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Lasersko rezanje kovinskih materialov, ocenjevanje kakovosti reza in optimizacija procesa

Laser Cutting Metal Materials, Estimation of Cut Quality and Process Optimisation

JANEZ GRUM - DARJO ZULJAN

Uporaba in uspešen nadzor laserskega rezalnega procesa sta močno povezana s poznavanjem toplotnih pojavov na rezalni fronti in sprememb v okolici te fronte pri procesu laserskega rezanja. Pri laserskem rezanju s soosnim curkom oziroma rezalnega plina kisika, je energija na rezalni fronti kombinacija energije laserskega snopa in eksotermne energije. Uporaba kisika kot pomožnega plina pri procesu laserskega rezanja poveča uporabnost tega postopka. Procesi, ki se pojavljajo na rezalni fronti, z uporabo kisika postanejo zelo zapleteni. Namen prispevka je analizirati procese laserskega rezanja z vidika kakovosti laserskega reza s statistično analizo geometrijskih značilnosti reza, z izračunavanjem korelacijskih koeficientov med spremenljivkami reza pri različnih rezalnih hitrostih.

Ključne besede: rezanje lasersko, kovine, kakovost reza, optimiranje procesov

The application of laser cutting and the efficiency of laser system control are closely connected with knowledge of the cutting process and its effect upon the surface layer of a workpiece. In laser cutting processes with oxygen as an assistant gas, cutting energy is a combination of laser beam energy and the energy of the exothermic reactions occurring on the cutting front. The presence of oxygen in the process increases cutting efficiency, but it also causes additional physical processes on the cutting front which render a more detailed analysis of the cutting phenomena difficult. The aim of the paper is to analyse the laser cutting process by monitoring laser cut quality by means of measurements and statistical analysis of geometrical characteristics of the cut, by calculating correlation coefficients for various characteristics of the cut made at different cutting speeds.

Keywords: laser cutting, metal, cutting quality, process optimisation

0 UVOD

Laser se je kot obdelovalno orodje uveljavil tudi v proizvodnem strojništvu predvsem zaradi številnih tehnoloških prednosti. Glavna značilnost laserskih virov je, da imajo izjemno zgoščen snop laserske svetlobe, ki jo lahko priredimo različnim vrstam obdelovalnih procesov. Obdelovalnim zahtevam se lahko pri izbrani moči laserskega vira prilagodimo z izbiro različnih optičnih in kinematičnih razmer. Posebnost pri laserskem rezanju je, da poteka proces rezanja brez mehanskega dotika med obdelovancem in orodjem, to je laserskim snopom. V mnogih uporabah je zelo pomembna kakovost reza, ki jo lahko zagotovimo s primerno izbiro rezalnih razmer v odvisnosti od vrste in debeline materiala. Zato so uporabniki laserskih virov najprej postavljali vse ostrejše zahteve glede kakovosti laserskega vira, na drugi strani pa so začeli razvijati tudi zanesljivejše pozicionirne in pomično rotacijske enote. Proizvajalci

0 INTRODUCTION

Laser as a machining tool has become established in production mechanical engineering mainly all due to its numerous engineering advantages. The main characteristic of laser sources is that their laser light beam is highly concentrated and may be adapted to various machining operations. With the laser source power chosen, we may adapt to machining requirements by the selection of different optical and kinematic conditions. A peculiarity of laser cutting is that the cutting process does not involve any mechanical contact between the workpiece and the tool, i.e. laser beam. In many applications the cut quality is of particular importance. It may be ensured by the selection of appropriate cutting conditions depending on the kind and thickness of the material involved. Users of laser sources have, therefore, demanded higher and higher quality of laser sources on the one hand, while on the other hand more reliable positioners and laserskih virov oziroma celotnih sistemov se zavedajo, da so investicijske vrednosti izjemno visoke, zato morajo zagotoviti vrhunsko kakovost celotnega laserskega obdelovalnega sistema. Številne raziskave procesa laserskega rezanja so zato vključevale vplive spreminjajočega se vnosa energije zaradi časovnega odstopanja moči laserskega vira, kakor tudi vpliv natančnosti vodenja obdelovanca na kakovost reza oziroma natančnost izrezovanja. Nuss je s soavtorji [1] raziskoval kakovost reza in natančnost izreza različnih velikosti okroglih rondel iz različnih vrst jekel z laserjem CO_2 s konstantnim in pulznim delovanjem. Analiza odstopanja izreza in analiza kakovosti reza je zajemala tudi natančnost vodenja obdelovanca z numerično krmiljeno delovno mizo in vpliva različnih smeri polarizacije laserske svetlobe. Tönshoff in Samrau [2] ter Bedrin [3] so raziskovali kakovost laserskega reza z merjenjem različnih parametrov hrapavosti pri različnih močeh laserskega vira in pri različnih hitrostih pomikov obdelovanca. Isti avtorji so prav tako raziskovali kakovost reza pri različnih optičnih sistemih z različnimi žarišči leč. Thomssen in Olsen [4] pa sta raziskovala vplive različnih oblik iztopnih odprtin šob in vplive različnih pretočnih količin oziroma različnih tlakov rezalnega plina kisika na kakovost laserskega reza.

