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ANALYSIS OF GEOMETRICAL CHARACTERISTICS OF PULSED ND:YAG LASER DRILLED HOLES IN SUPERALLOY NIMONIC 263 SHEETS

Sanja Petronić, Anđelka Milosavljević, Zoran Radaković, Predrag Drobnjak, Igor Grujić

Preliminary notes

Owing to their excellent mechanical and physical characteristics, superalloys are the most suitable material for use in hot sections of aircraft engines. Thousands of holes need to be drilled in constructive parts of machines, with laser technique emerging as the most effective. Laser drilling has been used to produce small diameter, accurately positioned holes, with little damage in regions around them, and in various materials. Effective laser employment of drilling of high quality holes for critical applications highly depends on correct selection and optimization of laser drilling parameters. In this work, the holes were drilled by a pulsed Nd^{3+}:YAG laser, with maximum average power of 160 W, in superalloy Nimonic 263 sheets, thickness 0,7 mm and 1,2 mm. The holes were observed by optical and scanning electron microscope. Geometrical characteristics of laser drilled holes that depend on laser parameters were investigated and analysed. The aim of this investigation was to find optimal laser parameters which would produce as much as possible regular holes.

Keywords: *drilling, laser, Nimonic 263 superalloy*

Analiza geometrijskih značajki rupa bušenih ND:YAG impulsnim laserom u limovima superlegure Nimonik 263

Prethodno priopćenje

Zbog svojih odličnih mehaničkih i fizikalnih značajki, superlegure su najpogodniji materijal za uporabu u toplim sekcijama zrakoplovnih motora. U konstrukcijskim dijelovima strojeva treba izbušiti tisuće rupa, za što se kao najučinkovitija pokazala laserska tehnika. Bušenje laserom koristi se za proizvodnju malih promjera, točno pozicioniranih rupa, s malim oštećenjima u području oko njih i u različitim materijalima. Učinkovita uporaba lasera za bušenje rupa visoke kvalitete za kritične primjene uvelike ovisi o ispravnom izboru i optimiranju parametara bušenja laserom. U ovom radu, rupe su izbušene Nd^{3+}:YAG impulsnim laserom, uz maksimalnu prosječnu snagu od 160 W, u limovima superlegure nikla Nimonic 263, debljine 0,7 mm i 1,2 mm. Rupe su promatrane optičkim i skenirajućim elektronskim mikroskopom. Istražene su i analizirane geometrijske značajke laserski bušenih rupa, koje ovise o parametrima lasera. Cilj ovog istraživanja bio je pronaći optimalne parametre lasera koji bi omogućili što pravilnije rupe.

Ključne riječi: *bušenje, laser, superlegura Nimonik 263*

1
Introduction
Uvod

There are many advantages of using laser for drilling, and the most important are: the holes can be located accurately, large aspect ratio and very small hole diameters can be reached, a variety of materials can be drilled, the drilling is very rapid, holes can be drilled at difficult entrance angles, the process can be automated, the operating cost is low and no tool wear and breakage. There are some limitations as well, such as: high equipment cost, some defects, a blind hole of precise depth is difficult to produce, the thickness is restricted, adherent material should be removed [1].

Pulsed Nd:YAG laser systems, with average power, up to 500 W, are capable of producing good hole quality and high aspect ratio holes in a variety of materials [2-4]. Typical laser drilling application includes drilling of fine cooling holes in nozzle guide vanes and blades. This is important for achieving higher operating temperatures [5]. Tighter tolerances and high hole quality requirements of the aero-machines and land based gas turbine demand near-zero taper, high aspect ratio, and circularity about 1 [6]. Achieving optimum hole quality is an important area of current research. Previous studies [7-9], devoted to pulsed Nd:YAG laser drilling, constituted that various characteristics of laser beam (pulse energy, pulse frequency, pulse duration), lens focus adjusted to the surface, nozzle stand off and type and pressure of assisted gas have very important influence for laser drilled holes. Effective laser employment for drilling of a high quality hole for critical usage depends on correct selection and optimization of these parameters [10-13].

The hole quality is determined by geometrical characteristics: the hole diameter, taper, aspect ratio, and circularity; and metallurgical characteristics: HAZ (Heat Affected Zone), recast layer, spattering and microcracks.

