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Analysis of Heat-Affected Zone Depth of Sample Surface at Electrical Discharge Machining with Brass Wire Electrode

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Ključne riječi

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The article deals with detailed evaluation of the depth of heat-affected zone in sub-surface layers of the samples made by technology of wire electrical discharge machining with brass electrode. It is vital to remark at the beginning that the heat impact is an undesirable phenomenon from the standpoint of operating life of parts produced by this progressive technology. Considerable depth of heat-affected zone, its characteristic, and its uneven course along cross-section, noticeably contributes to the decrease of quality and longevity of machine parts, as well as cutting tools. The samples were produced on electroerosion machine *AGIECUT* from tool steel of 950 MPa strength. Applied cutting tool was wire brass electrode of 0,25 mm diameter. To determine suitable *HAZ* depth measuring method, it was necessary to take into account properties of the given technology where impact and consecutive micro-hardness change occurs instantly after high temperature spot effect of electric discharge channel which arises between wire electrode (cutting tool) and material (workpiece) during intensive cooling in dielectric medium. Considering this aspect, the influence shows different values in longitudinal and lateral cross-sections (as of wire electrode movement relatively to the workpiece). The course of the values is in the same time greatly affected by combination of technological parameters that inevitably must observe electroerosion cutting process itself, as well as electro-chemical properties of the material. The aim of this paper is to describe the real course of micro-hardness in particular cross-sections and to give recommendations concerning adjustment of main technological parameters so as to achieve HAZ homogenity along the whole cut.

Analiza dubine toplinski pogođene zone površine uzorka kod strojne obrade električnim pražnjenjem s mesinganom žičanom elektrodom

Izvornoznanstveni članak

Članak se bavi detaljnom procjenom dubine toplinski pogođene zone u pod-površinskim slojevima od uzoraka izrađenih pomoću tehnologije strojne obrade žičanim električnim pražnjenjem upotrebom mesingane elektrode. Važno je napomenuti na početku da je utjecaj topline nepoželjan fenomen sa stajališta operativnog života dijelova proizvedenih od strane ove progresivne tehnologije. Znatna dubina toplinski pogođene zone, njene karakteristike i neujednačena putanja duž presjeka, primjetno doprinosi smanjenju kvalitete i dugovječnosti strojnih dijelova, kao i alati za rezanje. Uzorci su proizvedeni na elektro-erozivnom stroju AGIECUT od alatnog čelika snage od 950 MPa. Primijenjeni rezni alat bila je žica tj. mesingana elektroda promjera od 0,25 mm. Za određivanje prikladne mjerne metode za dubinu toplinski pogođene zone bilo je potrebno uzeti u obzir svojstva dane tehnologije gdje su uzastopne promjene i utjecaji u mikro-tvrdoći nastali istovremeno poslije efekta točke visoke temperature kanala električnog pražnjenja koji nastaje između elektrode žice (reznog alata) i materijala (obradak) tijekom intenzivnog hlađenja u dielektričnom mediju. S obzirom na ovaj aspekt, utjecaj pokazuje različite vrijednosti u uzdužnim i poprečnim presjecima (kao pokretima žičane elektrode u odnosu na obradak). Kretanje vrijednosti je u isto vrijeme uvelike pod utjecajem kombinacije tehnoloških parametara koji neizbježno moraju promatrati proces samog rezanja elektro-erozijom, kao i elektro-kemijska svojstva materijala. Cilj ovog rada je opisati stvarni tijek mikro-tvrdoće posebnim presjecima, te dati preporuke vezane uz prilagođavanje glavnih tehnoloških parametara na način da se postigne homogenost toplinski pogođene zone duž cijelog reza.

Symbols/Oznake

I	- working cutting current, A - radna rezna struja	x	- independent variable - neovisna varijabla
t	- ON-time pulse, µs - ON-vrijeme impulsa	A	- matrix of coefficients - matrica koeficijenata
t_d	- OFF-time pulse, µs - OFF-vrijeme impulsa	M_s	- brass - mesing
H	- thickness of material, mm - debljina materijal	*WEDM*	- wire electrical discharge machining - žica električnog pražnjenja strojna obrada
h_{HAZ}	- *HAZ* depth, µm - dubina toplinski pogođene zone	*HV*	- hardness Vickers - tvrdoća prema Vickers-u
h_s	- assumed *HAZ* depth, µm - pretpostavka toplinski pogođene zone	*HRC*	- hardness Rockwell - tvrdoća prema Rockwell-u
α	- angle of metallographic section, ° - kut metalografske sekcije	*HAZ*	- heat affected zone - toplinski pogođena zona
y	- function value, dependent variable - funkcija vrijednosti, zavisna varijabla	*IK*	- correlation coefficient - koeficijent korelacije

