Zpět

Laser beam machining of commercially pure titanium: influence of process parameters on surface roughness

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Laser machining is one of the most widely used advanced machining processes used for creating new surfaces, structures, cavities and also complex electro-mechanical devices, usually with very small dimensions, by laser radiation. Optimal selection of process parameters is highly critical for successful material removal and high machine surface quality. In the paper the relation between process parameters and machined surface quality characteristics is experimentally studied applying the five axis highly dynamic laser precision machining centre Lasertec 80 Shape equiped with the pulsed ytterbium fibre laser (wave lenght 1064 nm, maximal average output power 100 W) and CNC system Siemens 840 D and commercionally pure titanium (Grade 2) as working material. The influence of the pulse frequency and energy, laser scanning speed and step-size (spacing between adjacent passes) on the machined surface roughness is evaluated using Taguchi experimental design approach. The influence of process parameters on surface quality is investigated for two laser scanning strategies: hatching and cross-hatching. The significant influence of the step-size on the machined surface roughness was found.

Key words: laser, machining, titanium, surface roughness, Taguchi approach

1 Introduction

Laser beam machining of engineering materials has become a viable alternative to conventional methods of machining of difficult-to-machine materials with properties such as excellent strength, toughness, resistance to fatigue, resistance to corrosion and biological compatibility. These materials are widely used in aerospace, chemical, petrochemical, automotive and biomedical industries. It is very difficult to machine these types of materials by conventional methods of machining due to high tool wear rate and work-hardened layers generation on machined surface as a result of high strain loading [1]. Technology of laser machining also gives very important tool for development of rapidly growing micro-technology industry [2, 3].

When laser machining is performed the process of ablating a material takes place. The particular nature of the ablation process may be strongly dependent on the type of material and on laser intensity, wavelength, pulse duration and number of pulses. The absorbed energy from the laser pulse melts the material and heats it to a temperature at which the atoms gain sufficient energy to enter into a gaseous state. There is enough time for a thermal wave to propagate into the material. Evaporation occures from the liquid state of the material, but under certain conditions sublimation may occur, i.e. a direct transition between the solid phase and the gas phase. The molten material is partially ejected from the cavity by the vapour and plasma pressure, but a part of it remains near the surface. After the end of a pulse, the heat quickly dissipates into the machined material and a recast layer is formed. Thus, a compromise between high removal rates and the resulting surface integrity should be taken into account when selecting the most appropriate technological parameters of the process [4].

One of the most important consideration of the laser beam machining is complex quality of the machined surface, which generally includes surface roughness, residual stresses, micro-hardness, white layer formation, microstructure transformation and so on. Different surface quality and functional performance of machined product can be obtained mainly by varying laser pulses parameters and laser machining strategy. There are many studies which deal with how laser machining parameters affect the quality of machined surface of different materials [5], [6], [7], [8], [9]. Regarding to the laser machining of commercionaly pure titanium and titanium alloys the research work of Kong and Wang [1], Cicala et al [10], Quintana et al [11] and Cheng et al [12] should be mentioned.

Kong and Wang [1] evaluated the surface quality of ablated titanium alloys with a widely used 10-picosecond laser system with a wavelength of 1064 nm at a pulse frequency of 5 kHz. The attention was done on the study of the material removal mechanism, influence of process parameters on surface finishing of linear tracks and evaluation of the subsurface of laser-ablated pockets.

Cicala et al. [10] used for machining of titanium materials Nd:YAG pulsed laser. They investigated the influence of the pulse intensityand frequency, scanning speed, and line-spacing on the material removal rate and surface roughness. The results showed that the surface roughness of the machined surface depends mainly on pulse frequency and, secondarily, on scanning speed. The lowest levels of roughness were obtained with the highest frequencies and with low scanning speeds.

Quintana et al. [11] conducted experiments focused on study of surface quality and structure of titanium alloys in order to optimize the process to reach a good compromise between high ablation rates and good surface quality.