Geometrical and micro-structural characteristics of Nd:YAG drilled holes in 0,7 mm and 1,2 mm thick sheets of superalloy Nimonic 263 are investigated and analysed in this paper, with the aim of determining optimal drilling parameters.

2
Experiment
Eksperiment

Researches were carried out on nickel based superalloy Nimonic 263 sheets. The samples were cold rolled, and heat treated in two stages: 1) solid solution at 1150 °C/1 h/WC (water quenching) and 2) precipitation treated at 800 °C/8 h/AC (air cooling).

Chemical composition was determined by gravimetrical analysis and is listed in Table 1.

Table 1 *Chemical composition of superalloy Nimonic 263*
Tablica 1. *Kemijski sastav super legure Nimonic 263*

Element	C	Si	Mn	Al	Co	Cr	Cu	Fe	Mo	Ti	Ni
%	0,06	0,3	0,5	0,5	20	20	0,1	0,5	5,9	2,2	balance

The dimensions of investigated samples are: 150×150×0,7 and 150×150×1,2 mm.

The holes were produced by pulsed Nd^{3+}:YAG laser type HTS Mobile LS-P160 (OR Laser). Laser specifications are listed in Table 2. Holes were drilled by different parameters with the aim of determining the optimal parameters to produce the high quality holes. The average laser power was 128 W, and the drilling parameters such as pulse frequency – 5, 7 and 9 Hz and pulse duration – 0,5; 0,7; 1,0; 1,2 and 1,8 ms, were combined. The holes were drilled three times by the same processing parameters and the average values were calculated.

Table 2 *Specification of HTS Mobile LS-P160 Nd:YAG laser*
Tablica 2. *Specifikacija HTS pokretnog LS-P160 Nd:YAG lasera*

Laser parameter	Parameter range
Max. mean laser power	160W
Pulse peak power	7,5 kW
Max. pulse energy	80 J
Pulse duration	0,2 - 20 ms
Pulse frequency	1,0 - 20 Hz
Focal diameter	0,2 - 2,0 mm

The holes were observed by optical microscopy – model KEYENCE VH-Z100 and by scanning electron microscope (SEM) – model JEOL JSM-5800. Performed operations were analysed. Entry side and exit-side of hole diameters and spatter area were measured using AUTOCAD 2009, geometrical characteristics were calculated and presented by plots for easier understanding comprehension.

3
Results and discussion
Rezultati i diskusija

Laser application for the processes of laser drilling includes carefully analysed hole parameters such as: entrance diameter, exit diameter, taper, barrelling, recast layer, micro-cracking, entrance angle and drilling time. The hole characteristics such as: entrance diameter, exit diameter, taper, aspect ratio, circularity of entrance and exit hole and spatter area are carefully investigated and analysed in this paper. Plots are determined using pulse frequency and pulse duration.

Taper (non-cylindrical nature of the hole) is, in laser drilled holes, a result of erosion caused by the expulsion of molten and vaporised material from the hole. Taper degree reduces with increasing material thickness or depth of hole and this trend is similar for all materials. This phenomenon can be controlled by varying the pulse duration, the pulse energy, the number of pulses or the design of the optical system. Taper is determined by [1, 7]:

$$\theta = \tan^{-1}\left(\frac{D_{\mathrm{ent}} - D_{\mathrm{ex}}}{t}\right) \tag{1}$$

where D_{ent} and D_{ex} are entry hole and exit hole diameters, respectively and t is thickness.

The geometrical characteristics of laser drilled holes can be best described in terms of their aspect ratio (the thickness – diameter ratio). The limitation of aspect ratio value for some material depends on optical characteristics of laser beam and the optical and thermal characteristics of material. It has been noted that there were some limitations while obtaining required depth if the diameter is enlarged.

The hole circularity determines regularity of hole circle. If the circularity is near one, the hole is more regular. The circularity [6] can be obtained by the following:

$$C_i = \frac{D_{\min}}{D_{\max}} \tag{2}$$

where $D_{\max}$ is the maximum diameter of the hole, and $D_{\min}$ is the minimum diameter of the hole.