1. Introduction

Lately, the complexity of the set of surface characteristics has been accepted. These are not always practically identified in coupling with technological processes of various materials and material changes that take place in material surface layer during plastic deformation and under high-temperature field impact. The task of the research is to contribute to understanding of the processes that occurs in *WEDM*, the aim is formulation of relation in coupling with processes. Electroerosion process belongs to thermal processes where certain structural changes under cut material surface can be expected. An essential parameter which defines surface quality of the workpiece in *WEDM* is depth and course of heat affected zone. It must be pointed out that heat influence on workpiece surface during electroerosion cutting is in most cases undesirable. The *HAZ* depth and its course are closely tied to operating life of components produced by this progressive technology. Shear tools are exceptionally liable to this effect where undesirable *HAZ* influence can decrease operating life by 20 %. The unwanted effect is caused by a so-called *white layer* that is formed by the structure after secondary hardening as a result of electroerosion process. Nevertheless, we should be cautious concerning this statement too, since certain analyses of *white layer* properties draw attention to the fact that in some phase of a part´s operating life the *white layer* can possibly have a positive effect on operation properties and surface functionality. Understanding and consecutive control of the process would make it possible to create surface layers with pre-defined quality. In all other cases, the *white layer* is characterized as an adverse phenomenon that indicates intensive high temperature impact on the surface. Following rapid cooling together with extreme or even critical adjustment of technological parameters of *WEDM* cutting can lead to creation of burn-off cracks. Hardened steels are especially susceptible to burn-off cracks (including implemented samples material). In these steels there are always certain amounts of retained austenite which is plastic. During *WEDM* cutting of these steels, dislocations concentrate mostly in the austenitic phase creating thus favourable conditions for micro and macro crack formation.

2. Characteristic of samples´ eroded surface

The quality of achieved eroded surface is comparable with surface quality obtained by the finest planar grinding machines. Surface quality evaluation is a complex process, so in order to keep it objective, it is necessary to take into account specific properties of *WEDM* technology [3]. Evaluated parameters are roughness, surface hardness variability and *HAZ* depth. Experimental cuts were produced by wire electroerosion cutter machine AGIECUT DEM 200 (Figure 1).

The surface after electroerosion is matte; nevertheless it renders the same roughness as glossy surfaces. High quality of surface is favourably influenced by conductibility of the material and its melting point temperature. Concerning high hardness and strength of applied material, no negative changes of surface quality (such as increased *HAZ* depth) were observed. Discharge plasma channel with high density and high temperature caused structural change of basic material surface, whilst integrity of the material was retained. The melted layer contains fractions of hydrogen, oxygen, and small melted-off particles from brass electrode (Figure 2).

Figure 1. Wire electroerosion cutter machine AGIECUT DEM 200

Slika 1. Stroj za elektro-erozivno rezanje žicom AGIECUT DEM 200

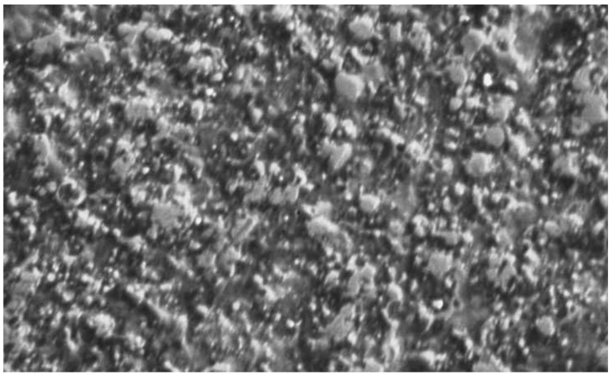


Figure 2. Sample surface after electroerosion cutting process (500 × magnification)

Slika 2. Površinski uzorak nakon elektro-erozivnog procesa rezanja (500 × uvećanje)

