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Experimental research on the feasibility and quality of laser-cut micro holes for the aviation industry

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ABSTRACT

In many industries, including aerospace, several operations involving making holes are performed. Small-diameter holes pose a technological problem when obtaining the right diameter and achieving size and shape accuracy is difficult. Various methods are used to achieve the manufacturing goal, including laser processing. The article presents the results of experimental research on producing micro-holes with a laser of 1 mm diameter and in the range of 0.1÷0.5 mm according to the multiple beam cutting strategy. The quality of the holes was assessed in microscopic tests, diameter measurements were performed, dimensional deviations and ovality were determined. The cutting efficiency affecting the number of beam pass repetitions was checked. It was found that cutting 1 mm is most effective at 20 W power, 20 kHz pulse frequency, 100 mm/s scanning speed and 90 paths. The dimensional spread (for 10 measurements) was 0.026 mm and the dimensional deviation was positive. For smaller holes, the most advantageous was the processing with a 20 W beam, 20 mm/s speed, 20 kHz frequency, and 20 passes for 0.5 mm (with a spread of 0.020 mm). This number decreased with decreasing diameter and for 0.1 mm it was 8. In the case of 0.1÷0.5 mm holes a minus dimensional deviation was observed, while repeatability and accuracy decreased with decreasing diameter.

Keywords: laser cutting, micro-holes, diameter, ovality and roundness measurement, aviation.

INTRODUCTION

The development of many industries is inseparably associated with miniaturization, which in turn requires mastering technologies that enable precise micro-machining of materials on an industrial scale. Mechanical devices are increasingly equipped with micro-parts, which are subject to high-quality requirements, e.g. by the electronics, biomedical, aviation, or automotive industries [1÷3].

Many manufactured products require machining, as a process of removing materials and making holes [4]. Making holes in different technologies has been widely used in many industries such as manufacturing, mining, and construction [5]. In most instances, the most cost-effective and efficient process for producing holes in solid metal workpieces is drilling. There are many varieties of drilling depending on the type and properties of the material to be machined, hole diameter and depth, tool geometry, etc. [6, 7]. Making holes requires tools, handles, also machine tools - types of conventional drilling machines include upright machines, radial machines, and various specialized machines such as gang drill presses [8, 9]. Technological problems that occur during drilling are the heating up of the parts and the tool inside the hole and the associated need for coolant, control of chips, the possibility of vibration, which accelerates drill wear, or jamming of chips or the tool inside the hole [6, 10]. Sometimes chips also scratch the fabricated surface, so issues of dimensional accuracy and shape rather than surface smoothness are considered. In addition, the quality of the hole can be affected by defects in the structure, friction, and different geometry of the formed chip. Therefore, the course of the process and the quality of the holes is an important issue [11, 12]. Many machines perform drilling operations including dedicated drilling machines, lathes, milling machines, machining centers, and special-purpose machines [5, 13].

In manufacturing industries drilling processes are not limited to conventional methods, where physical contact is made between the cutting tool and the solid material. Non-conventional drilling processes use forms of energy such as electrical, chemical, electrochemical, thermal, and heat, to generate holes in the different materials [5, 14].

An issue concerning machining, albeit less frequently addressed but presented e.g. in [8], is the environmental load of metal waste from chips and used tools, overheated coolants, and health risks, including toxicity, possible skin diseases, respiratory disorders, microbial infections and carcinogenicity due to the used lubricants and coolants used. Laser machining used to make holes in various materials is an effective method of precise drilling of holes with diameters smaller than 1 mm, which is difficult to obtain with other machining technologies, especially concerning difficult-to-machine alloys used in aviation [15, 16]. The quality requirements for drilling micro-holes are particularly high in the case of parts used in the production of aircraft engines [17].

In addition to quality requirements such as dimensional and shape tolerance, surface quality, and economic requirements that make a given technology generally available are extremely important. Such requirements are met by the laser micro-hole drilling technology [18]. There are many other methods of making holes in sheets, such as mechanical drilling, chemical etching, electrical discharge, etc., but with diameters ranging from several dozen to several hundred micrometers, the mentioned techniques have significant limitations, which makes the laser technology dominant in this diameter range [19÷21]. Therefore, it is justified to develop the discussed method. This is due to the many advantages of laser micro-hole drilling, the most important of which is the ability to make holes with diameters of several μm [22, 23]. An important advantage is that the laser technology is non-contact, so coolants or lubricants during drilling are not used [24]. The feature of non-contact machining is particularly important in the case of processing thin materials, where mechanical contact would cause deformation or cracking, which is not the case with laser drilling [1, 25].

Laser processing can be used for construction materials with various properties, both metals and non-metals such as ceramics, composites, and superalloys [6, 26].

Laser beam drilling (LBD) can be divided into four methods, which are trepanning, single pulse, helical drilling, and percussion [27]. Each of them has specific characteristics, and the choice of the appropriate method is determined by the requirements of the target accuracy, efficiency, surface quality of the holes, and the properties of the material in which the holes are to be made. The best surface quality of holes and dimensional and shape accuracy is most often obtained thanks to helical drilling, which uses a short pulse or ultra-short pulse. However, a significant disadvantage of this method is the relatively low drilling speed. For example, Kraus et al. [28] used this method (picosecond), drilling micro-holes with a diameter of about 100 μm in a sheet of 1 mm thick CrNi steel, making one hole took about 2 minutes. This gives an idea of how uneconomic this method is, which is why it is used where there are reasonable requirements for high surface quality and hole dimensions. From an economic point of view, it is more reasonable to use other methods if there are no such high-quality requirements. Although higher efficiency of the process is achieved using nanosecond laser machining, but at the expense of poorer quality [29÷31].

In industrial applications, trepanning and percussion techniques are most commonly used, which effectively combine the features of efficiency and satisfactory quality [32]. These methods use a millisecond pulsed laser with power in the range of 106÷109 W/cm^2 [27]. These techniques consist of making holes by melting, vaporization, and melt ejection [27]. Of the two mentioned methods, trepanning allows for better quality, but at the same time has significantly lower efficiency, because the drilling speed is 5÷10 times lower than in the case of percussion [33].

Generally, millisecond laser percussion drilling is primarily used to produce parts where a large number of holes are required due to the high efficiency of this method [27]. Many authors have addressed the issue of the selection of parameters ensuring the quality of holes drilled with a laser [34÷36]. However, not only energy and kinetic parameters play an important role here. The assist gas is also an important aspect.

Low et al. [37] carried out research on spatter properties during laser percussion drilling by using assist gas. An important issue addressed by many authors is numerical methods, especially finite element modeling, which enable the effective selection of optimal parameters for laser drilling of holes in various materials [38÷40].

The experiment presented in the article in the context of drilling holes in the aluminum alloy is justified by the extensive use of this type of structural component in the aerospace, electronics, and chemical industries, where millions of holes are drilled, especially for assembling [11].

The review of the achievements to date shows that making holes, especially of small diameters, is easiest using pico- or femtosecond lasers with a very small spot diameter and significant pulse energy. However, these devices are still expensive and less common in production plants. In turn, the laser described in the presented article is typically used for marking and engraving, and is cheap and easily available on the market, especially for small and medium-sized enterprises. From the point of view of a manufacturer interested in minimizing production costs, expanding the technological capabilities of an already owned device with an additional technological operation is an extremely attractive option. The results of the research presented in the article prove that such a possibility exists when certain conditions are met. The experiments conducted show that it is necessary to properly select the laser parameters concerning a given hole diameter, especially the accuracy of dimensions and shape. The nature of the beam's interaction has a significant impact on the obtained quality, where the impact on the edges of the hole and the accuracy of the shape have a thermal effect, consisting of melting and solidifying the material. Therefore, the conducted research and this article can contribute to the development of laser technology for its usefulness and versatility in the context of processing often encountered in many industries.

EXPERIMENTAL STUDY OF FEASIBILITY AND QUALITY OF MICRO-HOLES

Material and equipment

The samples for the experimental study were made from aluminum strep of 0.2 mm thickness (ISO Al99.5). The material of chemical composition in % of mass concentration: Al $\geq$ 99.5; Fe $\leq$ 0.40; Si $\leq$ 0.25; Zn $\leq$ 0.07; Ti $\leq$ 0.05; Mg $\leq$ 0.05; Mn $\leq$ 0.05; Cu $\leq$ 0.05 and other $\leq$ 0.03; was given in accordance with [41].

The alloy has a density of 2.71 g/cm^3 and a hardness of approx. 33 HB, high thermal conductivity, high plasticity, and good oxidation and corrosion resistance [42].

To cut holes a pulsed fiber laser with a power of 20 W, a wavelength of 1040÷1200 nm, a spot size of 0.03÷0.05 mm, maximum energy in the pulse < 2 mJ, and pulse duration >10 ns was used. The laser was cooled with air, the processing took place in the air. The laser was controlled by software. The following parameters were set in the program: pulse frequency (kHz), scanning speed (mm/s), and power (%) as well as the number of repetitions of machining a hole [43].

The holes made in the used material were evaluated by measuring the diameter using a DinoCapture 2.0 digital microscope. After calibration, this microscope made it possible to take pictures of the samples with a magnification of approx. 200 times.

The morphologies of the holes were examined using an S-3400 scanning electron microscope (SEM) Phenom ProX (Nanoscience Instruments, Phoenix, AZ, USA).