The aerospace industry has been using laser drilling for producing high quantity of closely spaced holes [9]. However, laser drilled holes are associated with a number of defects [11], and spatter is one of them. It is ejected, molten or vaporised material, that is not completely expulsed but resolidified and adhered around the hole periphery. The formation of spatter is undesirable, especially in specific applications such as effusion cooling, whereby the flow and efficiency of the cooling air is dependent on the characteristics of the holes, and causes a modification to the original surface characteristics. Removal of the spatter through additional finishing process needs additional production time and costs [12]. Spatter, as well, may reduce consistency/repeatability of the process [13].

Spatter deposition can be reduced with the proper selection of laser drilling process parameters, but unfortunately, cannot be totally avoided.

Figures 1 and 2 show the variation entry-side hole and exit-side hole diameters, respectively, with pulse duration for various values of pulse frequency. Entry side hole diameters are assigned with D_{ent} and exit side with D_{ex}. Cost-effective laser drilled holes are up to 1,5 mm [1]. With increasing of pulse duration the diameters increase as well, while with increasing of pulse frequency the diameters decrease.

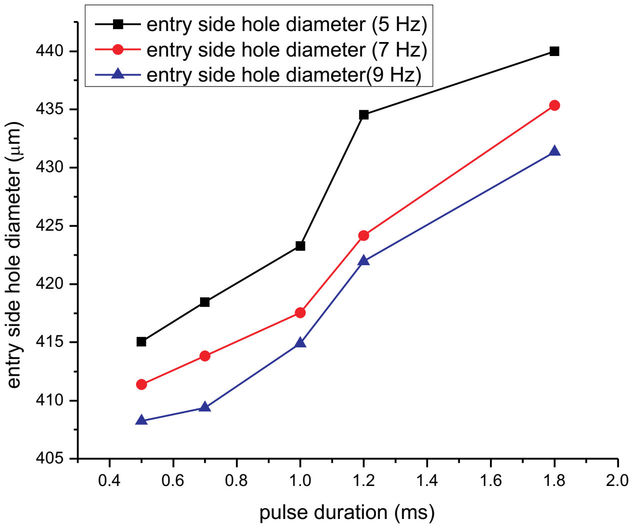

Figure1 *Entry side hole diameters versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheets*
Slika 1. *Promjeri ulazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

Figures 3 and 4 show taper and aspect ratio variation, respectively, with pulse duration for different pulse frequencies. Higher pulse frequencies result in smaller taper. According to the paper [1, 7], generally, shorter pulse duration results in higher taper. This statement is confirmed by our experiment. The best values of aspect ratio were obtained with pulse duration 0,5 ms, and after that values decrease. Also, higher pulse frequencies gave better aspect ratio.

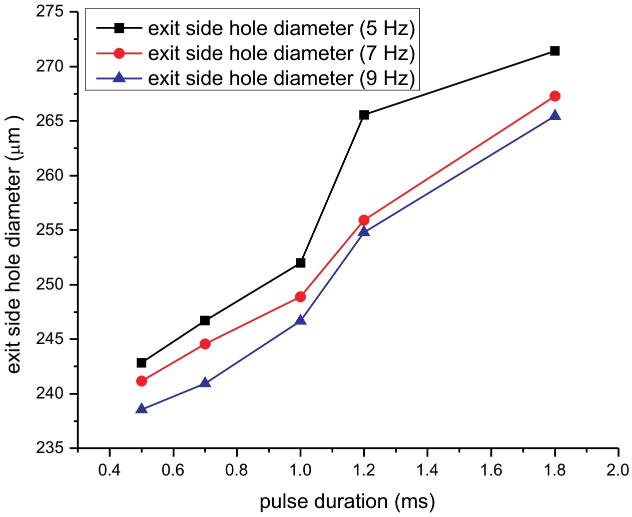

Figure 2 *Exit side hole diameters versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263*
Slika 2. *Promjeri izlazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