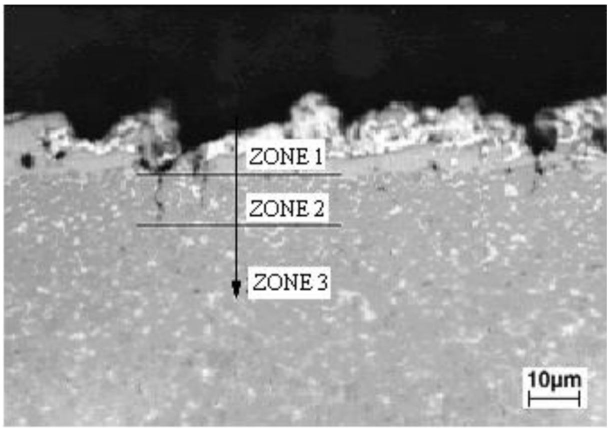


Figure 3. Heat affected zone of the sample after WEDM cutting

Slika 3. Toplinom pogođene zone uzorka nakon rezanja strojnom obradom žičanim električnim pražnjenjem

Figure 2 responds to the first cut condition. The presence of generating carbides increases hardness and fragility of surface layer. Under the melting surface layer there is a heat-affected zone in which structural changes take place [1].

The depth of *HAZ* depends on the initial structure of cut material, on character of phase changes that took place during the process, and on a combination of cutting parameters. Overall depth of impact on yet unmachined surface ranges from 10 to 30 μm [2].

3. Preparation of experimental samples

Experimental samples were made from steel EN ISO 9679 X210 CR12 (STN 19 436). It is chrome steel with 0,2 % C and 12 % Cr, used for production of moulds and cold-shearing tools. Before electroerosion cutting the metal block was oil-hardened to approx. 64 HRC from 950 °C and then tempered at 220 °C to approx. 61 HRC, in order to eliminate internal stress which emerged in hardening process [8].

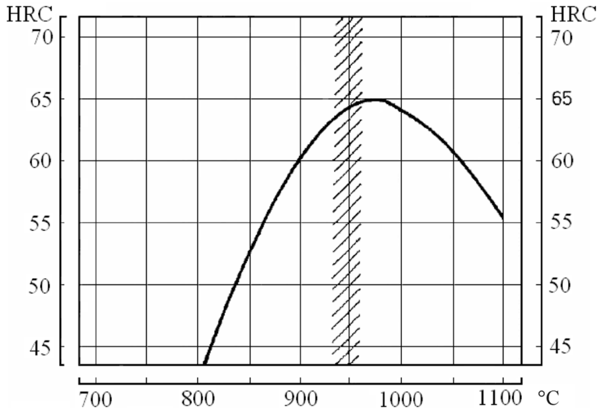


Figure 4. Hardening diagram of steel **EN ISO 9679 X210 CR12**

Slika 4. Kaljenje dijagram čelika **EN ISO 9679 X210 CR12**

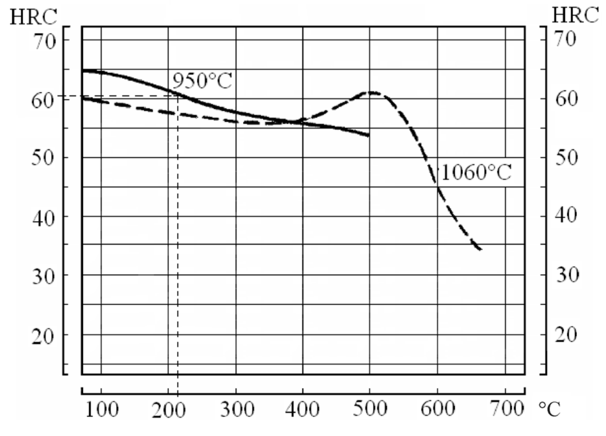


Figure 5. Tempering diagram of steel **EN ISO 9679 X210 CR12**

Slika 5. Temperiranje dijagram čelika **EN ISO 9679 X210 CR12**

Before experimental measurements, it was necessary to deprive the oxidation layer (rust) from eroded samples´ surface. This was done chemically, the samples were immersed in solution based on concentrated phosphoric acid (H_3PO_4 of 90 % concentration) and Armohib 25 stain solution at constant temperature 20 °C. To ensure accurate measurements, it was necessarty to remove brass deposit from the surface of the samples which originated from wire electrode. The deposit was removed by spraying solution of water and concentrated ammonia (0,9 g/cm^3) with ratio (water : ammonia = 9 : 1) plus additives – ammonium persulphate (0,2 g to 10 cm^3 of solution), and sodium phosphate (0,1 g to 10 cm^3 of solution). Remnants of etched-out layer were then removed from the surface by blasting with glass balls of 50 μm diameter and spot load of blasting balls for approximately 3 s on cm^2 of sample surface. The blasting nozzle was 40 mm distance from sample surface at 30 ° angle [9].

