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Analiza laserskega rezanja hladno valjane pločevine za zahteven globoki vlek

Analysis of Laser Cutting of Cold-Rolled Plate for Demanding Deep Draw

Janez Grum - Darjo Zuljan

Iz opravljenih raziskav o makro- in mikrostrukturnem stanju površine in podpovršja reza lahko potrdimo, da z merjenjem oziroma določevanjem različnih parametrov hrapavosti lahko zelo uspešno optimiramo proces laserskega rezanja. Pri različnih vnosih energije in različnih načinih delovanja laserskega snopa smo ugotovili, da ima največji vpliv na kakovost reza izbrana moč snopa in nato hitrost rezanja, ki določata vnos energije v rezalno fronto. Dosedanji rezultati raziskav in izkušnje pri ocenjevanju kakovosti laserskega reza potrjujejo, da je določevanje spodnje in zgornje kritične rezalne hitrosti primerno za določevanje optimalnih parametrov laserskega rezanja. Zaradi slabe krožne polarizacije je kakovost reza odvisna od smeri rezanja.

(Ključne besede: rezanje lasersko, hrapavost površin, makroanalize, mikrotrdota)

Studies conducted on the condition of a surface macrostructure and microstructure and the subsurface of a cut, confirm that by measuring various roughness parameters the laser cutting process can be optimized very successfully. Different energy inputs and various modes of laser beam operation allowed us to ascertain that the major influences on cut quality were exerted by beam power and cutting speed, which determine the amount of energy transferred to the cutting front. The results of our studies conducted so far, and the experience gained in assessment of the laser cut quality, confirm that knowledge of the lower and the upper cutting speeds is necessary to determination the optimum parameters for laser cutting. A result of poor circular polarization is that the cut quality depends on the cutting direction.

(Keywords: laser cutting, surface roughness, macroanalysis, microhardness)

0 UVOD

Avtomobilska industrija je znana kot vodilna industrija pri razvoju raziskovalne dejavnosti in prav tako so znane številne uporabe laserske tehnologije. Po ocenah v strokovni literaturi lahko ugotovimo, da je dandanes v avtomobilski industriji več ko 15 odstotkov od celotnega števila laserskih virov. V zadnjem obdobju je zelo pomembna integracija laserskega obdelovalnega sistema v obdelovalno oziroma izdelovalno celico, v kateri poteka izdelava določenega dela od surovca do končnega izdelka. Podatki o uporabnosti laserskih obdelovalnih sistemov v avtomobilski industriji govorijo o številnih uporabah rezanja in varjenja pločevinskih delov v celoto.V ta namen so razviti računalniško podprti sistemi za pozicioniranje posameznih pločevinskih delov za kasnejše varjenje v celoto oziroma pločevinsko konstrukcijo. Takšen postopek je znatno hitrejši, cenejši in omogoča boljši nadzor kakovosti izdelanih pločevinskih sestavin po

0 INTRODUCTION

The automobile industry is known to have a leading role in the development of research activities and numerous laser applications. The professional literature indicates that more than 15% of all laser sources are located in the automobile industry. Recently, the integration of laser machining systems into production cells, in which the manufacture of a certain part from a blank, has become very important. Data on the applicability of laser machining systems in the automobile industry show numerous applications of cutting and welding of sheet components. To this end, computer-aided systems for positioning of individual sheet components for subsequent welding into a whole and a sheet structure have been developed. Such an approach is considerably faster and more cost-effective, and permits better quality control of manufactured sheet components after laser cutting, as well as a better quality of sheet structure after laser cutting. Sheet components in the automolaserskem rezanju, kakor tudi boljšo kakovost pločevinske konstrukcije po laserskem varjenju. Pločevinski deli v avtomobilski industriji so izrezani, kar pomeni, da so poprej oblikovani z različno globokimi in zahtevnimi vleki pločevine z različnimi dodatnimi oblikami, ki jih dosežemo s prebijanjem ali izrezovanjem. Zaradi zagotavljanja čim manjših deformacij pločevinskih delov po izrezu se dandanes uspešno kombinirajo preoblikovalne tehnologije z lasersko tehnologijo. Osnovni cilj takšnega povezovanja obeh tehnologij je olajšati kasnejše sestavljanje posameznih pločevinskih sestavin, ki se varijo v celoto. Tudi pri varjenju moramo izbirati takšne postopke, ki zagotavljajo čim manjšo stopnjo deformacije pločevinske konstrukcije. Naloga konstrukterjev in tehnologov je, da se oblikovanje pločevinskih konstrukcij podredi izdelovalnim tehnologijam z namenom skrajšati čase in povečati zanesljivost pozicioniranja posameznih pločevinskih sestavin ter olajšati proces laserskega varjenja tankih pločevinskih delov. Zaradi izjemnih konstrukcijsko-tehnoloških zahtev po kakovosti pločevinske konstrukcije v avtomobilski industriji delujejo posebni razvojno raziskovalni centri in za avtomobilsko industrijo pripravljajo takšne avtomatizirane in prilagodljive laserske obdelovalne sisteme, ki zagotavljajo veliko pretočnost proizvodov z visoko stopnjo kakovosti.

Nuss je s soavtorji [1] raziskoval kakovost reza in natančnost izreza različnih velikosti okroglih rondel iz različnih vrst jekla z laserjem CO_2 s zveznim ali pulznim delovanjem. Analiza odstopanja izreza in analiza kakovosti reza sta obsegali tudi natančnost vodenja obdelovanca z numerično krmiljeno mizo in vpliv polarizirane laserske svetlobe na kakovost reza v različnih smereh rezanja. Tönshoff in Somrau [2] ter Bedrin [3] so raziskovali kakovost laserskega reza z merjenjem različnih parametrov hrapavosti na površini reza po rezanju z različnimi močmi laserskega vira in pri različnih hitrostih pomika obdelovanca. Isti avtorji so prav tako raziskovali kakovost reza pri uporabi različnih optičnih sistemov z različnimi goriščnimi razdaljami izstopne zbiralne leče. Thomssen in Olsen [4] sta raziskovala vplive različnih oblik izstopnih odprtin šob laserske glave in vplive različnih pretočnih količin oziroma različnih tlakov rezalnega plina kisika na kakovost laserskega reza.

1 EKSPERIMENTALNI POSTOPEK

Eksperimentalno delo smo opravili na laserskem obdelovalnem sistemu SPECTRA PHYSICS tip Spectra 820 z največjo močjo CO_2 laserskega vira 1500 W z možnostjo zveznega nastavljanja potrebne moči.

