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SELECTION OF THE MOST APPROPRIATE WELDING TECHNOLOGY FOR HARDFACING OF BUCKET TEETH

IZBIRA NAJBOLJ PRIMERNE TEHNOLOGIJE TRDEGA NAVARJANJA ZOPA ZAJEMALKE

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A possibility of extending the service life of the working parts of construction machinery with particular attention to hardfacing of loader bucket teeth was investigated. In the first part of this paper the tribological processes typical for this machinery is analysed. Worn excavator parts are made of conditionally weldable cast steel that requires a special hardfacing technology, so numerous investigations were performed to obtain the most appropriate technology. In the experimental part of the paper, the selection of the optimum hardfacing technology for bucket teeth and the procedure of the manual arc hardfacing are presented. The samples were first hardfaced using different techniques and technologies and then the microstructure and microhardness of characteristic hardfaced layers were studied. Specially prepared samples were used for tribological investigations. The results of experimental investigations enabled the selection of the most suitable hardfacing technology and its application to real parts. The bucket teeth, with their hardfaced layers applied vertically, horizontally or in a honeycomb pattern were mounted onto a loader bucket, alternated with the new non-hardfaced teeth and their performance during the operation was regularly monitored. After a certain period, the degrees of the wear for the non-hardfaced and differently hardfaced teeth were measured. Taking into account both technical and economic factors, the most suitable hardfacing technology was determined.

Keywords: hardfacing, wear, loader bucket teeth, hardness, microstructure, friction coefficient

Izvršena je bila analiza podaljšanja zdržljivosti delov na gradbenih strojih s posebno pozornostjo na trdem navarjanju na zobeh zajemalke. V prvem delu tega članka so analizirani tribološki procesi, ki se pojavijo pri teh strojih. Pri kopačih so deli, ki se obrabljajo, izdelani iz pogojno varivega litega železa, ki zahteva posebno tehnologijo nanašanja, zato so bile izvršene številne raziskave, da bi dobili najprimernejšo tehnologijo. V eksperimentalnem delu članka je predstavljena optimalna tehnologija nanašanja trdih slojev na zobe zajemalke in predstavljen je postopek za ročno varjenje. Na vzorce so bili naneseni različni trdi sloji z različnimi tehnikami in tehnologijami in preučevane so bile mikrostrukture in mikrotrdote trdih nanosov. Preiskani so bili posebno pripravljeni vzorci za tribološke preizkuse. Rezultati eksperimentov so omogočili izbiro najprimernejše tehnologije nanašanja trdega sloja in njeno uporabo na realnih delih. Zobje zajemalke z vertikalnim, horizontalnim ali satastim nanosom trdega sloja so bili nameščeni skupaj z novimi, neobdelanimi zobmi na nakladalnik in redno je bilo spremljano njihovo vedenje med delom. Po določenem času je bila izmerjena obraba zob z različnimi nanosi in obraba neobdelanih zob. Z upoštevanjem tehničnih in ekonomskih faktorjev je bila določena najprimernejša tehnologija nanašanja trdih plasti.

Ključne besede: trdo navarjanje, obraba, zobje zajemalke nakladalnika, trdota, mikrostruktura, koeficient trenja

1 INTRODUCTION

During operation, certain parts of the road-construction machinery are exposed to different abrasive materials that cause most of the damage of the parts in direct contact with the stone aggregate causing abrasive wear. Hard and sharp-edged particles of stone materials are highly abrasive and they damage the working parts of bucket teeth.

The working parts exposed to the abrasive wear due to occasional medium-impact loads include: the bucket teeth of loaders, trenchers and excavators, the blades of concrete- and asphalt-cutting devices, the blades and rippers of bulldozers and graders, the leading rings and blades of rock-drill bits, the spindles of screw conveyors, etc. The greatest abrasive wear occurs on bucket teeth. For that reason, our experimental investigations were conducted on the loader bucket teeth.

The studies of the causes for the damage of some parts of machines and devices revealed that in more than

50 % of the cases the damage was the result of tribological processes under more or less regular operating conditions¹⁻⁶. The damaged parts can be either replaced with new ones or, in most cases, they can be hardfaced. Both reparatory and production hardfacing reduce downtime and costs because new parts are expensive. Hardfacing is economically justified especially in the cases of large-sized parts or when there are many equal parts. However, there are occasions when reparatory hardfacing has to be performed regardless of the costs, for example, when unique machines and devices have to be repaired or no spare parts are available⁷⁻¹¹.