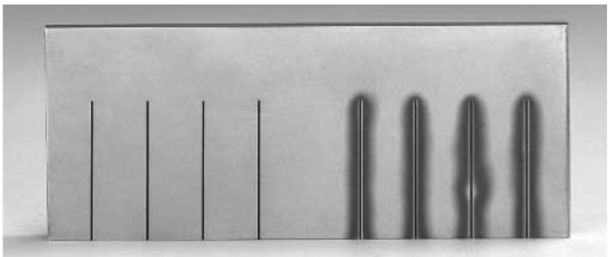
4. Influence of main technological parameters on the quality of the cut

The main technological parameters that considerably influence cut quality (from the view of *HAZ* depth) are working cutting current, duration of electric discharge and pause for renewal of the discharge channel (called OFF-time pulse). An influence of these parameters on *HAZ* quality together with range of their adjustments applied in experiment are shown in Table 1 [5].

The following figures document the influence of current pulse duration on roughness, cutting gap width (and consecutive *HAZ*) whereas higher current values cause higher cutting speed, increased quality surface roughness and wider cutting gap [6].

5. Methodology of experimental measurement

The character of *HAZ* depends significantly on implemented technique, applied power and adjustment of cutting process technological parameters. Maximum influence range appears at power (stock) cuts, the least effect is at fine (finishing) cuts. Experimental values of depth and degree of *HAZ* can be determined by micro-hardness measurement in affected zone on the sample surface. In *HAZ* evaluation it is very important to respect possible scattering of micro-hardness values with regard to cut material structure. Since micro-hardness course is not identical along the whole cut, a methodology was proposed for measurements in several planes near each other in different directions, while in every depth the mean micro-hardness value is to be determined.



a) b)

Figure 7. Influence of working cutting current on HAZ

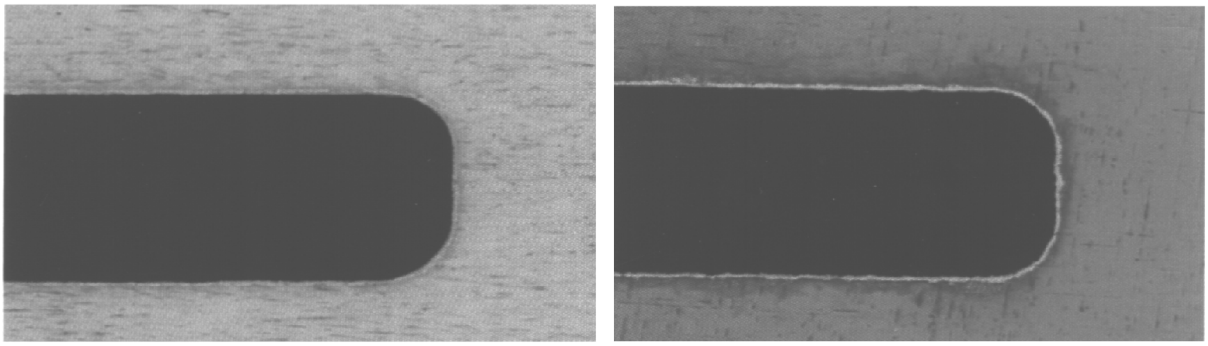
Slika 7. Utjecaj radne struje rezanja na toplinski pogođenu zonu

Table 1. Basic technological parameters influencing micro-hardness and their adjustment ranges applied in experiment

Tablica 1. Osnovni tehnološki parametri koji utječu na mikro-tvrdoće i njihovu prilagodbu raspona primijenjenu u eksperimentu

Technological parameter / Tehnološki parametar	Adjustment range of technological parameters / Prilagodba raspona tehnoloških parametara		Influence on HAZ / utjecaj na toplinski pogođene zone
	for material thickness 10 mm / za materijal debljine 10 mm	for material thickness 100 mm / za materijal debljine 100 mm	
Working cutting current "*I*", A / Struja reznog rada	0,3 ÷ 5,8	2,5 ÷ 8,25	With increasing current value, surface roughness grows, cutting gap is extended and depth of heat-affected zone grows. / Sa povećanjem strujne vrijednosti površinska hrapavost raste, rezni razmak proširuje i dubinu zone pod toplinskim utjecajem.
ON time pulse "*t*", μs / ON vrijeme impulsa	1,5 ÷ 7	0,2 ÷ 8	With "*t*" increase roughness grows, cutting gap is extended, cutting speed and *HAZ* increases. / S "*t*" povećava se hrapavost, povećava se rezana rupa, te se povećava brzina rezanja i toplinski pogođena zona.
OFF time pulse "t_d", μs / OFF vrijeme impulsa	1 ÷ 4	0,1 ÷10 μs	With growing "t_d" shape inaccuracy appears and *HAZ* is degraded / S rastućim "t_d" pojavljuje se oblik netočnosti i degradira se toplinski pogođena zona.