1 EKSPERIMENTALNI POSTOPEK

Eksperimentalno delo smo opravili na domačem laserskem obdelovalnem sistemu ISKRA-LMP 600 z močjo do 600 W in s hitrostjo pomika delovne mize z obdelovancem od 20 do 50 mm/s. Uporabljali smo laser CO_2 z Gaussovo porazdelitvijo intenzivnosti sevanja svetlobe v laserskem snopu zveznega delovanja. Pri laserskem rezanju smo soosno z laserskim snopom dovajali tudi rezalni plin kisik, ki omogoča razvoj eksotermnih reakcij.

Raziskave smo opravili na najpogosteje uporabljanem avstenitnem nerjavnem jeklu, legiranem s kromom in nikljem 18/10 z označbo po standardu ASTM A276-82A. Druga vrsta preizkušanega jekla je splošno nelegirano konstrukcijsko jeklo s pretežno feritno mikrostrukturo z označbo A620 po standardu ASTM.

V sklopu raziskave smo izbrali določene obdelovalne razmere kot konstantne parametre procesa (pregl. 1) in druge obdelovalne razmere, ki smo jih spreminjali pri procesu laserskega rezanja (pregl. 2).

rotary units are beeing developed. Producers of laser sources and complete systems are fully aware that the investment values involved are extremely high, therefore, top quality of the total laser machining system has to be guaranteed. Numerous studies of the laser cutting process have, in response, dealt with influences of the varying energy input due to deviation in laser source power in time, as well as the influence of the accuracy of workpiece guidance, i.e. cutting accuracy, on cut quality. Nuss et al. [1] studied the deviations in the size of round roundels in laser cutting different steels with a CO_2 laser in pulsating and/or continuous operation. The deviation was recorded with regard to the precision of NC-table control and the direction of light polarisation. Tönshoff and Samrau [2] and Bedrin [3] investigated the quality of the cut by measuring the roughness at varying laser source power and varying workpiece speeds. They also studied the quality of the cut while changing the optical system focus position with respect to the workpiece surface. Thomassen and Olsen [4] studied the effects produced on the quality of the cut by changing the nozzle shape and oxygen pressure.

1 EXPERIMENTAL PROCEDURES

Experimental testing was carried out on a laser machining system ISKRA-LMP 600 with a laser power of up to 600 W and with a positioning table speed from 20 to 50 mm/s. A CO_2 laser with Gaussian distribution of light-radiation intensity in the continuous laser beam was used. In laser cutting, cutting oxygen - which permits the development of exothermic reactions - was also supplied coaxially to the laser beam. In laser cutting, oxygen was supplied as auxiliary gas.

The investigations were carried out by applying a commonly used austenitic stainless steel alloyed with chromium and nickel 18/10, designated A276-82A according to ASTM standard. The second type of steel used was a common unalloyed structural steel A620 (according to ASTM standard) having a predominantly ferrite microstructure.

In order to study the processes in the cutting front and investigate the quality of cut, certain parameters were selected as process constants (Table 1) and other parameters as process variables (Table 2).

Preglednica 1. *Konstantni parametri laserskega rezalnega procesa s pomožnim plinom kisikom*
Table 1. *Constant machining conditions of the laser machining system with auxiliary oxygen gas*

OBDELOVALNI POGOJI MACHINING CONDITIONS	
moč laserja laser power	$P = 450$ W
goriščna razdalja leče focal distance of the lens	$f = 63{,}5$ mm
oddaljenost gorišča od površine obdelovanca focal point/workpiece distance	$g = 0{,}0$ mm
premer šobe nozzle diameter	$s = 2{,}0$ mm
tlak pomožnega plina kisika oxygen pressure	$p = 4{,}5$ bar
dimenzije ploščatega preizkušanca test pieces/plates dimensions	100 × 100 mm

Preglednica 2. *Spremenljivke obdelovalnih razmer*
Table 2. *Laser cutting process variables*

oznaka materiala obdelovanca po standardu ASTM material designation according to ASTM standard	debelina materiala material thickness D (mm)	rezalna hitrost cutting speed v (mm/s)
A276-82A	0,6 0,8 1,0 1,5	35 - 50 30 - 45 25 - 40 20 - 35
A620	2,0	30 - 45

2 EKSPERIMENTALNI REZULTATI

Za popis posamezne značilnosti kakovosti reza smo izdelali deset naključnih meritev. Izbrane geometrijske značilnosti so prikazane na sliki 1. Da bi lahko dovolj zanesljivo spremljali in ocenili kakovost reza pri različnih rezalnih hitrostih in pri rezanju različnih debelin materiala, smo na pripravljenih vzorcih opravili osemsto meritev geometrijskih značilnosti za oceno kakovosti reza.

Geometrijske značilnosti laserskega reza smo popisovali z: WD - spodnjo širino reza, WT - zgornjo širino reza, BH - višino srha, BW - širino srha, TM - debelino pretaljenega sloja in Ra - srednjo aritmetično hrapavostjo laserskega reza.