Pri laserskem rezanju smo zagotovili:

- isto zbiralno lečo optičnega sistema, z različnimi legami gorišča proti površini obdelovanca;

bile industry are stamped, i.e., shaped in advance with different deep and demanding draws of the sheet with various additional shapes, which are achieved by punching or cutting. In order to ensure as little deformation as possible of the sheet components, forming technologies are nowadays successfully combined with laser technology. A basic aim of combining both technologies is to make it easier to position the individual sheet components to be welded. As far as welding is concerned, the processes to ensure the lowest possible deformation of the sheet structure are to be selected. The task of design engineers and technologists is to subordinate sheet structure forming to production technologies in order to shorten the positioning time, increase the reliability of positioning of individual sheet components and to make the process of laser welding of thin sheet structures, in the automobile industry easier. Because of the extraordinary structural and technological requirements, concerning the quality of the sheet structure, special development centres operate in the automobile industry. They prepare such automated and adaptable laser machining systems which ensure a high-speed circulation of high quality products.

Nuss and co-authors [1] investigated cut quality and cut accuracy of round blanks of various sizes and of different steel qualities, obtained using CO_2 laser in the continuous or pulse mode. Analyses of the cut deviation and cut quality also included the accuracy of workpiece control by a numerically controlled table and the influence of polarized laser light on the cut quality in different cutting directions. Tönshoff and Somrau [2] and Bedrin [3] studied laser cut quality by measuring different roughness parameters at the cut surface after cutting with different laser-source powers and at different travel speeds of the workpiece. The same authors also studied the cut quality obtained with different optical systems having different focusing distances of the output focusing lens. Thomssen and Olsen [4] studied the influences of different shapes of output openings of laser-head nozzles and of different flow-rate quantities, i.e. of different pressures of cutting oxygen, on the laser cut quality.

1 EXPERIMENTAL PROCEDURE

Experiments were carried out with SPECTRA PHYSICS model Spectra 820 a laser machining system with the maximum power of the CO_2 laser source equal to 1500 W and the option of stepless setting of the required power.

For laser cutting the following was ensured:

- the same focusing lens of the optical system with different positions of the focal point with regard to the workpiece surface;

- stabilnost porazdelitve energije laserskega snopa na površini obdelovanca;
- široka izbira hitrosti pomika obdelovanca in prav tako široka izbira rezalnih hitrosti;
- čim manjše dinamične vplive med laserskim virom in mehanskim sistemom vodenja obdelovanca;
- ustrezno obliko šobe, ki mora omogočati pravilen pretok pomožnega plina z možnostjo nastavitve pretočne količine plina.

Laserska glava sprejema prek zrcala izhodni laserski snop premera 19 mm, ki se nato prek zbiralne leče z goriščno razdaljo 127 mm in s premerom snopa v gorišču 90 μm vodi do obdelovanca. Laserska glava skupaj z računalniško krmiljeno koordinatno delovno mizo omogočata trodimenzionalno rezanje, kar omogoča rezanje in tudi varjenje delov in sestavin s prostorsko konstrukcijo. Uporabljeni CO_2 laserski vir ima po prehodu skozi zbiralno lečo Gaussovo porazdelitev intenzivnosti sevanja in z možnostjo zveznega ali pulznega delovanja. Pri laserskem rezanju smo skozi lasersko glavo soosno z laserskim snopom dovajali tudi rezalni kisik, ki omogoča razvoj eksotermih reakcij v rezalni fronti in omogoča odstranjevanje oziroma izpihavanje taline in nastalih oksidov iz rezalne fronte.

1.1 Material obdelovanca in priprava vzorcev

Raziskovalno delo smo opravili na najpogosteje uporabljanem splošnem konstrukcijskem jeklu z oznako CR 24 (po DIN-u St 1403) v mehkem stanju. Jeklo je namenjeno za najbolj zahtevne globoke vleke pločevinastih delov. Jeklo ima majhen delež ogljika (<0,08%) z majhnim deležem mangana (<0,20%) in z omejenim deležem žvepla in fosforja pod 0,03 %. Jeklo z zelo majhnim deležem ogljika ima pretežno feritno mikrostrukturo z majhno količino perlita. Mikrostruktura je zelo fina, zato je pločevina primerna za globoke vleke z različnimi globinami vlekov. Pri velikih preoblikovalnih delih iz debelejše pločevine se pogosto za to tehnologijo odločajo le za vlečna orodja a redkeje za kombinirana orodja, ki omogočajo vlek in izrezovanje. Tako dosežemo znatno daljšo dobo trajanja orodij, orodja so zato cenejša in preprostejše je njihovo vzdrževanje.

Za raziskavo smo izbrali zelo široko izbiro obdelovalnih parametrov, ki smo jih spreminjali. Zato smo eksperimentalno lasersko rezanje izvedli pri zveznem in pulznem delovanju laserja ob različnih nastavitvah moči laserskega snopa, različnih rezalnih hitrostih in različnih tlakih kisika. Glede na izbrano enotno debelino materiala pa smo spreminjali tudi oddaljenost gorišča izhodne zbiralne leče proti zgornji površini obdelovanca.

- stability of laser beam energy distribution at the workpiece surface;
- a wide range of cutting speeds and travel speeds for the workpiece;
- as weak as possible dynamic influences between the laser source and the mechanical system for workpiece control;
- an appropriately shaped nozzle ensuring correct flow of the auxiliary gas with the option of setting the gas flow rate.

A laser beam with an initial diameter of 19 mm is supplied to the laser head by way of a mirror. Using a focusing lens with a focusing distance of 127 mm, the beam with a 90 μm diameter at the focusing point, is then directed to the workpiece. The laser head and the computer-controlled coordinate working table permit three-dimensional cutting, i.e. cutting and welding of the components into a space structure. The CO_2 laser source used has the Gaussian distribution of radiation intensity after being transmitted through the focusing lens and the option of the continuous or pulse mode. In laser cutting, oxygen as the cutting gas was supplied through the laser head coaxially to the laser beam. This allows the development of exothermic reactions at the cutting front and elimination, i.e. blowing out, of the melt and oxides formed from the cutting front.

1.1 Workpiece material and preparation of samples

Studies were made using the most commonly used structural steel CR 24 (St 1403 according to DIN) in the soft state. This steel is intended for the most demanding deep draws of sheet components. It has a low content of carbon (< 0.08%), low content of manganese (< 0.20%) and a limited amount of sulphur and phosphorus (below 0.03%). Steel with a very low carbon content has a predominantly ferittic microstructure with little pearlite. The microstructure is very fine; therefore, the sheet is suitable for deep draws with different draw heights. In the case of very large components to be formed from thick plates, technologists, therefore, often decide in favour of drawing tools and very rarely for combined tools, which permit drawing and cutting. Thus a considerably longer life time of tools is achieved, the tools are cheaper and their maintenance is simpler.

A wide range of working parameters to be varied were selected for the study. The experimental laser cutting was thus carried out with the continuous and the pulse modes of laser operation, with different laser beam powers, different cutting speeds and different oxygen pressures. The degree of defocus, which is defined by the distance between the focal point of the output focusing lens from the upper workpiece surface, was varied with respect to the selected uniform material thickness.

