 100 μm due to low beam parameter product [13].

In this paper laser drilling of alumina ceramics was carried out using two different lasers, with the aim of creating high quality holes. For this reason the effect of drilling parameters (pulse energy, pulse length, number of pulses) on the holes characteristics is examined and optimum parameters are determined. The holes and their dimensions were characterized by scanning confocal microscopy.

2. Materials and methods

The first laser source was flash lamp pumped Nd:YAG laser LASAG KLS 246-102 emitting at wavelength of 1064 nm. We can obtain laser spot in focus plane 0.6 mm allowing maximum power 150 W. Firstly, fixed parameters during the process were frequency 20 Hz and pulse length 0.5 ms. The pulse energy in the range 0.7-2.7 J was adjusted by setting the flash lamp charging voltage (220-350 V) to investigate the effect of pulse energy on the holes geometry. Simultaneously the dependence on the number of pulses (20-180 pulses) was examined as well. During the second experiment, the effect of pulse length, pulse energy and number of pulses (80-120) was tested. The pulse length was increased from 0.6 ms to 1 ms with the increment 0.1 ms, namely for each value from the interval of flash lamp voltages (250-300 V, Table 1).

The second laser was QCW ytterbium fiber laser YLR-150/1500-QCW (IPG) with a multi-mode core fiber that can work at pulse mode providing various pulse lengths and high peak powers, as well as at continuous-wave mode providing high average powers. QCW mode was used for drilling enabling a maximum peak power of 1.5 kW. High beam quality and small spot size allow achieving high power densities for precise process. During drilling the pulse frequency was set to 50 Hz and the influence of pulse length (0.5-1 ms, with the increment 0.1 ms) and pulse energy (0.34-1.54 J) on the hole characteristics were evaluated (Table 2).

Table 1 Process parameters for drilling alumina ceramics using Nd:YAG laser

Voltage (V)	Pulse length (ms)	Pulse energy (J)	Energy density (kJ/cm^2)	Average power (W)	Peak power (kW)	Power density (MW/cm^2)
250-300	0.6-1.0	1.37-4.00	0.48-1.42	27.4-80.0	2.28-4.00	0.81-1.42

Table 2 Process parameters for drilling alumina ceramics using QCW fiber laser

Pulse length (ms)	Pulse energy (J)	Energy density (kJ/cm^2)	Average power (W)	Peak power (W)	Power density (MW/cm^2)
0.5-1.0	0.34-1.54	4.36-19.63	17.13-77.05	685-1540	8.71-19.63

For experimental studies alumina ceramic (Al_2O_3, purity 96 %) plates with thickness 2 mm were used. Before starting experiments, the sample surface was cleaned by acetone to remove oil and dust residues. Tests were performed at ambient temperature in air with the aid of compressed air supplied at pressure of 2 bars. Holes diameters and depths were measured with the help of scanning confocal microscope OLYMPUS LEXT 3100. Measurements of dimensions and 3D reconstructions of the irradiated surfaces were provided by attached software.

3. Results and discussion

Laser drilling is a complex process, dependent on several laser parameters. Therefore, there could be problems with melt produced during the drilling. The shape of the hole is affected by melt expulsion and irregular or incomplete expulsion causes formation of recast layer and can even close the hole. In this paper modifications of the holes geometry are analysed under several process conditions. The effects of the wavelength, pulse energy, pulse, length, peak power and number of pulses on the holes characteristics were investigated.

3.1 Ceramics drilling using Nd:YAG laser

Dependence of the entrance holes diameter drilled in alumina ceramics on the pulse energy for three selected number of pulses is presented in Fig. 1. As one can see, the entrance holes diameter increases with increasing value of pulse energy. The lowest value of pulse energy capable of machining a hole through the entire sample thickness was 1.47 J. For lower values an interaction between laser radiation and the alumina ceramic surface was not observed. The graph also shows that the number of pulses is not a decisive parameter as its influence on the holes diameter was not significantly proved, in contrast with Hanon *et al*. 2012 [6] who claimed that the proportions of the holes were strictly influenced by the number of pulses. By setting different values of pulse energy the required holes with entrance diameters between 374 μm and 537 μm were created. The exit holes diameters did not exhibit clear dependence on pulse energy and their dimensions were between 200 μm and 300 μm.