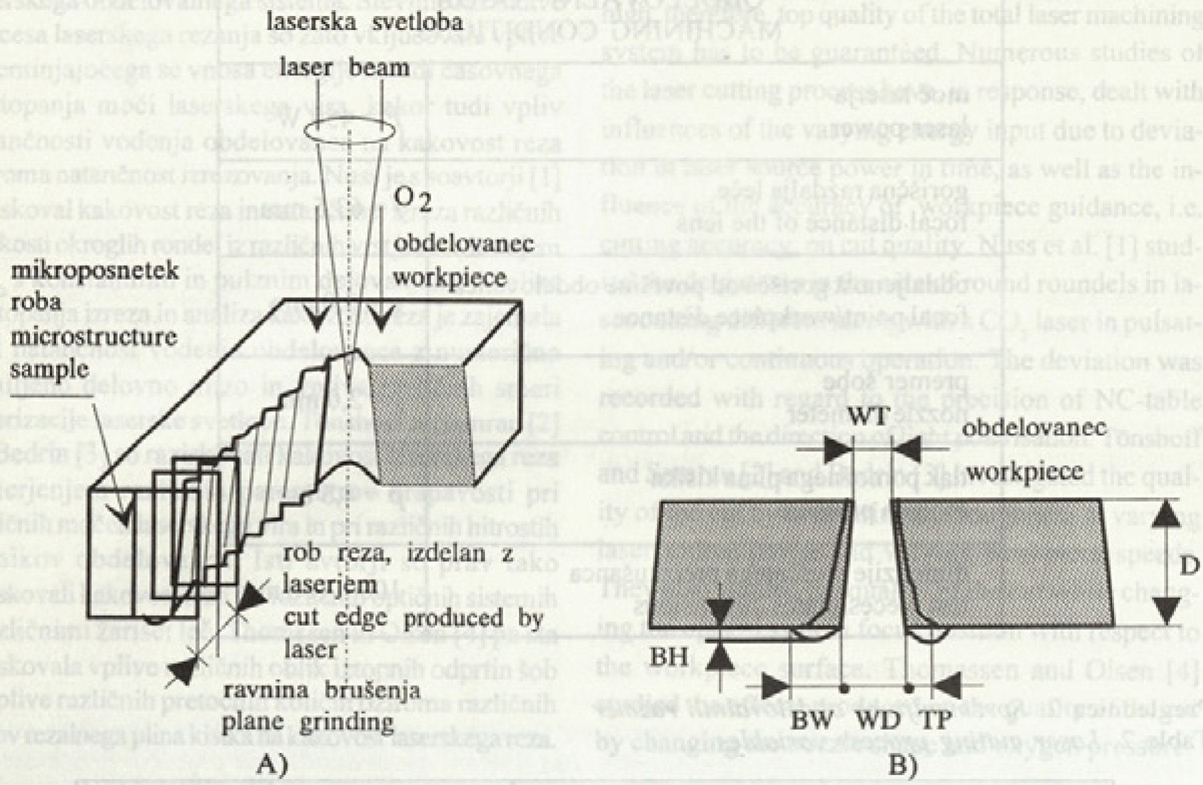
2 EXPERIMENTAL RESULTS

In order to describe the individual characteristics of cut quality, ten random measurements were made. Figure 1 shows the individual geometrical characteristics. Then, to accurately follow and assess cut quality with different cutting speeds and various material thicknesses cut, eight hundred measurements of macrogeometrical characteristics of cut quality were made on the test pieces prepared.

The characteristics relevant to the description of the cut quality are as follows: WT - upper width of cut, WD - bottom width of cut, TM - depth of the molten zone, BW - burr width, BH - burr height, and Ra - arithmetic value of cut roughness.

Posamezne geometrijske značilnosti reza smo statistično popisali s srednjimi vrednostmi in standardnimi odkloni.

The individual geometrical characteristics of the cut were statistically described by mean values and standard deviations.



Sl. 1. *Merilna mesta na rezu (A) in pregled geometrijskih značilnosti za popis kakovosti reza (B)*
Fig. 1. *Selection of measuring planes at the laser cut (A) and description of cut quality by geometrical characteristics (B)*

Na slikah 2 do 5 so v stolpičnem diagramu prikazane srednje vrednosti in standardni odkloni geometrijskih značilnosti za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo debeline 0,6, 0,8, 1,0 in 1,5 mm pri rezalnih hitrostih med 20 in 50 mm/s.

Na sliki 2 je prikazan stolpični diagram srednjih vrednosti in standardnih odklonov zgornje širine reza (WT) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo različnih debelin pri različnih rezalnih hitrostih. Iz podatkov v stolpičnem diagramu izhaja, da je srednja vrednost odklonov zgornje širine reza (WT) znatno večja pri nelegiranem jeklu in se giblje v mejah 0,28 do 0,29 mm.

Za avstenitno nerjavno jeklo velja, da se z večanjem debeline materiala obdelovanca zmanjšuje zgornja širina reza s pričakovanim korelacijskim koeficientom ($-0,08 < \rho < -0,422$ - preglednica 3). Pozicioniranje visoko energijskega laserskega snopa je zelo pomembno, vpliva na velikost posameznih geometrijskih značilnosti reza in še posebej na zgornjo širino reza (WT), kar so potrdili tudi številni preizkusi.

The bar charts in Figures 2 to 5 show mean values and standard deviations of the geometrical characteristics of the unalloyed steel with a thickness of 2 mm and the austenitic stainless steel with thicknesses of 0.6, 0.8, 1.0 and 1.5 mm at the cutting speeds ranging from 20 to 50 mm/s.