Pri zveznem delovanju laserja CO_2 smo izbrali:

- različne odmike gorišča: z_f v mm = + 0,5 , - 0,5 , - 1,0;
- različne moči laserja: P v W = 231, 363, 483, 539, 660, 759, 847, 1380, 1540;
- različne tlake kisika: p_{O_2} v bar = 1.2; 2,0: 2.3;
- različne rezalne hitrosti: v v mm/min = 700; 800; 900; 1000; 1100; 1200; 1300; 1400; 1500; 1600; 1700; 1800; 1900; 2000; 2100; 2200; 2300; 2400;

Iz različnega izbora rezalnih parametrov smo za posamezne primere rezanja izračunali vnos energije:

In the continuous mode of the CO_2 laser, the following were selected:

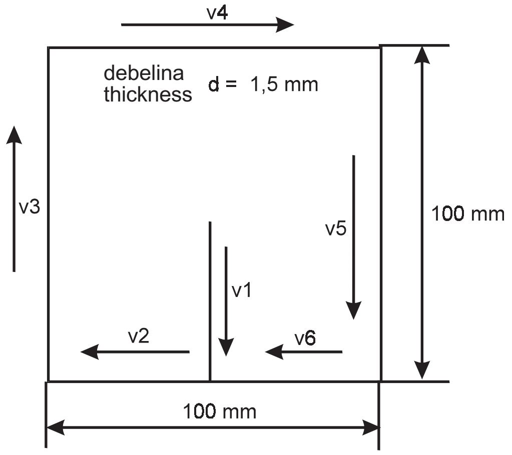
- different defocuses: z_f [mm] = +0.5, -0.5, -1.0;
- different laser powers: P [W] = 231, 363, 483, 539, 660, 759, 847, 1380, 1540;
- different oxygen pressures: p_{O_2} [bar] = 1.2; 2.0; 2.3;
- different cutting speeds: v [mm/min] = 700; 800; 900; 1000; 1100; 1200; 1300; 1400; 1500; 1600; 1700; 1800; 1900; 2000; 2100; 2200; 2300; 2400.

From the wide range of cutting parameters the energy input was calculated for individual cases of cutting:

$$E = \frac{4P}{\pi \cdot v_b \cdot D_b} \left[J / mm^2 \right] \qquad (1).$$

Eksperimentalno delo smo izvedli tako, da smo iz pločevine debeline 1,5 mm, ravne ploščice z dimenzijami 100 mm x 100 mm.

The experimental work included cutting small flat plates of size 100 mm x 100 mm from a sheet with a 1.5 mm thickness.



Sl. 1. *Način laserskega izreza ravnih plošč pri različnih rezalnih razmerah*
Fig. 1. *Plan of laser cutting of flat plates under different cutting conditions*

Na sliki 1 je prikazana izrezana ravna ploščica s podano sistematiko rezanja. Izrez ravne ploščice smo pričeli v sredini in opravili prvi rez z dano močjo vira in z najmanjšo hitrostjo pomika laserskega snopa v_1. Na tako izvedenem rezu z najmanjšo rezalno hitrostjo je bilo zaradi napravljene zareze mogoče merjenje vseh značilnosti geometrijskih oblik reza; to je od širine reza na zgornjem in spodnjem delu reza do velikosti brazd na spodnji strani reza. Sledile so nato v zaporedju rezi pri isti moči laserskega snopa toda s postopno vse večjimi hitrostmi laserskega rezanja od v_2 do v_6. Tako smo zagotovili različne vnose energije, ki so dali različne kakovosti posameznih rezov. Na vseh preostalih površinah reza smo lahko opravili vizualno oceno površine reza in/ali merjenje hrapavosti reza.

Fig. 1 shows a small flat plate and the cutting systematics. Cutting of the small flat plate started in the centre. The first cut was made with a particular source power and the lowest travel speed of the laser beam, v_1. In such a cut, made with the lowest cutting speed, it was possible to measure all the geometrical characteristics of the cut, i.e., the cut width at the upper and lower edges of the cut, the size of striations at the lower side of the cut, due to a notch. Subsequent cuts were made with the same laser beam power, but with gradually increasing laser cutting speeds from v_2 to v_6. Thus different heat inputs were ensured. They each gave a different quality of cut. With the remaining cut surfaces, the visual inspection of the cut surface and/or measurement of the cut roughness were made.

2 EKSPERIMENTALNI REZULTATI

Pri izbiri razmer za lasersko rezanje moramo zagotoviti ustrezno kakovost površine nastalega reza.

2 EXPERIMENTAL RESULTS

The choice of laser cutting conditions should ensure a suitable quality of the cut surface; therefore, Zato je pomembno, da tehnologi v prvi fazi predpišejo zahteve o kakovosti nastalega laserskega reza z vidika uporabnosti izrezanega dela. Nato morajo tehnologi izbrati ustrezne rezalne razmere, ki dajejo najmanjši vnos energije za zahtevano kakovost reza. Običajno najprej izbiramo primeren odmik gorišča od površine pločevine in nato s spreminjanjem moči laserskega snopa in prirejene hitrosti pomika laserskega snopa - zagotavljamo najmanjši izbrani vnos energije. S tako izbranimi kriteriji smo pri isti moči opravili rezanje s šestimi rezalnimi hitrostmi, kar pomeni šest različnih vnosov energije v rezalno fronto.

Raziskave površine reza in površinskega sloja v okolici reza opišemo s tako imenovano “integriteto površin”([6] in [7]). Raziskave integritete površine po laserskem rezanju omogočajo zelo popoln popis stanja površine reza in omogoča ocenjevanje kakovosti reza. Integriteta površine laserskega reza vključuje naslednje preiskave:

- makrogeometrijsko analizo reza,
- mikrogeometrijsko analizo reza,
- mikrostrukturno analizo površinskega sloja reza,
- merjenje mikrotrdote pretaljenega in toplotno vplivanega področja reza,
- mikrokemično analizo pretaljenega in toplotno vplivanega področja reza,
- merjenje velikosti pretaljenega in toplotno vplivanega področja reza.

Makrogeometrijska analiza laserskega reza je popisana s standardom DIN 2310 in vključuje merjenje naslednjih geometrijskih značilnosti:

- spodnjo širino laserskega reza,
- zgornjo širino laserskega reza,
- širino srha,
- višino srha,
- globino toplotno vplivanega področja,
- izmerjeno hrapavost laserskega reza vzdolž reza.

Mikrogeometrijska analiza omogoča popis tehnične površine z merjenjem profila površine, iz katerih lahko določamo različne parametre za popis hrapavosti površine reza. Odstopanja idelane ali teoretične površine od dejanske površine reza imenujemo odstopek mere - odstopanje dejanske površine laserskega reza od teoretične pa določamo s parametri hrapavosti in valovitosti. Za mikrogeometrijski popis hrapavosti reza smo izbrali:

- merjenje srednje aritmetične hrapavosti R_a,
- merjenje srednje višine neravnosti R_z,
- merjenje največje višine neravnosti R_y.