Fig. 2 depicts the created entrance and exit holes using laser radiation with pulse energy 1.47 J, and number of pulses 20 and 160. The recast layer produced after re-solidification of the melt phase formed during the drilling encloses the hole. Furthermore, a part of the melt material can be observed also on the edges of the exit hole created by low number of pulses. This phenomenon arises from the melt expulsion from the cavity. However, more pulses cleanse the cavity and drops of melt disappear from the exit hole. Thus, the increase in the number of pulses does not significantly affect the holes diameter but can affect the amount of the recast material. Fig. 2 also shows that the entrance holes are quite circular, while the exit ones have non-circular, irregular shape. However, circularity of exit holes could be improved by increasing the number of pulses. Thus, according to our results it is important to set suitable parameters that are in our case pulse energy at least 1.47 J and number of pulses 100.

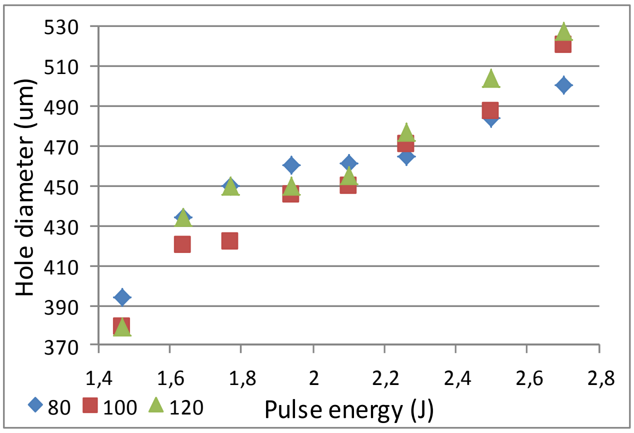

Fig. 1 The diameter of the holes drilled in alumina ceramics by Nd:YAG laser in dependence on pulse energy for number of pulses 80, 100 and 120 by keeping frequency 20 Hz and pulse length 0.5 ms.

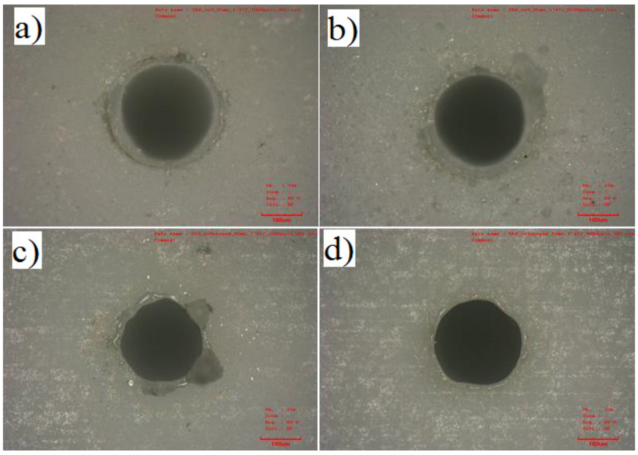

Fig. 2 Images of holes in alumina ceramics drilled by Nd:YAG laser obtained at process parameters of pulse length 0.5 ms, frequency 20 Hz and pulse energy 1.47 J: a) entrance, 20 pulses, b) entrance, 160 pulses, c) exit, 20 pulses, d) exit, 160 pulses. *Magnification 240x, red scale 160 μm.*

The study of the holes characteristics and geometry gave us the information about the influence of number of pulses and pulse energy on the drilling of alumina ceramics. After that a second experiment was held. At first, the holes diameter was investigated by increasing pulse length at six different charging voltages of the flash lamp. Corresponding pulse energies are given in Table 1. The entrance holes diameter as a function of pulse length for different charging voltages is shown in Fig. 3. The holes diameter goes up with increasing pulse length, and higher charging voltage also leads to the rise of the holes diameter for each pulse length. Thus, for one value of pulse length higher charging voltage causing higher power leads to the rise of the holes diameter. Consequently, with given laser configuration and theoretical spot diameter it was possible to achieve desired holes formation with diameters in the range from 350 μm to 600 μm by controlling the laser parameters. Similar results presented Kacar *et al.* 2009 [9] and Hanon *et al.* 2012 [6] who determined that holes diameter increased with pulse length and peak power. In addition, similar results can be obtained also for different materials. Petronic *et al.* 2010 drilled Ni-based superalloy NIMONIC 263 with two different thicknesses and reported that the diameter increases with increasing pulse length and decreases with increasing frequency [14].