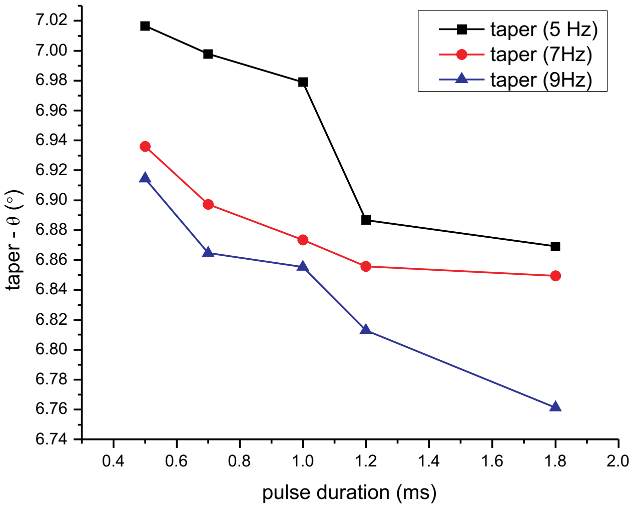

Figure 3 *Taper versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheets*
Slika 3. *Konus u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

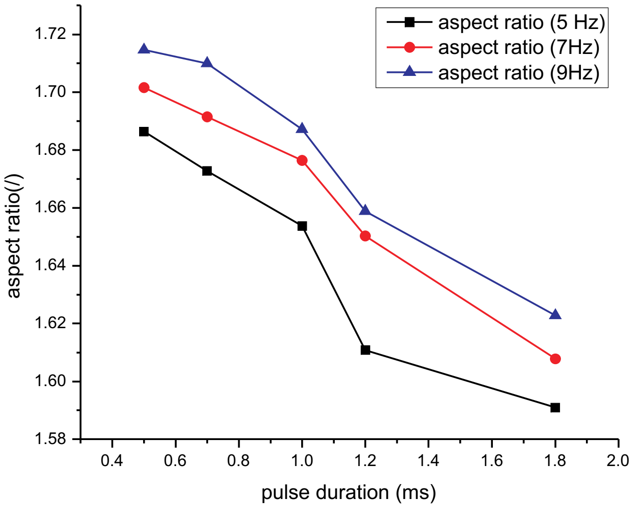

Figure 4 *Aspect ratio versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheets*
Slika 4. *Omjer slike u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

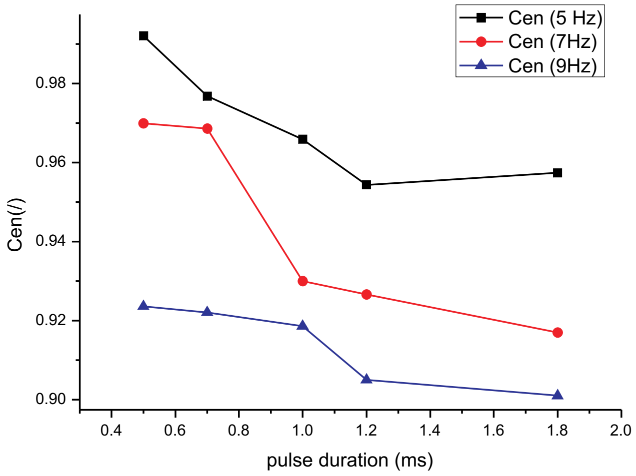

Figure 5 *Enter side hole circularity versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheets*
Slika 5. *Kružnost ulazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

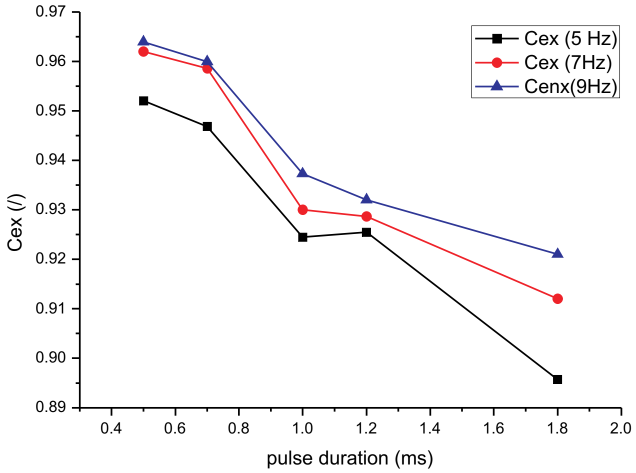

Figure 6 *Exit side hole circularity versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheets*
Slika 6. *Kružnost izlazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