Površino laserskega reza lahko ocenimo s pregledom in izmerjenimi parametri hrapavosti reza. Enoličen in dovolj zanesljiv popis stanja površine laserskega reza dobimo z merjenjem mikrogeometrije profila površine na izbranem mestu reza ter z nadaljnjo digitalizacijo podatkov o profilu površine, ki omogočajo določiti posamezne dobro primerljive parametre o kakovosti površine.

it is extremely important that the technologists first specify the quality requirements for the laser cut with regard to the fitness of the part cut for the purpose. Then they should select appropriate cutting conditions giving the lowest energy input for the cut quality required. Usually, an appropriate level of defocus is selected first. Then, by changing the laser beam power and the adapted travel speed of the laser beam, the lowest energy input is ensured. After these criteria were selected, cutting was carried out with six different cutting speeds but with the same beam power, which produces six different energy inputs into the cutting front.

The cut surface and the surface layer in the cut vicinity are described as the so-called “surface integrity” ([6] and [7]). Studies on surface integrity after laser cutting allow a very thorough description of the cut surface finish and assessment of the cut quality. An assesment of the surface integrity of the laser cut comprises the following tests:

- macrogeometrical analysis of the cut;
- microgeometrical analysis of the cut;
- microstructure analysis of the cut surface layer;
- measurement of microhardness of the remelted and the heat-affected zones of the cut;
- microchemical analysis of of the remelted and the heat-affected zones of the cut;
- measurement of the size of the remelted and the heat-affected zones of the cut.

Macrogeometrical analysis of the laser cut is specified in DIN 2310 the standard and includes measurements of the following geometrical characteristics:

- lower laser-cut width,
- upper laser-cut width,
- burr width,
- burr height,
- depth of the heat-affected zone,
- laser-cut roughness measured along the cut.

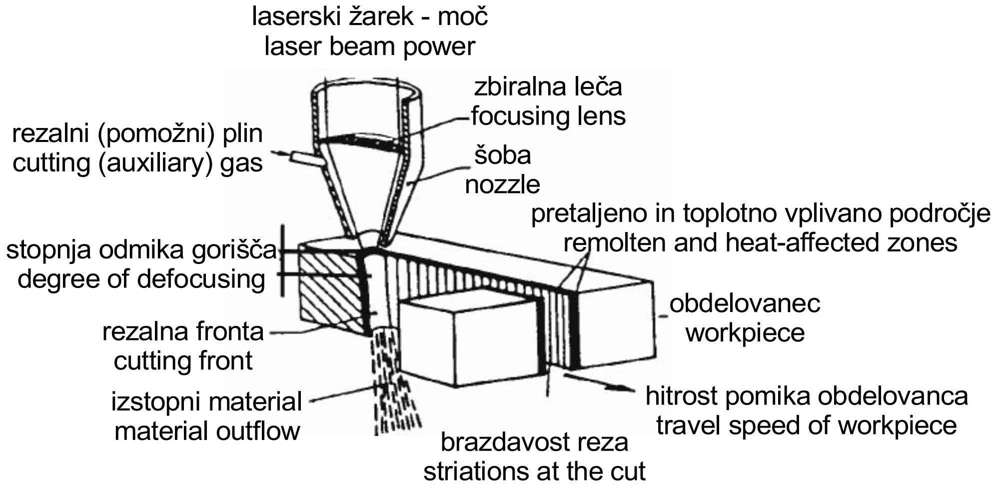
Microgeometrical analysis permits the description of a technical surface by means of a measurement of the surface profile. This allows determination of various parameters for the description of the cut-surface roughness. Deviation of the actual cut surface from the ideal or theoretical surface is called an offsize. This deviation of the actual laser-cut surface from the theoretical one is determined by the parameters of roughness and striations. For a description of the microgeometry of the cut roughness, the following were selected:

- measurement of the mean arithmetic roughness R_a,
- measurement of the mean roughness height R_z,
- measurement of the maximum roughness height R_y.

The laser-cut surface may be assessed on the basis of a visual inspection and the measured parameters of the cut roughness. A uniform and sufficiently accurate description of the laser-cut surface may be obtained by measuring the microgeometry of the surface profile at the selected cut point and further digitization of data on the surface profile which permit the determination of individual, easily comparable parameters of surface quality.

Naslednji način za popis značilnosti reza obsega standardne podatke o stanju površine in površinskega sloja, ki je v strokovni terminologiji znana kot integriteta površin ([6] in [7]). Navadno se pri obravnavanih površinah rezov zadovoljimo z analizo mikrostrukture materiala po globini, to je v smeri pretaljene in toplotno vplivane cone in z merjenjem mikrotrdote na različnih vnaprej določenih mestih reza.

Another way of describing the cut characteristics are standard data on the surface finish and surface layer, which in technical terminology is referred to as the “surface integrity” ([6] and [7]). With the cut surfaces concerned, it is usually sufficient to analyse the through-thickness microstructure of the material, i.e. the microstructure in the direction of the remelted and heat-affected zones, and the measurement of microhardness at various cut points determined in advance.



Sl. 2. *Rezalna fronta in nastanek reza*
Fig. 2. *Cutting front and formation of the cut*

Slika 2 prikazuje vplive laserskega rezanja v izbranih rezalnih razmerah na nastanek brazd na površini. Zaradi izrednih razmer pri hitrem segrevanju oziroma hitrem ohlajanju pri laserskem rezanju materiala v rezalni fronti, prihaja do naslednjih procesov:

- taljenja in oksidacije materiala pri kisikovem rezanju,
- izpihavanja taline in nastalih oksidov iz rezalne fronte pri kisikovem rezanju,
- ponovnega strjevanja tankega površinskega sloja, ki ga poimenujemo pretaljeni sloj,
- difuzijskih procesov znotraj pretaljenega in toplotno vplivanega sloja,
- zadrževanja oksidov na spodnjem delu rezalnega roba reza.

Fig. 2 shows the influence of laser cutting under the selected cutting conditions on the formation of striations at the surface. Owing to extreme conditions of fast heating and fast cooling of the material in the cutting front in laser cutting, the following processes occur:

- melting and oxidation of the material during oxygen cutting,
- ejection of the melt and oxides from the cutting front during oxygen cutting,
- resolidification of a thin surface layer called the “remelted layer”,
- diffusion processes inside the remelted and the heat-affected layers,
- persistence of oxides at the bottom of the edge of the cut.

