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Simple Optical Apparatus for Trepanning and Percussion Microdrilling Using Pulsed Green Nd:YAG Laser[1]

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Abstract—Laser microdrilling is becoming an important tool in a wide spectrum of industrial applications due to the possibility to produce microholes in almost any type of materials. The purpose of this study was to create a simple and efficient optical apparatus that could produce microdrillings by either percussion or trepanning methods. The developed system is composed by a nanosecond Nd:YAG laser operating at 532 nm and one convergent lens with off-center optical axis of 1′. For the trepanning method the lens spins in its geometrical center at constant angular speed of 350 rpm. Typical microholes diameters obtained in metallic aluminum were in the range of 22 to 95 μm and 70 to 150 μm for the percussion and trepanning methods, respectively. Typical drilling velocities were in the order of 10 μm/s for applied fluences ranging from 22 to 150 J/cm^2 for both methods. The values of the ratio between input and output diameters were 0.30 and 0.25 for microholes obtained by percussion and trepanning methods, respectively. The best microholes morphology was obtained using the trepanning method. The results for both methods are discussed based on the optical and thermal properties of the material processed and the constructed apparatus.

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1. INTRODUCTION

Laser microdrillings with short pulses in the nanosecond range have been widely used due to its efficiency and the possibility to work with different types of materials [1–3]. When the nanosecond pulse duration interacts with the workpiece it can remove the material in the laser beam area, resulting in a very small heat affected zone (HAZ) compared to continuous wave or long pulse (millisecond) laser material processing [4]. Laser microdrillings can be used to produce orifices for nozzles injection, ink-jet printers and micro-dosages medical devices [5].

One technique for laser microdrilling generally used is the percussion method. In this technique a sequence of laser pulses is directly focused on the surface of the workpiece, which results in the material ablation by melting and/or vaporization and consequently the production of a hole [6]. The difficulty to reproduce identical holes and the recast layer formation at the edges of the orifices, for some applications, can be considered as the main disadvantages of this method [6]. A possible solution to overcome these drawbacks would be the use of ultrashort pulses, such as pico or femtoseconds lasers. Although these lasers can produce high quality microholes, due to the weak electron-phonon interaction (resulting in a practically inexistent HAZ), their cost are still almost prohibitive [2, 7–9].

Another alternative largely employed in the past two decades, in order to obtain precise drillings with short pulse lasers, has been the trepanning method [10]. In a conventional trepanning technique usually the workpiece rotates. In this way, the laser can remove the material in a specified circular perimeter on the sample, allowing the control of the microhole diameter. The main advantages of the trepanning method is the small generation of defects and composition changes due to a smaller HAZ, compared to the percussion method, and the possibility to control the hole size by the rotation of the laser beam or the workpiece [10]. However its main drawback lies in the fact that the minimum hole diameter attainable is larger than the ones produced by percussion setup.

The purpose of the present work is to present the use of a nanosecond pulsed Nd:YAG laser, operating in its second harmonic wavelength (532 nm), attached to a simple optical apparatus that can work in either percussion or trepanning methods. Metallic aluminum was used as a material model to test the developed microdrilling device. The microholes characterization was performed by measuring its dimensions and drilling velocities. The trepanning and percussion microdrilling results were discussed based on the characteristics of each method and the laser drilling apparatus features. Our results showed that the developed optical system can produce microholes with acceptable precision and repeatability using trepanning microdrillings

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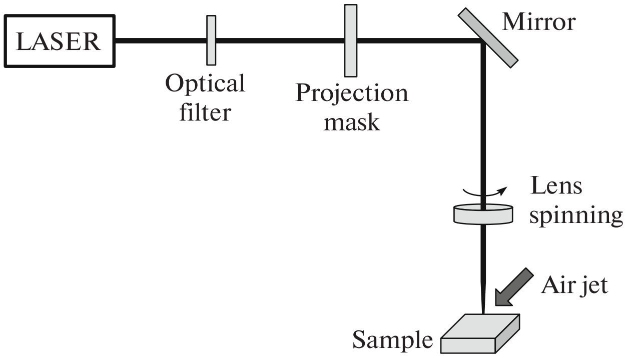

Fig. 1. Schematic drawing of the developed optical apparatus.

for a nanosecond pulsed Nd:YAG laser operating at wavelength of 532 nm.