Images of the holes generated by Nd:YAG laser using charging voltages of flash lamp 250 V and 280 V are displayed in Fig. 4 and Fig. 5. Each figure includes entrance and exit holes created by laser radiation with different pulse lengths. These figures confirm that increase in the pulse length and thus also pulse energy leads to enlarging of the hole. Longer pulse lengths also improve the exit holes quality as the hole is becoming more circular. From Fig. 4 and Fig. 5 it is evident that re-solidification of the melt occurred around the holes entrance. Drops of melt are also visible at the edge of exit holes. Some holes could be even partially closed by the re-solidified melt (Fig. 4b). This phenomenon has its origin in the melt erosion of the holes sidewalls induced by the high pressure of vapour located nearby the material surface within irradiation that press the melted material up and away from the hole [15]. However, these imperfections can be reduced by using longer pulses and higher energies. From our observations it can be concluded that relatively long pulses (1 ms) with pulse energy 3,4 J and energy densities above 1 kJ/cm^2 are the right parameters for alumina drilling by Nd:YAG laser.

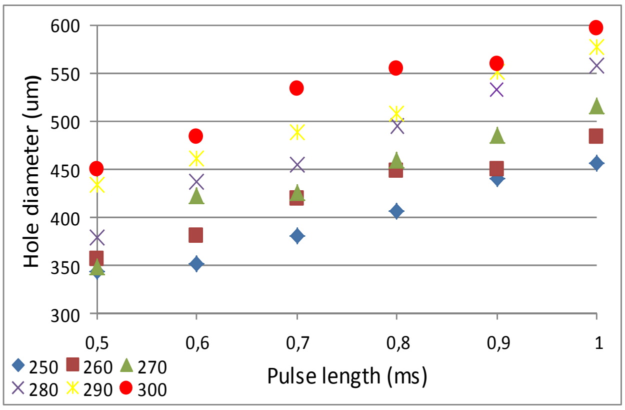

Fig. 3 The entrance diameter of the holes drilled in alumina ceramics by Nd:YAG laser in dependence on pulse length for six charging voltages in the range from 250 V to 300 V by keeping frequency 20 Hz

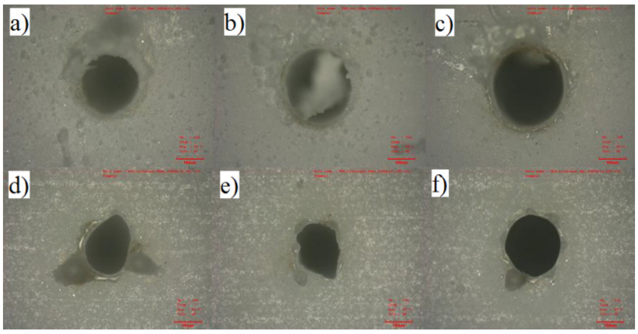

Fig. 4 Images of the holes in alumina ceramics drilled by Nd:YAG laser obtained at process parameters of frequency 20 Hz, charging voltage 250 V and number of pulses 120: a) pulse length 0.6 ms, pulse energy 1.37 J, entrance, b) pulse length 0.8 ms, pulse energy 1.9 J, entrance c) pulse length 1 ms, pulse energy 2.4 J, entrance, d) pulse length 0.6 ms, pulse energy 1.37 J, exit, e) pulse length 0.8 ms, pulse energy 1.9 J, exit, f) pulse length 1 ms, pulse energy 2.4 J, exit. *Magnification 240x, red scale 160 µm.*

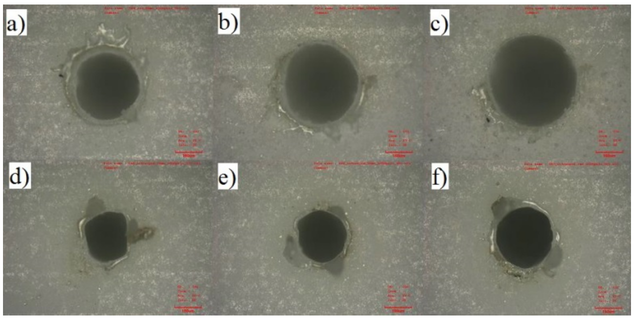

Fig. 5 Images of the holes in alumina ceramics drilled by Nd:YAG laser obtained at process parameters of frequency 20 Hz, charging voltage 280 V and number of pulses 120: a) pulse length 0.6 ms, pulse energy 1.84 J, entrance, b) pulse length 0.8 ms, pulse energy 2.64 J, entrance c) pulse length 1 ms, pulse energy 3.4 J, entrance, d) pulse length 0.6 ms, pulse energy 1.84 J, exit, e) pulse length 0.8 ms, pulse energy 2.64 J, exit, f) pulse length 1 ms, pulse energy 3.4 J, exit. *Magnification 240x, red scale 160 µm.*