2.1 Vpliv vnosa energije na hrapavost površine reza pri zveznem delovanju laserskega snopa

V diagramih na slikah 3 so prikazane odvisnosti izmerjenih parametrov hrapavosti površine reza od hitrosti rezanja pri različnih vnosih energije za zvezno delovanje snopa. Z različnimi odmiki gorišča zbiralne leče od površine materiala, je bila v vseh prikazanih primerih nespremenjena $z_f = +0{,}5$ mm in je v zgornji tretjinski debelini materiala obdelovanca. Izbrali smo tudi tlak rezalnega kisika $p_{O_2} = 2{,}2$ bar, ki omogoča intenzivnejše zgorevanje materiala in sočasno omogoča, zaradi pretoka

2.1 Influence of energy input on cut-surface roughness with the continuous mode of the laser beam

The diagrams in Fig. 3 show the dependence of the measured parameters of cut-surface roughness on the cutting speed in the case of different heat inputs and the continuous mode of beam operation. The degree of defocus z_f, i.e. the distance between the focal point of the focusing lens and the material surface, was in all cases, shown to be constant $z_f = +0{,}5$ mm. The focus of the optical system is located in the upper third of the workpiece material thickness. The pressure of oxygen as a cutting gas $p_{O_2} = 2.2$ bar. It kisika skozi lasersko glavo, tudi hlajenje laserske glave oziroma zbiralne leče. Pri zveznem delovanju laserskega snopa v rezalni fronti smo rezalne hitrosti priredili izbranim močem. Tako smo pri manjših močeh od 231 W do 660 W izbrali le šest rezalnih hitrosti v razponu od 700 do 1100 mm/min. Pri največji moči 759 W smo izbrali kar dvanajst rezalnih hitrosti v razponu od 700 do 1800 mm/min. Rezultati so izjemno zanimivi, saj se izmerjeni parametri kakovosti pri dani moči spreminjajo in tudi nepričakovano spreminjajo s povečano rezalno hitrostjo. Zanimivo je, da imajo vsi izbrani parametri hrapavosti pri istem vnosu energije (P,v) zelo podobne težnje, kar pomeni, da so vsi trije parametri primerni za ocenjevanje kakovosti reza. Spreminjajoči parametri hrapavosti reza so po naši oceni tesno povezani z neprimerno polarizacijo laserskega snopa, kar pomeni, da je kakovost reza močno odvisna od smeri rezanja. Raziskovalci, ki so analizirali vplive smeri rezanja na kakovost reza, so potrjevali podobna neskladja v parametrih hrapavosti s slabo krožno polarizacijo laserskega snopa. Zato se v takšnih primerih priporoča, da se navajajo rezultati rezanja (parametri hrapavosti) z najnižjo in najvišjo vrednostjo.

Pri rezanju z najnižjo močjo laserskega snopa P = 231 W lahko ugotovimo naslednje:

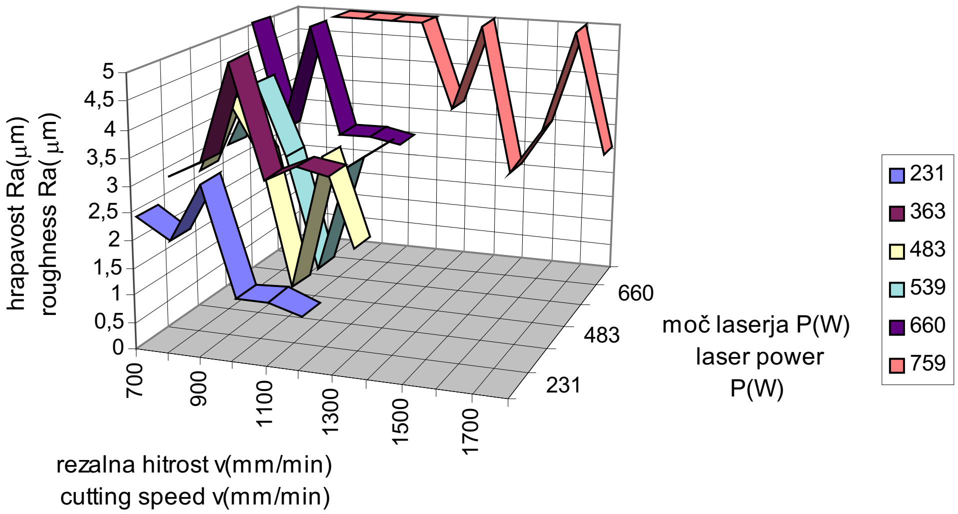
- Izbira rezalnih hitrosti, ki zagotavlja še sprejemljivo kakovost reza, je zelo omejena.

permits more intensive combustion of the material and at the same time, because of the oxygen flow through the laser head, also cooling of the laser head and the focusing lens. With the continuous mode of the laser beam in the cutting front, cutting speeds were adapted to the powers selected. Thus with lower powers of 231 W to 660 W only six cutting speeds in the range from 700 to 1100 mm/min were selected.With the highest power of 759 W, however, twelve cutting speeds in the range from 700 to 1800 mm/min were selected. The results obtained were extremely interesting since the measured quality parameters varied with the power given and vary unexpectedly with the increase in the cutting speed. It is interesting that all the selected roughness parameters show, with the same heat input (P, v), very similar trends. This indicates that all three parameters are suitable for the assessment of cut quality. The varying cut roughness parameters are, in our opinion, closely related to an unfavourable polarization of the laser beam, which indicates that the cut quality is strongly dependent on the cutting direction. The researchers who analysed the influence of the cutting direction on the cut quality confirmed similar discrepancies in the roughness parameters by poor circular polarization of the laser beam. It is, therefore, recommended to state the cutting results (roughness parameters) with the lowest and the highest values.

During cutting with the lowest laser beam power , i.e., P = 231 W, the following can be concluded:

- The selection of cutting speeds which ensures still acceptable cut quality is very limited.

način delovanja laserja: zvezno; z_f= 0,5 mm; po_2=2,1 bar
operating mode of the laser: continuous; z_f= 0,5 mm; po_2=2,1 bar



Sl. 3. *Popis srednje aritmetične hrapavosti površine laserskega reza* R_a *v odvisnosti od rezalne hitrosti in moči laserskega snopa z zveznim delovanjem. Lega gorišča optičnega sistema je v zgornji tretjini debeline obdelovanca* z_f *= 0,5 mm. Tlak pomožnega plina kisika je 2,1 bar.*

Fig. 3. *The mean arithmetic roughness of the laser-cut surface* R_a *as a function of the cutting speed and laser beam power in the continuous mode. The focus of the optical system is located in the upper third of the workpiece thickness* z_f *= 0.5 mm. Pressure of oxygen as an auxiliary gas is 2.1 bar*

- Izmerjeni parametri hrapavosti so: srednja aritmetična hrapavost R_a = 0,9 μm; srednja višina neravnosti R_z = 6,2 μm in največja višina neravnosti R_y = 8,8 μm so najugodnejši pri hitrostih rezanja v = 1200 mm/min.
- Pri dani moči je izračunana povprečna srednja aritmetična hrapavost $\overline{R_a}$ znatno večja in znaša 1,9μm, kar pomeni za več ko 100% večjo vrednost od izmerjene srednje aritmetične hrapavosti pri hitrosti rezanja 1200 mm/min.
- Pri dani moči je izračunana povprečna srednja višina neravnosti $\overline{R_z}$ znatno večja in znaša 12,42 μm, kar pomeni za več ko 100% večjo vrednost od izmerjene srednje višine neravnin pri hitrosti rezanja 1200 mm/min.
- Zanimivo je, da so pri močeh laserskega snopa 483 W in 537 W in rezalni hitrosti 1000 mm/min pojavijo znatno manjše vrednosti posameznih parametrov hrapavosti. Vidni pregled površine laserskega reza in ocena kakovosti površine potrjuje, da so dosežene najprimernejše razmere v rezalni fronti glede vnosa energije in kinetike izpihovanja taline in oksidov iz rezalne fronte. Določene vplive lahko pripišemo že prej omenjeni slabi polarizaciji laserskega snopa.