2. EXPERIMENTAL SETUP

The laser system used in this work was an industrial Q-switched Nd:YAG laser (Spectron Laser System mod. SL404) operating at wavelength of 532 nm with an 8 ns pulse duration and repetition rate constant of 30 Hz. As illustrate in the Fig. 1, the optical apparatus developed is composed by an infrared (IR) optical filter, a projection mask with circular aperture of 2 mm in diameter, a totally reflector flat mirror and a singlet BK7 lens with focal length of 100 mm and off-center optical axis of 1′ (measured with Autocollimation Testing, OptoTech mod. AZP-2). The IR optical filter was applied to obstruct the fundamental laser mode at wavelength of 1064 nm and the mask projection is used to generate a well-defined intensity distribution radiation at the surface of the workpiece. The optical centralization of the lens is an essential factor to obtain high quality microdrillings, especially in the case of trepanning method. In ideal conditions when a laser beam reaches a convergent lens, parallel to its optical axis, all light propagate towards a single point (focus point). In this condition, even if the lens is put in rotation, the focus point stands still in its original position. However, as in our case, if a lens with an off-center optical axis of 1′ and focal length of 100 mm is spinning, the focused laser point will move along a circular trajectory with a theoretical diameter of 56 μm. The schematic drawing of the optical setup for the trepanning method is illustrated in Fig. 2

The samples were disposed on a micrometric positioning X–Y table for spacing control between the generated microholes. The focus of the laser beam was positioned just below the materials surface (workpiece) in order to obtain higher fluence concentration which leads to a higher efficiency and precision of the microdrillings [10]. During the whole drilling process, one unidirectional air jet flow was applied with a rate of 10 l/s at workpiece surface on the drilling point proximities. This was done in order to shield the lens from the expelled material, avoid recast and increase the efficiency of the ablation process due to the removal of the ejected particles that could diffuse the laser beam [10, 11]. In the case of the trepanning method, the lens support was coupled to a mechanical system that allows the rotation around its geometric axis, provided by an electric motor, which generated a constant angular speed of 350 RPM (calibrated with a Digital Tachometer MDT-2245 Minipa). Considering our experimental setup with the laser operating at a repetition rate of 30 Hz and lens spinning at 350 RPM, it is possible to show that an average of 5.1 laser pulses is obtained in the perimeter of the hole in each completed turn. The non-integer number of laser pulses in each turn of the lens is important to avoid that exactly the same point of the sample was hit after each turn. Microdrillings for percussion method was obtained with the same system, but with static lens (Fig. 2).

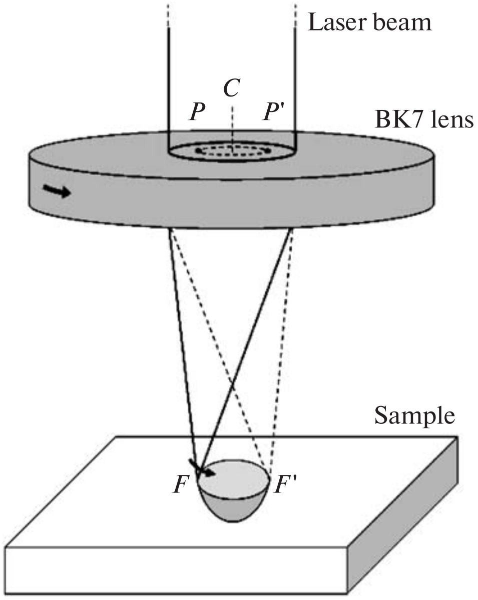

Fig. 2. Schematic representation of the optical configuration for the trepanning method. The laser beam reaches the geometric center, C, of the convergent lens. P and P' are off-centered by 1′. F and F' are the focal points of the convergent lens.

The probe material studied to check the quality of the optical apparatus was 99.8% pure metallic aluminium (Alcoa, Inc.) with a thickness of 1 mm. The drilling velocity for the both methods was determined dividing the material thickness by the drilling time. The dimensions, reproducibly and quality microdrillings was analyzed by scanning electron microscopy (Digital Scanning Microscope DSM-960, Zeiss) and optical microscopy (Olympus, mod. BX-51).

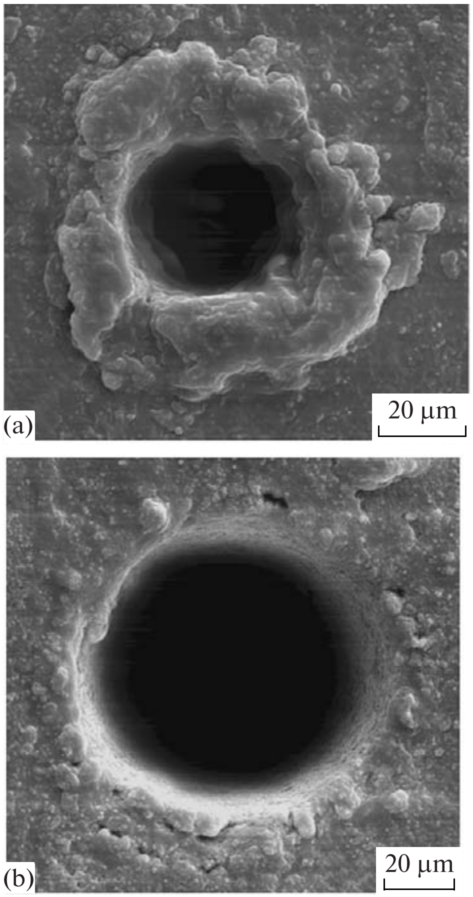

Fig. 3. Scanning electron microscopy (SEM) images of the microholes produced by (a) percussion and (b) trepanning methods.