Purpose and assumptions of the experiment

Experimental studies were conducted to determine the technological possibilities of cutting holes with diameters of 1.0, 0.5, 0.4, 0.3, 0.2, and 0.1 mm with a fiber laser. The experiment was carried out according to the scheme:

- I – laser pre-treatment with different parameters adopted;
- II – analysis of preliminary test results (visual and microscopic observation of effects)
- III – determination of optimal laser operating parameters and the necessary number of cutting cycle repetitions to obtain effective material separation;
- IV – making holes with established laser parameters and number of repetitions, assessment of repeatability of processing effects, measurements of hole diameters to determine deviations in size and shape

The procedure for selecting hole processing variants (stage I÷III) was carried out separately for diameters of 1 mm and 0.1÷0.5 mm due to significant differences in the beam interaction time, resulting in the efficiency of material separation.

RESULTS AND DISCUSSION

Preliminary tests were carried out in the variants given in Table 1 to make holes with a diameter of 1 mm. Due to the program's limitations, which do not allow setting the beam impact at one point and drilling a hole, the strategy of cutting the hole in a circle was adopted. The variants that made it possible to obtain a trace of the beam passage visible to the naked eye were considered satisfactory (Fig. 1).

The traces of the laser beam in variants 1, 2, and 5 were practically invisible, and in variant 6 – slightly visible. In variants 3 and 4 they were visible to the naked eye. In the case of both variants (3 and 4), the holes were made with a 20 W (100%) laser, with a pulse frequency of 20 kHz, but with different speeds. The hole in variant 3 was made with a speed of 100 mm/s, and in variant 4 with a speed of 50 mm/s. The comparison of the machining results is presented in Fig. 2.

Cutting the hole at a slower speed creates a more visible heat-affected zone, so variant 3 was ultimately considered the most advantageous (power 100%, frequency 20 kHz, speed of scanning 100 mm/s). Observing the above results, it can be stated that it was impossible to make a hole in one beam pass. Finally, it was assumed that the parameter enabling effective machining would be the number of repetitions of the laser beam passes. Variants of repetitions from 10 to 100, with a step of 10, were assumed. The cutting results are shown in Figure 3.

The observations of the cut holes show that only two variants: 90 and 100 repetitions, make it possible to obtain a fully cut hole (without any material left or the need to mechanically remove the interior). Therefore, the number of passes from 10 to 80 was not sufficient. The dilemma remained whether to ultimately make holes with 90 or 100 repetitions. Visually, the differences are small and the processing time is comparable. In this situation, to determine the optimal processing conditions, 10 holes with a diameter of 1 mm were made in each variant, and then the diameter was measured in two perpendicular directions to determine the shape deviations and the dimensional deviations. The method of marking the measured dimensions is shown in Figure 4.

The difference between the dimension measured in a given direction and the nominal dimension is assumed as the dimensional deviation D_d (this deviation can be positive or negative):

$$D_{d1} = d_1 - d_{nom} \tag{1}$$

$$D_{d2} = d_2 - d_{nom} \tag{2}$$

The ovality deviation D_{oval} is the largest difference between the measured dimension and the nominal dimension (ideal, i.e. 1.0 mm):

$$D_{oval} = \max \left(\left| d_{nom} - d_1 \right|, \left| d_{nom} - d_2 \right| \right) \tag{3}$$

where: d_{nom} – nominal value of the hole diameter; d_1, d_2 – values measured perpendicular to each other.

The maximum roundness deviation D_{round} was assumed to be the absolute value of the difference between measurements of one hole made in both directions:

$$D_{round} = \left| d_1 - d_2 \right| \tag{4}$$

The results of measurements and calculations are presented in the Tables 2 and 3.

Observing the holes made under a microscope, it was found that the 90-pass processing does not cause excessive burning or edge deformation, and the heat-affected zone is not extensive. Holes made with 100 beam passes have more irregular edges, in some cases, there is small melting and unevenness, although the heat-affected zone is comparable. Comparing the results of

Table 1. Preliminary test plan for 1 mm holes

Sample number	Impulse frequency, kHz	Power, %	Speed of scanning, mm/s
1	20	50	100
2	20	75	100
3	20	100	100
4	20	100	50
5	200	100	100
6	20	100	1000

the measurements, it can be seen that the holes made in 90 passes have a higher dimensional accuracy. The maximum dimension obtained is 1.033 mm, while in 100 passes it is 1.044 mm. The dimensional spread in the 90× variant (difference between the maximum and minimum dimension) was 0.026 mm (1.033 minus 1.007) and was smaller than in the 100× variant at 0.039 mm (1.044 minus 1.005). In both cases, the dimensions defined in the program (software) with a nominal value of 1 mm, in reality, had a tolerated diameter 'plus' (larger than assumed).

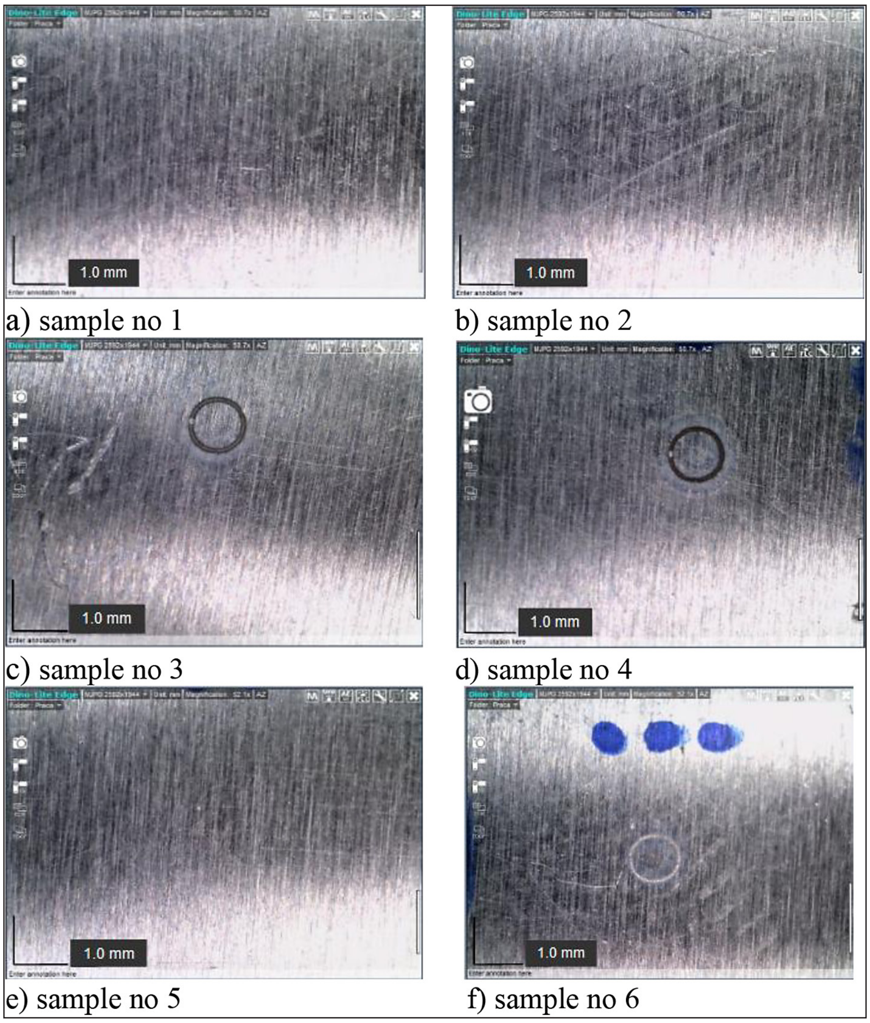


Figure 1. Results of trial cutting of 1 mm diameter holes: (a÷f) samples in the preliminary test (mag. app. 50×)

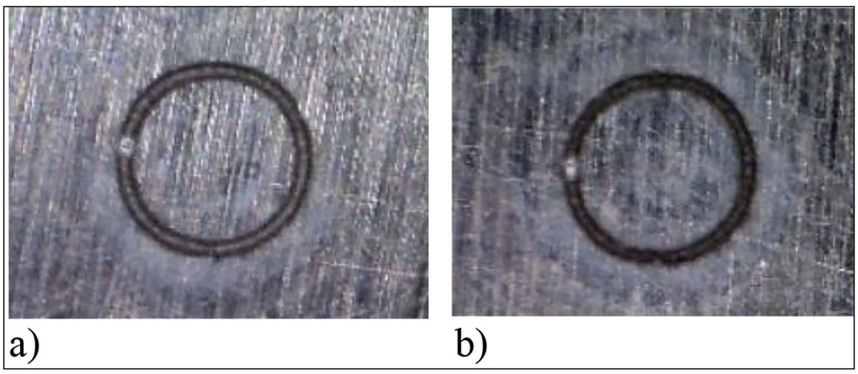


Figure 2. Comparison of holes made with the same pulse frequency and power but different speeds, (a) 100 mm/s, (b) 50 mm/s

