ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 621.7.01:621.375.826]:669.14.018.8

EXPERIMENTAL STUDY OF Nd:YAG LASER MACHINING OF Cr-Ni AUSTENITIC STAINLESS STEEL

Peter Šugár, Juraj Mikoláš, Jana Šugárová

Original scientific paper

Laser micromachining is a powerful process of creating new surfaces, structures, cavities and also complex electro-mechanical devices with very small dimensions by laser radiation. This process highly depends on choosing proper parameters and their settings. An experimental investigation of laser micromachining with low-power, diode-pumped Nd:YAG laser is presented in the paper. Material used in the experiment was austenitic, Cr-Ni stainless steel type X5CrNi18-10 (1 mm thin metal sheet). The experiment was planned by Taguchi method and the created cavities were evaluated by conventional optical and also confocal microscopy in order to state the surface roughness and the volume of removed material. It was demonstrated practically that low-power laser is able to remove material from workpiece, and it was confirmed that this process is crucially sensitive to input parameter settings.

Keywords: *laser, micromachining, stainless steel, Taguchi approach*

Pokusno istraživanje obrade Cr-Ni austenitskog nehrđajućeg čelika pomoću Nd:YAG lasera

Izvorni znanstveni članak

Mikroobrada laserom je moćan postupak za stvaranje novih površina, konstrukcija, šupljina te složenih elektro-mehaničkih uređaja vrlo malih dimenzija pomoću laserskog zračenja. Taj postupak uveliko ovisi o pravilnom izboru i podešavanju parametara. U radu se opisuje eksperimentalno istraživanje laserske mikroobrade pomoću Nd:YAG lasera male snage i pobuđivanog diodom. U eksperimentu se koristio austenitski, Cr-Ni nerđajući čelik tipa X5CrNi18-10 (1 mm tanak metalni lim). Eksperiment je planiran pomoću Taguchi metode, a stvorene šupljine procijenjene konvencionalnim optičkim i također konfokalnim mikroskopom da bi se ustanovila površinska hrapavost i volumen odstranjenog materijala. Praktički je pokazano da se laserom male snage može skidati materijal s obradnog komada te je potvrđeno da je podešavanje ulaznih parametara od bitne važnosti za ovaj postupak.

Ključne riječi: *laser, mikroobrada, nehrđajući čelik, Taguchi pristup*

1 Introduction

Laser beam machining (LBM) is one of the most widely used thermal energy based non-contact type advanced machining processes. Laser beam is used for melting and vaporizing the unwanted material from the parent material [1]. The processes, which cover machining of components with dimensions below 1 mm are named laser micromachining [2].

Laser micromachining specifically refers to drilling and cutting with intensive laser beam usually in the form of pulse trains with energy far exceeding the ablation threshold of the target material. Different types of lasers are used for micromachining applications. Mc-Geough presents [3] that CO_2, Nd:YAG and excimer lasers are mainly used for this purposes. Nd:YAG lasers were successfully applied for micromachining of ceramics, composites, glass, semiconductors and stainless steels [4], [5], [6].

With respect to micromachining of stainless steels, the primary market is implantable medical devices (aneurism clips, bone plates and screws, fixation devices etc.) and nonimplantable medical devices (dental and surgical instruments, etc.) manufacturing.

Stainless steels can be machined using a wide range of laser wavelenghts, and the laser and optical setup choice depends on the task being performed and the amount of post-laser processing required [7].

There are many studies about laser micromachining of stainless steel in which the results of investigation on how modification of input parameters can influence given outputs are presented. In some of them, the possibility of using laser radiation from various sources for many applications, such as creating periodic structures on stainless steel [8], formation of self-organizing structures [9], biocompatibility and wettability of stainless steel after laser irradiation [10] and also possibility of creating cavities on the surface with the aim of maximizing the volume of removed material, was studied [11].

2 Experiment

The experiment was accomplished in International Laser Centre in Bratislava on low-power Nd:YAG laser (type Valentino made by company AVANTEK) with maximal 8 W of optical power, wavelength of radiation 1064 nm, working in pulse mode. The experimental setup (shown in Fig.1) also consists of laser optics (1), assist gas nozzle (2), workpiece – austenitic stainless steel of type X5CrNi18-10 (3) and 2D moveable, numerically controlled worktable (4).