2 DAMAGE DUE TO TRIBOLOGICAL CAUSES

Wear is generally considered to be the result of friction or a combination of friction, thermal, chemical, electrochemical and other factors on the elements of a tribo-mechanical system. When studying friction, one

has to consider the factors dominant in each particular case, such as the material, working-surface properties, the contact-surface quality and properties, properties of the medium between the contact surfaces, characteristics of the relative motion between the working surfaces, the load, the temperature, the quantity and properties of the particles produced due to the wear, etc.¹⁻⁶

During the surface contact between two tribo-elements, elastic and plastic deformations occur. They depend on the load intensity, friction conditions, material mechanical properties and micro-geometry of the contact surfaces. When two rough surfaces interact, a momentary loss of the contact may occur due to the micro-roughness caused by their elastic and plastic deformations. The process of micro-wear involves a plurality of such micro-deformations and a destruction of the surface roughness peaks. Experimental investigations¹⁻⁶ showed that the process of the final wear is in fact a fatigue process. Different authors give different classifications of the wear, but all of them are based on the way the contact between two bodies is realized. Therefore, the following types of wear can be distinguished: adhesive, abrasive, erosive, fatigue, cavitation, vibrational and corrosive wear. Since the aim of this research was to study and estimate also the filler materials used for hardfacing the parts exposed to the abrasive wear, the abrasive wear under moderate to medium impact loads was considered.

According to several authors¹⁻⁶, abrasive wear accounts for approximately half of all the wear. The elements most exposed to abrasive wear are the parts of construction, mining and agricultural machinery, elements of transport devices, working parts of the equipment in metallurgy, some parts of tool machines, parts of railway and tram equipment, impellers of hydraulic and gas turbines, oil-well drilling bits, and parts of the equipment for sandblasting.

Experimental investigations showed that the resistance to abrasive wear is linearly dependent on the metal mechanical properties^{1,4}. Therefore, the wear behaviour of a metal can be predicted on the basis of its mechanical properties, primarily the hardness. The penetration depth of foreign particles in the coupled machine elements is inversely proportional to the hardness of the surface layers. However, the resistance to wear of the alloys of the same hardness can vary depending on the chemical composition and structure of the alloy. Hence, the wear is influenced not only by the hardness, but also by the shape, the size and the structural component arrangement. There is no agreement on the most favourable type of structure in relation to the resistance to abrasive wear. Some authors believe that the austenite-carbide is the most favourable, while others prefer the martensite-carbide structure¹⁻⁶. This disagreement stems from a great variety of abrasive-wear types and a wide range of working conditions¹.

Abrasive materials penetrate the metal-surface layers causing surface damage. How deep the abrasive particles

penetrate into the metal depends on the shape and hardness of the grains. For example, sharp-edged particles of relatively soft abrasive materials can cause greater damage than rounded particles of hard abrasive materials. Investigations¹ showed that the bigger the size of the particles, the more abrasive they are. Other factors of influence include the length of the wear path, the specific pressure, the relative humidity and the chemical environment.

The wear-resistance level is influenced by each structural component of steel, but the level of influence depends on its hardness and its presence in the structure. Abrasive wear primarily depends on the possibility of abrasive materials to penetrate into the surface of steel and on the strength of the bonds between the structural components at the metal grain boundaries. This means that the quenched and tempered steel is more resistant than the steel with a ferrite-pearlite structure. Experiments showed that pure martensite structures, even those of a lower hardness, exhibit a greater resistance than martensite-carbide structures. Furthermore, if the martensite amount is reduced at the expense of the retained austenite in a martensite-carbide structure, the resistance to wear is increased despite a decrease in the hardness. It is the austenite-carbide structure that has the highest resistance to wear and not the martensite-carbide one, as might have been expected because of the hardness. This is due to the fact that the grain-boundary bonds are stronger in austenite-carbide structures than in a combination of martensite and carbide. In other words, abrasive particles pull carbides more easily out of a martensite matrix than out of an austenite base, whose crystal-lattice parameter is similar to the carbide-lattice parameter¹⁻⁶.