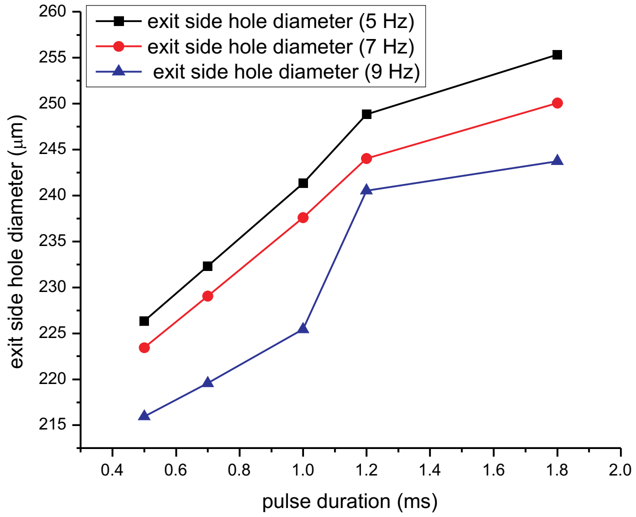

Figure 7 *Entry side hole diameters versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 7. *Promjeri ulazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

Figures 5 and 6 show values of enter and exit side hole circularity, respectively. C_{en} denotes enter side hole circularity and C_{ex} exit side hole circularity.

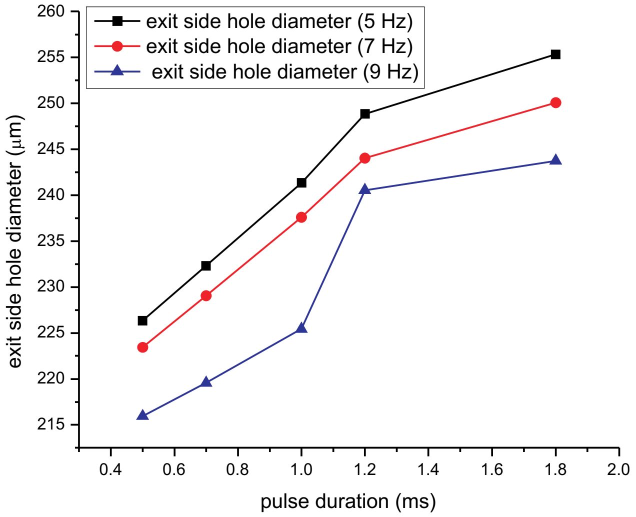

Figure 8 *Exit side hole diameters versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 8. *Promjeri izlazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

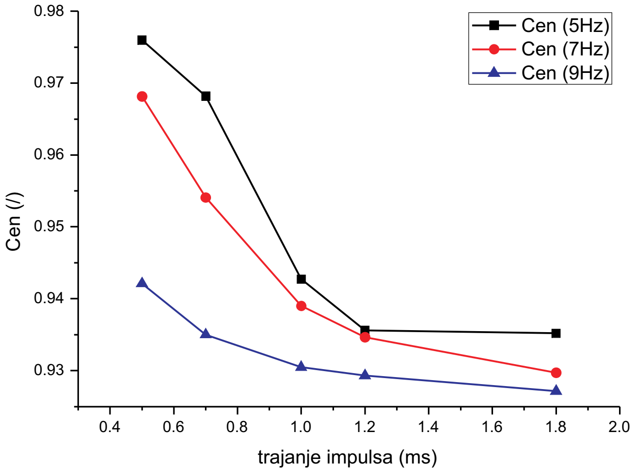

Figure 9 *Enter side hole circularity versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 9. *Kružnost ulazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