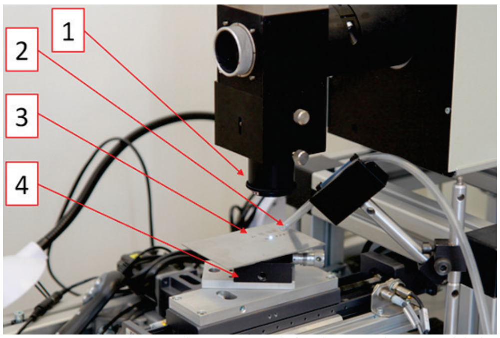

Figure 1 Experimental setup used for laser micromachining
1 – laser optics, 2 – gas nozzle, 3 – workpiece, 4 – *XY* positioning table

The experimental layout using the Taguchi $L_{27}(3^3)$ orthogonal array was used in this study. With this design not only all main effects of the factors are estimable, but also all important two-way interactions between the parameters.

The influence of the optical power, position of focal spot, interaction time of laser with material and type of assist gas have been studied.

Table 1 Parameters and their levels used in experiment

Parameter	Level		
	1	2	3
Optical power / W	5	6,5	8
Interaction time / s	0,05	0,1	0,15
Focal spot position / mm	–2	0	+2
Assist gas / –	Air	O_2	Ar

Twenty seven cavities (with square shape and 1,5 mm long sides) were created, respecting three different assist gases, by "raster" strategy of laser beam movement and combination of input parameters acquired by the application of the Taguchi method. Differences in interaction mechanisms were obvious during the laser micromachining process due to different optical and also acoustical phenomena presented.

3 Results and discussion

Although the target of experiment was to achieve minimum surface roughness Ra and maximum volume of removed material V, evaluation of experiment was getting complicated because of massive formation of oxides observed during micromachining process, thus confocal microscopy was hard to use for the surface roughness and the volume of removed material determination and only thirteen of twenty seven created cavities were evaluated. Measured values are given in Tab. 2.

Table 2 Surface roughness and volume of removed material

Experiment number	Ra / µm	V / mm^3
1	11,90	–82,5
2	7,74	59,6
7	1,07	–1,3
8	1,44	32,5
9	1,74	101,1
10	2,12	41,0
12	15,23	50,6
16	0,98	34,3
17	1,68	91,0
20	11,71	–27,9
21	4,44	189,1
25	1,61	52,4
27	9,86	118,3

It can be seen that in three cases the negative values of removed material were measured. It means that the volume of material below the surface sample was shy of the volume of material above that surface, probably because laser power did not reach the level in which the material could be removed and so it was only re-melted. The highest value of removed material (Fig. 2a) was reached with the combination of parameters set to their highest values, position of laser focal spot on the surface of sample and in oxygen. The lowest surface roughness was observed on cavity (Fig. 2b) made with 6,5 W of optical power. Interaction time was 0,05 s, focal spot was placed below the surface of sample and air was used as an assist gas.

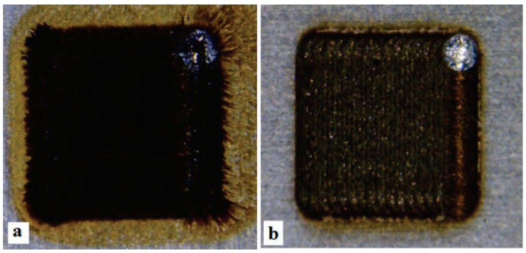

Figure 2 Cavity made by micromachining of austenitic stainless steel (50 × magnification) a – sample with highest measured volume of removed material, b – sample with minimum surface roughness 50 × magnifications

Measurement of cavity No. 21 by confocal microscope (Fig. 3) showed that material was removed up to 100 µm depth and solidified around borders of cavity up to 30 µm height. It is clear that in this case settings of input parameters led to conditions in which material could be removed up to relative high depth.