Cheng et al. [12] analyzed the effects of pulse overlap, repetition rate and number of overscan on micro-processing quality and efficiency of titanium alloys machining by femtosecond and picosecond laser application.

In order to provide insight into the relations between process parameters and surface quality of titanium materials the series of experiments were carried out. The influence of pulse frequency, pulse energy, scanning speed, step-size and laser beam movement strategy on the surface roughness was observed through statistical analysis.

2 Methods and materials

In this experimental investigation the laser machining of commercionally pure titanium (Grade 2) was conducted. The five axis highly dynamic laser precision machining centre Lasertec 80 Shape equiped with the pulsed ytterbium fibre laser (wave lenght 1064 nm, maximal average output power 100 W) and CNC system Siemens 840 D was used. The experimental setup used for laser machining is shown in the Fig. 1.

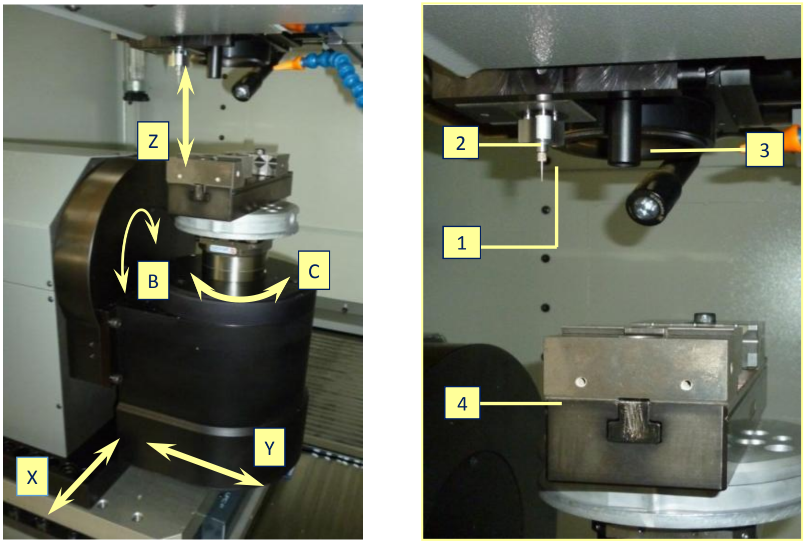

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Fig 1. Experimental setup used for laser machining
a – laser machine tool kinematics (X, Y, Z – translation motions, B, C – rotation motions)
b – main parts of workspace (1 – beam guidance with the highly dynamic scanner acts as an optical axis system, 2 – Z-level measuring probe, 3 – CCD camera for positioning and measuring, 4 – work piece)

Fig 1. Experimentálne pracovisko laserového obrábania
a – kinematické možnosti obrábacieho stroja (X, Y, Z – translačné pohyby, B, C – rotačné pohyby),
b – hlavné prvky experimantálneho zariadenia (1 – systém vedenia laserového zväzku s vysoko dnamickým skenerom, 2 – meracia sonda pre os Z, 3 – polohovacia a meracia CCD kamera, 4 – obrobok)

The influence of pulse frequency, pulse energy, laser beam scanning speed and step-size (spacing between adjacent passes) on the response –surface roughness of machined surface – has been studied. The experimental layout using the Taguchi $L_9(3^4)$ orthogonal array was used in this study (four factors at three levels each). The factors and their levels are listed as Table 1.

Tab. 1 Factors of the experiment and their levels
Tab. 1Experimentálne veličiny a ich úrovne

Experimental factor	Level		
	1	2	3
Pulse frequency (PF) (kHz)	40	60	80
Pulse energy (PE) (mJ)	0.53	0.8	1.06
Scanning speed (SS) ($m.s^{-1}$)	1	1.6	2.2
Step-size (SSz) (μm)	5	10	15

Nine cavities (with square shape and 5 mm long sides) were machined by two laser scanning strategies: hatching and cross hatching. The material was removed by layer-by-layer manner with total number of 40 layers. The shop-floor type surface roughness measuring instrument Surftest SJ-210 was used for evaluation of arithmetic mean deviation of the assessed profile Ra. The roughness parameter was obtained as the average of three measurements at different possitions of the machined surface in two different directions perpendicular to each other. The maximal value of roughness and the influence of each factor on surface finish was determined.