The bar chart in Figure 2 shows mean values and standard deviations of the upper width of cut (WT) for the 2 mm thick unalloyed steel and the austenitic stainless steel of various thicknesses at various cutting speeds. The data in the bar chart indicate that the mean value of deviations of the upper width of cut (WT) is much higher with the unalloyed steel and ranges from 0.28 to 0.29 mm.

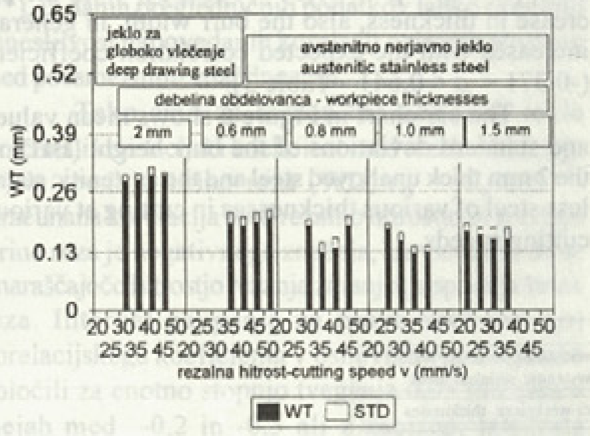
As far as the austenitic stainless steel is concerned it is true that by increasing the thickness of workpiece material the upper width of cut decreases the expected correlation coefficient ($-0.08 < \rho < -0.422$ - Table 3). Positioning of the high-energy laser beam is of extreme importance since it affects the size of the individual geometrical characteristics of the cut and particularly the upper width of cut (WT), which has been confirmed by numerous experiments.

Slika 3 prikazuje stolpični diagram srednjih vrednosti in standardnih odklonov spodnje širine reza (WD) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo različnih debelin pri različnih rezalnih hitrostih.

Na sliki 4 je prikazan stolpični diagram srednjih vrednosti in standardnih odklonov debeline pretaljenega sloja (TM) pri laserskem rezanju materiala z različnimi rezalnimi hitrostmi. Ugotovili smo, da med debelino pretaljenega sloja (TM) in debelino materiala (D) ni pomembnih korelacij (pregl. 3).

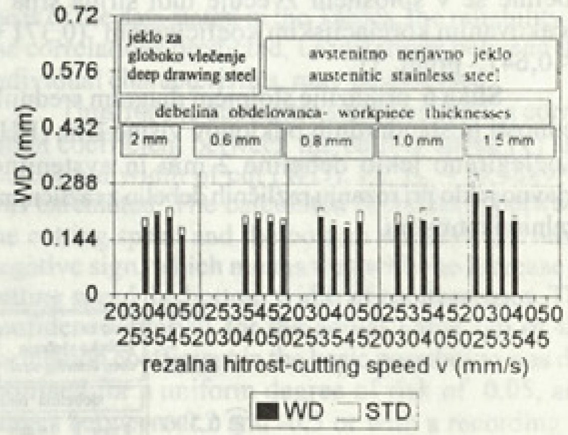
The bar chart in Figure 3 shows mean values and standard deviations of the lower width of cut (WD) for the 2 mm thick unalloyed steel and the austenitic stainless steel of various thicknesses at various cutting speeds.

The bar chart in Figure 4 shows the mean values and standard deviations of the depth of the molten zone (TM) in laser cutting of a material at various cutting speeds. It was found that there were no important correlations between the thickness of the depth of the molten zone (TM) and the material thickness (D) (Table 3).



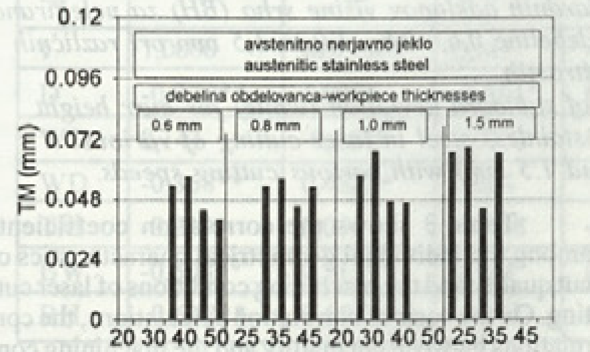
Sl. 2. *Stolpični diagram srednjih vrednosti in standardnih odklonov zgornje širine reza (WT) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo debeline 0,6, 0,8, 1,0 in 1,5 mm pri različnih rezalnih hitrostih*

Fig. 2. *Bar charts of mean values (black) and of standard deviation (white) for upper cut width WT for unalloyed stell and austenitic stainless steel in laser cutting of various workpieces thicknesses (0.6, 0.8, 1.0 and 1.5 mm) with various cutting speeds*



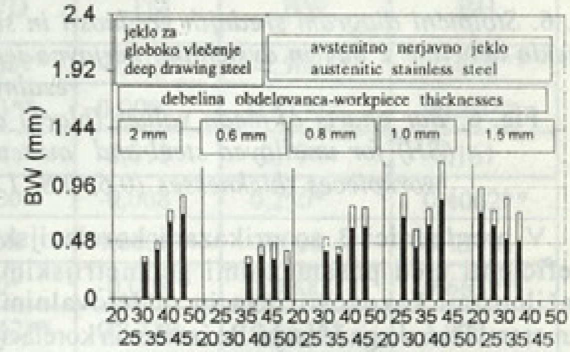
Sl. 3. *Stolpični diagram srednjih vrednosti in standardnih odklonov spodnje širine reza (WD) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo debeline 0,6, 0,8, 1,0 in 1,5 mm pri različnih rezalnih hitrostih*