Considering the small depth of *HAZ*, a certain problem with micro-hardness measuring method arose. The best method which respects specifics of this progressive technology appears to be the method of oblique section. In order to achieve accurate results, it was necessary to produce metallographic polished section at a very small angle because *HAZ* depth ranges from 10 to 30 μm.



a) short pulse duration b) long pulse duration

Figure 6. Influence of pulse duration on HAZ: a) low value of discharge current; b) high value of discharge current

Slika 6. Utjecaj trajanja impulsa na toplinski pogođenu zonu: a) niska vrijednost struje izbijanja; b) visoka vrijednost struje izbijanja

Measurement was done on metallographic polished section at angle α, the stab distance from the surface was established by the formula [9]:

$$h = h_s \cdot \sin \alpha, \tag{1}$$

where: h_s - assumed *HAZ* depth, μm,

α - angle of metallographic section, °.

In *HAZ* observation, stabs were done by steps from an edge of the section to material interior until micro-hardness value stabilized on its constant value equal to basic material hardness 750 HV2. In order to respect surface micro-profile, and micro-hardness course, the measuring stabs were done in three lines at identical distance from the real surface.

6. Experimental measurement of *HAZ* size

Because of high hardness value of basic material, it was not possible to apply Vickers micro-hardness test. At Vickers test applied loads range from 0,098 N to 0,98 N which is insufficient for the given basic material hardness. This method can be used for micro-hardness measurement up to 464 HV0,1 that equals Rockwell hardness of approximately 45 HRC. Basic material was hardened to 61 HRC therefore low load Vickers hardness test according ISO 6507 was applied on the device HPO 250 Vickers Hardness Tester. Applied load at test was 19,61 N for hardness HV2 [10].