Po opravljeni analizi površine reza z vidika izmerjenih parametrov hrapavosti reza in njegove vidne ocene bi priporočali izbiro najmanjše izbrane moči laserskega snopa 231 W in večjih hitrosti rezanja v = 1200 mm/min, da bi zagotovili odlično kakovost reza. V primerih, ko kakovost reza ni odločilna, se priporoča izbira večjih moči in tudi večje hitrosti rezanja.

Na sliki 4 so v rezultirajočem diagramu prikazane vse rezalne razmere z vidika vnosa energije pri različnih hitrostih rezanja. Opravljenih je bilo 75 laserskih rezov s spreminjanjem osmih moči laserskega izvora v razponu od 231 W do 847 W. V diagramu je z daljicami označeno področje rezalnih pogojev, ki zagotavljajo želeno kakovost reza z vidika vidne ocene reza in izmerjenih različnih parametrov hrapavosti reza.

2.2 Mikrostrukturna analiza reza

Za poglobljeno analizo rezalnega procesa je treba opraviti tudi različne druge mikroskopske preiskave, ki omogočajo popis stanja materiala zaradi soodvisnih učinkov toplotne energije, nastale z interakcijo laserske svetlobe v rezalni fronti in termokemičnih ter kinetičnih učinkov pomožnega kisika. Običajno se pri obravnavi rezalnih robov zadovoljimo z mikrostrukturno analizo materiala po globini, to je v smeri pretaljene in toplotne vplivane cone in z merjenjem mikrotrdote na različnih nivojih reza. Pri tanjših materialih se omejimo na

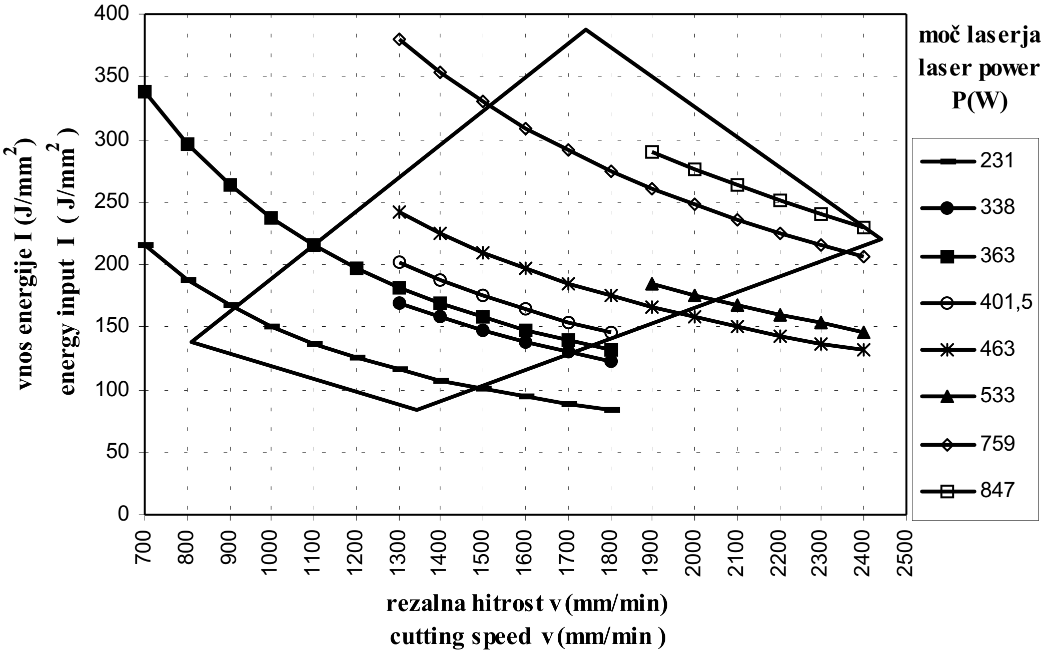
- The measured roughness parameters are the following: the mean arithmetic roughness, R_a = 0.9 μm; the mean roughness height, R_z = 6.2 μm; the maximum roughness height, R_y = 8.8 μm. They are most favourable at a cutting speed v = 1200 mm/min.
- With the given power, the calculated average mean arithmetic roughness height $\overline{R_a}$ is considerably higher and amounts to 1.9 μm, which is more than 100% higher than the measured mean arithmetic roughness at the cutting speed of 1200 mm/min.
- With a given power, the calculated average mean roughness height $\overline{R_z}$ is considerably higher and amounts to 12.42 μm, which is more than 100% higher than the measured mean roughness height at cutting speed of 1200 mm/min.
- It is interesting that with laser beam powers of 483 W and 537 W and a cutting speed of 1000 mm/min, considerably lower values of individual roughness parameters are obtained. A visual inspection of the laser cut surface and an assessment of the surface quality confirm that the most favourable conditions in the cutting front, as far as energy input and kinetics of ejection of the melt and oxides from the cutting front are concerned, have been attained. Certain influences can be attributed to the afore-mentioned poor laser beam polarization.

On the basis of the analysis made of the cut surface, from the viewpoint of the measured cut roughness parameters and visual assessment of the cut, we would recommend, in order to ensure high quality of the cut, to select the lowest laser beam power, 231 W, and a higher cutting speed, v = 1200 mm/min. When cut quality is not of primary importance, the selection of higher powers and a higher cutting speed is recommended.

In the diagram in Fig. 4, all the cutting conditions are shown from the viewpoint of energy input at different cutting speeds. Some 75 laser cuts were made while changing the power of the laser source eight times in the range from 231 W to 847 W. In the diagram, the straight lines indicate the region of cutting conditions which ensure the desired cut quality from the viewpoint of visual assessment of the cut and the different measured parameters of cut roughness.