The change in operating conditions brings about a change in the intensity and mechanisms of abrasive wear. These conditions include the properties of abrasive materials, the shape and size of grains, the type of bonds, the specific pressure at the contact surfaces, the relative sliding speed, the wear-path length, the humidity, the chemical aggressiveness of the working environment, etc.

3 SELECTION OF THE PROCEDURE, FILLER MATERIAL AND HARDFACING TECHNOLOGY

The role of bucket teeth (**Figure 1a**) is to separate and crush stone material and to protect the bucket against wear. The number and shape of teeth depends on the application (trench digging, gravel digging, material loading, etc.) and the size of the bucket, varying from three (trencher buckets) to fifteen teeth (buckets of bigger loaders). They can be installed in two ways: bolted directly to a bucket or their holder can be welded to a bucket and the teeth are bolted onto the holder. Teeth are made of cast steel or cast iron; their mass ranges from 3 kg to 15 kg per piece.

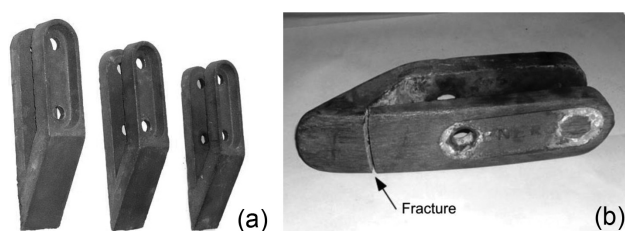


Figure 1: Loader bucket teeth: a) new parts, b) damaged part
Slika 1: Zobje zajemalke: a) novi deli, b) poškodovani del

Two problems were noticed during the operation of the bucket teeth: the tougher and less hard teeth are subjected to plastic deformation and intensive wear, while the teeth made of brittle materials of high hardness break at higher impact loads (**Figure 1b**). A special problem is encountered with the construction machines operating in quarries or open-pit mines of ore and coal, where a piece of a broken tooth can get into the crushers and cause damage. Broken bucket teeth can also get into the equipment used for asphalt and concrete production and cause major damage and downtime.

An analysis of the chemical composition of the teeth material showed they were made of cast steel ČL3134 (JUS) (**Table 1**). A broken tooth was cut to be used for an investigation of the hardness and microstructure of the

base material. The hardness ranged from 340 HV1 to 420 HV1, while the microstructure was martensite with retained austenite. This microstructure was not resistant enough because the teeth wore out quickly, especially under the conditions of severe abrasion. For that reason, instead of installing new teeth, it was decided to try to extend the service life of both worn and new teeth with reparatory and production hardfacing.

Hardfacing was performed with the manual arc-welding method using a high-alloy rutile electrode with the properties from **Table 2**, as #1. According to the manufacturer, the layers hardfaced with this electrode exhibit a high resistance to intensive abrasive wear and can withstand moderate impact loads during operation. The layers are very hard and can be grinded. This electrode is especially suited for hardfacing the parts of the machinery exposed to the metal-to-mineral wear. They include bulldozer blades, excavator bucket teeth, excavator shovels, parts of conveyors and crushing machines for various applications, blades and parts of mixers, etc. The reparatory hardfacing of these parts should be produced with the interlayer deposition using an electrode (**Table 2**). The hardfacing parameters, given in **Table 3**, were chosen in accordance with the recommendations in^{11–15}.

Table 1: Chemical composition, mechanical properties and notation of steel ČL3134^{5,8}

Tabela 1: Kemijska sestava, mehanske lastnosti in oznaka jekla ČL3134^{5,8}

	Chemical composition, w/%					Mechanical properties					Relation to other standards
	C	Si	Mn	P	S	R_m MPa	R_{eH} MPa	A_5 %	Hardness HV1	Microstructure	DIN
Prescribed	0.45	0.50	1.80	0.040	0.040	780–930	390	7	340–430*	Martensite-bainite and retained austenite	GS-36MnS
Analyzed	0.35	0.20	1.65	0.020	0.020	–	–	–	340–420	Martensite-bainite and retained austenite	