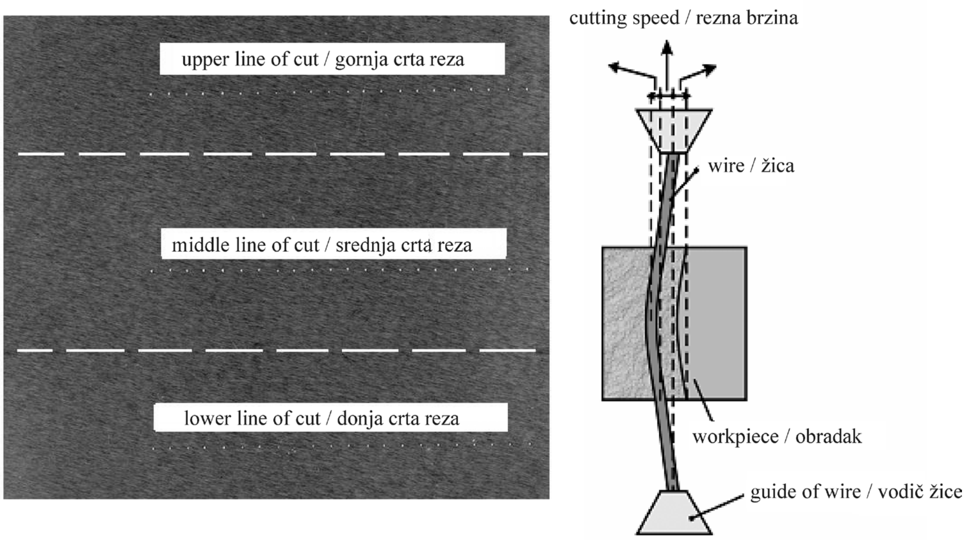


Figure 8. Experimental measurement of HAZ depth

Slika 8. Eksperimentalno mjerenje dubine toplinski pogođene zone

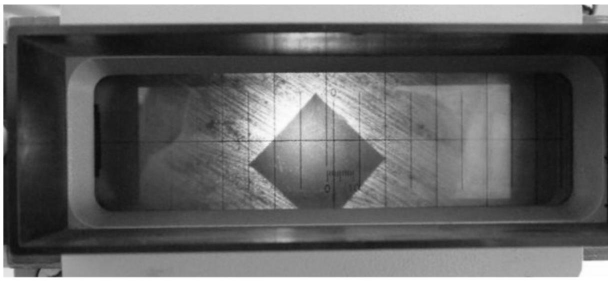


Figure 9 A view of lens of HPO 250 Vickers Hardness Tester

Slika 9. Pogled u leću HPO 250 ispitivač tvrdoće prema Vickers-u

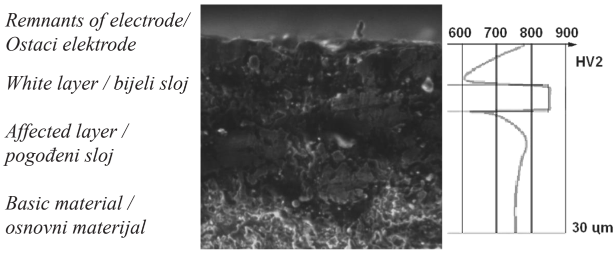


Figure 10. The course of impact after electroerosion machining (1000x magnification)

Slika 10. Tijek utjecaja nakon elektro-erozivne obrade (1000x uvećanje)

7. Evaluation of experimental measurements

The following figure shows the experimental frame of heat-affect zone recorded with an electron microscope.

Figure 10 shows diagram of micro-hardness course in surface layers of steel hardened to app. 850 HV2. It was proved that hardness directly under surface sharply drops to a value around 620 - 640 HV2; however, in *white layer* it substantially grows to 800 - 830 HV2. From this value,

Table 2. Measured micro-hardness values of the samples made from tool steel EN ISO 9679 X210 CR12 with basic metal hardness 750 HV2 in first cut profile (material thickness 10 and 100 mm)

Tablica 2. Izmjerene vrijednosti mikro-tvrdoće uzoraka od alatnog čelika EN ISO 9679 X210 CR12 sa osnovnom tvrdoćom 750 HV2 u prvom rezanom profilu (debljina materijala 10 i 100 mm)

No.	Thickness of material *H*, mm	Top line of cut		Middle line of cut		Bottom line of cut	
		Depth *h*, µm	Hardness HV2	Depth *h*, µm	Hardness HV2	Depth *h*, µm	Hardness HV2
1	10/100	0,65 / 0,66	770 / 770	0,63 / 0,65	781 / 780	0,62 / 0,68	770 / 771
2		1,32 / 1,31	615 / 614	1,35 / 1,31	609 / 608	1,33 / 1,32	614 / 612
3		1,95 / 1,93	845 / 843	1,99 / 1,95	853 / 851	1,93 / 1,91	845 / 843
4		2,60 / 2,62	842 / 841	2,66 / 2,62	852 / 851	2,62 / 2,64	841 / 840
5		3,25 / 3,27	620 / 620	3,25 / 3,29	670 / 675	3,28 / 3,28	620 / 618
6		3,91 / 3,94	622 / 621	3,92 / 3,94	613 / 609	3,90 / 3,92	623 / 621
7		4,55 / 4,58	659 / 657	4,55 / 4,53	641 / 637	4,58 / 4,55	659 / 657
8		5,21 / 5,15	682 / 680	5,24 / 5,15	673 / 670	5,22 / 5,16	681 / 680
9		5,85 / 5,81	702 / 701	5,87 / 5,87	695 / 691	5,84 / 5,84	700 / 698
10		6,52 / 6,51	717 / 714	6,58 / 6,57	707 / 703	6,54 / 6,53	716 / 714
11		7,15 / 7,17	723 / 721	7,15 / 7,14	715 / 711	7,17 / 7,15	721 / 720
12		7,82 / 7,84	729 / 727	7,87 / 7,84	721 / 718	7,83 / 7,82	729 / 727
13		8,45 / 8,42	732 / 730	8,45 / 8,46	723 / 720	8,46 / 8,44	731 / 730
14		9,12 / 9,14	737 / 735	9,14 / 9,15	729 / 727	9,11 / 9,16	736 / 734
15		9,75 / 9,77	740 / 739	9,78 / 9,78	731 / 729	9,74 / 9,74	740 / 738
16		10,41/10,38	742 / 743	10,44/10,33	734 / 731	10,43/10,35	741 / 740
17		11,05/11,08	744 / 742	11,06/11,07	737 / 735	11,03/11,09	742 / 741
18		11,71/11,68	746 / 744	11,73/11,65	739 / 736	11,72/11,67	745 / 743
19		12,35/12,36	748 / 747	12,35/12,37	742 / 738	12,36/12,34	747 / 745
20		13,02/13,03	749 / 748	13,07/13,08	744 / 740	13,03/13,04	748 / 747
21		13,65/13,67	750 / 749	13,63/13,64	746 / 742	13,67/13,66	749 / 749
22		14,31/14,29	750 / 750	14,31/14,33	747 / 744	14,30/14,31	750 / 750
23				14,93/14,95	748 / 746		
24				15,63/15,58	749 / 748		
25				16,22/16,29	750 / 750		
Mean value		**7,48/7,49**	**726/724**	**8,47/8,46**	**726/724**	**7,49/7,48**	**725/723**