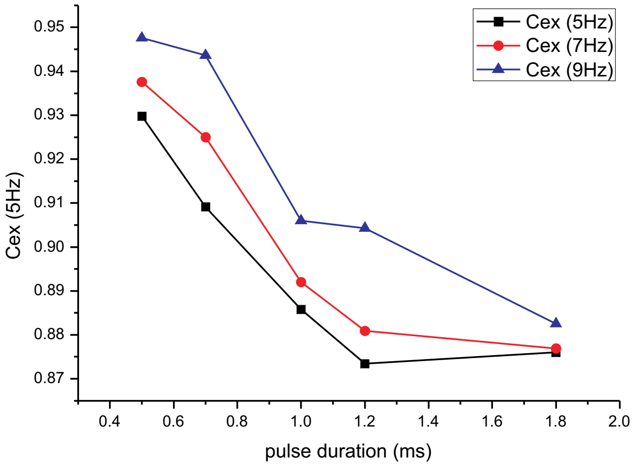

Figure 10 *Exit side hole circularity versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 10. *Kružnost izlazne strane rupe u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

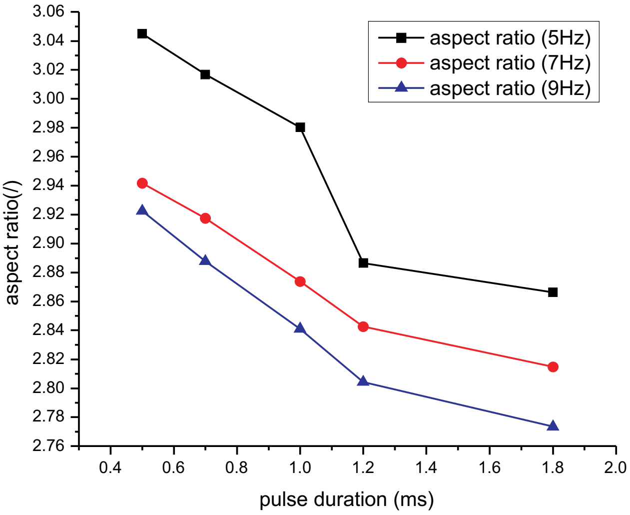

Figure 11 *Aspect ratio versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 11. *Omjer slike u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

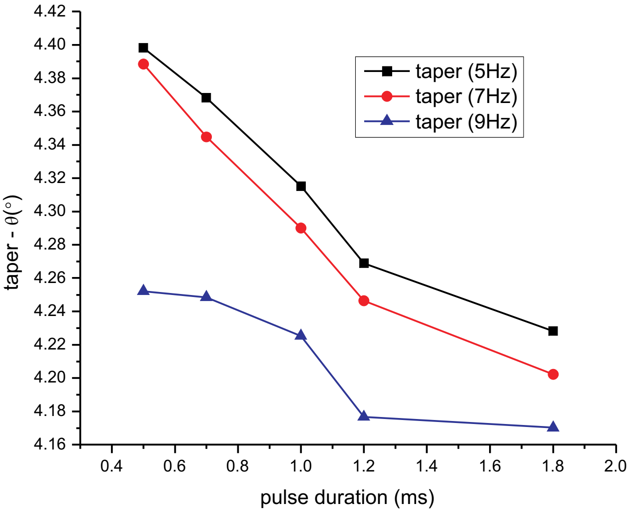

Figure 12 *Taper versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 12. *Konus u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

Plots indicate that longer pulse duration results in more regular hole circle for both, entry and exit side holes. The circularity of entry side holes is closer to one for drilling processes with lower pulse frequencies, while exit side hole circularity is better for higher ones.

Figures 7-12 show plots for geometrical characteristics of laser drilled holes in 1,2 mm thick Nimonic 263 sheets with laser average power of 128 W, pulse frequencies 5, 7 and 9 Hz and pulse durations of 0,5; 0,7; 1,0; 1,2 and 1,8 ms.

Enter and exit side diameters increase with pulse duration increasing, but decrease with pulse frequency increasing. The values of taper increase with pulse duration increasing and decrease with pulse frequency increasing. Tapers formed in laser drilled holes in 1,2 mm sheets are about 4–8,5 % higher than the ones formed in 0,7 mm nimonic 263 sheets. The aspect ratio is highest in holes drilled with 0,5 ms pulse duration, and then decreases. The values of aspect ratio in 1,2 mm sheets are about 71–78 % higher than in 0,7 mm sheets. Also, the aspect ratio decreases with pulse frequency increasing.