3 Results of experiment

The results of laser machined surfaces microgeometry characteristics for hatching strategy motion are listed in Tab. 2.

Tab. 2 Experimental plan with responses – hatching laser scanning strategy (Taguchi $L_9(3^4)$)
Tab. 2 Plán experimentu s nameranými hodnotami – stratégia pohybu: pozdĺžne rastrovanie (Taguchi $L_9(3^4)$)

Specimen number	Experimental factors				Responses			
	Pulse frequency (kHz)	Pulse energy (mJ)	Scanning speed ($m.s^{-1}$)	Step-size (µm)	Arithmetic mean deviation of the assessed profile Ra (µm)			
					$Ra_{.1}$	$Ra_{.2}$	$Ra_{.3}$	Ra
1	40	0.53	1.0	5	10.220	10.383	9.81	10.138
2	40	0.8	1.6	10	6.019	6.304	6.181	6.168
3	40	1.06	2.2	15	2.743	2.596	2.426	2.588
4	60	0.53	1.6	15	2.809	2.354	2.216	2.460
5	**60**	**0.8**	**2.2**	**5**	**10.606**	**10.682**	**11.092**	**10.793**
6	60	1.06	1.0	10	4.926	4.971	4.817	4.905
7	80	0.53	2.2	10	5.116	4.092	5.158	4.789
8	**80**	**0.8**	**1.0**	**15**	**2.294**	**2.571**	**2.262**	**2.376**
9	80	1.06	1.6	5	2.917	2.761	2.618	2.765

It may be seen that minimal surface roughness was reached with next combination of process parameters: maximal value of pulse frequency (80 kHz), midle value of pulse energy (0.8 mJ), minimal scanning speed (1.0 $m.s^{-1}$) and maximal step-size (15 µm). On the other hand maximal value of roughness was reached when next combination of process parameters was set-up: midle value of pulse frequency (60 kHz), midle value of pulse energy (0.8 mJ), maximal scanning speed (2.2 $m.s^{-1}$) and minimal step-size (5 µm).

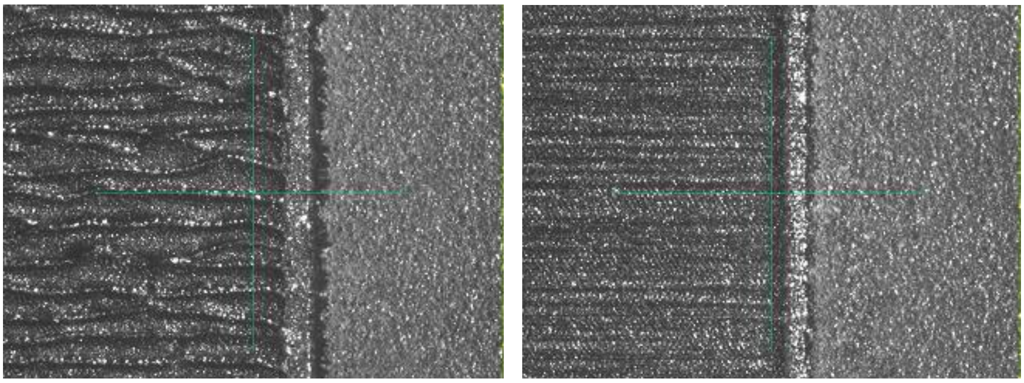

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Fig. 2 Surface machined by hatching laser scanning strategy (left side) vs. surface before laser machining (right side) (50 x magnification)
a – maximal surface roughness (Ra 10.793) (PF = 60 kHz; PE = 0.8 mJ; SS = 2.2 $m.s^{-1}$; SSz = 5 µm)
b – minimal surface roughness (Ra 2.376) (PF = 80 kHz; PE = 0.8 mJ; SS = 1.0 $m.s^{-1}$; SSz =15 µm)