hardness falls again to 620 - 640 HV2. In transition layer, the hardness rises once again to reach a hardness value of basic material (Diagram 1).

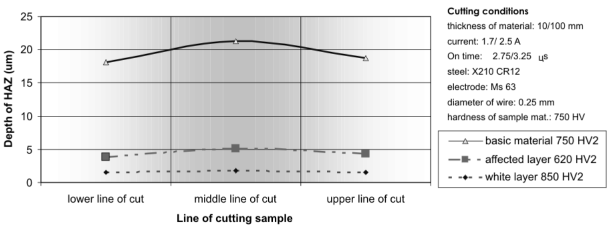


Diagram 1. Measured values of HAZ depth in the three lines

Dijagram 1. Izmjerene vrijednosti dubine toplinski pogođene zone u tri crte

The best evaluation method in this experiment appears to be the least square method. It is a numerical method which, in general, approximates *n*-tuple of measured values $[x_1, x_2, ..., x_m, y]$ by function of *m* variables in form:

$$y = f(x_1, \dots, x_m). \tag{2}$$

According to type of function course, an exponential function with a natural number base can be predicted as a suitable function type, which we will use to interlace values:

$$y = a_{00} \cdot a_{10}^{x_1} \cdot a_{01}^{x_2} \cdot a_{11}^{x_1 x_2} \,. \tag{3}$$

In all cases, independently of function selection, we will achieve unknown coefficients by fulfilling condition so that function $S(A)$ expressing the sum of differentes squares of calculated and measured values in form [4]:

$$S(A) = \sum_{i=1}^{r} [y_i - f(x_1, ..., x_m, A)]^2, \tag{4}$$

reaches its minimum. Values $f(x_1,...x_m, A)$ are substituted by selected function. Since it is a function of several variables, namely unknown matrix *A*, according to necessary condition of existence of the function extreme, the first partial derivatives of $S(A)$ must equal zero. Then we get relations for uknown coefficients calculation:

$$\frac{\partial S(a_{00}, ..., a_{rr})}{\partial a_{ij}} = 0 \text{ for } i, j = 0, \dots, r. \tag{5}$$

From adjusted partial derivatives we get a set of linear equations. The solution of this set are coefficients that we look for.

The quality of substitution is expressed by correlation index (also called *correlation coefficient* in some literature) which can be calculated from the relation:

$$IK = \sqrt{1 - \frac{\sum_{i=1}^{n} \left(y_i - F_i\right)^2}{\sum_{i=1}^{n} \left(\overline{y}_i - F_i\right)^2}}, \tag{6}$$

where F_i represents achieved values, $\overline{F}_i$ is the arithmetical average of measured values and y_i are values calculated by selected function, for $i = 1, \dots, m$.

As mentioned previously, the task is to approximate measured values of *HAZ* depth h_{HAZ}. On the basis of measured values we assume that the best approximation will be function in form (3) [5], which is a function with seven variables, and can be written in the form:

$$h_{HAZ} = a_{00}.a_{10}^{\,I}.a_{20}^{\,I^2}.a_{30}^{\,I^3}.a_{01}^{\,t}.a_{02}^{\,t^2}.a_{03}^{\,t^3}, \tag{7}$$

that is, it approximates *n*-tuple of measured values $[I_i, t_i, h_{HAZi}]$with functional relation:

$$h_{HAZ} = f(i,t, A) = f(I, t, a_{00}, ..., a_{rr}), \tag{8}$$

where unknown parameters a_{ij}, $i, j = 0, \dots, r$ are calculated so that the area would best approximate measured functional values. The statement mentioned holds true if:

$$S(A) = \sum_{i=1}^{n} [h_{HAZi} - f(I_i, t_i, A)]^2, \tag{9}$$

reaches its minimum. In this case the unknown is matrix of variables a_{ij} [4].