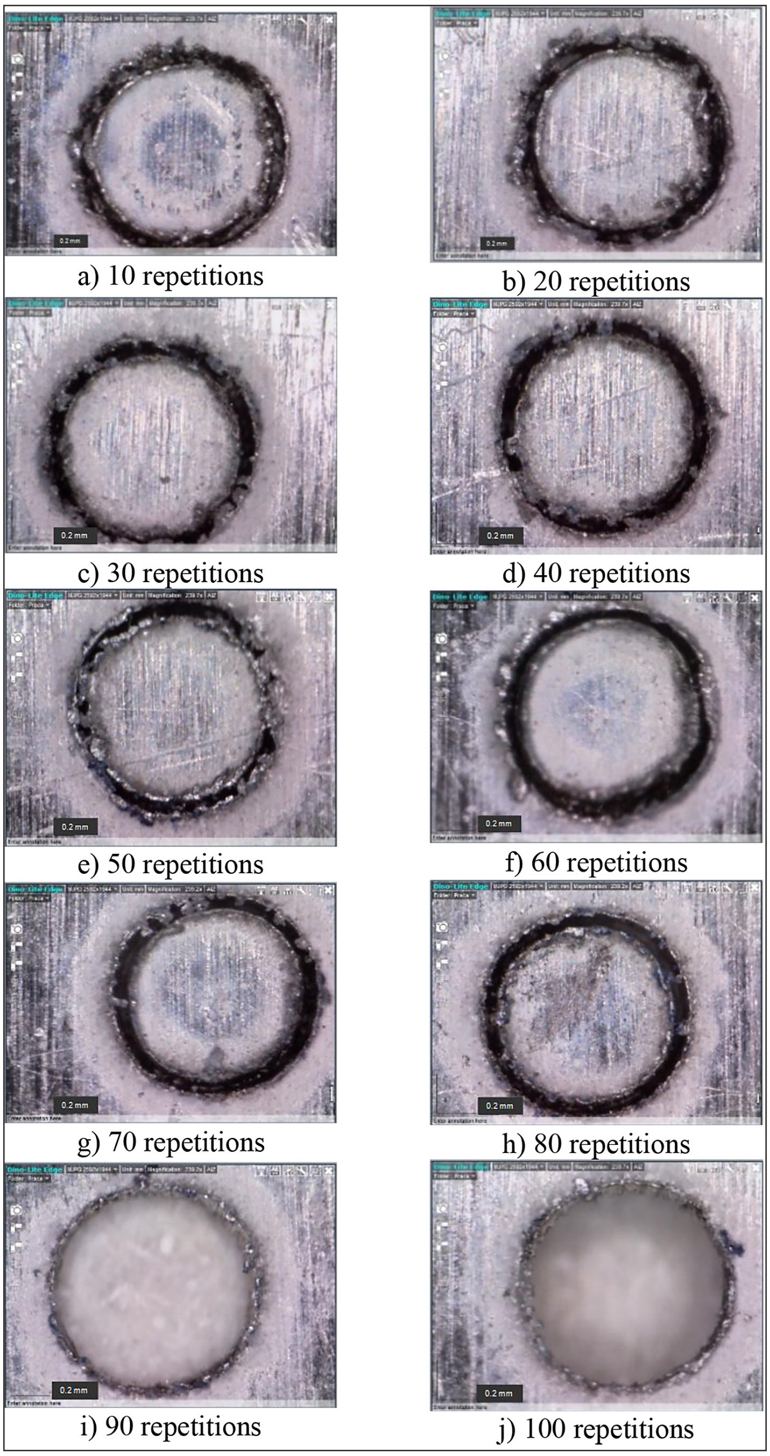


Figure 3. Cutting the 1 mm diameter hole by repeating the number of beam passes: (a) 10×, (b) 20×, (c) 30×, (d) 40×, (e) 50×, (f) 60×, (g) 70×, (h) 80×, (i) 90×, (j) 100× (mag. app. 200×)

The accuracy of the hole shape representation was also better for the 90× variants. The discrepancy between the actual outline and the nominal circle was less, at 0.014 mm, compared to 0.033 mm for the 100× variant (Fig. 5).

In the context of roundness, the 90× variant was again more advantageous, the situation shown in Figure 6 indicates that the deviations from the ideal circle were smaller in value and had a smaller scatter (max. 0.021 mm and range 0.019, respectively). In the 100-pass variant, the maximum diameter value was 0.031 mm, and the range was 0.025 mm). Therefore, it can be said that holes more repeatable in size and shape can be made with 90 passes of the laser beam with the adopted parameters.

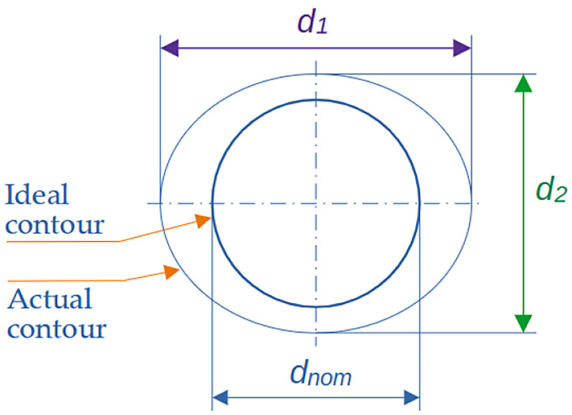


Figure 4. The adopted rules for measuring the diameter of the hole: d_{nom} – nominal value of the hole diameter, d_1 and d_2 – diameter values measured perpendicular to each other

Following the adopted experimental plan, an attempt was made to make holes with a diameter of 0.5 mm in one pass according to the variants given in Table 4. The variable parameters of the laser operation were power, scanning speed, and constant pulse frequency. The holes were assessed under a microscope. The results of the observations are shown in Figure 7.

It was found that none of the variants allowed effective cutting of the selected material with a thickness of 0.2 mm in one beam pass. On samples 1–5 made with a power of 10 W (50%), the trace after processing is poorly visible. On samples 6–10 made with a power of 20 W (100%), the trace is clearly visible, but in addition to the satisfactory effect on the material, the heat-affected zone was also visible. On samples 11÷15 (power of 15 W, 75%), this effect is not present, the trace after processing is clearly visible. Therefore, variant 15 was selected for the hole-cutting test, according to which it was expected to obtain a cut of the material without a clear defect around the hole (this was the first criterion for selecting the processing parameters). Further test cuts were made according to Table 5.

The results of the microscopic observations are shown in Figure 8. Despite increasing the number of laser beam pass repetitions, it was not

Table 2. The diameter of the hole made by 90 beam passes

N° of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	1.010	1.031	0.010	0.031	0.031	0.021
2.	1.021	1.019	0.021	0.019	0.021	0.002
3.	1.028	1.007	0.028	0.007	0.028	0.021
4.	1.010	1.019	0.010	0.019	0.019	0.009
5.	1.023	1.019	0.023	0.019	0.023	0.004
6.	1.026	1.021	0.026	0.021	0.026	0.005
7.	1.028	1.011	0.028	0.011	0.028	0.017
8.	1.015	1.033	0.015	0.033	0.033	0.018
9.	1.014	1.019	0.014	0.019	0.019	0.005
10.	1.033	1.012	0.033	0.012	0.033	0.021

Table 3. The diameter of the hole made by 100 beam passes

N° of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	1.023	1.017	0.023	0.017	0.023	0.006
2.	1.005	1.011	0.005	0.011	0.011	0.006
3.	1.034	1.023	0.034	0.023	0.034	0.011
4.	1.008	1.019	0.008	0.019	0.019	0.011
5.	1.041	1.023	0.041	0.023	0.041	0.018
6.	1.011	1.027	0.011	0.027	0.027	0.016
7.	1.038	1.022	0.038	0.022	0.038	0.016
8.	1.028	1.011	0.028	0.011	0.028	0.017
9.	1.005	1.036	0.005	0.036	0.036	0.031
10.	1.044	1.027	0.044	0.027	0.044	0.017

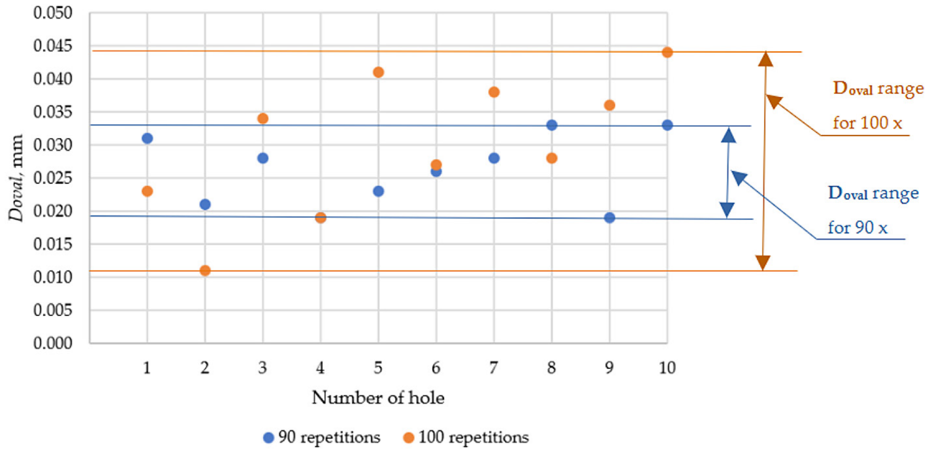


Figure 5. Comparison of the degree of deviation of the holes from the actual outline with a diameter of 1 mm