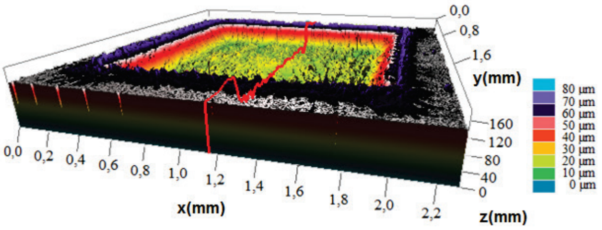

Figure 3 The result of scanning of cavity No. 21

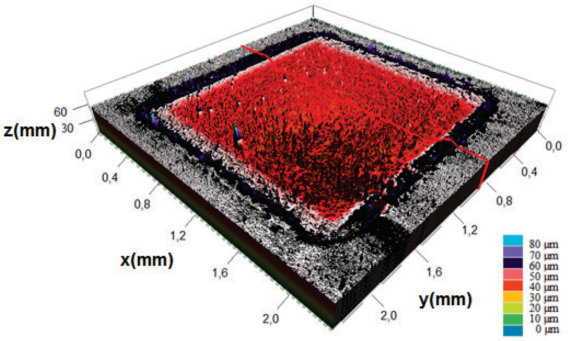

Figure 4 The surface morphology of cavity No.16

The morphology of the surface of cavity No. 16 is shown in Fig. 4. On some places, laser pulses removed material up to 15 µm and some volume of material was solidified around the borders of the cavity with maximum height about 5 microns.

The second highest value of removed material (about 33 percent lower than the highest one) was measured in cavity No. 27 (see Tab. 2). Input parameters were: 8 W (maximum) optical power, 0,15 s (the longest) interaction time, position of laser spot below the surface of the sample and air as an assist gas.

The third highest value of removed material was found in cavity No. 9. Medium, interaction time, position of laser spot were the same as in the previous case, but optical power was set to the minimum (5 W) and about 15 % lower value of removed material in comparison with the previous cavity was found.

As it was already said, minimum surface roughness was found in cavity No. 16, which was made by the combination of medium value of optical power and minimal interaction time. The next follows the roughness measured in cavity No. 7, which was made in the medium of argon, the lowest values of optical power and interaction time and in the position of the spot below the surface of the sample, but in this case, material was not removed. Results obtained in the cases when argon was used as an assist gas did not correspond with theoretical predictions. During the micromachining process in this medium, the formation of oxides was not eliminated in many cases, but it was eliminated successfully in two of them. Fig. 5 shows the cavity No. 7, whose surface is almost oxides-free.

The Taguchi method allows determining which input parameter influences given output the most together with the possibility to choose the settings of parameters for achieving the required output characteristics. Statistical methods led to the finding that in the case of volume maximization of removed material, the position of focal spot is the parameter that influences it the most significantly. Then follows medium, interaction time and, finally, optical power.

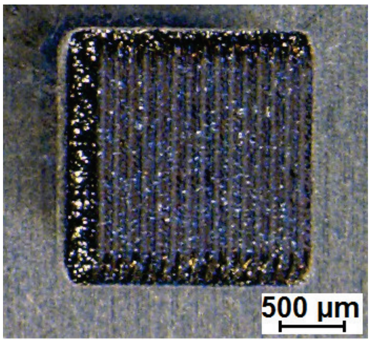

Figure 5 Oxides- free surface of cavity No. 7 (assist gas – argon)

Analogous method was used for the minimization of surface roughness. It was shown that in this case the medium is the parameter with the highest influence on the surface roughness. Subsequently follows the position of focal spot then the interaction time and the optical power.