2.2 Microstructural analysis of the cut

For a thorough analysis of the cutting process, various other microscopic examinations are to be made. They will allow a description of the state of the material due to complementary effects of the thermal energy produced by the interaction of the laser light in the cutting front and thermo-chemical and kinetic effects of oxygen as an auxiliary gas. In dealing with cutting edges one is usually content with a through-thickness analysis of the microstructure of the material, i.e., in the direction of the remelted and the heat-affected zones, and measurement of the microhardness at various cut lev-



Sl. 4. *Območje zadovoljive kvalitete laserskega reza v odvisnosti od vnosa energije oziroma moči laserskega snopa in rezalne hitrosti pri pulznem delovanju snopa*

Fig. 4. *Area of satisfactory laser cut quality as a function of energy input, laser beam power and cutting speed with the pulse mode of beam operation*

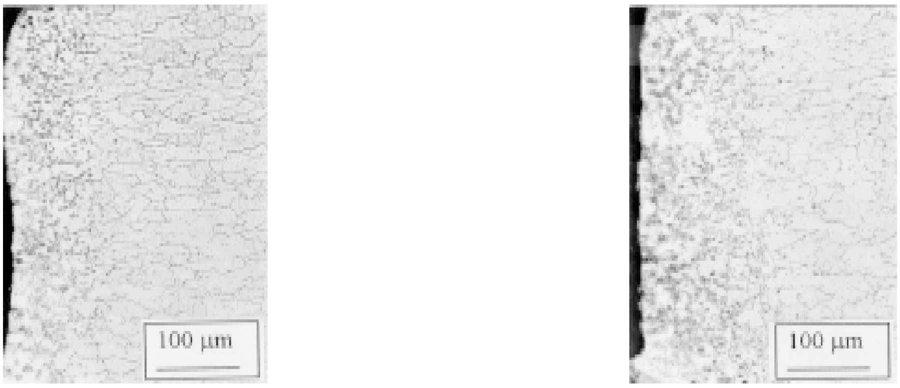
mikroanalizo podpovršja reza le na zgornjem in spodnjem delu reza, medtem ko pri debelejših materialih dodatno izvajamo mikroanalizo še v sprednjem delu reza. Prav tako se priporoča poglobljena mikroanaliza podpovršja v primerih, ko imamo premajhne vnose energije. Značilno za premajhen vnos energije je nastanek neizrazitih brazd na površini reza z opaznimi pretaljenimi in zvarjenimi oksidnimi delci na površju reza. Zaradi zadrževanja taline v rezalni fronti in zaradi povečanega odvoda toplote v hladen material obdelovanca nastane večja globina pretaljenega sloja in večja globina toplotnega vpliva. Na sliki 5 so prikazani mikrostrukturni posnetki zgornjega in spodnjega dela podpovršja reza pri majhnih povečavah. Slika "a" in "b" prikazujeta mikrostrukturno stanje podpovršja pri optimalnem vnosu energije, na sliki "c" in "d" pa pri večjem vnosu energije. Pri opazovanju mikrostrukture na vzorcih smo ugotovili, da se globina pretaljene in toplotno vplivane cone s povečevanjem vnosa energije v okviru optimalnih rezalnih pogojev ne razlikuje in se giblje med 55 in 65 μm. Izrazitejše je povečanje globine toplotno vplivane cone pri premajhnih vnosih energije, ko je zaradi zaostajanja rezalne fronte po višini reza dosežen znatno večji odvod toplote v hladen material okolice reza. Tako lahko ugotovimo, da so običajno znatno manjše razlike v velikostih globin toplotne vplivane cone v zgornjem delu reza, kakor v spodnjem delu reza ([8], [9] in [10]). Pri optimalnih razmerah rezanja smo izmerili povprečno velikost toplotno vplivane cone na zgornjem delu reza okoli 60 μm in je bila po celotni širini reza dokaj

els. With thinner materials the microanalysis of the cut subsurface is limited only to the upper and lower part of the cut while with thicker materials the microanalysis is additionally made at the front part of the cut. It is also recommended to make a thorough microanalysis of the subsurface in the case of a too low energy input. It is characteristic of a too low energy input that unexpressive striations form at the cut surface including remelted and welded oxide parts at the cut surface. Because of melt persistance at the cutting front and an increased transfer of heat to the cold workpiece material, a greater depth of the remelted layer and of heat influence is obtained. Fig. 5 shows micrographs of the upper and lower parts of the cut subsurface at low magnifications. Figures "a" and "b" show the microstructural condition of the subsurface with an optimum energy input and figures "c" and "d" with a higher energy input. Observation of the microstructure of the samples showed that the depth of the remelted and the heat-affected zones did not vary with an increase in energy input within the optimum cutting conditions. The depth varied between 55 and 65 μm. The increase in the depth of the heat-affected zone is more distinctive with too low energy inputs when a much higher removal of heat to the cold material in the cut vicinity along the cut height is achieved due to lagging of the cutting front. Thus it may be stated that considerably smaller differences in the depth of the heat-affected zone are usually found in the upper part of the cut than in its lower part ([8], [9] and [10]). With optimum cutting conditions an average size of 60 μm of the heat-affected zone at the upper part of the cut was measured. It was rather uniform through enakomerna. Pri manjših vnosih energije od optimalne pa se je izkazalo, da je znatno povečana globina toplotno vplivane cone v spodnjem delu reza. Tako smo pri najmanjšem vnosu energije, pri kateri smo še dosegli rezanje materiala dobili povprečno globino pretaljenega sloja in toplotno vplivane cone okoli 120 µm. Pri najmanjšem vnosu energije smo dobili postopno spreminjanje globine toplotno vplivane cone od zgornjega robu do globine 60 µm in na spodnjem robu 175 µm. Prav tako pa lahko ugotovimo izrazitejše brazde na površju, ki jih pri fizikalnem popisu površine zajamemo z valovitostjo površine. Mikrostruktura pretaljenega sloja je zelo fina, pretežno feritna z zelo majhnim deležem perlita. Osnovna mikrostruktura je zelo groba z usmerjenimi feritnimi zrni zaradi hladne deformacije pločevine.

the total cut width. With the energy inputs lower than the optimum it showed that the depth of the heat-affected zone considerably increased in the lower part of the cut. Thus an average depth of the remelted layer and of the heat-affected zones of 120 µm was obtained with the lowest energy input, which still allowed material cutting. With the lowest energy input a gradual variation of the depth of the heat-affected zone from the upper edge to a depth of 60 µm and at the lower edge to 175 µm was obtained. Similarly, more expressive striations may be found at the surface. In a physical inventory of the surface they are comprised in the surface waviness. The microstructure of the remelted layer is very fine, mainly ferritic with a small portion of pearlite. The basic microstructure is very coarse, with oriented ferrite grains due to cold deformation of the plate.

a) Videz zgornjega dela robu pri majhnem vnosu energije
a) Appearance of the upper part of the edge with a low heat input

b) Videz spodnjega dela robu pri majhnem vnosu energije
b) Appearance of the lower part of the edge with a low heat input



c) Videz zgornjega dela robu pri velikem vnosu energije
c) Appearance of the upper part of the edge with a high heat input

d) Videz spodnjem dela robu pri velikem vnosu energije
d) Appearance of the lower part of the edge with a high heat input

