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Laserska toplotna obdelava sive in nodularne litine
Laser Heat Treatment of Gray and Nodular Irons

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Laserski obdelovalni sistemi so zaradi številnih prednosti nasproti konvencionalni obdelavi vedno bolj zastopani v proizvodnji. Ti sistemi lahko delujejo samostojno, ali pa so vključeni v obdelovalno celico za mehansko in toplotno obdelavo. Posebno zanimiva je toplotna obdelava litega železa, predvsem zaradi dobre kombinacije žilavega jedra in novo nastale trde finostrukturne površine, ki izredno poveča korozijsko in obrabno odpornost materiala. Zato smo preverili obnašanje sive in nodularne litine po laserski toplotni obdelavi s strukturnega vidika in z merjenjem spremembe v trdoti kaljene sledi. Dobljena spoznanja o toplotni obdelavi litine smo podkrepili z izbiro optimalnih obdelovalnih razmer.

Laser machining systems have numerous advantages over the conventional methods and are increasingly used in manufacturing. These systems can operate as individual systems or they can form part of a manufacturing cell for machining and heat treatment. Recently, special attention has been devoted to laser heat treatment of cast iron mostly because of the good combination between the ductile core and the newly formed hard, fine structured surface which significantly increases corrosion and wear resistance of the material. The investigation studies the behaviour of gray iron and ductile iron after laser heat treatment from the point of view of structure, and verifies it by measuring the changes in hardness of the hardened trace. The findings about laser heat treatment of these casts are supplemented by careful selection of optimum laser treatment conditions.

0 UVOD

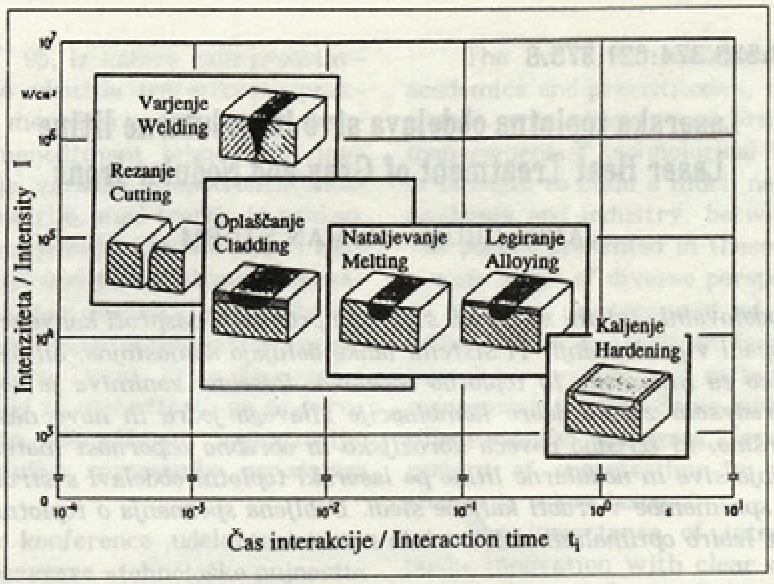
Laserska tehnologija ponuja številne prednosti pred dosedaj poznanimi tehnologijami. Posebej bi lahko izpostavili brezkontaktno obdelavo, kjer se ne pojavlja orodje v običajni obliki, ampak kot laserski snop, ki se ne obrablja. Tako se ognemo številnim problemom, ki jih povzročajo obrabljena orodja, od deformacije obdelovancev, poškodb površinskega sloja, do poškodb vitalnih elementov stroja oziroma naprave.

Pri toplotni obdelavi moramo doseči s pomikom laserskega snopa prek površine obdelovanca hitro segrevanje in ohlajanje površinskega sloja. Hitro ohlajanje površinskega sloja dosežemo že zaradi hitrega odvoda toplote v preostali del hladne mase. S pravilno izbiro energijske gostote oziroma z izbiro ustreznega vnosa energije dosežemo hitro lokalno segrevanje v avstenitno področje ali celo temperature nataljevanja površine obdelovanca, kar po ohlajanju omogoča nastanek želene globine modificiranega sloja. Na sliki 1 so prikazana celotna razmerja med gostoto moči laserskega snopa na površini obdelovanca, izraženo v W/cm^2, in potrebnimi časi interakcije snopa z materialom obdelovanca, da dosežemo različne toplotne razmere na njem, ki ustrezajo zahtevam različnih obdelovalnih postopkov.

0 INTRODUCTION

Laser technology offers many advantages over previously known technologies. One of the most important advantages is the possibility of contactless machining where there is no tool, in the classical sense, but a laser beam which is not subject to wear. By using laser technology many problems related to tool wear are eliminated, such as workpiece deformation, surface layer damage, as well as damage to some of the vital parts of machine tools or other machining equipment.

In heat treatment, we have to achieve by moving the laser beam across the workpiece rapid heating and cooling rates of the surface layer. Rapid surface layer cooling rates can be quite easily achieved by fast heat transfer into the remaining part of the cold mass. By a correct choice of energy density or by choosing a suitable energy input, we can achieve rapid local heating rates up to the austenitic region or even the temperature of the surface layer melting which, after the cooling process is completed, enables us to get a modified layer of the desired depth. In Figure 1 we can see some global relations between the laser beam power density on the workpiece surface expressed in W/cm^2 and the necessary times of laser beam interaction with the workpiece material in order to create different heat conditions corresponding to different machining procedures.