Obr. 2 Povrch obrobený pozdĺžnym rastrovaním (ľavá strana) vs. povrch pred obrábaním (pravá strana)(zv. 50 x)
a – povrch s najväčšou drsnosťou (Ra 10.793) (PF = 60 kHz; PE = 0.8 mJ; SS = 2.2 $m.s^{-1}$; SSz = 5 µm)
b – povrch s najmenšou drsnosťou (Ra 2.376) (PF = 80 kHz; PE = 0.8 mJ; SS = 1.0 $m.s^{-1}$; SSz =15 µm)

Main effects plots of machined surface roughness versus investigated process parameters for hatching laser scanning strategy are shown in Fig. 3.

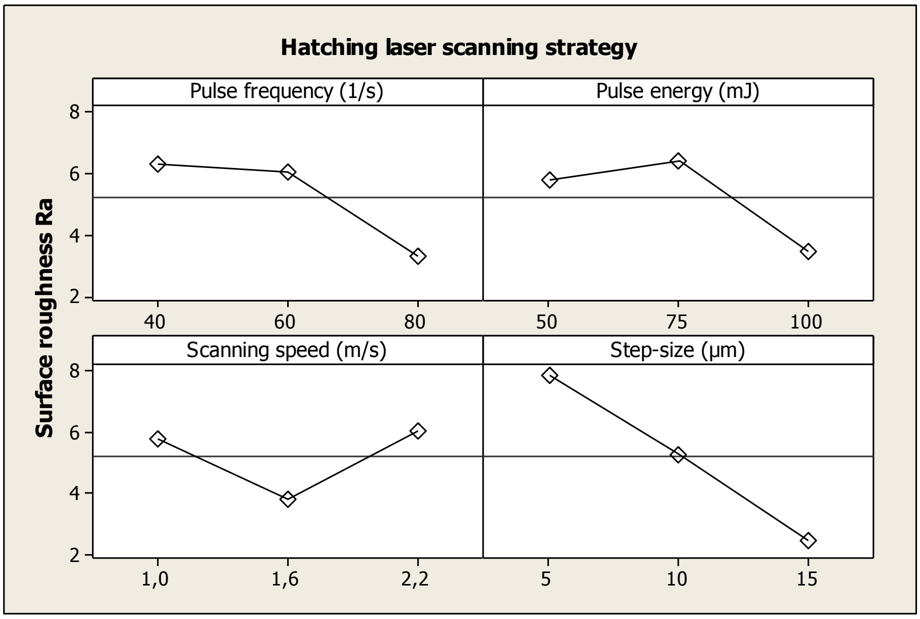


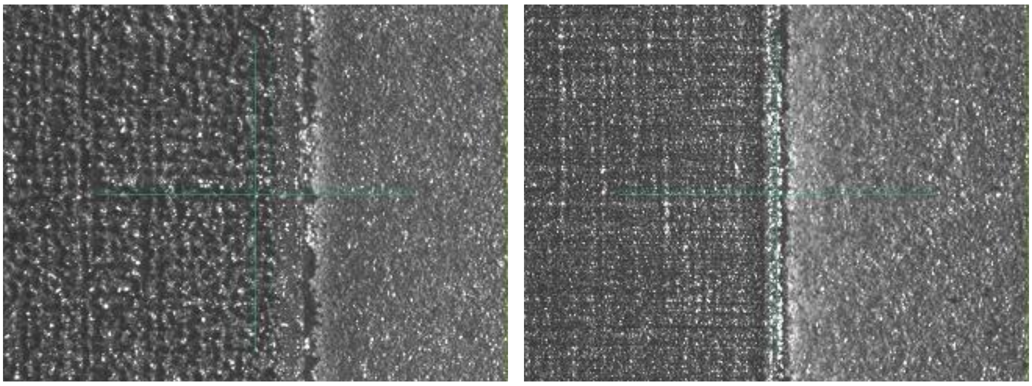
Fig. 3 Main effects plots of machined surface roughness versus process parameters
Obr. 3 Grafy vplyvu procesných parametrov na drsnosť obrobeného povrchu