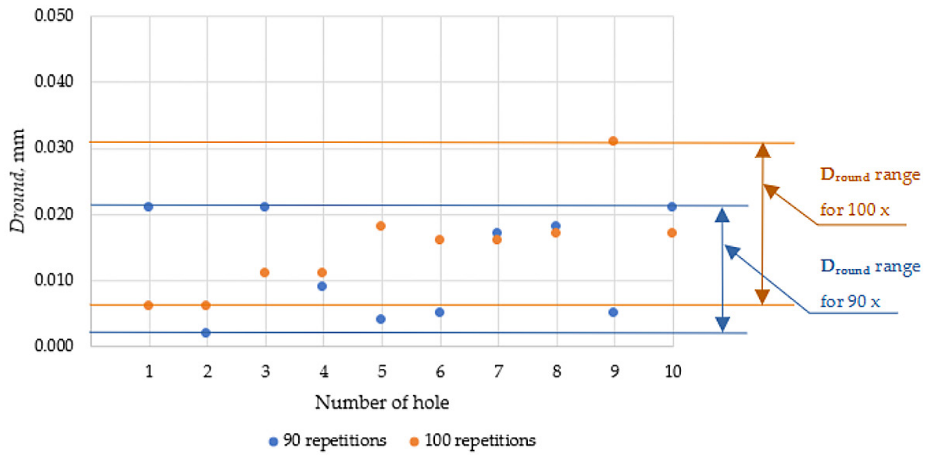


Figure 6. Comparison of the roundness of 1 mm diameter holes

Table 4. Pre-testing plan to assess the effectiveness of the beam

Number of samples	Speed of scanning, mm/s	Power, %
1.	100	50
2.	80	
3.	60	
4.	40	
5.	20	
6.	100	100
7.	80	
8.	60	
9.	40	
10.	20	
11.	100	75
12.	80	
13.	60	
14.	40	
15.	20	

possible to cut the material. Increasing the number of repetitions only caused more extensive melting of the material on the diameter of the cut. It was considered that cutting with a power of 15 W (75%) is ineffective. Therefore, the next variant of the execution with a laser power of 20 W (100%), marked in Table 1 as sample 10, was selected for conducting the main tests. A compromise was adopted consisting of accepting a clearly visible heat-affected zone, and the variant with the lowest speed was considered likely to obtain effective cutting the fastest (due to the most intensive impact of energy on the material).

Finally, the parameters of variant 10 were adopted, i.e. speed 20 mm/s, frequency 20 kHz, and power 20 W for performing tests of cutting a hole with a diameter of 0.5 mm with a repetition of 10, 20, 30, 40, and 50 repetitions. The hole was created during cutting 20 times, so the cases with 15, 16, 17, 18, and 19 repetitions were additionally

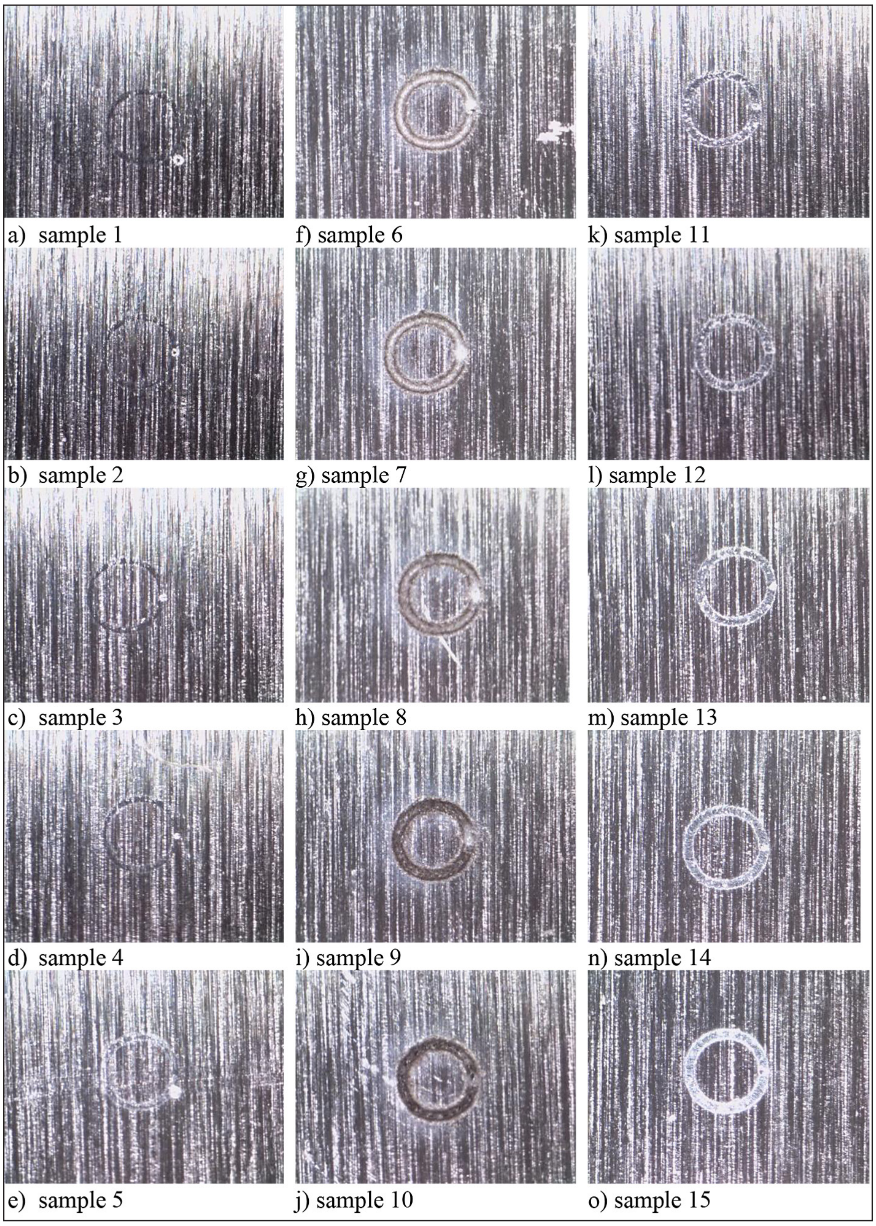


Figure 7. Results of the trial machining of a 0.5 mm hole with one pass of the laser beam: (a–o) subsequent variants according to Table 4 (mag. app. 200×)

Table 5. Variants of cutting a test hole

Hole diameter, mm	Speed of scanning, mm/s	Power, %	Frequency, kHz	Number of repeats
0.5	20	75	20	10, 100, 200, 300, 400, 500

checked. The results are shown in Figure 9. During the microscopic evaluation, it was found that the hole with the best edges, without burns and material residues was obtained after 20 beam passes. This variant of processing the hole with a diameter of 0.5 mm was adopted as the standard. The presented procedure for selecting the best variant was repeated to determine the method of making the remaining micro holes, i.e. with diameters of 0.4, 0.3, 0.2, and 0.1 mm. Table 6 gives the obtained test result together with the established multiplicity of beam passes, and Figure 10 shows examples of holes with the best quality. To assess the repeatability of machining effects, perform diameter measurements, and determine dimensional and shape deviations, 10 holes were made with the above diameters, taking into account the optimal number of repetitions (Fig. 11).

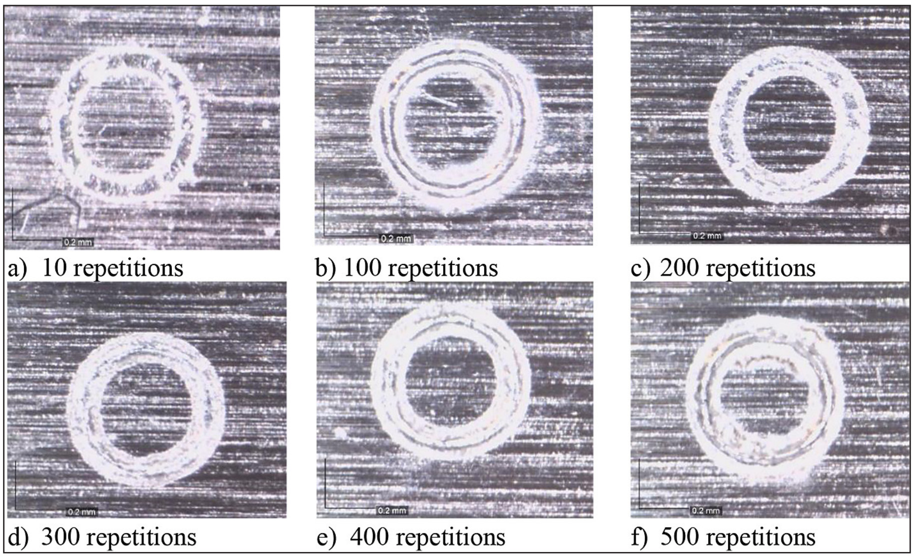


Figure 8. Results of hole cutting tests according to the selected variant: a) 10 repetitions, b) 100 repetitions, c) 200 repetitions, d) 300 repetitions, e) 400 repetitions, f) 500 repetitions (mag. app. 200×)