Then the mathematical model of dependence of *HAZ* depth on working cutting current and pulse duration calculated with program OpenOffice *EXCEL* by logarithmic regression can be written in the form:

$$h_{HAZ} = 11{,}7818 \cdot 1{,}001^{I} \cdot 1{,}00012^{I^2} \cdot 0{,}9928^{I^3} \cdot$$
$$\cdot 1{,}00021^{t} \cdot 0{,}0999^{t^2} . 1{,}00551^{t^3}, \ \mu\text{m}, \tag{10}$$

correlation index is IK^2=0,9887,

where h_{HAZ} – *HAZ* depth, μm,

I – working cutting current, A,

t – pulse duration, μs.

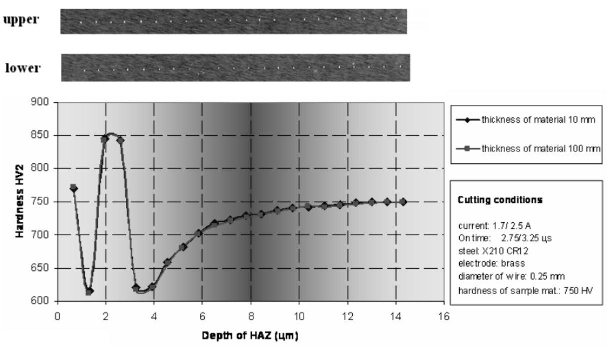


Diagram 2. Course of HAZ in surface layers (cut thickness 10 and 100 mm), in upper and lower lines of the cut

Dijagram 2. Tijek toplinski pogođene zone u površinskim slojevima (debljine reza 10 i 100 mm), u gornjoj i donjoj crti reza

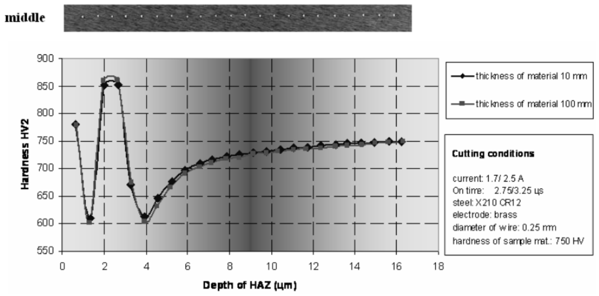


Diagram 3. Course of HAZ in surface layers (cut thickness 10 and 100 mm), in middle line of the cut

Dijagram 3. Tijek toplinski pogođene zone u površinskim slojevima (debljine reza10 i 100 mm), u srednjoj crti reza

Experimental measurements prove that the thickness of cut material renders almost no influence on *HAZ* size. The size of impact in the first (stock) cuts (*Ra* = 3,6 µm) ranges from 15 to 20 µm. The curves of hardness course in marginal lines show steeper characteristic compared to the middle line. In the middle area, decreased surface roughness approaches hardness value of basic material in greater depth.

8. Conclusive Evaluation of the Experiment

The aim of the experiment was observation of the size and quality of heat affected zone (*HAZ*) at electroerosion cutting with brass wire electrode. The course of *HAZ* in cutting tool axis was observed in a perpendicular direction in three lines. The first line was in the upper part of the cut, second line was in the middle and the third in the lower part of the cut. Experimental observation of *HAZ* depth showed different values of affected zone in particular lines. The upper and lower edge of the cut rendered approximately the same depth and hardness of sub-surface layers. A more marked difference was discovered in the middle part of the cut where measured values were on average higher by 20 HV2, and impact extended deeper compared to the edges of the cut.

High values of working cutting current in unsuitable combination with pulse duration can yield considerable increase of *HAZ* size in electroerosion machining. However optimum relation of these parameters makes it possible to achieve acceptable *HAZ* values. At the same time it is vital to take into account economic efficiency of the cutting process; it means that parameters´ adjustment ranges must – besides the cutting process itself – follow efficiency of cutting without considerable loss of cutting performance.

Recommendations for practice are to adjust OFF time pulse to 20 % higher value. This will cause a decrease of cutting power in the middle part of the cut. Decrease of idling impulses ratio will raise cooling time for basic metal core and thus will cause higher homogenity of heat affected zone in the whole profile of the cut. The OFF-time-pulse duration increase exceeding 20 % and related further reduction of idling impulses ratio can cause an adverse effect, which is characterized by a greater heat impact at the edges of the cut.

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