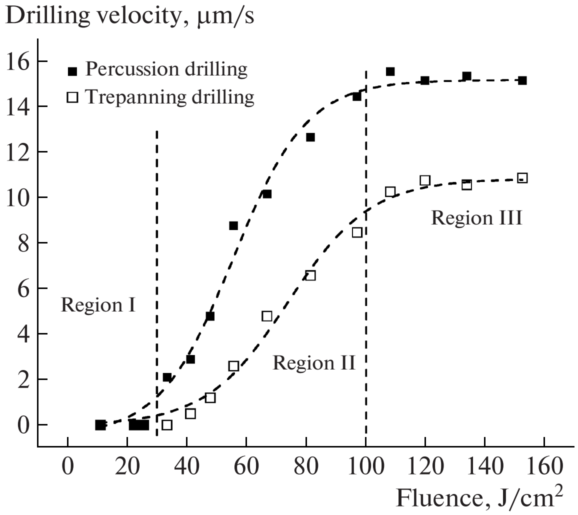

Fig. 4. Drilling velocities for metallic aluminum with thickness of 1 mm obtained by the percussion and trepanning methods.

3. RESULTS AND DISCUSSION

Scanning electron microscopy (SEM) images of the microholes produced by percussion and trepanning methods are shown in Fig. 3. It is possible to observe that for the percussion method, the holes present burrs and an asymmetric geometry (Fig 3a). The optical quality of the laser beam and the large amount of recast material are pointed out as the main cause of those irregularities around the hole perimeter, contributing consequently, to the production of imprecise diameters and not reproducible microdrillings [7]. Furthermore, fluences of 41.2 J/cm^2 and the air jet flow rate of 10 l/s did not improve significantly the removal of the ejected material.

The characteristics of the microholes presented in Fig. 3b are a consequence of the described circular trajectory for the laser beam due to the rotation of the lens by the trepanning method. The use of the lens rotation results in a better energy distribution on the microholes perimeter, as discussed earlier. Moreover, the gradual material ejection facilitates its removal by the air jet, contributing to obtain symmetrical holes, practically absent of burrs. These characteristics facilitate the attainment of repeatable holes by trepanning method. It was verified that trepanning hole reproducibly is affected by increasing the incident fluence. This occurs due to a higher amount of ejected material which solidifies on the proximities of the microhole that could not be totally eliminated by the air jet. Furthermore, the higher fluences can produce superficial plasma that deflects the trajectory of laser beam by changing the refraction index along the laser beam path or dispersed the laser beam interaction with the ejected particle.

Figure 4 shows the drilling velocity as a function of the fluence for metallic aluminum with thickness of 1 mm by the percussion and trepanning methods. The curves were adjusted by a sigmoid function as a guide to the eyes. According to the data presented in Fig. 4, the drilling velocities for percussion are superior compared with trepanning method. These characteristics are related with the different amounts of material processed in each method and the differences in the interaction of laser light with matter, depending on the value of the incident fluence.

For a better understanding of the drilling process, the data present in Fig. 4 can be divided into three regions. In the region I, at fluences below 35 J/cm^2, the ablation efficiency is lower because of the reflection losses and high thermal conductivity of the metallic aluminium that disperse rapidly the absorbed energy by the photon-phonon interaction only leading to the heating of the solid material [12]. In this region, some holes are created at low drilling velocities when using the percussion method. On the other hand, the trepanning velocities are practically null due to the rel-