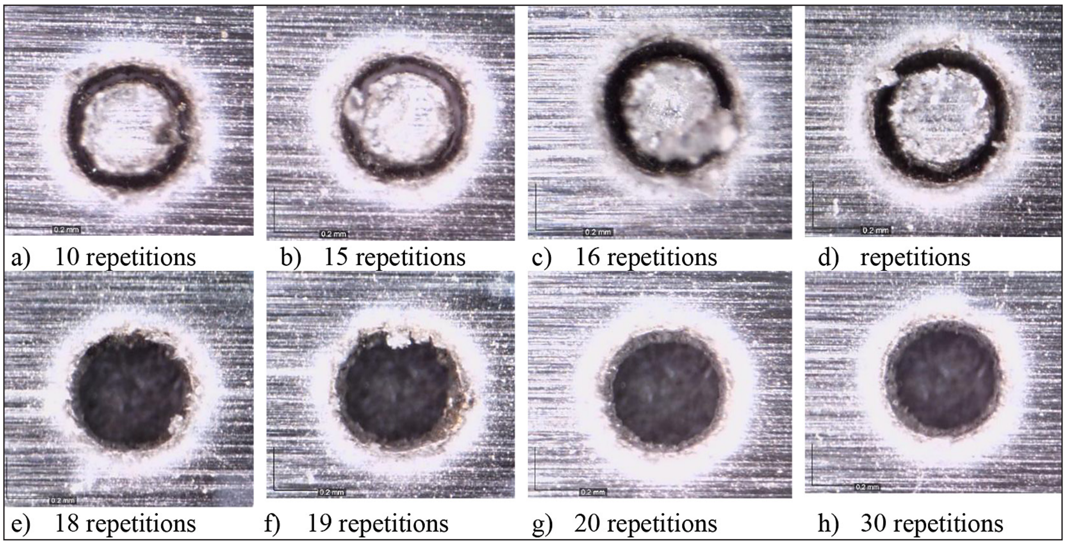
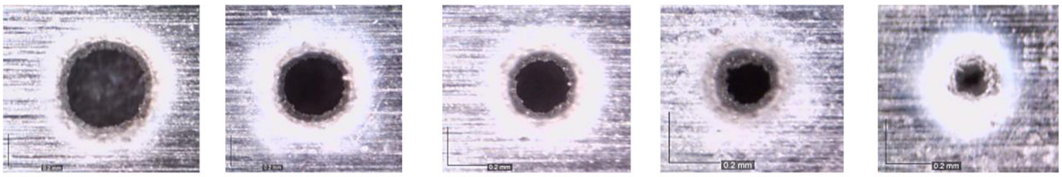


Figure 9. Test hole cutting results with the selected number of passes: a) 10, b) 15, c) 16, d) 17, e) 18, f) 19, g) 20, h) 30 (mag. app. 200×)

In the experiment, the diameter was measured in two perpendicular directions to determine the shape and the dimensional deviations, according to the relations (1)÷(4) and Figure 4. The obtained results are given in Tables 7–11.

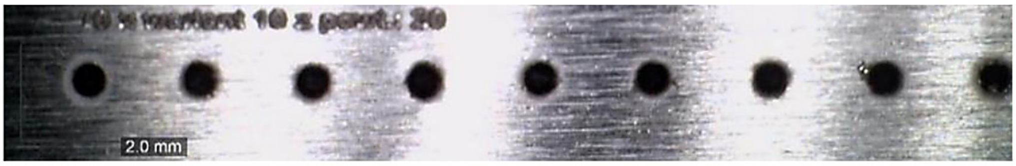
SEM MICROSCOPIC OBSERVATIONS

The quality of laser cutting, defined by the dimensional and shape accuracy and edge properties, as well as the structural properties of the cut material, is primarily determined by the parameters of the cutting process. Considering different diameters of holes cut using the same parameters, it can be observed that the highest dimensional and shape accuracy was obtained for holes with the largest of the considered diameters, i.e. $d = 0.5$ mm. Despite the acceptable accuracy, however, this variant showed defects typical of laser cutting technology. These are primarily melting in the cutting line, which results from too high a cutting feed rate, as shown in SEM micrographs (Fig. 12). Additionally, splinters of molten metal were observed on the surface of the sheet metal in the area of the heat-affected zone.



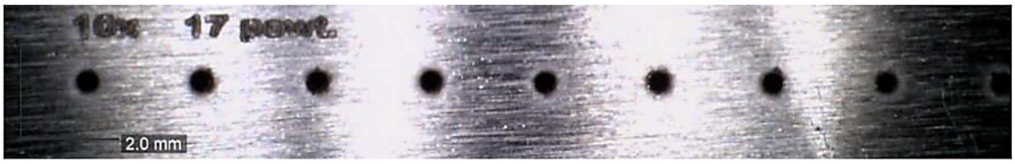
a) 0.5 mm; b) 0.4 mm c) 0.3 mm d) 0.2 mm e) 0.1 mm

Figure 10. Micro holes obtained with a fixed number of repetitions (mag. app. 200×)

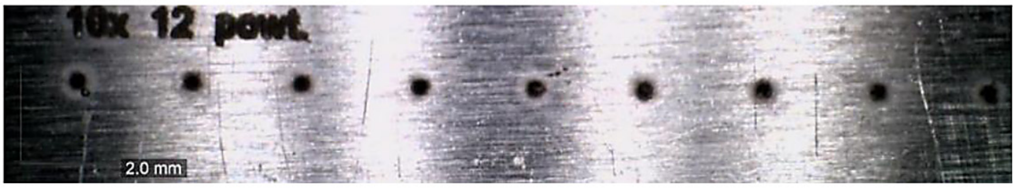


a) 0.5 mm

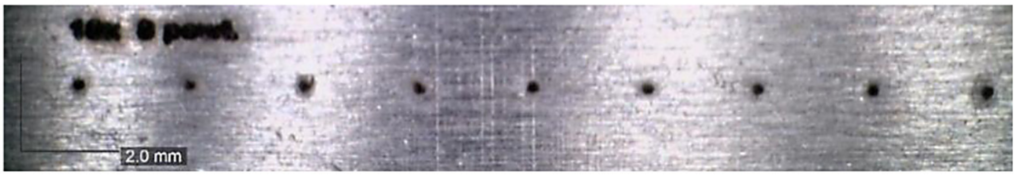
b) 0.4 mm



c) 0.3 mm



d) 0.2 mm



e) 0.1 mm

Figure 11. Micro holes made for measuring purposes (mag. app. 20×)

Table 6. Number of laser beam pass repetitions for holes with a diameter of 0.1÷0.5 mm

Diameter, mm	0.5	0.4	0.3	0.2	0.1
Number of repetitions	20	18	17	12	8

Incorrect correlation of feed speed with technical gas pressure leads to the phenomenon of ineffective removal of molten metal when using too high a cutting feed speed, which causes melting. On the other hand, too low a feed speed results in overheating of the material, which causes local changes in the properties of its structure. In the discussed issue of thin sheet cutting, a precise indication of the optimal feed speed at which there would be no melting and at the same time no

Table 7. Results of measurement of 0.5 mm micro holes

Nº of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	0.498	0.490	-0.002	-0.010	0.010	0.008
2.	0.492	0.481	-0.008	-0.019	0.019	0.011
3.	0.484	0.477	-0.016	-0.023	0.023	0.007
4.	0.490	0.472	-0.010	-0.028	0.028	0.018
5.	0.499	0.490	-0.001	-0.010	0.010	0.009
6.	0.490	0.489	-0.010	-0.011	0.011	0.001
7.	0.487	0.479	-0.013	-0.021	0.021	0.008
8.	0.490	0.482	-0.010	-0.018	0.018	0.008
9.	0.498	0.496	-0.002	-0.004	0.004	0.002
10.	0.484	0.490	-0.016	-0.010	0.016	0.006

Table 8. Results of measurement of 0.4 mm micro holes

Nº of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	0.387	0.369	-0.013	-0.031	0.031	0.018
2.	0.378	0.373	-0.022	-0.027	0.027	0.005
3.	0.386	0.378	-0.014	-0.022	0.022	0.008
4.	0.376	0.379	-0.024	-0.021	0.024	0.003
5.	0.347	0.365	-0.053	-0.035	0.053	0.018
6.	0.387	0.363	-0.013	-0.037	0.037	0.024
7.	0.384	0.363	-0.016	-0.037	0.037	0.021
8.	0.397	0.381	-0.003	-0.019	0.019	0.016
9.	0.397	0.388	-0.003	-0.012	0.012	0.009
10.	0.399	0.397	-0.001	-0.003	0.003	0.002

Table 9. Results of measurement of 0.3 mm micro holes

Nº of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	0.272	0.264	-0.028	-0.036	0.036	0.008
2.	0.271	0.274	-0.029	-0.026	0.029	0.003
3.	0.284	0.272	-0.016	-0.028	0.028	0.012
4.	0.276	0.273	-0.024	-0.027	0.027	0.003
5.	0.270	0.273	-0.030	-0.027	0.030	0.003
6.	0.272	0.266	-0.028	-0.034	0.034	0.006
7.	0.266	0.261	-0.034	-0.039	0.039	0.005
8.	0.256	0.253	-0.044	-0.047	0.047	0.003
9.	0.285	0.258	-0.015	-0.042	0.042	0.027
10.	0.293	0.276	-0.007	-0.024	0.024	0.017

overheating phenomenon would occur requires many experimental tests due to the lack of an additional gas nozzle for removing melted material.