The results of laser machined surfaces microgeometry characteristics for cross-hatching laser scanning strategy are listed in Tab. 3.

Tab. 3 Experimental plan with responses – cross-hatching laser scanning strategy (Taguchi $L_9(3^4)$)
Tab. 3 Plán experimentu s nameranými hodnotami – stratégia pohybu: pozdĺžne a priečne rastrovanie (Taguchi $L_9(3^4)$)

	Experimental factors				Responses			
Specimen number	Pulse frequency (kHz)	Pulse energy (mJ)	Scanning speed ($m.s^{-1}$)	Step-size (µm)	Arithmetic mean deviation of the assessed profile Ra (µm)			
					$Ra._1$	$Ra._2$	$Ra._3$	Ra
1	40	0.53	1.0	5	3.873	3.588	2.929	3.463
2	40	0.8	1.6	10	3.001	3.116	2.457	2.858
3	40	1.06	2.2	15	5.083	5.063	4.406	4.851
4	**60**	**0.53**	**1.6**	**15**	**1.731**	**1.551**	**1.653**	**1.645**
5	60	0.8	2.2	5	3.351	3.953	4.003	3.769
6	60	1.06	1.0	10	1.914	1.74	1.94	1.865
7	80	0.53	2.2	10	2.329	1.869	1.744	1.981
8	80	0.8	1.0	15	1.867	2.054	2.258	2.060
9	**80**	**1.06**	**1.6**	**5**	**8.569**	**7.955**	**7.124**	**7.883**

In the case of cross-hatching strategy motion the minimal surface roughness was reached with next combination of process parameters: midle value of pulse frequency (60 kHz), minimal value of pulse energy (0.53 mJ), midle scanning speed (1.6 $m.s^{-1}$) and maximal step-size (15 µm). Maximal value of roughness was reached when the combination of process parameters was set-up: maximal pulse frequency (80 kHz), maximal value of pulse energy (1.06 mJ), midle scanning speed (1.6 $m.s^{-1}$) and minimal step-size (5 µm).



a b

Fig. 4 Surface machined by cross-hatching laser scanning strategy (left side) vs. surface before laser machining (right side) (50 x magnification)
a – maximal surface roughness (Ra 7.883) (PF = 80 kHz; PE = 1.06 mJ; SS = 1.6 $m.s^{-1}$; SSz = 5 μm)
b – minimal surface roughness (Ra 1.645) (PF = 60 kHz; PE = 0.53 mJ; SS = 1.6 $m.s^{-1}$; SSz =15 μm)

Obr. 4 Povrch obrobený pozdĺžnym a priečnym rastrovaním (ľavá strana) vs. povrch pred obrábaním (pravá strana) (zv. 50x)
a – povrch s najväčšou drsnosťou (Ra 7.883) (PF = 80 kHz; PE = 1.06 mJ; SS = 1.6 $m.s^{-1}$; SSz = 5 μm)
b – povrch s najmenšou drsnosťou (Ra 1.645) (PF = 60 kHz; PE = 0.53 mJ; SS = 1.6 $m.s^{-1}$; SSz =15 μm)

Main effects plots of machined surface roughness versus investigated process parameters are shown in Fig. 5.