Table 2: Properties of filler materials^{5,8}

Tabela 2: Lastnosti dodatnega materiala^{5,8}

Electrode notation			Chemical composition, w/%					Current type	Mechanical properties of the hardfaced layer	Application
FIPROM Jesenice	DIN		C	Si	Mn	Cr	Ni			
1	ABRADUR 58	DIN 8555 E 10-UM-60-GR	3.6	–	–	32	–	~ = (+)	57–62 HRC	For hardfacing the parts exposed to severe abrasive wear from minerals in the cold state
2	INOX B 18/8/6	DIN 8556 E 18 8 6 Mn B 20+	0.12	0.8	7	19	9	= (+)	$KV > 80$ J	Interlayer austenite basic electrode

Table 3: Parameters of hardfacing with the MMA welding method

Tabela 3: Parametri trdega navarjanja z metodo varjenja MMA

Electrode notation			Electrode core diameter d_e /mm	Welding current I /A	Voltage U /V	Hardfacing speed v_z /(cm/s)	Input heat q_l /(J/cm)
FIPROM Jesenice		DIN					
1	ABRADUR 58	E 10-UM-60-GR	3.25	130	25	0.124	20968
2	INOX B 18/8/6	E 18 8 6 Mn B 20+	3.25	100	24	0.136	14118

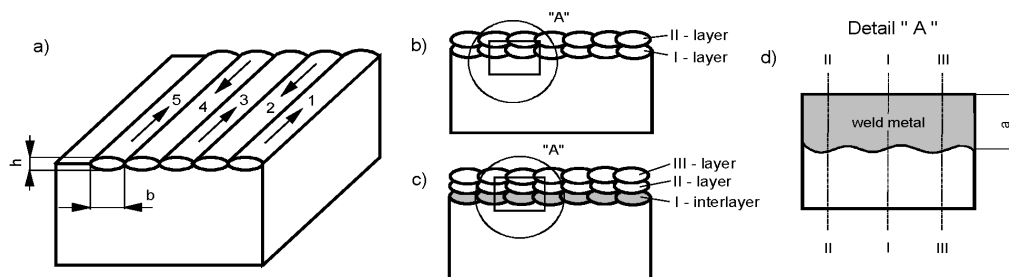


Figure 2: Order of hardfaced-layer deposition: a) 1st layer, b) 2nd layer, c) 3rd layer, d) metallographic sample (block)

Slika 2: Zaporedje trdih navarova: a) 1. sloj, b) 2. sloj, c) 3. sloj, d) vzorec za metalografiju

4 EXPERIMENTAL INVESTIGATIONS ON MODELS AND BUCKET TEETH

4.1 Model investigations

4.1.1 Investigations of the hardness and microstructure of the hardfaced-layer zones

The aim of these experimental investigations was to establish the optimum hardfacing technology. The specimens were hardfaced in a single pass or several passes (layers) (**Figures 2a to 2c**), either with or without preheating. Hardfaced samples were cut into metallographic samples for tribological investigations (**Figure 2d**). Their hardness was measured along three different directions (see detail "A" in **Figure 2d**) and the microstructure of characteristic hardfaced-layer zones was estimated. The hardfaced-layer hardness was 551 to 742 HV1, while the microstructure was estimated as martensite-ledeburite with retained austenite and excreted carbides at the grain

boundaries. The microstructure of the heat-affected zone (HAZ) was martensite with transitions into interphase structures, and the hardness was from 465 HV1 to 613 HV1. The microstructure of the interlayer was austenite-carbide, while its hardness was about 482 HV1. The hardness distribution and the microstructures of the characteristic zones are shown in **Figure 3** for the three-layer hardfacing and in **Figure 4** for the two-layer hardfacing with preheating⁵⁻⁸.

4.1.2 Tribological investigations

Tribological investigations were performed for a block-on-disk contact, on a TPD-93 tribometer (**Figure 5**) made at the Faculty of Engineering in Kragujevac. The aim of these investigations was to evaluate the resistance to wear of the base materials and deposited layers. Three prismatic samples (two from the hardfaced layer and one from the base material) were prepared for tribological investigations (6.5 mm × 15 mm × 10 mm).