Since the work considered different diameters of cut holes using the same parameters, therefore, cutting of different lengths of circumferences was carried out, which resulted in different relative speeds. In the case of the smallest of the considered hole diameters, i.e. d = 0.1 mm, effective material removal was not achieved precisely due to too high relative cutting speed. This is manifested by the area of solidified metal, which was melted, but it was not removed by the technical gas (because it is not there), hence the desired hole cut was not achieved (Fig. 13). In this case, it is possible to observe a similar width of the heat affected zone (HAZ) as for the hole with a diameter of d = 0.5 mm. Based on the EDS analysis,

Table 10. Results of measurement of 0.2 mm micro holes

Nº of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	0.191	0.199	-0.009	-0.001	0.009	0.008
2.	0.174	0.143	-0.026	-0.057	0.057	0.031
3.	0.199	0.176	-0.001	-0.024	0.024	0.023
4.	0.160	0.172	-0.040	-0.028	0.040	0.012
5.	0.187	0.173	-0.013	-0.027	0.027	0.014
6.	0.195	0.176	-0.005	-0.024	0.024	0.019
7.	0.158	0.182	-0.042	-0.018	0.042	0.024
8.	0.173	0.164	-0.027	-0.036	0.036	0.009
9.	0.180	0.159	-0.020	-0.041	0.041	0.021
10.	0.173	0.181	-0.027	-0.019	0.027	0.008

Table 11. Results of measurement of 0.1 mm micro holes

Nº of hole	d_1, mm	d_2, mm	D_{d1}, mm	D_{d2}, mm	D_{oval}, mm	D_{round}, mm
1.	0.065	0.071	-0.035	-0.029	0.035	0.006
2.	0.068	0.100	-0.032	0.000	0.032	0.032
3.	0.066	0.088	-0.034	-0.012	0.034	0.022
4.	0.039	0.052	-0.061	-0.048	0.061	0.013
5.	0.083	0.058	-0.017	-0.042	0.042	0.025
6.	0.099	0.081	-0.001	-0.019	0.019	0.018
7.	0.087	0.099	-0.013	-0.001	0.013	0.012
8.	0.062	0.096	-0.038	-0.004	0.038	0.034
9.	0.073	0.075	-0.027	-0.025	0.027	0.002
10.	0.082	0.094	-0.018	-0.006	0.018	0.012

aluminum oxide layers were shown at the outer circumference of the cutting line.

DISCUSSION OF LASER TREATMENT ACCURACY

Making micro holes with a fiber laser according to the adopted scheme requires prior determination of whether the obtained accuracy of the execution is satisfactory. Comparing the obtained results, it can be stated that to cut the hole effectively, the number of beam passes should be reduced along with the decrease in the diameter of the hole being made. Deviations from the nominal dimension are an indication of the tolerance of the drawing dimensions, taking into account the fact that the obtained holes may be larger, as noted for the diameter of 1 mm (Tables 2 and 3), or smaller than the nominal dimension in the case of smaller diameters. Graphs illustrating this tendency for hole diameters smaller than 1 mm and the repeatability of their execution are shown in Figure 14.

However, the change in hole diameter can be significant, as seen in the calculations given in Table 12 and Figure 15, which take into account the percentage decrease in diameter as:

$$P_{min} = \frac{d\,nom - dmax}{dnom} \cdot 100\% \quad (5)$$

and

$$P_{max} = \frac{d\,nom - dmin}{dnom} \cdot 100\% \quad (6)$$

where: *Pmin, Pmax* – accordingly: minimum or maximum percentage diameter difference; d_{nom} – nominal (ideal) diameter of hole; d_{min}, d_{max} – accordingly: minimum or maximum diameter of hole obtained from the measurements; and presented as a range $P_{min} \div P_{max}$.

The numerical analysis of the diameter values and deviations should be supplemented by a visual