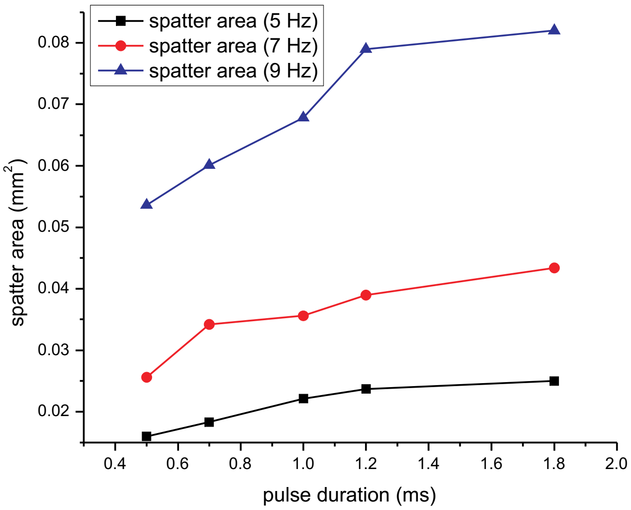

Figure 13 *Spattering area versus pulse duration for different pulse frequencies for 0,7 mm thickness Nimonic 263 sheet*
Slika 13. *Područje prskanja u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 0,7 mm*

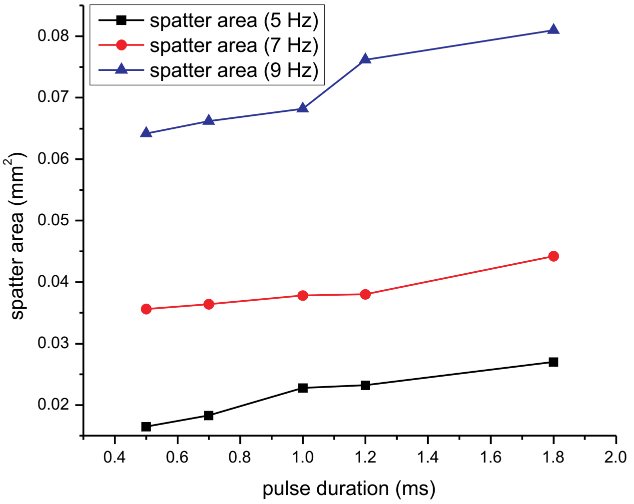

Figure 14 *Spattering area versus pulse duration for different pulse frequencies for 1,2 mm thickness Nimonic 263 sheet*
Slika 14. *Područje prskanja u odnosu na trajanje impulsa za različite frekvencije impulsa za limove superlegure Nimonic 263 debljine 1,2 mm*

Figures 13 and 14 show depending of spattering area on pulse duration for different pulse frequencies in 0,7 mm and 1,2 mm Nimonic 263 sheets, respectively. It is noticeable that spattering area increases with both pulse duration and pulse frequency. Also, it can be concluded that the pulse frequency variation affects spattering area much more than variation of pulse duration.

Table 3 shows the survey of laser drilled holes geometrical characteristics variation with increasing of pulse duration and pulse frequency. The optimal parameters can be obtained depending on requested hole characteristics. If the larger diameter and the smallest taper are wanted, the optimal should be high pulse frequency and longer pulse duration. However, higher pulse frequencies result in bigger spattering area and should be avoided. If the higher aspect ratio and circularity are requested, process parameters with lower pulse duration and lower pulse frequency should be used.

Figures 15 and 16 show the entry side and exit side hole respectively taken by optical microscope. The hole was drilled by following process parameters: the laser average power – 128 W, pulse duration – 0,7 ms and pulse frequency – 5 Hz. Geometrical characteristics were measured and calculated using AutoCAD 2009. All drilled holes were analysed in the same way.