3.2 Ceramics drilling using QCW fiber laser

QCW fiber laser was the second laser used to drill alumina ceramics. The holes diameter was investigated in dependence on pulse energy, peak power, pulse length and number of pulses. The dependence of the holes diameter on pulse length is depicted in Fig. 6. It is evident that the holes diameter is lowest for pulse length 0.8 ms. The figure also shows that the hole diameter goes up with increasing peak power for each pulse length. In order to get more information about the holes, the entrance and exit diameters were examined in dependence on pulse energy. It was observed that the exit diameter increases with increasing pulse energy although it was always smaller than the entrance one. Furthermore, a rise of the entrance diameter is detected with increasing pulse energy for each analysed pulse length. Thus, using different parameters it is possible to create holes with entrance diameters in the range from 133 μm to 266 μm.

Images of the entrance and exit holes drilled by laser radiation with pulse lengths 0.6 ms and 1 ms are displayed in Fig. 7 and Fig. 8. Each figure is specific for certain pulse length and increasing series of peak powers. The entrance holes are quite circular, but a small amount of the melt is visible around the holes. On the contrary, the exit holes are not circular and the melt is evident there too. The entrance and exit holes circularity can be improved using higher peak powers, as they deliver high energy radiation that transports the melted material further from the hole and does not allow it to accumulate. It can be said that the amount of melt presented at the edges of entrance and exit holes is lowered for higher peak powers too, since the increase in laser power leads to increase in thermal energy which causes better material removal in the whole cross-section of the hole. This explanation is in concordance with the results acquired also by Biswas *et al.* 2010 [16] and Bharatish *et al.* 2013 [11]. Therefore, according to these statements and our observations high peak powers at least 1 kW are adequate for alumina drilling by fiber laser. In addition, the amount of the melt is also reduced for shorter pulses so pulses 0.5 ms and 0.6 ms are optimum pulse lengths. Mutlu *et al.* 2009 [17] and Ng and Li 2001 [7] who studied the drilling of ceramic samples and the effect of laser parameters on the process also reported similar results. For example Ng and Li suggested that the holes circularity was the best when drilling was performed at shorter pulse length and higher peak power.

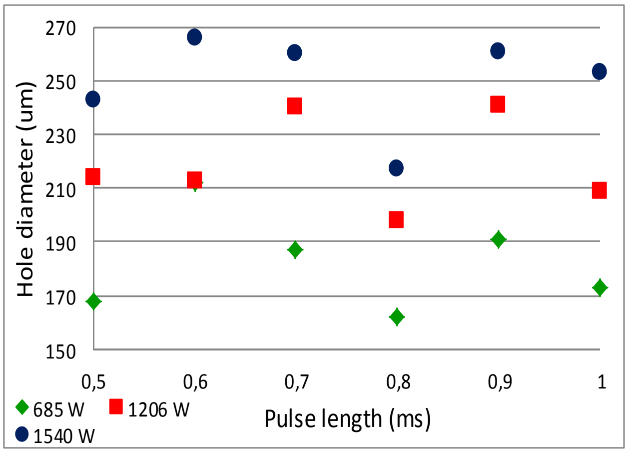

Fig. 6 The entrance diameter of the holes drilled in alumina ceramics by QCW fiber laser in dependence on pulse length for three peak powers by keeping frequency 50 Hz and number of pulses 100

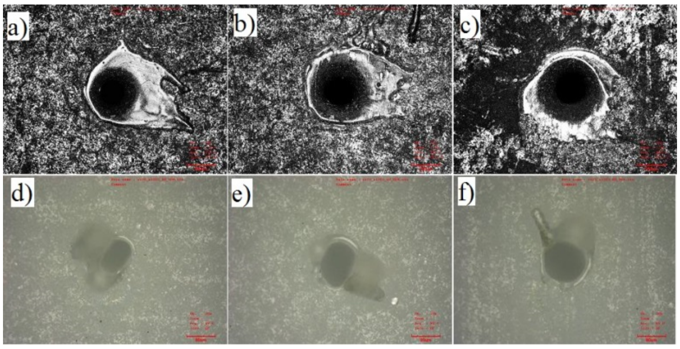

Fig. 7 Images of entrance and exit holes in alumina ceramics drilled by QCW laser obtained at process parameters of pulse length 0.6 ms, frequency 50 Hz: a) peak power 685 W, pulse energy 0.41 J, entrance, b) peak power 1027 W, pulse energy 0.62 J, entrance, c) peak power 1374 W, pulse energy 0.82 J, entrance, d) peak power 685 W, pulse energy 0.41 J, exit, e) peak power 1027 W, pulse energy 0.62 J, exit, f) peak power 1374 W, pulse energy 0.82 J, exit. *Magnification 240x, red scale 160 μm.*