Fig. 3. *Bar charts of mean values (black) and of standard deviation (white) for bottom width of cut WD for unalloyed stell and austenitic stainless steel in laser cutting of various workpieces thicknesses (0.6, 0.8, 1.0 and 1.5 mm) with various cutting speeds*



Sl. 4. *Stolpični diagram srednjih vrednosti debeline pretaljenega sloja (TM) pri rezanju avstenitno nerjavnega jekla debeline 0,6, 0,8, 1,0 in 1,5 mm pri različnih rezalnih hitrostih*

Fig. 4. *Bar charts of mean values (black) for depth molten zone TM for austenitic stainless steel in laser cutting of various workpieces thicknesses (0.6, 0.8, 1.0 and 1.5 mm) with various cutting speeds*



Sl. 5. *Stolpični diagram srednjih vrednosti in standardnih odklonov širine srha (BW) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo debeline 0,6, 0,8, 1,0 in 1,5 mm pri različnih rezalnih hitrostih*

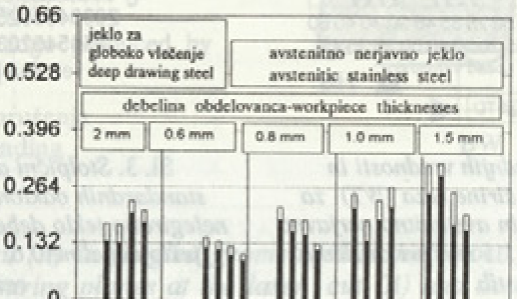
Fig. 5. *Bar charts of mean values (black) and of standard deviation (white) for burr width BW for unalloyed stell and austenitic stainless steel in laser cutting of various workpieces thicknesses (0.6, 0.8, 1.0 and 1.5 mm) with various cutting speeds*

Na sliki 5 je prikazan stolpični diagram srednjih vrednosti in standardnih odklonov širine srha (BW) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo različnih debelin pri različnih rezalnih hitrostih. Pri nelegiranem jeklu debeline 2 mm se z naraščanjem rezalne hitrosti povečuje širina srha od 0,28 mm do 0,7 mm. Standardni odklon širine srha se zvečuje z rezalno hitrostjo od 0,03 mm do 0,11 mm. Pri avstenitnem nerjavnem jeklu ugotavljamo, da se z naraščanjem rezalne hitrosti zmanjšuje širina srha na spodnjem delu reza s pričakovanim korelacijskim koeficientom ($-0,363 < \rho < -0,635$ - pregl. 3). Z večanjem debeline se v splošnem zvečuje tudi širina srha s pričakovanim korelacijskim koeficientom ($0,371 < \rho < 0,641$ - pregl. 3)

Slika 6 prikazuje stolpični diagram srednjih vrednosti in standardnih odklonov višine srha (BH) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo pri rezanju različnih debelin z različnimi rezalnimi hitrostmi.

The bar chart in Figure 5 shows mean values and standard deviations of the burr width (BW) on the 2 mm thick unalloyed steel and the austenitic stainless steel of various thicknesses at various cutting speeds. With the 2 mm thick unalloyed steel, the burr width increases from 0.28 mm to 0.7 mm with the increase in cutting speed. The standard deviation of the burr width increases from 0.03 mm to 0.11 mm with the increase in cutting speed. It was found for the austenitic stainless steel that with the increase in cutting speed, the burr width at the lower part of the cut decreased with the expected correlation coefficient ($-0.363 < \rho < -0.635$ - Table 3). With the increase in thickness, also the burr width, in general, increases with the expected correlation coefficient ($-0.371 < \rho < 0.641$ - Table 3).

The bar chart in Figure 6 shows mean values and standard deviations of the burr height (BH) on the 2 mm thick unalloyed steel and the austenitic stainless steel of various thicknesses in cutting at various cutting speeds.



Sl. 6. *Stolpični diagram srednjih vrednosti in standardnih odklonov višine srha (BH) za nelegirano jeklo debeline 2 mm in avstenitno nerjavno jeklo debeline 0,6, 0,8, 1,0 in 1,5 mm pri različnih rezalnih hitrostih*

Fig. 6. *Bar charts of mean values (black) and of standard deviation (white) for burr height (BH) for unalloyed steel and austenitic stainless steel in laser cutting of various workpieces thicknesses (0.6, 0.8, 1.0 and 1.5 mm) with various cutting speeds.*

V preglednici 3 so prikazani korelacijski koeficienti med posameznimi geometrijskimi značilnostmi kakovosti reza in obdelovalnimi razmerami laserskega rezanja. Po izračunih korelacij želimo ugotoviti povezave med kakovostjo reza in obdelovalnimi razmerami laserskega rezanja. Stopnja tveganja, s katero dajemo izjavo o izračunanih korelacijah, je lahko različna in jo lahko potrdimo s statističnim preizkusom (Ho: $\rho = 0$; H1: $\rho \neq 0$). Za naš primer smo upoštevali naslednje stopnje tveganja: 0,05, 0,01 in 0,001. Če je pri izračunanem korelacijskem koeficientu podan rezultat *z* stopnja tveganja 0,05 pomeni, da je tveganje v napovedi precejšnje. Rezultati korelacij s stopnjo tveganja 0,05