Sl. 1. *Laserska obdelava glede na intenzivnost moči in čas interakcije*
Fig. 1. *Laser treatment as a function of power intensity and interaction time*

Delež razpoložljive energije laserskega snopa (pri valovni dolžini 10,6 μm) je na površini obdelovanca močno odvisen od absorpcijske zmožnosti kovinskih materialov in znaša od 2 do 5 odstotkov, preostali del pa se odbija. Stopnja absorpcije je odvisna od vrste materiala, od stanja površine materiala, valovne dolžine in intenzivnosti laserske svetlobe. Tako je treba za povečanje absorptivnosti laserske svetlobe (do 80 odstotkov) pri postopkih toplotne obdelave kovinsko površino poprej pripraviti z ustreznim absorpcijskim sredstvom. Kot takšno sredstvo se uporabljajo različni kovinsko-oksidni praški, koloidni grafit, cink fosfat, mangan fosfat in tudi črne barve.

1 IZVEDBA LASERSKEGA KALJENJA ZA DOLOČITEV OPTIMALNE HITROSTI POMIKA OBDELOVANCA

Globina nataljene in kaljene cone je odvisna od parametrov laserskega snopa, od hitrosti pomika obdelovanca in od lastnosti materiala, ki so definirane s toplotno prevodnostjo, gostoto, specifično toploto, in od temperature avstenitizacije oziroma temperature tališča.

Zaradi različne toplotne prevodnosti luskaste in nodularne litine po laserskem kaljenju smo za ugotavljanje optimalne hitrosti pomika laserskega snopa uporabili obdelovance iz sive litine SL200 in nodularne litine NL400. Kemična sestava obeh materialov je podana v preglednici 1. Pri tem pa lahko povemo, da je matrica SL200 perlitna, matrica NL400 pa feritno-perlitna.

Za kaljenje smo uporabili plinski CO_2 laser Iskra LMP600 z močjo 450 W in Gaussovo porazdelitvijo moči, pri čemer je bila izžariščna

The amount of the available energy of the laser beam (at a wave length of 10.6 μm) on the workpiece surface is strongly dependent on the absorptivity of metal materials, and ranges within 2 to 5%, while the remaining amount is reflected back. The rate of absorption is dependent on the kind of material, surface condition, wave length and laser light intensity. Thus to increase the laser light absorptivity (up to 80%) it is necessary to pretreat the metal surface by a suitable absorber. As such we may use various kinds of metal oxide powders, colloidal graphite, zink phosphate, manganese phosphate, as well as black paints.

1 LASER HARDENING TESTS TO DETERMINE OPTIMUM WORKPIECE TRAVELLING SPEEDS

The depth of the melted and hardened zone depends on laser beam parameters, workpiece travelling speed and material properties defined by heat conductivity, density, specific heat and on the temperature of the austenitization or melting point temperature.

On account of the different heat conductivity of the lamelar and nodular casts after laser hardening we used workpieces from gray iron SL200 and nodular iron NL400 in order to establish the optimum laser beam travelling speed. The chemical composition of both materials can be seen from Table 1. In addition it should be mentioned that SL200 has a pearlite matrix and NL400 a ferrite-pearlite one.

To perform the laser hardening, we used a LMP600 CO_2 laser manufactured by Iskra, having a power of 450 W, a Gaussian power distribution

Preglednica 1: *Osnovni podatki o materialu obdelovancev*
Table 1: *Some basic data on workpiece material*

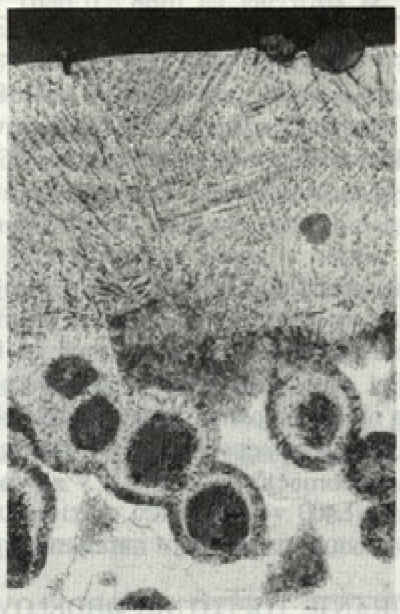
Material	ISO	C (%)	Si (%)	CE (%)	Grafit (%) Graphite (%)	Struktura matrice Matrix structure
SL200	Grade 200	3.40	1.95	4.08	12.88	P
NL400	400 - 12	3.64	2.37	4.44	12.01	F + P

F - ferit/ferrite, P - perlit/pearlite.

razdalja laserskega snopa 10 mm. Preizkus laserske toplotne obdelave z nataljevanjem smo izvedli v območju hitrosti pomikov obdelovanca nasproti laserskemu snopu od 2 do 42 mm/s s korakom 2 mm/s. S tem smo si zagotovili različne vnose energije v površino preizkušanca. Površino preizkušancev pa smo poprej pripravili z absorberjem Zn-fosfat. Na sliki 2 sta prikazani metalografski sliki prečnega prereza lasersko modificirane sledi na SL200 in NL400.