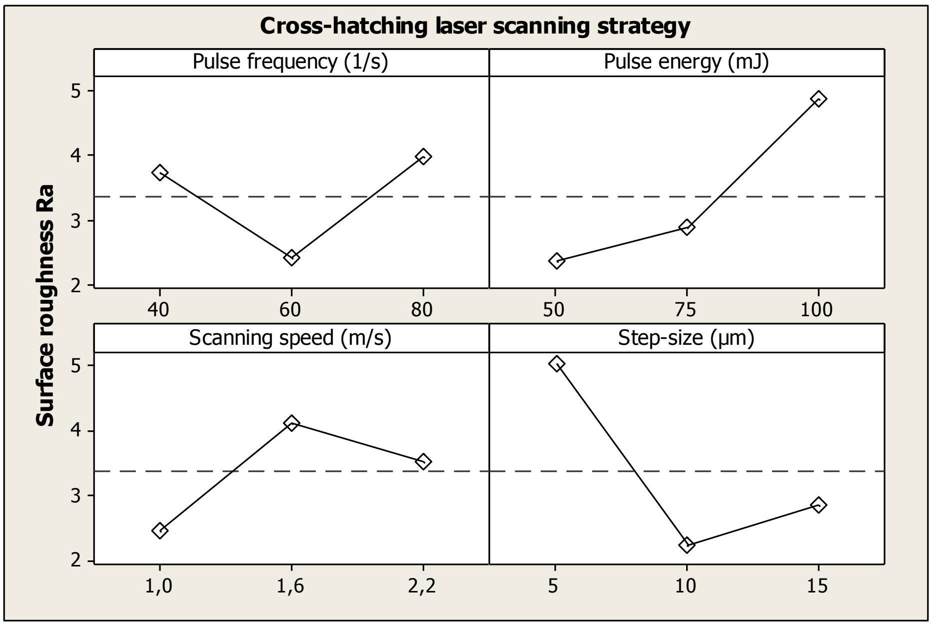


Fig. 5 Main effects plots of machined surface roughness versus process parameters
Obr. 5 Graf vplyvu procesných parametrov na drsnosť obrobeného povrchu

4 Conclusions

In the present study, four factors of laser machining process are considered from the surface finish point of view. Commercinally pure titanium (Grade 2) was used to laser machining (milling) and process parameters were experimented to obtain an optimum level in achieving minimal surface roughness for two different laser scanning strategies: hatching and cross-hatching.

The following trends and specific conclusions can be drawn:

- It was confirmed and demonstrated both process complexity of laser machining and also its sensitivity to choosing proper input parameters and their settings.

- Different surface topography has been identified on surfaces made by hatching and cross-hatching laser scanning strategies. Surface topography in the case of hatching scanning strategy consists of linear parallel grooves, in the case of cross-hatching strategy cavity-like structures are observed along the ablated surface.
- Process parameter with the highest influence on the machined surface roughness both in the case of hatching and cross-hatching scanning strategies is step-size. In the cases of minimal value of step-size the higher values of surface roughness have been achieved. The significance of the parameter influence is 52 % in the case of hatching strategy and 41 % in the case of cross-hathing strategy.
- Other evaluated process parameters show different influence on surface roughness for hatching and cross-hatching scanning strategy. For hatching scanning strategy the significance of the process parameters is in the next order: pulse frequency (19 %), pulse energy (18 %) and scanning speed (11 %). In the case of cross-hatching strategy the order of parameters significance is next: pulse energy (33 %), pulse frequency and scanning speed (both 13 %).
- The Taguchi method appeared to be easy method for planning and evaluation of experiment, but for obtaining results close to the optimum should be applied higher type of Taguchi orthogonal array L_{27} (3^4). This type of design makes use of four control factors with three levels each and the design has capability to check the interaction between the factors.

References

[1] KONG, M. C., WANG, J. (2014). Surface Quality Analysis of Titanium and Nickel-based Alloys Using Picosecond Laser. *Procedia CIRP* 13 (2014), pp. 417 – 422.