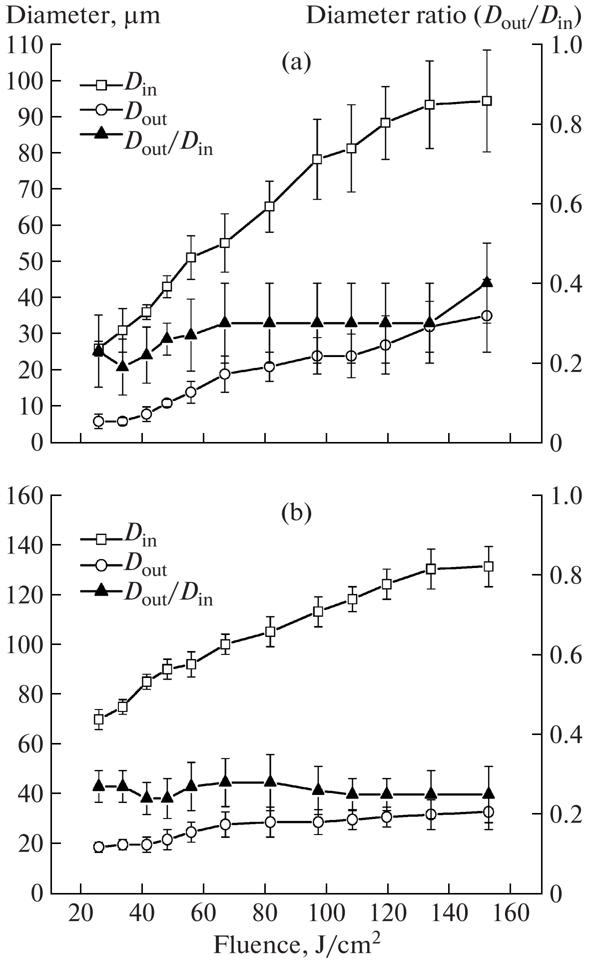

Fig. 5. Dimensions of microdrillings obtained for (a) percussion and (b) trepanning setups. The left Y axis shows the microholes diameter at entrance, D_{in}, and exit, D_{out}, of the laser beam and the right Y axis shows the out and in diameters ratio, D_{out}/D_{in}.

atively large amount of material to be ablated, when compared to the percussion setup.

In region II, at fluences between 35 and 100 J/cm^2, the drilling velocities starts to increase for both methods. The ablation in this region is characterized by melting and vaporization of the material and it is possible to observe that in the percussion method the drilling velocities increase faster compared to the trepanning setup, resulting in an average slope of 2.4×10^{-5} and 1.5×10^{-5} cm^3/s J for percussion and trepanning methods respectively. This can be explained due to the higher energy concentration at a single point in the percussion method, which leads to a larger amount of material removal over time. In the trepanning setup, there is a larger amount of material to be removed and the energy is more easily dispersed due to the high thermal conductivity of the compound. Furthermore, part of the previously ejected material might be deposit around the next work point, resulting thus in lower drilling velocities.

The region III, above at 100 J/cm^2, is characterized by the saturation of the drilling velocities for both methods. It was observed that the saturation occurs at approximately 15 and 11 μm/s for percussion and trepanning setups, respectively, at fluences next to 110 J/cm^2. These results are related to the higher quantities of superficial plasma and fragment ejection, which causes higher scattering and absorption of the laser beam, resulting in a reduction of the coupling between the incident laser radiation and the workpiece [1, 12].

Figure 5 illustrates the microdrillings dimensions obtained for the percussion and trepanning methods. According to this data, the ratio between the output and input diameters, D_{out}/D_{in}, was approximately 0.30 and 0.25 for the percussion and trepanning methods, respectively. This indicates that the internal morphology, for both microdrillings methods, has a predominantly conical shape. The difference between the diameters ratio for both microdrillings methods is attributed to the laser beam circular trajectory that produces large entrance microholes for trepanning method. However, at lower fluences it is observed that the diameters ratio decrease for both drilling methods. This can be explained by the confinement effect of highly dense plasma inside the microdrillings holes. The expansion of this plasma is restricted by the sidewalls of the holes which undergoes ablation resulting in a barrel-shaped cross-section profile at the bottom of the holes [13].

The best results for microholes production in metallic aluminum, using the developed optical microdrilling apparatus, was for the trepanning method at fluences of approximately 67 J/cm^2, next to the inflection point of the adjusted curve presented in Fig. 4. These conditions results in acceptable precision in the holes dimensions due to small amount superficial recast material and plasma formation.

4. CONCLUSIONS

A simple optical apparatus for microdrillings, using a pulsed Nd:YAG laser, for percussion and trepanning methods has been described and discussed in detail. SEM micrographs shows that precise, symmetrical and reproducible microholes with little recast material, were obtained at low fluences by employing the developed optical apparatus operating in trepanning method. Typical microhole diameters were in the range of 22 to 95 μm and 70 to 150 μm for the percussion and trepanning methods, respectively. The difference in velocities and holes dimensions could be associated to the different amount of material processed in each microdrilling method. The diameters ratio between input and output of the laser beam had proven that both experimental setups generate predominantly conical shape. The best microholes morphology was obtained using the trepanning method at fluences of approximately 67 J/cm^2.

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