and a defocussing distance of the laser beam of 10 mm. The laser surface melt-hardening tests were carried out in a range of workpiece travelling speeds from 2 to 42 mm/s by increments of 2 mm/s. In this way, different amounts of energy input into the workpice surface were ensured. The surface of the specimens was first pretreated by a Zn-phosphate absorber. Figure 2 shows two metallographs of the modified trace cross-sections of SL200 and NL400.

a) SL200



b) NL400

Sl. 2. *Prečni prerez lasersko modificirane sledi, povečava 100 krat*
Fig. 2. *Cross-section of the modified trace, magnification 100 times*

Za določitev optimalnih obdelovalnih razmer smo izvajali segrevanja z laserskim snopom, tako da smo napravili le enojno sled na obdelovancu. Po določitvi optimalnih obdelovalnih razmer smo izvajali toplotno lasersko obdelavo, ki je zagotovila 30-odstotno prekrivanje nataljenih sledi. Toplotno obdelavo smo izvajali na valjastih vzorcih premera 37 mm in širine 10 mm, s katerimi smo v nadaljevanju izvajali tudi preizkuse obrabne obstojnosti na stroju Amsler.

In order to determine the optimum machining speeds, the heating with the laser beam was done is such a way that only a single trace was made on the workpiece. Once the optimum heat treatment conditions had been defined, the rest of the laser heat treatment was done so that a 30% overlapping of the melted trace was ensured. The heat treatment was performed on roller specimens with a diameter of 37 mm and a width of 10 mm, suitable also for subsequent wear resistance tests which were performed on an Amsler machine.

Na sliki 2 lahko ugotovimo, da v prečnem prerezu sledi lasersko obdelane litine razlikujemo tri glavne cone:

a) osnovni material,

b) kaljeno cono:

– pri NL400 jo sestavljajo martenzit, zaostali avstenit, ferit in grafit v obliki nodulov, katere obdajajo martenzitne lupine,

– pri SL200 jo sestavljajo martenzit, zaostali avstenit in grafit v obliki lusk,

c) nataljeno cono, sestavljeno iz dendritov avstenita, ledeburita, posameznih grobih martenzitnih iglic in neraztopljenega grafita, kar smo potrdili z difrakcijo žarkov X (preglednica 2).

From Figure 2 we can see that in the modified trace of the laser machined cast it is possible to distinguish three main zones:

a) basic material,

b) hardened zone:

– in NL400 consisting of martensite, residual austenite, ferrite and graphite nodules surrounded by martensitic shells,

– in SL200 consisting of martensite, residual austenite and flake graphite,

c) melted zone consisting of austenite dendrites, ledeburite, individual coarse martensite needles and undissolved graphite, which was confirmed by X-ray difraction (Table 2).

Preglednica 2: *Rezultati fazne analize lasersko nataljene površine na sivi litini SL200 in nodularni litini NL400, ki so izraženi v volumskih deležih*

Table 2: *Phase analysis results of the laser-melted surface on SL200 gray iron and NL400 nodular iron, expressed in volume parts*

Material	C_γ - avstenit austenite	C_α - martenzit martensite	M_3C	Fe_3O_4	Grafit Graphite
SL200	28	20	46	6	/
NL400	34	28	26	7	5

Hitrosti pomikov obdelovanca pod 18 mm/s pri SL200 niso priporočljive zaradi pojavov poroznosti, pri hitrostih pomikov, manjših od 16 mm/s, pride do brazdanja površine. Povsod v območju nataljevanja so problem razpoke. Pri NL400 teh problemov ni nikjer v območju hitrosti, ki smo jih uporabili pri preizkusu. V kaljenem območju nodularne litine so nastale martenzitne lupine okrog nodulov grafita, ki pozitivno vplivajo na lastnosti sledi [1]. Pri obeh materialih je jedkalo počasneje vplivalo na nataljeno območje, zato lahko sklepamo, da se je korozijska odpornost površine izboljšala. V nataljenem območju se je grafit v glavnem raztopil, le pri NL400 včasih lahko opazimo ujete neraztopljene nodule na površini nataljenega področja.