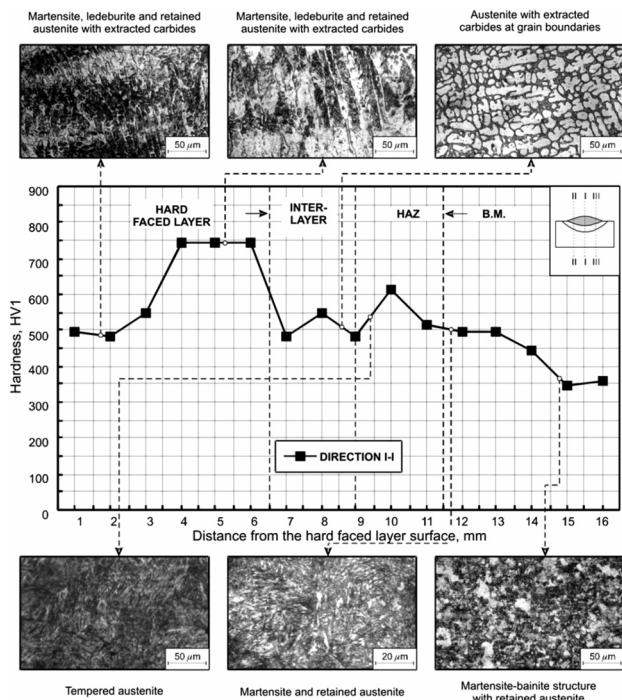


Figure 3: Hardness distribution and microstructures of characteristic hardfaced-layer zones (interlayer + two layers, $T_0 = 20^\circ\text{C}$)

Slika 3: Rasporeditev trdote in mikrostruktura področja trdega navara (vmesna plast + dva sloja, $T_0 = 20^\circ\text{C}$)

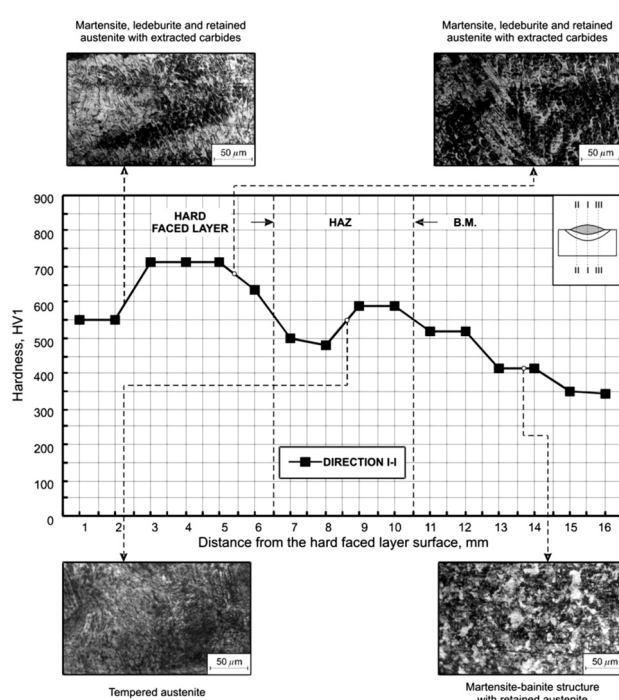


Figure 4: Hardness distribution and microstructures of characteristic hardfaced-layer zones (two layers, $T_p = 200^\circ\text{C}$)

Slika 4: Rasporeditev trdote in mikrostruktura področij značilnih trdih navarova (dva sloja, $T_p = 200^\circ\text{C}$)

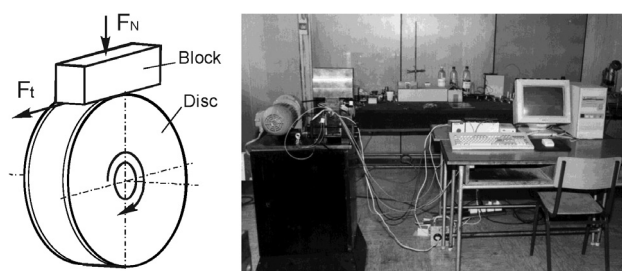


Figure 5: Tribometer TPD-93 and other measuring equipment for the performance of tribological tests

Slika 5: Tribometer TPD-93 in druga merilna oprema za izvajanje triboloških preizkusov

During the investigations, the line block-on-disk contact was realized. The external variables of the tested samples were the contact forces, the sliding speed and the lubricant (motor oil GLX 2 SAE 15-W-40)^{4,5,8}.