Table 3 shows the correlation coefficients among the individual geometrical characteristics of cut quality and the machining conditions of laser cutting. On the basis of correlation calculations, the correlations between cut quality and the machining conditions in laser cutting are to be established. The degree of risk involved in giving a statement on the calculated correlations may be different, but it can be confirmed by a statistical test (Ho: $\rho = 0$; H1: $\rho \neq 0$). In our case the following degrees of risk involved were taken into account: 0.05, 0.01 and 0.001. If for the calculated correlation coefficient the result is given with a degree of risk of 0.05, this means that the risk involved in predicting is rather high. The results of correlations with a degree of risk of 0.05 indicate povedo, da v povprečju lahko pričakujemo v enem od dvajsetih preizkusov nezanesljivo napoved za dano korelacijo. Bolj zanesljive so trditve pri rezultatih za izračunano stopnjo tveganja 0,01 ali 0,001. V preglednicah izračunanih korelacijskih koeficientov je podana tudi stopnja tveganja za izračunane korelacije med posameznimi značilnostmi in je v preglednici označena z zvezdico ali brez nje, in sicer: stopnja tveganja da trditev velja 0,05 je označeno z ( ), stopnja tveganja da trditev velja 0,01 je označeno z (*)in stopnja tveganja, da trditev velja 0,001 je označeno z (**). Iz danih pregledničnih podatkov lahko ocenimo zanesljivost napovedanih korelacij oziroma povezav med posameznimi značilnostmi.

Tako smo za avstenitno nerjavno jeklo izračunali korelacijski koeficient med rezalno hitrostjo (v) in spodnjo širino reza (WD) r_{xy} = -0,3689**. Izračunana korelacija med rezalno hitrostjo in spodnjo širino reza je negativnega značaja, kar pomeni, da se z naraščajočo hitrostjo rezanja zmanjšuje spodnja širina reza. Interval zaupanja za pravo vrednost (ρ) korelacijskega koeficienta v osnovni populaciji smo določili za enotno stopnjo tveganja 0,05 in znaša v mejah med -0,2 in -0,5 ali z zapisom intervala ($-0{,}2 < \rho < -0{,}5$).

that on the average it may be expected that in one out of twenty experiments the prediction for the correlation given will not be reliable. Statements are more reliable with the results of a calculated degree of risk of 0.01 or 0.001. In the tables containing the calculated correlation coefficients, the degree of risk involved with the calculated correlations between the individual characteristics is also stated. It is marked either with an asterix or without it - i.e. the degree of risk indicating that the statement is 0.05 true is marked by ( ), the degree of risk that the statement is 0.01 true is marked by (*), and the degree of risk that the statement is 0.001 true is marked by (**). On the basis of the data stated in the Tables, the reliability of the correlations predicted, i.e. relations between the individual characteristics, may be assessed.

Thus for the austenitic stainless steel, a correlation coefficient between the cutting speed (v) and the bottom width of cut (WD), i.e. r_{xy} = -0.3689**, was calculated. The calculated correlation between the cutting speed and the bottom width of cut has a negative sign, which means that with the increase in cutting speed the bottom width of cut decreases. The confidence interval for the actual value (ρ) of the correlation coefficient in the basic population was determined for a uniform degree of risk of 0.05, and ranges between -0.2 and -0.5 or with a recording of the interval ($-0.2 < \rho < -0.5$).

Preglednica 3. *Korelacijski koeficienti izračunani za različne pare spremenljivk*
Table 3. *Correlation coefficients calculated for various pairs of variables*

r_{xy}	V	D	WT	WD	TM	BW	BH
v	1,0000	-0,775**	0,143	-0,368**	-0,219*	-0,508**	-0,698**
D	-0,779**	1,0000	-0,264*	0,463**	0,099	0,517**	0,688**
WT	0,143	-0,264*	1,0000	0,084	-0,098	-0,194	-0,161
WD	-0,368**	0,463**	0,084	1,0000	-0,008	0,250*	0,4062**
TM	-0,219*	0,099	-0,098	-0,008	1,0000	-0,008	0,1779
BW	-0,508**	0,517**	0,194	0,250*	-0,008	1,0000	0,663**
BH	-0,698**	0,688**	-0,161	0,4062**	0,1779	0,663**	1,000

Na temelju izračunanih korelacijskih koeficientov med posameznimi spremenljivkami in za dani interval zaupanja za njihovo pravo vrednost korelacijskega koeficienta lahko ocenjujemo povezave med posameznimi značilnostmi in njihov vpliv na kakovost reza pri spreminjanju rezalnih razmer.

On the basis of the calculated correlation coefficients for the individual variables and for the confidence intervals specified for their actual value of the correlation coefficient, the correlations between the individual characteristics and their influence on cut quality, when cutting conditions are varied, may be assessed.