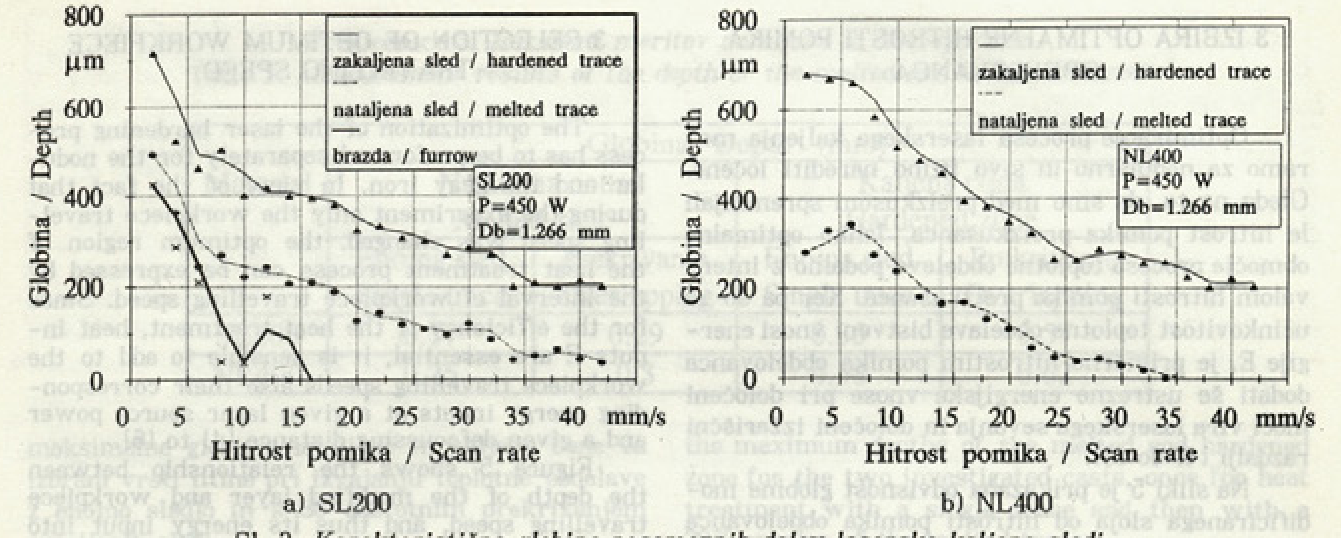
On SL200, workpiece travelling speeds below 18 mm/s are not recommendable because of the occurrence of porosity, while at travelling speeds lower than 16 mm/s an occurrence of furrows can be noted. Another problem everywhere in the melting range is cracking. In NL400 these problems were not noted in the range of speeds that were used in the experiment. In the hardened region of this material, martensitic shells were formed around the graphite nodules having a positive effect on the properties of the trace [1]. In both materials, a slower etching agent effect on the melted region was noted, leading to the conclusion that the corrosion resistance of the surface was improved. In the melted range the graphite was dissolved to a considerable extent; only in NL400 we may find some undissolved nodules caught on the surface of the melted region.

2 OPTIMIRANJE TOPLOTNIH OBDELOVALNIH POGOJEV

Na sliki 3 je prikazano spreminjanje globine enojne laserske sledi v odvisnosti od hitrosti pomika laserskega snopa. Pri SL200 na sliki 3a se lepo vidi, da so hitrosti pomika laserskega snopa neprimerne, če so le te manjše od 16 mm/s. V teh primerih se energijski vnos v obdelovanec toliko poveča, da v sredini površine sledi nastajajo brazde, ki zmanjšujejo uporabnost nastalega površinskega sloja. Nasprotno pa pri hitrostih pomika laserskega snopa, večjih od 30 mm/s, dobimo globine toplotno vplivnih con, ki so manjše od 0,3 mm in ne ustrezajo našim zahtevam o minimalni doseženi globini modificiranega sloja. Pri NL400 je

2 OPTIMIZATION OF HEAT TREATMENT CONDITIONS

In Figure 3 we can see the changing depth of a single laser trace as a function of the laser beam travelling speed. In SL200, Fig. 3a, we can clearly see that the laser beam travelling speeds are unsuitable if they are lower than 16 mm/s. In these cases the energy input into the workpiece is too high, resulting in the formation of furrows in the middle of the trace surface, and thus lowering the applicability of the created surface layer. Conversely, at laser beam travelling speeds higher than 30 mm/s we get hardened zone depths that are lower than 0.3 mm and do not meet the requirements for a minimum achieved depth of the modified layer. In NL400, the achieved trace surface



Sl. 3. *Karakteristične globine posameznih delov lasersko kaljene sledi glede na različne hitrosti pomika obdelovanca*

Fig. 3. *Characteristic depths of the particular areas of the laser hardened trace versus different workpiece travelling speeds*

dosežena površina sledi lepo gladka pri vseh hitrostih pomika laserskega snopa. Globina kaljene cone (sl. 3b) je manjša od 0,3 mm že pri hitrostih pomika obdelovanca, ki so večje od 25 mm/s.

Globino lasersko kaljene sledi lahko predstavimo tudi v odvisnosti od vnosa energije E v površino obdelovanca, kar je lepo prikazano na sliki 4. Pri obeh materialih je opazna parabolična usmeritev odvisnosti globine kaljenja od vnosa energije E. Vnos energije E je definiran [2]:

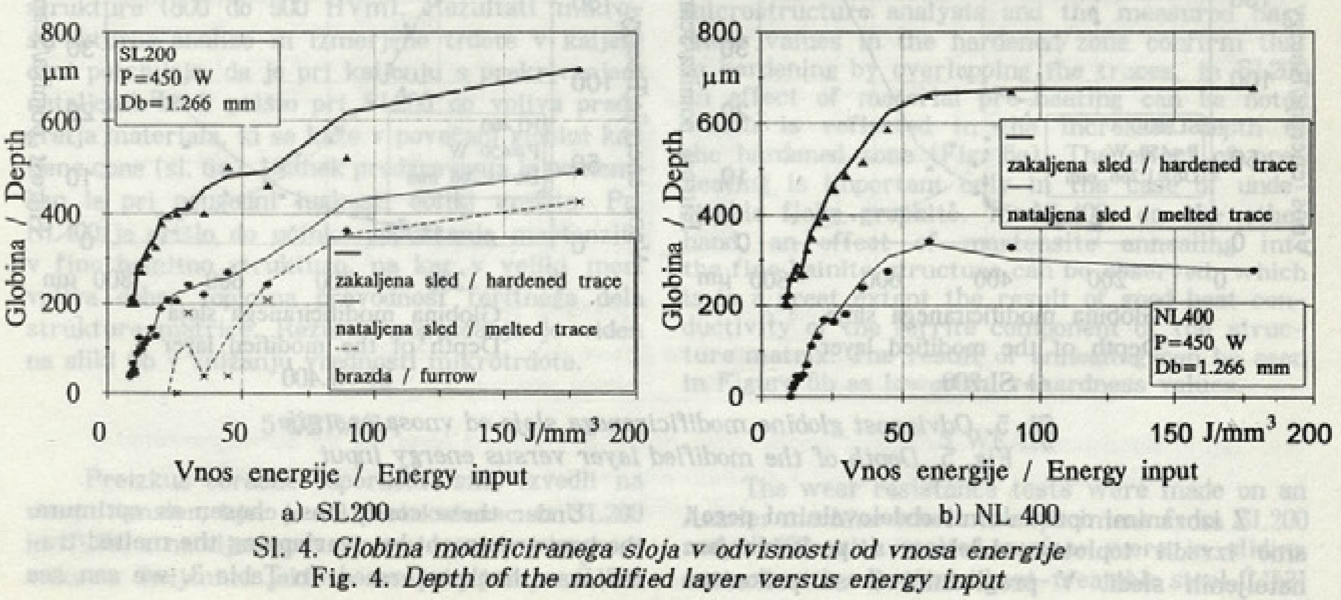
is quite smooth at all laser beam travelling speeds. However, the depth of the hardened zone (Fig. 3b) is lower than 0.3 mm as early as at workpiece travelling speeds higher than 25 mm/s.

The depth of the laser-hardened trace can be presented also as a function of the energy input E into the workpiece surface, as clearly shown in Fig. 4. In both materials we may note a parabolic trend of dependence of the hardened depth on the energy input E. The energy input E is defined as [2]:

$$E = \frac{4\ P}{\pi v_b\ D_b^2} \quad (\mathrm{J/mm^3}) \qquad (1),$$

to je moč laserskega snopa na projekcijo prostornine, pri čemer so: v_b – hitrost laserskega snopa, D_b – premer laserskega snopa na površini obdelovanca in P – moč laserja.

that is the power of laser beam per volume projection, where: v_b – laser beam speed, D_b – laser beam diameter on the workpiece surface and P – laser power.



Sl. 4. *Globina modificiranega sloja v odvisnosti od vnosa energije*

Fig. 4. *Depth of the modified layer versus energy input*

3 IZBIRA OPTIMALNE HITROSTI POMIKA OBDELOVANCA

Optimiranje procesa laserskega kaljenja moramo za nodularno in sivo litino narediti ločeno. Glede na to, da smo med preizkusom spreminjali le hitrost pomika preizkušanca, lahko optimalno območje procesa toplotne obdelave podamo z intervalom hitrosti pomika preizkušanca. Ker pa so za učinkovitost toplotne obdelave bistveni vnosi energije E, je primerno hitrostim pomika obdelovanca dodati še ustrezne energijske vnose pri določeni moči vira laserskega sevanja in določeni izžariščni razdalji [4] do [6].

Na sliki 5 je prikazana odvisnost globine modificiranega sloja od hitrosti pomika obdelovanca in s tem od vnosa energije v površino.

Na podlagi ocenjenih kriterijev smo določili za SL200 optimalno hitrost pomika laserskega snopa v_b = 24 mm/s in s pripadajočim vnosom energije E = 15 J/mm³. V takih razmerah toplotne obdelave z nataljevanjem površine dosežemo, da globina modificiranega sloja ne pade pod 0,3 mm, prav tako pa je sama površina modificiranega sloja precej ravna brez brazdavosti.

V primeru toplotne obdelave NL400 lahko ugotovimo, da pade globina modificiranega sloja pod 0,4 mm pri hitrostih pomika laserskega snopa v_b = 18 mm/s oziroma pri vnosu energije E = 20 J/mm³. Ker mikrostrukture na posameznih mestih sledi niso kazale motečih dejavnikov, prav tako pa smo dobili gladko površino nataljene sledi, smo ocenili, da so navedene obdelovalne razmere optimalne [7], [8].