Prior to the investigations, the surface topography of blocks and discs was assessed with the computer measuring system Talysurf 6. The force $F_N = 300$ N and sliding speed $v_{kl} = 1$ m/s were adopted. During the contact time of ≈ 60 min, the friction-coefficient variation was registered (**Figure 6**). When the contact was terminated, the surface topography was assessed again and the

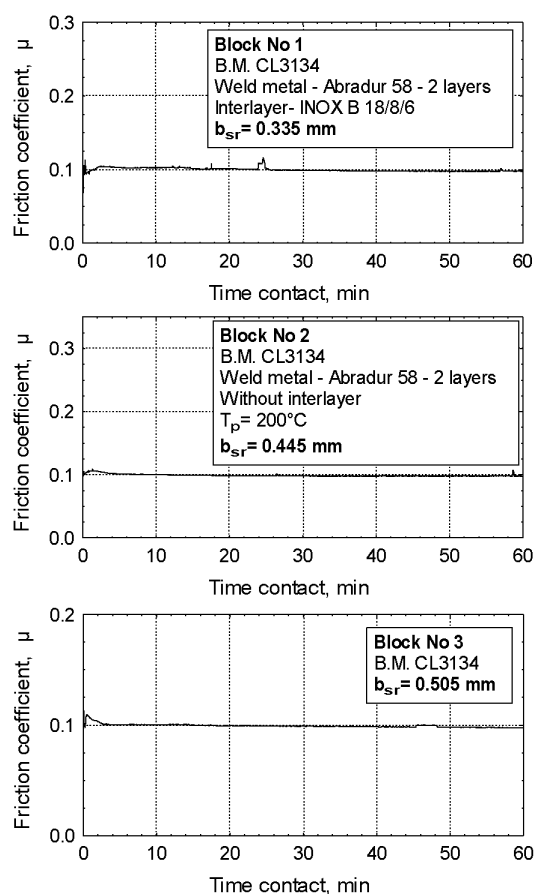


Figure 6: Friction-coefficient variation during the contact of 60 min (blocks 1, 2 and 3)

Slika 6: Spreminjanje koeficienta trenja med stikom 60 min (blok 1, 2 in 3)

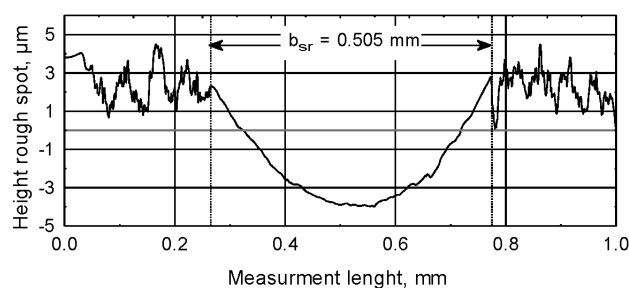


Figure 7: Wear scar – block No. 3 (after the contact of 60 min)

Slika 7: Brazgotina zaradi obrabe – blok št. 3 (po stiku 60 min)

wear-scar widths of the blocks were measured (**Figure 7**). The wear-scar width was measured using a universal microscope UIM-21, with a magnification of 50 times⁴⁻⁹.

Based on the results obtained with tribological investigations, the macroscopic and microscopic damages of the damaged blocks from **Figure 8** were assessed.

4.2 Hardfacing of real parts with different methods of hardfaced-layer deposition

The measurements of the wear-scar widths showed that hardfaced layers have a significantly higher resistance to wear (especially those hardfaced without pre-heating) than the base material. This illustrates the importance of selecting the right hardfacing technology and filler materials for excavator/loader bucket teeth.