Preglednica 4. *Korelacijski koeficienti med različnimi pari spremenljivk ter intervali zaupanja za njihovo pravo vrednost korelacijskega koeficienta*
(r_{xy} - vzorčni korelacijski koeficient, ρ - korelacijski koeficient v osnovni populaciji)
Table 4. *Correlation coefficients calculated for various pairs of variables as well as the corresponding confidence intervals*
(r_{xy} - sample correlation coefficient, ρ - population correlation coefficient)

št. meritev vzorca number of samples	spremenljivke variables	vzorčni korelacijski koeficient sample correlation coefficient	interval zaupanja confidence interval
118	V - D	-0,7795**	$-0{,}696 < \rho < -0{,}843$
118	V - WD	-0,3689**	$-0{,}207 < \rho < -0{,}515$
118	V - BW	-0,5081**	$-0{,}363 < \rho < -0{,}635$
118	V - BH	-0,6986**	$-0{,}592 < \rho < -0{,}782$
118	D - WT	-0,2644**	$-0{,}08 < \rho < -0{,}422$
118	D - WD	0,4639**	$0{,}3 < \rho < 0{,}592$
118	D - BW	0,5170**	$0{,}371 < \rho < 0{,}641$
118	D - BH	0,6880**	$0{,}585 < \rho < 0{,}774$
118	WD - BH	0,4062**	$0{,}245 < \rho < 0{,}551$
118	BW - BH	0,6637**	$0{,}544 < \rho < 0{,}753$

Na sliki 7 je prikazana odvisnost med spremembami izmerjene temperature v rezalni fronti pri rezanju različnih debelin avstenitnega nerjavnega jekla z različnimi rezalnimi hitrostmi. Iz diagrama lahko na podlagi spreminjanja srednje izmerjene temperature v rezalni fronti določimo tako imenovane mejne rezalne hitrosti. Mejna rezalna hitrost je tista največja rezalna hitrost, ki še zagotavlja ustrezno kakovost reza. Po analizi signala temperature, izmerjene iz rezalne fronte pri rezanju različnih debelin materialov, lahko določimo srednje vrednosti signala temperature na rezalni fronti in izmed njih določimo signal z največjo srednjo vrednostjo in tako določimo tudi mejno rezalno hitrost. Rezalno hitrost, pri kateri smo za dano debelino materiala dosegli najvišjo srednjo vrednost signala temperature, smo poimenovali mejno rezalno hitrost.

Eksperimentalne rezultate o kakovosti reza lahko uvrstimo v dve skupini, in sicer:

- Pri debelini materiala 0,6 mm je dosežena najvišja vrednost signala temperature pri znatno večjih rezalnih hitrostih, od izbranih v naših raziskavah. Rezultati meritev torej potrjujejo, da bi morali za dano debelino materiala dopolniti analizo o kakovosti reza še pri večjih rezalnih hitrostih.

Figure 7 shows the magnitude of the mean values of signals IR-radiation (infra-red radiation) as a function of the cutting speed in cutting various thicknesses of austenitic stainless steel. From the diagram and on the basis of changes of the mean calculated signal IR-radiation at the cutting front, the so-called critical cutting speeds may be established. The critical cutting speed is the highest cutting speed which still ensures an adequate cut quality. On the basis of the signal IR-radiation emitted from the cutting front in the cutting of materials with various thicknesses, mean values of the signal IR-radiation from the cutting front may be established. A signal with the maximum the mean value is selected from them; thus the critical cutting speed may be determined. The cutting speed at which the highest mean value of the signal IR-radiation for the material thickness specified was attained is called the critical cutting speed.

Experimental results on cut quality may be grouped as follows:

- With a material thickness of 0.6 mm, the highest value of the signal IR-radiation was obtained at cutting speeds much higher than those selected for our studies. The results of measurements thus confirm that for the specified material thickness the analysis of cut quality should be complemented by higher cutting speeds.

- Pri preostalih debelinah materiala lahko ugotovimo, da so srednje vrednosti signala temperature pri manjših hitrostih rezanja skoraj konstantne in se nato znižajo pri večjih rezalnih hitrostih. Iz analize signala temperature ugotavljamo, da za debelino materiala 0,8 mm dobimo mejno hitrost rezanja 40 mm/s, za debelino materiala 1,0 mm je pri 35 mm/s, za debelino 1,5 mm pa pri 30 mm/s.

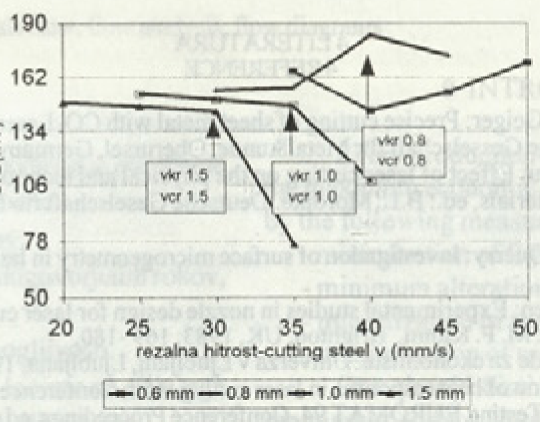
Razvili smo kriterij za določevanje mejne rezalne hitrosti laserskega rezanja, ki pomeni tudi optimalno rezalno hitrost, določeno na podlagi signala temperature. Dokazali smo, da lahko uspešno določimo rezalno hitrost z merjenjem signala temperature in določevanjem njene srednje vrednosti. Dobljeni rezultati o optimalnih laserskih rezalnih razmerah so bili potrjeni tudi s statistično analizo in dodatno primerjavo z vizualno oceno kakovosti reza.