4 Conclusion

The following conclusions have been drawn from this research:

- Both the process complexity of laser micromachining and its sensitivity to choosing proper input parameters and their settings were confirmed and demonstrated.
- It was shown that the experimental device used in this experiment (Nd:YAG low-power laser) is able to remove the material from the workpiece, but on the other hand, the parameters (and their values) used in the experiment: frequency, wavelength, optical power, etc. significantly limited the possibilities of maximizing the volume of removed material. For higher volumes, more powerful laser device should be applied.
- Differences in interaction mechanisms could be seen during the laser micromachining process, because of the optical and also acoustical phenomena taking part in the process.
- The presence was also confirmed of the theoretically predicted mechanism of material removal, in which more melting and less evaporating of material was observed.
- There was observed massive formation of oxides in most cases, which complicated the evaluation of cavities by confocal microscopy. Ultrasonic cleaner was also used, but with minimum success.
- The best surfaces, from the viewpoint of pureness, were achieved in the presence of argon, by which the elimination of oxides formation was gained, but there was also observed an exactly opposite process in the given medium. It can be presumed that a different direction of gas flow could lead to different results. In our experiment, side flow was used.
- The Taguchi method appeared to be an easy method for the planning and evaluation of experiment.

Acknowledgements

The authors would like to acknowledge the financial support from the Ministry of Education, Science, Research and Sport of the Slovak Republic, project VEGA 1/0254/11. Authors also want to thank Dr. Jaroslav Bruncko, from International Laser Centre in Bratislava, for his help in laser micromachining experiments.

5 References

[1] Wang, X.; Mak, G. Y.; Choi, H. W. Laser Micromachining and Micro-Patterning with a Nanosecond UV Laser, Micromachining Techniques for Fabrication of Micro and Nano Structures, Dr. Mojtaba Kahrizi (Ed.), ISBN: 978-953-307-906-6, InTech, 2012. Available from: http://www.intechopen.com

[2] Dubey, A. K.; Yadava, V. Laser beam machining – a review. // International Journal of Machine Tools and Manufacture. 48, 6(2008), pp. 609-628.

[3] Mc-Geough, J. A. Micromachining of engineering materials. Springer, New York, 2001.

[4] Kacar, E. et al. Characterization of the drilling alumina ceramic using Nd-YAG pulsed laser. // Journal of Materials Processing Technology. 209(2009), pp. 2008-2014.

[5] Krüger, J.; Kautek, W. Femtosecond pulse visible laser processing of fibre composite materials. // Applied Surface Science. 106, 9(1996), pp. 383-389.

[6] Meaden, G. Laser cutting of diamond fibres and diamond fibre/titanium metal matrix composites. // Diamond Related Materials. 5, 6-8(1996), pp. 825-828.

[7] Schaeffer, R. D. Fundamentals of laser micromachining. CRC Press, Taylor & Francis Group, USA, 2011.

[8] Trtica, M. et al. Surface modification of stainless steels by TEA CO_2 laser. // Applied Surface Science. 177, 1(2001), pp. 48-57.

[9] Byskov-Nielsen, J.; Balling, P. Laser structuring of metal surfaces, "Micro-mechanical interlocking". // Applied Surface Science. 255, 10(2009), pp. 5591-5594.

[10] Hao, L.; Lawrence, L.; Li, L. The wettability modification of bio-grade stainless steel in contact with simulated physiological liquids by the means of laser irradiation. // Applied Surface Science. 247, 1-4(2005), pp. 453-457.

[11] Dahotre, N.; Samant, A. Laser machining of advanced materials. CRC Press/Balkema, Taylor & Francis Group, London, 2011.

Authors' addresses

Peter Šugár, Prof. MSc. PhD.
Slovak University of Technology
Faculty of Material Science and Technology
Institute of Production Engineering,
J. Bottu 25, 917 24 Trnava, Slovakia
Tel. +421917367301
E-mail: peter.sugar@stuba.sk

Juraj Mikoláš, PhD. MSc.
Slovak University of Technology
Faculty of Material Science and Technology
Institute of Production Engineering
J. Bottu 25, 917 24 Trnava, Slovakia
Tel. +421917367301
E-mail: juraj.mikolas@stuba.sk

Jana Šugárová, PhD. MSc.
Slovak University of Technology
Faculty of Material Science and Technology
Institute of Production Engineering,
J. Bottu 25, 917 24 Trnava, Slovakia
Tel. +421917367301
E-mail: jana.sugarova@stuba.sk