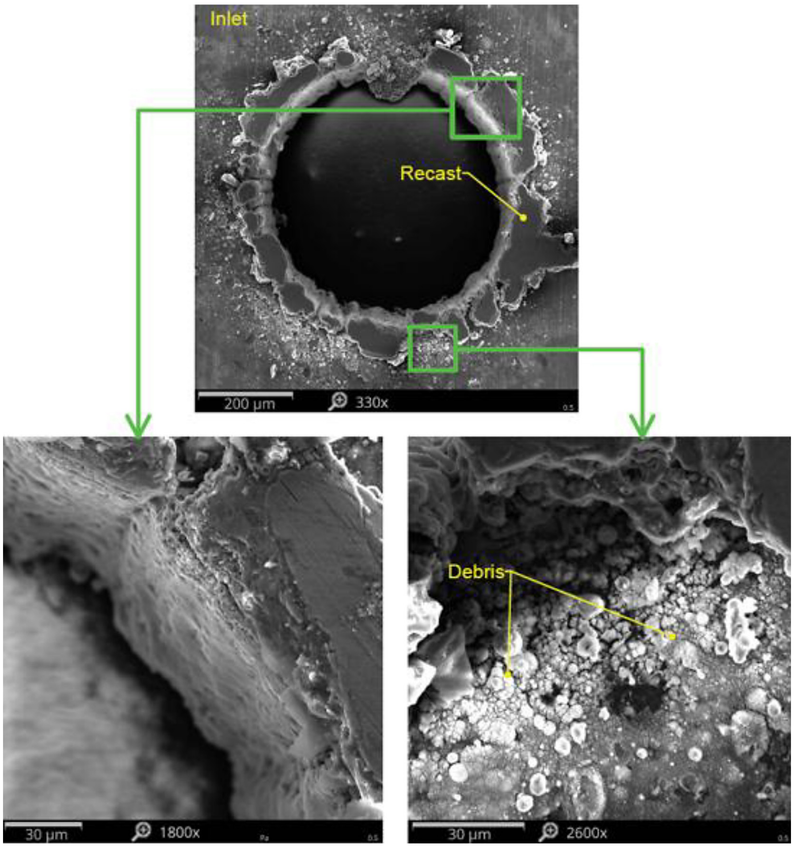


Figure 12. SEM images of the 0.5 mm diameter hole

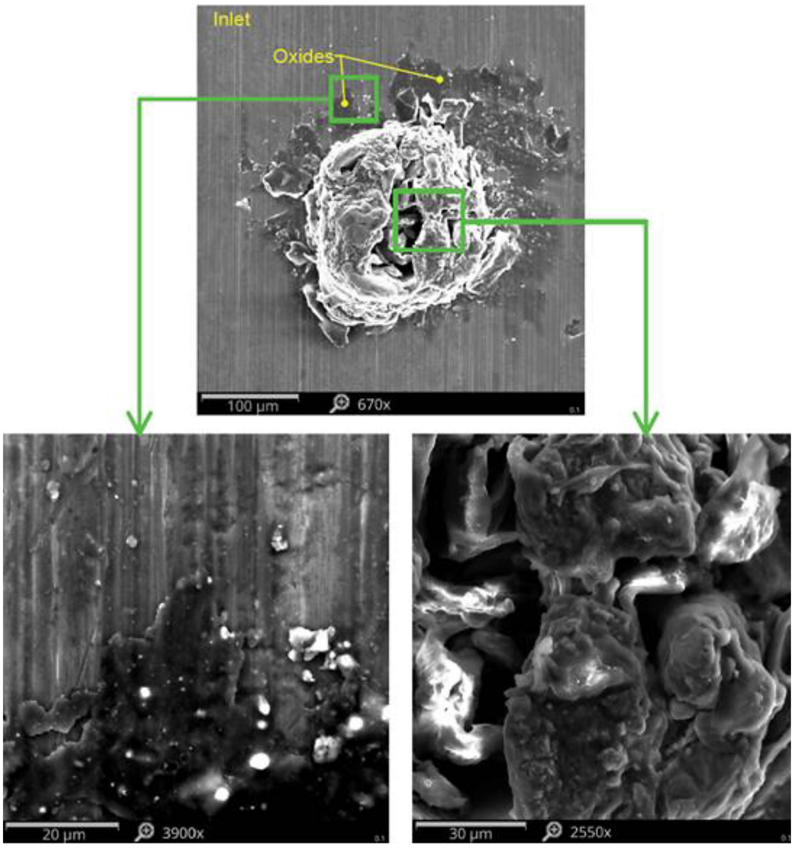


Figure 13. SEM images of the 0.1 mm diameter hole

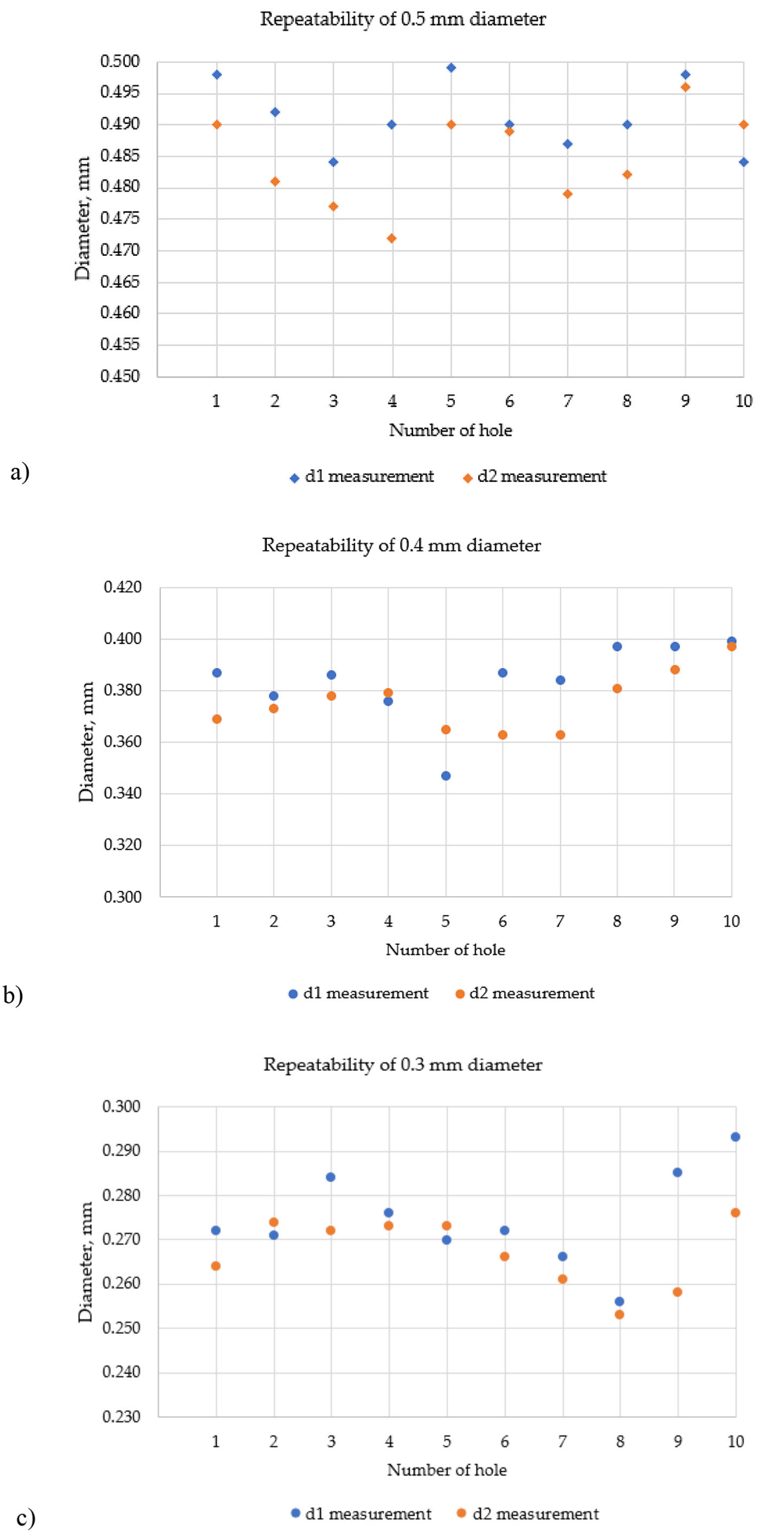
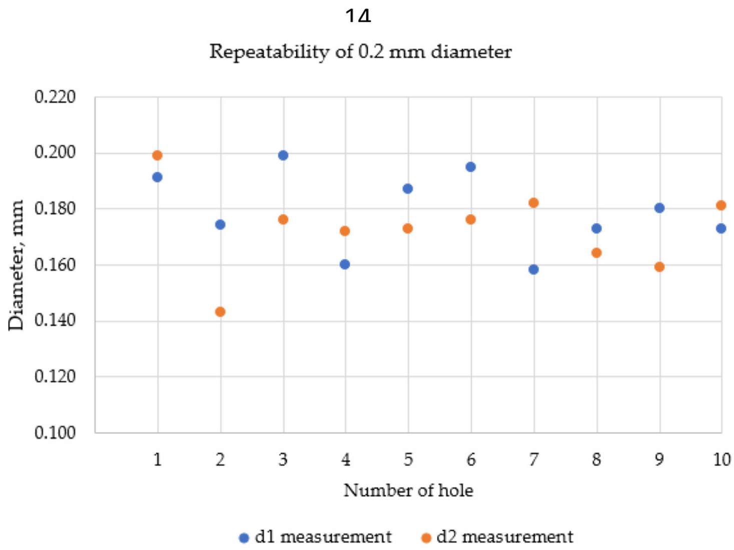
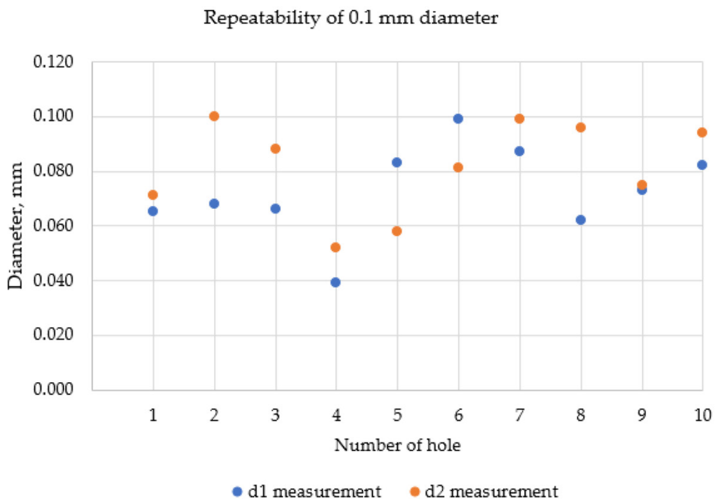


Figure 14. Hole sizes and their repeatability for diameters: a) 0.5 mm, b) 0.4 mm, c) 0.3 mm, d) 0.2 mm, e) 0.1 mm



d)



e)

Figure 14. Cont. Hole sizes and their repeatability for diameters: (a) 0.5 mm, (b) 0.4 mm, (c) 0.3 mm, (d) 0.2 mm, (e) 0.1 mm

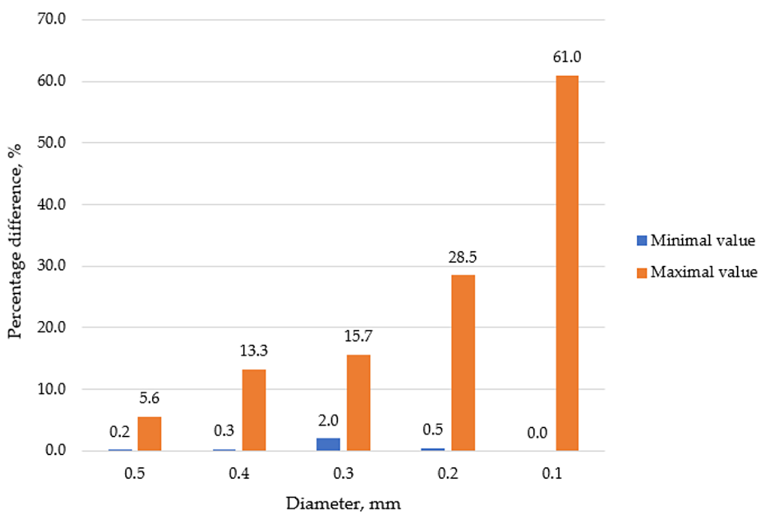


Figure 15. Percentage loss of hole accuracy

Table 12. Summary of the results and equations

Value	Diameter of hole, mm				
	0.5	0.4	0.3	0.2	0.1
Minimum diameter, *d min*, mm	0.472	0.347	0.253	0.143	0.039
Maximum diameter, *d max*, mm	0.499	0.399	0.293	0.199	0.100
Minimum diameter deviation, mm	-0.028	-0.053	-0.047	-0.057	-0.061
Maximum diameter deviation, mm	-0.001	-0.001	-0.007	-0.001	0.000
Percentage decrease in diameter, *P min* ÷ *P max*, %	0.20÷5.60	0.25÷13.25	2,00÷15.66	0.50÷28.50	0.0÷61.0

assessment. Some holes (including those with diameters of 0.1 and 0.2 mm) were characterized by many shape defects and measurements in two planes may not reflect the actual outline of the hole.

CONCLUSIONS

Each implementation of new technology for practical use requires an analysis of the efficiency and effectiveness of the new solution. The presented work has shown that an unconventional use of a laser marker for cutting holes is possible. The testing method was utilized to determine the optimal operating parameters of the laser for processing a specific material, in this case, aluminum tape. In the context of the created holes, one of several possible cutting techniques was used: a strategy of multiple beam cutting along a designated circle. For holes with a diameter of 1 mm, it was established that the best variant can be achieved using a beam with a pulse frequency of 20 kHz, a scanning speed of 100 mm/s, a power output of 20 W, and 90 passes. The resulting outcome is favorable. In addition to the material separation effect, it was discovered that the cut edges remain undeformed, the dimensional scatter, recorded at 0.026 mm, is acceptable, and the heat-affected zone is minimal. Dimensional deviations were "in plus", which is significant for product design and marking manufacturing accuracy on drawings. Smaller holes can also be cut, but the technological parameters must be adjusted due to the considerably shorter duration of the beam's impact and lower effectiveness in material separation. The holes should be cut with a 20 W laser, at a speed of 20 mm/s, a frequency of 20 kHz, and the number of passes should decrease accordingly for smaller hole diameters (20 passes for 0.5 mm, 18 for 0.4 mm, 17 for 0.3 mm, 12 for 0.2 mm, and 8 for 0.1 mm). However, cutting holes with diameters between 0.1 and 0.5 mm presents challenges with accuracy. In cases of 0.5, 0.4, and 0.3 mm diameters, the quality of the hole is acceptable, but for 0.2 and 0.1 mm, this type of beam becomes ineffective. It has been shown that the edges of the holes deform during processing, the holes lose their intended shape, and the dimensional accuracy is inadequate. Additionally, the repeatability of processing is greater for larger holes (i.e., 1 mm and 0.5 mm), and the observed dimensional deviations tend to be "in minus". The quality and repeatability diminish significantly with decreasing diameter, and for holes of 0.1 mm, the cutting technique with the selected laser is rendered unusable. Furthermore, the non-overlapping position of the ranges of dimensional deviations obtained in two planes may suggest inaccuracy in the laser execution system, specifically the galvo head. However, understanding the size and nature of execution errors is essential in any applied technology, thus making the conducted research highly utilitarian.