S statistično obdelavo podatkov o geometrijskih značilnosti reza glede na spremenljivke obdelovalnih razmer in spremenljivke laserskega procesa rezanja, smo ugotovili, da lahko s spreminjanjem rezalne hitrosti odločilno vplivamo na kakovost reza.

- With other material thicknesses it may be found that the mean values of the signal IR-radiation at lower cutting speeds are almost constant, and then decrease with the increase in cutting speed. On the basis of the analysis of the signal IR-radiation it is found that for a material thickness of 0.8 mm a critical cutting speed of 40 mm/s is obtained, for a material thickness of 1.0 mm that of 35 mm/s, and for a material thickness of 1.5 mm that of 30 mm/s.

A criterion for determination of the critical cutting speed in laser cutting was developed. It also represents the optimum cutting speed determined on the basis of the signal IR-radiation. It was proved that a cutting speed may successfully be determined by measuring the signal IR-radiation and determining its mean value. The results obtained with the optimum laser cutting conditions were confirmed also by the statistical analysis and by an additional comparison with the visually assessed cut quality.

By means of the statistical processing of the data on the geometrical characteristics of the cut with regard to the variables of the machining conditions and the variables of the laser cutting process, it was found that changes in cutting speed may essentially affect cut quality.



Sl. 7. *Določevanje mejnih rezalnih hitrosti laserskega rezanja pri različnih debelinah pločevine avstenitnega nerjavnega jekla*

Fig. 7. *Determination of critical cutting speed in laser cutting of austenitic stainless steel of various thicknesses*

Postopek določevanja mejne rezalne hitrosti je naslednji:

1. Izberemo določeno rezalno hitrost in izmerimo signal temperature z zbiranjem infrardečega sevanja iz rezalne fronte ter določimo njegovo srednjo vrednost.
2. Nato postopek ponavljamo z zveznim ali koračnim spreminjanjem rezalne hitrosti.
3. Pri naglem zmanjšanju srednje vrednosti signala temperature je dosežena mejna rezalna hitrost, ki je po naših merilih mejna oziroma optimalna rezalna hitrost.

Predlagani postopek omogoča določevanje mejne rezalne hitrosti med samim procesom laserskega rezanja, kar lahko uporabljamo za krmiljenje procesa. Postopek je zelo preprost in

The procedure for determining the critical cutting speed is as follows:

1. A specified cutting speed is selected, the signal is measured by means of IR-radiation intensity at the cutting front, and its mean value is determined.
2. The procedure is repeated by continuous or stepwise changing of cutting speeds.
3. On a rapid decrease of the mean value of the signal IR-radiation, the critical cutting speed is achieved which, in accordance with our criteria, represents the optimum cutting speed.

The proposed procedure allows for the determination of the critical cutting speed during the cutting process itself, which can be utilized for controlling the process. The procedure is both practical and simple. By changing the laser source power and/or praktičen saj pri spreminjanju moči laserskega vira, optičnih razmer in/ali kinematičnih razmer, lahko določamo optimalne pogoje laserskega rezanja za posamezne vrste in debeline materialov.

3 SKLEPI

Na podlagi rezultatov opravljene raziskave o kakovosti laserskega reza lahko ugotovimo, da je za doseganje kakovostnega laserskega reza možno uspešno krmiljenje procesa na temelju srednje vrednosti signala temperature, ki ga dobimo z zajemanjem infrardečega sevanja iz rezalne fronte. To lahko dosežemo s kratkotrajnimi preizkusi, ki omogočajo za dano vrsto materiala in dano debelino materiala določevanje mejne oziroma optimalne rezalne hitrosti.

Raziskave so potrdile, da izbrane rezalne hitrosti pri laserskem rezanju ne smejo preseči mejnih vrednosti, če želimo zagotoviti želeno kakovost reza. Mejna rezalna hitrost je torej hkrati tudi optimalna rezalna hitrost, saj je poleg zagotovljene kakovosti reza dosežen tudi optimalen vnos energije laserskega snopa. Zato predlagamo uporabo srednje vrednosti signala temperature za optimiranje procesa laserskega rezanja, pri sočasnem zagotavljanju kakovosti reza.

optical and kinematic conditions it is possible to determine the optimum laser cutting conditions. The same optimization procedure of the laser cutting process may also be used for other related materials.

3 CONCLUSIONS

On the basis of the results of the investigation conducted on laser-cut quality it may be concluded that, in order to achieve a quality laser-cut, efficient process control is possible by means of the mean value of the signal IR-radiation obtained by capturing IR radiation from the cutting front. This may be achieved by experiments of short duration which permit, for a specified kind of material and material thickness, which determination of the critical, i.e. optimum, cutting speed.

The investigations confirmed that the cutting speeds selected in laser cutting should not exceed the critical values if the cut quality required is to be ensured. The critical cutting speed is at the same time the optimum cutting speed since not only the cut quality required is obtained but also an optimum energy input of the laser beam. Therefore, it is proposed that the mean value of the signal IR-radiation may be used for optimisation of the laser cutting process with simultaneous assurance of cut quality.

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