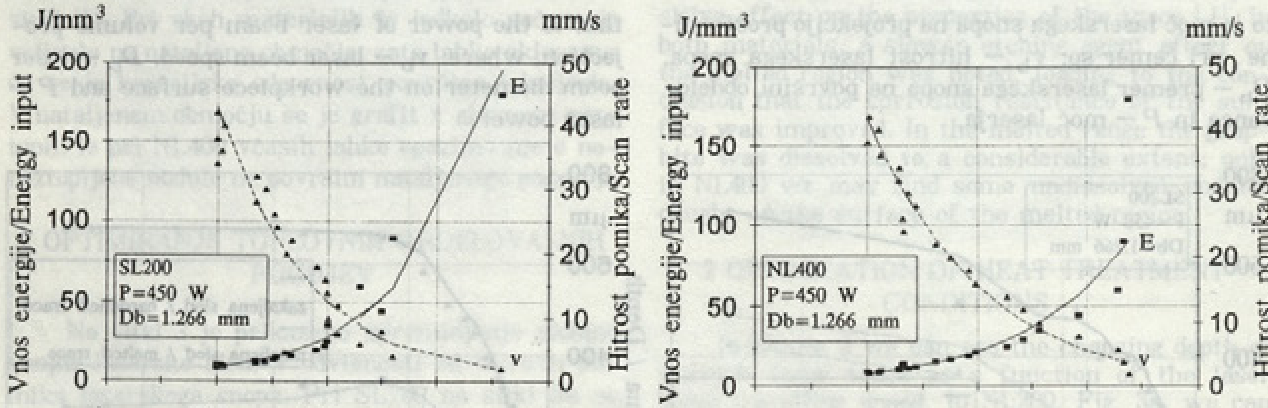
3 SELECTION OF OPTIMUM WORKPIECE TRAVELLING SPEED

The optimization of the laser hardening process has to be performed separately for the nodular and the gray iron. In view of the fact that during the experiment only the workpiece travelling speed was changed, the optimum region of the heat treatment process can be expressed by the interval of workpiece travelling speed. Since for the efficiency of the heat treatment, heat inputs E are essential, it is sensible to add to the workpiece travelling speeds also their corresponding energy inputs at a given laser source power and a given defocussing distance [4] to [6].

Figure 5 shows the relationship between the depth of the modified layer and workpiece travelling speed, and thus its energy input into the surface.

On the basis of the assessed criteria we defined, for SL200, the optimum laser beam speed to be v_b = 24 mm/s with a corresponding energy input of E = 15 J/mm³. In these laser surface melt-hardening conditions it can be ensured that the modified layer depth does not fall below 0.3 mm while at the same time the surface of the modified layer itself is fairly smooth and without any furrows.

In the case of NL400 we can note that the depth of the modified layer falls below 0.4 mm at a laser beam speed v_b = 18 mm/s or at an energy input of E = 20 J/mm³. Since the microstructures at the particular places did not display any irregularities, while at the same time the surface of the melted layer was smooth, it was assessed that the above mentioned heat treatment conditions are optimal [7], [8].



a) SL200 b) NL400

Sl. 5. *Odvisnost globine modificiranega sloja od vnosa energije*

Fig. 5. *Depth of the modified layer versus energy input*

Z izbranimi optimalnimi obdelovalnimi pogoji smo izvedli toplotno obdelavo s prekrivanjem nataljenih sledi. V preglednici 3 so prikazane

Under these conditions, chosen as optimum, the heat treatment by overlapping the melted traces was then performed. In Table 3, we can see

Preglednica 3: *Rezultati meritev nataljene in kaljene cone*
Table 3: *Measurement results of the depth of the melted and hardened zones*

Material	Globina / Depth (mm)			
	Nataljena cona Melted zone		Kaljena cona Hardened zone	
	Enojna sled Single trace	Prekrivanje Overlapping	Enojna sled Single trace	Prekrivanje Overlapping
SL200	0.17	0.29	0.35	0.57
NL400	0.25	0.3	0.58	0.62

maksimalne globine nataljene in kaljene cone za izbrani vrsti litine pri izvajanju toplotne obdelave z enojno sledjo in s 30-odstotnim prekrivanjem nataljenih sledi.

Zbrani podatki v preglednici 3 potrjujejo, da so globine nataljene cone in kaljene cone večje v primerih, ko izvajamo toplotno obdelavo s prekrivanjem nataljenih sledi. Izjemno velike razlike se pojavijo v sivi litini z luskastim grafitom, kar pripisujemo vplivom predgrevanja materiala, ki ublažijo neugoden vpliv luskaste oblike grafita na toplotno prevodnost.

4 TRDOTA

Z meritvami mikrotrdote smo dokazali uspešnost laserskega kaljenja z nataljevanjem površine in potrdili strukturne spremembe v materialu. V nataljenem sloju se trdota giblje v območju med 700 in 1100 HVm. Z metalografsko analizo smo potrdili, da je povečana trdota posledica fine disperzije cementita v ledeburitu. V kaljenem območju se je povečala trdota le delu matrice, ki je pred obdelavo imel perlitno strukturo, in sicer na vrednosti okoli 830 HVm. Trde lupine okrog grafitnih nodulov v NL400 imajo trdoto martenzitne strukture (800 do 900 HVm). Rezultati mikrostrukturne analize in izmerjene trdote v kaljeni coni potrjujejo, da je pri kaljenju s prekrivanjem nataljenih sledi prišlo pri SL200 do vpliva predgretja materiala, ki se kaže v povečani globini kaljene cone (sl. 6a). Učinek predgrevanja je pomemben le pri neugodni luskasti obliki grafita. Pri NL400 je prišlo do učinka popuščanja martenzita v fino bainitno strukturo, na kar v veliki meri vpliva dobra toplotna prevodnost feritnega dela strukture matrice. Rezultat popuščanja je viden na sliki 6b v znižanju vrednosti mikrotrdote.