[2] QUINTANA, I. et al. (2008). Laser micro-milling and drilling using microsecond pulses. Applications for mould and aeronautical industry. In *Proc. of the 3rd International Conference of Manufacturing Engineering,* Chalkidiki, pp . 167 – 174.

[3] DUBLEY, A. K., YADAVA, V. (2008) Laser beam machining – a review. *International Journal of Machine Tools and Manufacture 48*, no. 6, pp. 609 – 628.

[4] LEITZ, K. H. et al. (2011). Metal Ablation with Short and Ultrashort Laser Pulses. In *Physics Procedia* 12, pp. 230–238.

[5] CIRUANA, J., ARIAS, G., OZEL, T. (2009). Neural network modeling and particle swarm optimization (PSO) of process parameters inpulsed laser micromachining of hardened AISIH13 steel.*Materials and Manufacturing Processes*, 24 (3, pp. 358–368.

[6] BARTOLO, P. et al. (2006). Laser micromachining for mould manufacturing: I. The influence of operating parameters. *Assembly Automation*, 26 (3), pp. 227–234.

[7] CAMPANELLI, S. L. et al. (2007). Experimental analysis of the laser milling process parameters. *Journal of Materials Processing Technology*, 191 (1–3), pp. 220–223.

[8] SEMALTIANOS, N. G. et al. (2010). Picosecond laser ablation of nickel-based superalloy C263. *Applied Physics A: Materials Science and Processing*, 98 (2), pp. 345–355.

[9] KALDOS, A. (2004). Laser machining in die making - a modern rapid tooling process. *Journal of Materials Processing Technology*, 155–156, pp.1815–1820.

[10] CICALA, E. et al. (2008) The application of the random balance method in laser machining of metals. Journal of Materials Processing Technology, 196, (1–3), pp. 393–401.

[11] QUINTANA, I. (2008). Laser micro-milling and drilling using microsecond pulses. Applications for mould and aeronautical industry. In *ICMEN 2008 3rd international conference of manufacturing engineering*, Chalkidiki, pp. 167–174.

[12] CHENG, J. (2009). Effects of laser operating parameters on metals micromachining with ultrafast lasers. Applied Surface Science 2009;256(5):1514–1520.

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Abstrakt

Článok: Laserové obrábanie komerčne čistého titanu: vplyv parametrov procesu na drsnosť obrobenej plochy

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Kľúčové slová: laser, obrábanie, titan, drsnosť povrchu, Taguchiho prístup

Laserové obrábanie je jednou z najrozšírenejších progresívnych metód obrábania, používanou na generovanie nových povrchov, zvyčajne malých rozmerov, aplikáciou laserového žiarenia. Optimálny výber procesných parametrov je rozhodujúcim prvkom, určujúcim priebeh úberu materiálu a kvalitu obrobenej plochy. Článok prináša výsledky experimentálneho výskumu vzťahu medzi vstupnými procesnými parametrami a kvalitou obrobenej plochy pri laserovom obrábaní komerčne čistého titanu (Grade 2), použitím 5-osového laserového obrábacieho centra Lasertec 80 Shape, vybaveného pulzným ytterbiovým vláknovým laserom (vlnová dĺžka 1064 nm, maximálny výstupný optický výkon 100 W). Experimentálne je sledovaný vplyv frekvencie a energie laserových pulzov, rýchlosti skenovacieho pohybu a vzájomnej polohy dráh laserového zväzku na drsnosť obrobej plochy, aplikovaním Taguchiho prístupu k plánovaniu a vyhodnoteniu experimentu. Vplyv jednotlivých procesných parametrov na drsnosť obrobeného povrchu je sledovaný pre dve rôzne stratégie laserového obrábania: pozdĺžne rastrovanie a kombináciu pozdĺžneho a priečneho rastrovania. Preukázaný je významný vplyv vzájomnej polohy dráh laserového zväzku na kvalitu obrobenej plochy.

Zpět