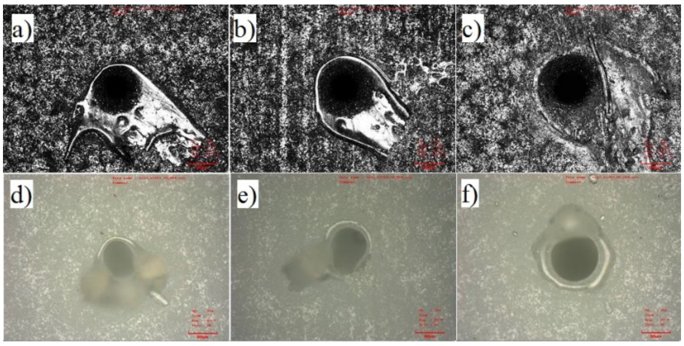

Fig. 8 Images of entrance and exit holes in alumina ceramics drilled by QCW laser and obtained at process parameters of pulse length 1 ms, frequency 50 Hz: a) peak power 685 W, pulse energy 0.68 J, entrance, b) peak power 1027 W, pulse energy 1.02 J, entrance, c) peak power 1374 W, pulse energy 1.37 J, entrance, d) peak power 685 W, pulse energy 0.68 J, exit, e) peak power 1027 W, pulse energy 1.02 J, exit, f) peak power 1374 W, pulse energy 1.37 J, exit. *Magnification 240x, red scale 160 μm.*

Using Nd:YAG and QCW fiber laser complete holes were drilled by setting a large range of lasers parameters. A gradual increase of the holes diameter was detected due to increasing energy applied to the sample surface. The holes diameters also seem to be dependent on the pulse length and peak power whereas the hole circularity can be improved using high number of pulses. Our results can be useful for practitioners in industry. According to their specific requirements for the drilled holes dimensions and quality they can choose optimum parameters suitable for given application. If the smaller diameter and the high circularity are needed, the short pulses and high peak powers of QCW fiber laser should be settled. If the larger diameter and good circularity are requested, Nd:YAG laser with longer pulse lengths and energy density above 1 kJ/cm^2 should be used.

4. Conclusion

In this paper drilling of 2 mm thick alumina ceramics was studied in dependence on laser wavelength, pulse energy, peak power and number of pulses. The process was performed using Nd:YAG and QCW fiber laser. The laser drilled holes characteristics (holes dimensions, circularity) were analysed and the influence of process parameters was determined. Created holes and their geometry were observed and evaluated using scanning confocal microscope.

Both lasers ensure formation of complete holes in most cases with recast layer surrounding the entrance hole. Drops of melt are visible at the edges of the exit hole as a result of incomplete ejection of the material from the cavity, which remains attached to the hole margins. Analysis of the holes reveals that the entrance diameter was always larger than exit, thus the holes were positively tapered. The entrance holes were also wider than the laser spot diameter.

The results show that it is possible to control the holes dimensions by changing lasers and their parameters. It was possible to create holes with diameters in the range from 350 μm to 600 μm using Nd:YAG laser and from 133 μm to 266 μm using fiber laser. It is obvious that fiber laser ensures formation of narrower holes due to its small spot and better beam quality together with high power and energy densities. The holes diameter can be also controlled by setting the laser parameters, e. g. pulse length pulse energy and peak power. Both entrance and exit holes diameters go up proportionally with the pulse length and pulse energy for Nd:YAG laser. Consequently, the optimum parameters for this laser were selected relatively longer pulse (1ms) as good circularity, and less amount of dross was obtained, and higher energies with corresponding energy densities around 1 kJ/cm^2 leading to formation of hole with better quality using these parameters. We can also conclude that a bigger number of pulses ensures getting better holes circularity. On the other hand, for fiber laser it was detected that relatively shorter pulses (0.5 ms and 0.6 ms), high peak power (1 kW) and high energy density (around 10 kJ/cm^2) are satisfactory for drilling as they assured good holes circularity and less amount of melt.

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