5 OBRABA

Preizkus obrabne odpornosti smo izvedli na stroju Amsler, kjer je bil preizkušanec iz SL200 in NL400 z nataljeno površino v drsnem mazanem stiku s kaljenim jeklom za poboljšanje Č1531

the maximum depths of the melted and hardened zone for the two investigated casts, once for heat treatment with a single trace and then with a 30% overlap of the melted traces.

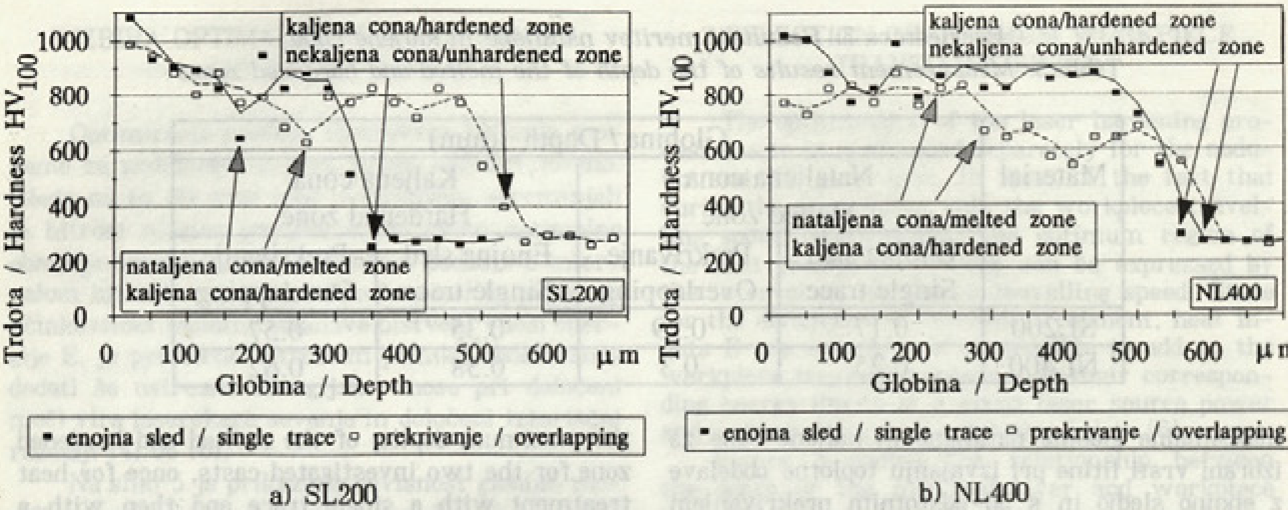
The data gathered in Table 3 confirm that the depth of the melted zones and the hardened zones are greater in cases when heat treatment is done by overlapping the melted traces. Extremely big differences occur in the gray iron with flake graphite, which is attributed to material preheating effects that lessen the detrimental effects of flake graphite on heat conductivity.

4 HARDNESS

The measurements of microhardness have proved the success of the laser surface melt-hardening method and confirmed the structural changes in the material. In the melted layer the hardness ranges within 700 and 1100 HVm. The metallographical analysis has shown that the increased hardness is a result of the fine dispersion of cementite in ledeburite. In the hardened region hardness increased only in the part of the matrix, which before the heat treatment had a pearlite structure, i.e. around a value of 830 HVm. Hard shells around the graphite nodules in NL400 have a martensite structure hardness (800 to 900 HVm). The results of the microstructure analysis and the measured hardness values in the hardened zone confirm that in hardening by overlapping the traces, in SL200 an effect of material pre-heating can be noted which is reflected in the increased depth of the hardened zone (Fig. 6a). The effect of preheating is important only in the case of undesirable flake graphite. In NL400, on the other hand, an effect of martensite annealing into the fine bainite structure can be observed, which is to a great extent the result of good heat conductivity of the ferrite component of the structure matrix. The result of annealing can be seen in Figure 6b as lower microhardness values.

5 WEAR

The wear resistance tests were made on an Amsler machine where the specimens from SL200 and NL400 with melted surface were in sliding contact with a hardened heat-treatable steel Č1531



Sl. 6. *Rezultati meritev mikrotrdote materiala modificiranega sloja na obdelovancu pri enojni sledi in pri več sledeh s prekrivanjem nataljenih sledi*

Fig. 6. *The results of the microhardness measurements in the modified layer on the workpiece for a single trace and for overlapped traces*

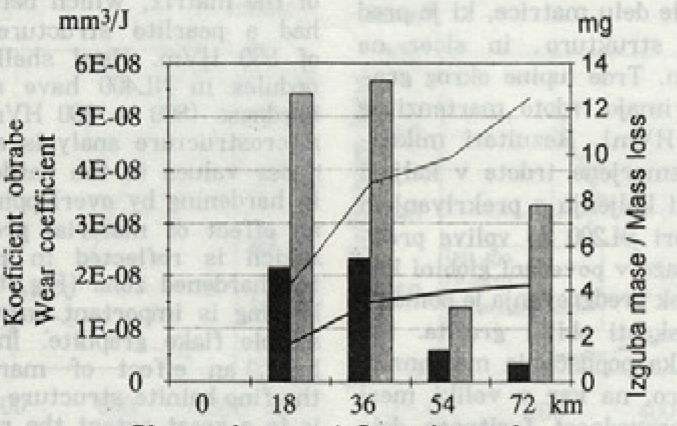
(Ck 45 – standard ISO) s trdoto 920 HVm. Normalna sila obremenjevanja je bila 700 N pri drsnem pritisku 7 MN/m². Obrabno odpornost preizkušancev smo prikazali z meritvami izgube mase in z določitvijo obrabnega koeficienta *k*, ki je definiran takole [3]:

(ISO Ck 45) with a hardness of 920 HVm. The normal loading force was 700 N at a sliding pressure 7 MN/m². The wear resistance of the specimens was established by measuring mass losses and by defining the wear coefficient defined as [3]:

$$k = \frac{W}{F_N\, s} \quad (\mathrm{mm^3/J}) \qquad (2),$$

kjer so: W – prostornina obrabe (mm³), F_N – pritisna sila (N), s – obratovalna pot (m).

where: W – volume of wear (mm³), F_N – pressure force (N), s – operating path (m).



Sl. 7. *Izguba mase in koeficient obrabe litin SL200 in NL400 z lasersko nataljeno površino s prekrivanjem nataljenih sledi v drsnem kontaktu s kaljenim jeklom za poboljšanje Č1531 (ISO Ck45)*

Fig. 7. *Mass loss and wear coefficient of SL200 and NL400 with a laser melted surface by overlapped traces in sliding contact with a hardened steel Č1531 (ISO Ck45)*

Na sliki 7 so grafično predstavljeni rezultati o nakopičeni izgubi mase in o vrednostih izračunanih koeficientov obrabe glede na spreminjanje obratovalne poti. Trdota nataljene površine je pri SL200 za skoraj 100 HVm večja kakor pri NL400, kar se močno kaže na obrabni odpornosti. Zato se NL400 bolj obrablja kakor SL200. Pri obeh litinah se obrabni koeficient po začetni dobi utekanja občutno zmanjša in je v vseh primerih mnogo manjši od dovoljenega, ki ga priporoča strokovna literatura za strojne dele ($k < 10^{-6}$ mm^3/J [4]). Zato lahko sklenemo, da se obe vrsti litin po kaljenju z laserskim snopom ugodno obnašata v obratovalnih razmerah za obravnavano drsno dvojico.

Figure 7 is a bar chart illustrating the results of cumulative mass losses and calculated values of wear coefficients as a function of the operating path. The hardness of the melted surface of SL200 is almost by 100 HVm higher than that of NL400, as is strongly reflected in wear resistance. Therefore NL400 wears down more than SL200. In both casts, after the initial running-in period, the wear coefficient drops substantially and is in all cases much lower than the allowable one recommended in the professional literature for machine parts ($k < 10^{-6}$ mm^3/J, [4]). Thus we can conclude that both kinds of laser hardened casts behave favourably in the operating conditions of the sliding couple.

6 SKLEPI

Eksperimentalni rezultati so potrdili, da lahko z laserskim snopom majhne moči dosežemo zadostno debelino modificiranega sloja, če kalimo z nataljevanjem površinskega sloja. Siva litina je zaradi morfologije grafita zelo zahtevna za toplotno obdelavo, saj dolge luske zadržijo veliko toplotne energije na površju in s tem bistveno spremenijo temperaturne razmere v materialu. To se kaže v manjši globini modificiranega sloja in slabši kakovosti nataljene površine. Povišana trdota nataljene in kaljene cone (do 1000 HVm) pa bistveno poveča obrabno odpornost površine. Dobljeni koeficienti obrabne odpornosti oziroma izgube mase potrjujejo, da se siva litina v kombinaciji z jeklom Č 1531 (ISO Ck45) znatno bolje obnaša kakor nodularna litina. To potrjujemo predvsem z višjo trdoto površine po laserskem kaljenju. Žal pa smo ugotovili, da je siva litina z luskastim grafitom bistveno bolj zahtevna glede določevanja optimalnih pogojev kaljenja z nataljevanjem površine. Glavni vzroki za to so nastajanje brazdavosti nataljenega sloja in morebitnih razpok v njem, ki se pojavljajo med procesom ohlajanja.

6 CONCLUSIONS

The experimental results have confirmed that a low-power laser beam can achieve a sufficiently thick modified layer provided that hardening is performed by surface layer melting. Gray iron, due to its graphite morphology, is very difficult to heat treat since long graphite flakes hold back a great deal of heat energy on the surface and thus essentially change the temperature conditions in the material. This is reflected in a lower depth of the modified layer and poorer quality of the melted surface. The increased hardness of the melted and hardened zone (up to 1000 HVm) substantially increases the wear resistance of the surface. The obtained wear coefficients or mass losses otherwise confirm that gray iron in pair with Č1531 (ISO Ck45) behaves in a much better way than the nodular iron. This is explained mainly by the greater hardness of the surface after laser hardening. Yet we were disappointed to find that gray iron, due to flake graphite, is a much more demanding material in terms of determining the optimum conditions of surface melt-hardening. The main reason for this is the occurrence of furrows in the melted layer and possible cracking during the process of cooling.

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7 REFERENCES

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