Table 3 *Survey of laser drilled holes geometrical characteristics variation with increasing of pulse duration and pulse frequency*
Tablica 3. *Pregled promjena geometrijskih značajki laserom bušenih rupa s povećanjem trajanja impulsa i frekvencije impulsa*

	Pulse duration ↗	Pulse frequency ↗
Entry side hole diameter	↗	↘
Exit side hole diameter	↗	↘
Taper	↘	↘
Aspect ratio	↘	↗
Entry side hole circularity	↘	↘
Exit side hole circularity	↘	↗
Spattering area	↗	↗

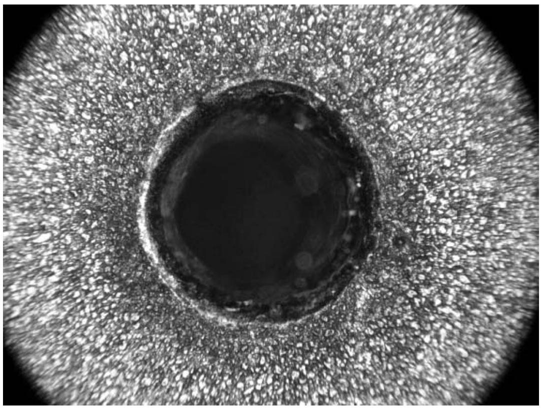

Figure 15 *The entry side hole taken by optical microscope. Magnitude 50*
Slika 15. *Ulazna strana rupe dobivena optičkim mikroskopom. Uvećanje 50*

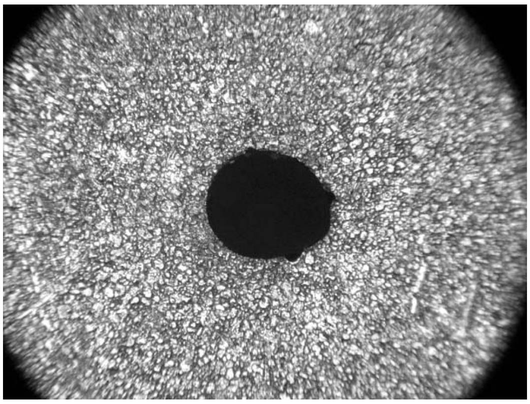

Figure16 *The exit side hole taken by optical microscope. Magnitude 50*
Slika 16. *Izlazna strana rupe dobivena optičkim mikroskopom. Uvećanje 50*

4
Conclusion
Zaključak

Based on research and analysed results presented in this paper the following can be concluded:

1. In laser drilled holes in 0,7 mm and 1,2 mm thickness Nimonic 263 sheets with increasing of pulse duration the entry-side and exit-side hole diameters become enlarged with increasing of pulse frequency;
2. In laser drilled holes in 0,7 mm and 1,2 mm thickness Nimonic 263 sheets with increasing of pulse duration and pulse frequency taper increases, while aspect ratio increases with pulse duration increasing and decreases if pulse frequency is reduced;
3. In laser drilled holes in 0,7 and 1,2 mm thickness Nimonic 263 sheets the aspect ratio reaches its highest

value with pulse duration of 0,7 ms, and reduces for higher pulse duration; with lower pulse frequency it has a higher value;

4. Taper is about 4–8 % lower in 1,2 mm thickness Nimonic 263 sheets than in 0,7 mm thickness sheets;
5. Aspect ratio is almost twice higher in 1,2 mm sheets than in 0,7 mm sheets;
6. Circularity of the entry-side hole diameters is closer to one, as compared to the circularity of exit side hole diameters in 0,7 and 1,2 mm thickness Nimonic 263 sheets;
7. Spattering area in laser drilled holes in 0,7 and 1,2 mm thickness sheets increases with pulse duration and pulse frequency; pulse frequency has greater effect on spattering area than pulse duration;
8. The optimal parameters depend on requested specification. However, high frequencies should be avoided as they provide significant bigger spattering area.

5
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Authors' address
Adrese autora

Sanja Petronić, mechanical engineer
Innovation Centre
Faculty of Mechanical Engineering
University of Belgrade
Kraljice Marije 16, Belgrade, Serbia

Professor Dr Anđelka Milosavljević, metallurgical engineer
Faculty of Mechanical Engineering
University of Belgrade
Kraljice Marije 16, Belgrade, Serbia

Docent Dr Zoran Radaković
Faculty of Mechanical Engineering
University of Belgrade
Kraljice Marije 16, Belgrade, Serbia

Predrag Drobnjak, mechanical engineer
Politechnical Academy
Belgrade, Serbia

Igor Grujić, electrical engineer
Simens d.o.o. Belgrade
Omladinskih brigade 21, Belgrade, Serbia