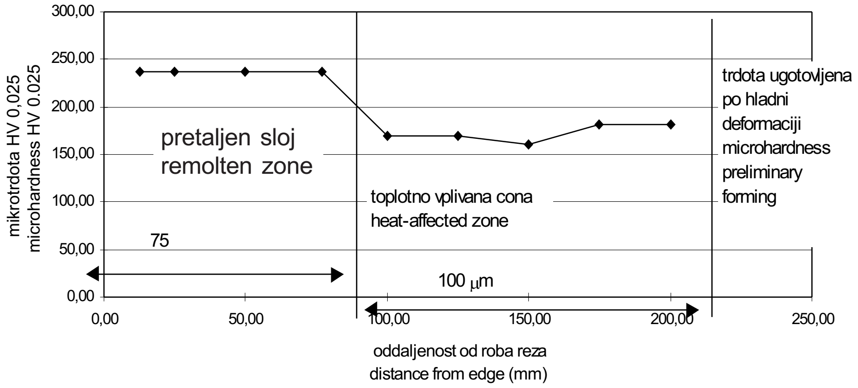
Sl. 5. *Mikrostrukturni posnetki laserskega reza pri pulznem delovanju laserskega snopa*
Fig. 5. *Micrographs of the laser cut with the pulse mode of laser beam operation*

Na sliki 6 je prikazan potek izmerjene mikrotrdote v osrednjem delu reza. Zaradi plitke globine pretaljenega in toplotno vplivanega sloja smo izbrali obremenitev pri merjenju trdote 0,25 N, da smo zagotovili zadostno število meritev.

Fig. 6 shows the variation of the microhardness measured in the central part of the cut. Because of the small depth of the remelted and the heat-affected zones, a load of 0.25 N was selected for the measurement of the microhardness so as to ensure a sufficient

Zaradi narave oziroma uporabnosti materiala, ki je namenjen za globoki vlek, je mikrostruktura materiala pretežno feritna, ki pa ima zaradi učinkov prejšnjega preoblikovanja pločevine povečano trdoto na okoli 185 $HV_{0,025}$. Zaradi toplotnih učinkov je bila kljub poprej hladno utrjeni mikrostrukturi dodatno znotraj pretaljene cone povečana mikrotrdota. Povečanje mikrotrdote je bilo zelo enakomerno po celotni globini in je okoli 240 $HV_{0,025}$. Zanimiv je potek mikrotrdote v osrednjem delu krivulje, kjer je znižanje trdote na 160 $HV_{0,025}$ in ga pripišemo omehčanju oziroma rekristalizaciji in sprostitvi hladno deformirane mikrostrukture. Globino toplotno vplivane cone je prav zaradi vpliva toplotnih učinkov na omehčanje mikrostrukture materiala mogoče zelo zanesljivo določiti in je v danem primeru od globine 120 µm celo do globine 175 µm.

number of measurements. Because of the nature of the material, which is intended for a deep draw, the microstructure of the material is mainly ferritic but it has its hardness increased to around 185 $HV_{0.025}$ because of the effects of preliminary forming of the plate. Because of thermal effects, the microhardness increased in spite of the preliminary cold-hardened microstructure within the remelted zone. The increase in the microhardness was very uniform through the whole depth, and amounted to around 240 $HV_{0.025}$. It is interesting to see the variation of microhardness in the central part of the curve where hardness is reduced to 160 $HV_{0.025}$. This is attributed to softening and recrystalisation and relaxation of the cold-deformed microstructure. The depth of the heat-affected zone can be determined very reliably, precisely because of the influence of the thermal effects on softening of the material microstructure. In the case given, it ranges from 120 µm up to 175 µm.



Sl. 6. *Potek mikrotrdote $HV_{0,025}$ po globini pretaljene in toplotno vplivane cone*
Fig. 6. *Variation of microhardness $HV_{0.025}$ through the depth of the remelted and the heat-affected zone*

3 SKLEPI

Po opravljenih raziskavah o makro- in mikrostrukturnem stanju površine in podpovršja reza lahko potrdimo, da z merjenjem oziroma določevanjem različnih parametrov hrapavosti lahko zelo uspešno optimiramo proces laserskega rezanja. Laserski sistem je dovolj zanesljiv, saj razpolaga z ustreznim optičnim in kinematičnimi pogoji, ki omogočajo dobro prilagajanje obdelovalnih razmer različnim vrstam in debelinam materialov.

Na podlagi opravljenih raziskav o kakovosti laserskih rezov pri različnih vnosih energije in različnih načinih delovanja snopa lahko povzamemo naslednje:

- Največji vpliv na kakovost reza imata moč laserskega snopa in hitrost rezanja, ki določata vnos energije v rezalno fronto.
- Iz podatkov o srednji aritmetični hrapavosti površine reza ali iz srednje višine neravnin reza lahko glede na različne vnose energije uspešno optimiramo laserski proces.
- Nastavitev odmika gorišča optičnega sistema od površine materiala ima po rezultatih naših meritev manjši ali neznaten vpliv na hrapavost reza, vpliva pa na širino reza.

3 CONCLUSIONS

On the basis of the investigations conducted on the macro and microstructural condition of the cut surface and its subsurface, it may be confirmed that by measuring various roughness parameters the laser cutting process may be successfully optimized. The laser system is reliable enough, since it has at its disposal appropriate optical and kinematic conditions which allow good adaptation of the working conditions to various kinds and thicknesses of material.

On the basis of the investigations conducted on laser cut quality with different energy inputs and different modes of beam operation it can be concluded that:

- The greatest influence on cut quality is exerted by the laser beam power and the cutting speed, which determine the energy input into the cutting front.
- The laser process can be successfully optimized with regard to different heat inputs on the basis of the data on the arithmetic cut-surface roughness or of the mean cut roughness height.
- The setting of the degree of defocus of the optical system has, as the results of our measurements show, a small or insignificant influence on cut roughness but it affects the cut width.

- S primerjavo parametrov hrapavosti površin reza, nastalih z zveznim ali pulznim delovanjem, dajemo določeno prednost pulznemu rezanju materialov.
- Lastna frekvenca delovanja resonatorja ima prevladujoči vpliv na parametre hrapavosti površine, predvsem pri visokih rezalnih hitrostih. Nekoliko bolj izrazit je vpliv lastne frekvence pri pulznem delovanju laserja, kakor pri zveznem delovanju.
- Dokazali smo, da je laserski snop s slabo krožno polarizacijo, kar pomeni, da je v enakih razmerah laserskega rezanja kakovost reza odvisna od smeri rezanja.

Dosedanji rezultati raziskav in izkušnje pri ocenjevanju kakovosti laserskega reza potrjujejo, da je določevanje spodnje in zgornje kritične rezalne hitrosti mogoče vključiti kot zanesljiv način za določevanje optimalnih parametrov laserskega rezanja.

- A comparison of roughness parameters for cut surfaces produced by the continuous or pulse mode of operation indicates a preference for the pulse cutting of materials.
- The resonator's own frequency of operation has a predominant influence on the surface roughness parameters, particularly at high cutting speeds. This influence is more dearly observed with the pulse mode of the laser operation than with the continuous mode.
- It has been proved that the laser beam has a poor circular polarization, that is to say, that with the same laser cutting conditions the cut quality depends on the cutting direction.

The results of the investigations at this stage and the experience gained in assessment of laser cut quality confirm that determination of the lower and the upper critical cutting speeds may be considered a reliable way of determining the optimum laser cutting parameters.

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