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REFERENCES

1. Biswas R., Das M.Ch., Bhattacharyya S., Kuar A.S., Mitra S. Selection of Nd:YAG laser beam micro-drilling parameters using multicriteria decision making methods. Optics and Laser Technology 2019; 119: 105596.
2. Sezer H.K., Li L. Mechanisms of acute angle laser drilling induced thermal barrier coating

delamination. J. Manuf. Sci. Eng. Oct 2009, 131(5): 051014.

3. Beck N, Landa T, Seitz A, Boermans L, Liu Y, Radespiel R. Drag reduction by laminar flow control. Energies 2018; 11(1): 252.
4. Zhang T., Liu Z., Xu Ch., Influence of size effect on burr formation in micro cutting. Int J Manuf Technol 2013; 68: 1911–1917, DOI 10.1007/s00170-013-4801-8.
5. Biswas R., Kuar A.S., Mitra S., Multi-objective optimization of hole characteristics during pulsed Nd:YAG laser microdrilling of gamma-titanium aluminide alloy sheet. Optics and Lasers in Engineering 2014; 60: 1–11.
6. Jin S. Y., Pramanik A., Basak A.K., Prakash C., Shankar S., Debnath S., Burr formation and its treatments-a review. The International Journal of Advances Manufacturing Technology 2020; 107: 2189–2210 DOI 10.1007/s00170-020-05203-2.
7. Chae J., Park S.S., Freiheit T., Investigation of micro-cutting operations. Int. Journal of Machine Tools & Manufacture 2006; 46: 313–332.
8. Chang D.Y., Lin S.Y., Tool Wear, Hole Characteristics, and Manufacturing Tolerance in Alumina Ceramic Microdrilling Process. DOI 10.1080/10426914.2011.577881.
9. Thepsonthi T., Özel T., 3-D finite element process simulation of micro-end milling Ti-6Al-4V titanium alloy: Experimental validations on chip flow and tool wear. Journal of Materials Processing Technology 2015; 221: 128–145.
10. Frazier A.B., Warrington R. O., Friedrich C., The Miniaturization Technologies: Past, Present, and Future. IEEE Transactions on Industrial Electronics, 1995; 42(5).
11. Arrizubieta I., Lamikiz A., Martínez S., Ukar E., Tabernero I., Girot F., Internal characterization and hole formation mechanism in the laser percussion drilling process. International Journal of Machine Tools & Manufacture 2013; 75: 55–62.
12. Weule H., Hüntrup V., Trischler H., Mocro-Cutting of Steel to Meet New Requirements in Miniaturization. CIRP Annals, 2001; 50(1), 61–64.
13. Shi C., Ren N., Wang H., Xia K., Wang L., Effects of ultrasonic assistance on microhole drilling based on Nd:YAG laser trepanning. Optics and Laser Technology 2018; 106: 451–460. DOI 10.1016/j.optlastec.2018.05.003.
14. Mishra S., Yadava V., Laser beam micromachining (LBMM) – A review. Optics and Lasers in Engineering 2015; 73: 89–122.
15. Zhang S., Fan Y., Huang Y., Yang X., Zhang M., Luo J., Deng G., Zhou Q., Song H., Wang Y. Improvement of the surface condition of laser-drilled holes via a dual-wavelength double-pulse train. Optics & Laser Technology 2023; 157: 108681.
16. Goyal R., Dubey A.K. Modeling and optimization of geometrical characteristics in laser trepan drilling of titanium alloy, J. Mech. Sci. Technol. 2016; 30: 1281–1293.
17. Goyal R., Dubey A.K. Quality improvement by parameter optimization in laser trepan drilling of superalloy sheet, Mater. Manuf. Process. 2014; 29: 1410–1416.
18. Shi Ch., Ren N., Wang H., Xia K., Wang L. Effects of ultrasonic assistance on microhole drilling based on Nd:YAG laser trepanning. Optics and Laser Technology 2018; 106: 451–460.
19. Ashkenasi D., Kaszemeikat T., Mueller N., Dietrich R., Eichler H.J., Illing G., Laser trepanning for industrial applications, Phys. Procedia 2011; 12: 323–331.
20. Jahns D., Kaszemeikat T., Mueller N., Ashkenasi D., Dietrich R., Eichler H.J. Laser trepanning of stainless steel, Phys. Procedia. 2013; 41: 630–635.
21. Shivakoti I., Kibria G., Pradhan B.B. Predictive model and parametric analysis of laser marking process on gallium nitride material using diode pumped Nd:YAG laser, Opt. Laser Technol. 2019; 115: 58–70.
22. Weck A., Crawford T.H.R., Wilkinson D.S., Haugen H.K., Preston J.S. Laser drilling of high aspect ratio holes in copper with femtosecond, picosecond and nanosecond pulses. Appl Phys Mater Sci Process 2008; 90(3): 537–43.
23. Liu X., DeVor R.E., Kapoor S.G., Ehman K.F. The mechanics of machining at the micro scale: assessment of the current state of the science. Journal of Manufacturing Science and Engineering. 2004; 126: 666–678.
24. Kolahdouz S., Hadi M., Arezoo B., Zamani S. Investigation of surface integrity in high speed milling of gamma titanium aluminide under dry and minimum quantity lubricant conditions. Proc. CIRP 2015; 26: 367–372.
25. Alting L., Kimura F., Hansen H.N., Bissacco G. Micro engineering, Annals of CIRP Keynote 2003 STC-O.
26. Steen W.M., Mazumder J. Laser material processing. 4th ed. New York, Springer, 2010.
27. Marimuthu S., Antar M., Dunleavey J. Characteristics of micro-hole formation during fibre laser drilling of aerospace superalloy. Precision Engineering 2019; 55: 339–348.
28. Kraus M., Collmer S., Sommer S., Friedrich D. Microdrilling in steel with frequency-doubled ultrashort pulsed laser radiation. J Laser Micro/Nanoeng. 2008; 3(3): 129–34.
29. Friedman H.W., Pierce E.L. Precision micron hole drilling using a frequency doubled, diode pumped solid state laser. Lawrence Livermore National Laboratory Report; 2004. https://doi.org/10.2172/15014643.". UCRL-TR-208902, Web.

30. Khan A.H., Celotto S., Tunna L., O'Neill W., Sutcliffe C.J. Influence of microsupersonic gas jets on nanosecond laser percussion drilling. Optic Laser Eng 2007; 45(6): 709–18.
31. Weck A., Crawford T.H.R., Wilkinson D.S., Haugen H.K., Preston J.S. Laser drilling of high aspect ratio holes in copper with femtosecond, picosecond and nanosecond pulses. Appl Phys Mater Sci Process 2008; 90(3): 537–43.
32. Bentley S.A., Mantle A.L., Aspinwall D.K. The effect of machining on the fatigue strength of a gamma titanium aluminide intertmetallic alloy. Intermetallics. 1999; 7: 967–9.
33. Yilbas B.S. Investigation into drilling speed during laser drilling of metals. J. Opt. Laser Technol. 1988; 20(1): 29–32.
34. Hartmann C.A., Fehr T., Brajdic M., Gillner A. Investigation on laser micro ablation of steel using short and ultrashort IR multipulses, J. Laser. Micro. Nanoen. 2007; 2(1): 44–48.
35. Ahmed R., Iqbal J., Baig M.A. Effects of laser wavelengths and pulse energy ratio on the emission enhancement in dual pulse LIBS, Laser. Phys. Lett. 2015; 12(6): 066102, https://doi.org/10.1088/1612-2011/12/6/066102
36. Wang Q.X., Luo S.Z., Chen Z., Qi H.X., Deng J.N., Hu Z. Drilling of aluminum and copper films with femtosecond double-pulse laser, Opt. Laser. Technol. 2016; 80: 116–124.
37. Low D.K., Li L., Corfe A.G. Effects of assist gas on the physical characteristics of spatter during laser percussion drilling of NIMONIC 263 alloy. Appl. Surf. Sci. 2000 Feb 1; 154: 689–95.
38. Marimuthu S., Kamara A.M., Sezer H.K., Li L., Ng G.K.L. Numerical investigation on laser stripping of thermal barrier coating. Comput Mater Sci 2014; 88: 131–8.
39. Erdogan M., Ibrahim G. The finite element method and applications in engineering using ANSYS®. Springer; 2015.
40. Kamara A.M., Marimuthu S., Li L. Finite element modeling of microstructure in laserdeposited multiple layer Inconel 718 parts. Mater. Manuf. Process. 2014; 29(10): 1245–52.
41. EN 485-2:2017+A1:2019 Aluminium and aluminium alloys - Sheet, strip and plate - Part 2: Mechanical properties
42. Tolouei-Rad, M.; Aamir, M., 2021. Drilling Technology, IntechOpen, United Kingdom
43. Laser G3:https://www.lasertechnik.pl/
44. Znakowarka%20laserowa%20galvo%20Fiber%20Laser%20START%20series (access: 5.10.2024)