After the samples had been hardfaced and tribologically investigated, the optimum technology was selected and applied to the real parts. Taking into consideration the limitations imposed by the base-material thickness, the hardfaced-layer height and electrode diameter, the

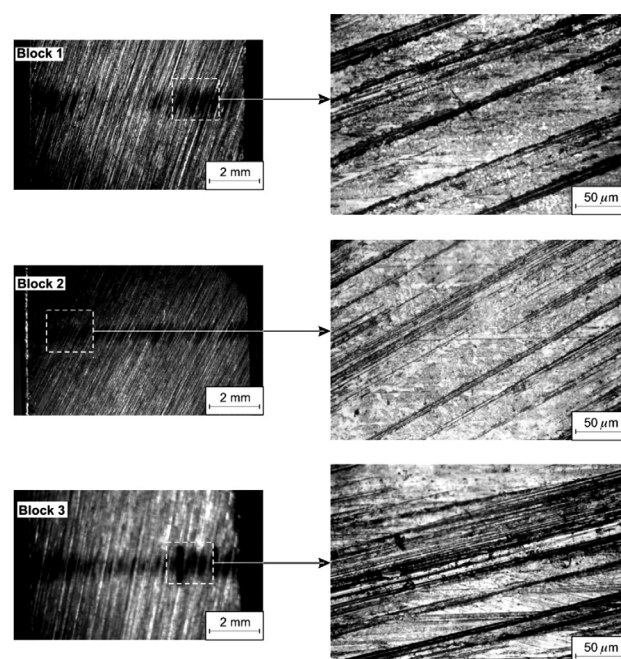


Figure 8: Wear of block Nos. 1, 2 and 3

Slika 8: Obraba na bloku št. 1, 2 in 3



Figure 9: Hardfaced teeth with the layers deposited: a) longitudinally, b) horizontally and c) in a honeycomb pattern

Slika 9: Zob s trdim navarom, položenim: a) vzdolžno, b) vodoravno in c) satasto

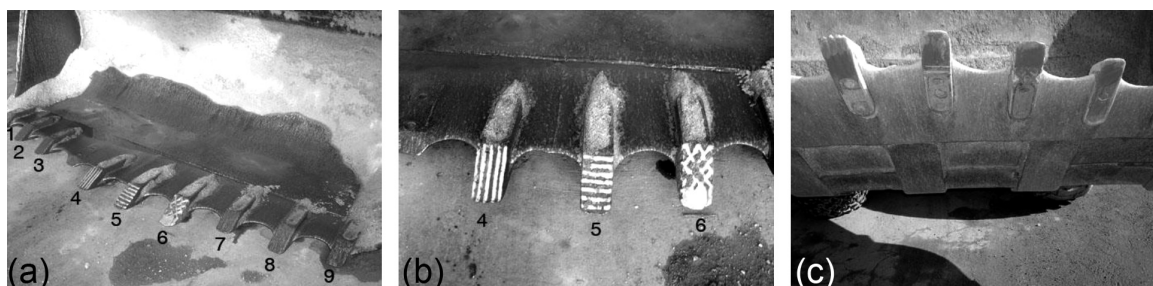


Figure 10: Bucket-tooth mounting sequence: a) front surface, b) back surface, c) teeth surface after 360 h of operation

Slika 10: Zaporedje namestitve zob zajemalke: a) zgornja površina, b) spodnja površina, c) zobje po 360 h dela

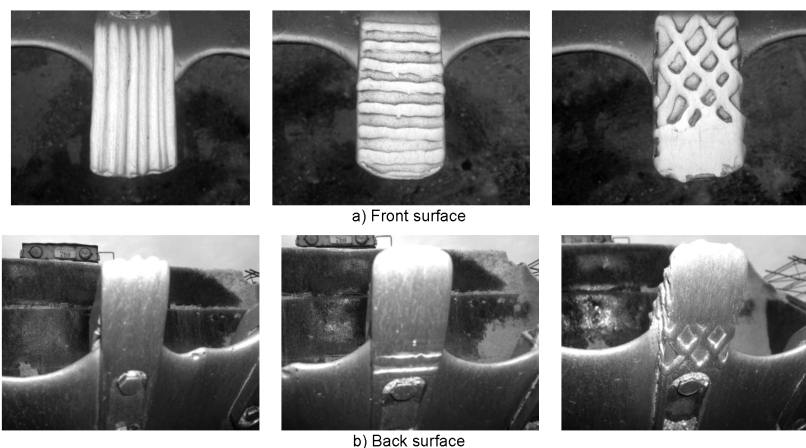


Figure 11: Hardfaced teeth after 1600 h of operation: a) front surface, b) back surface

Slika 11: Zob s trdim navarom po 1600 h dela: a) zgornja površina, b) spodnja površina

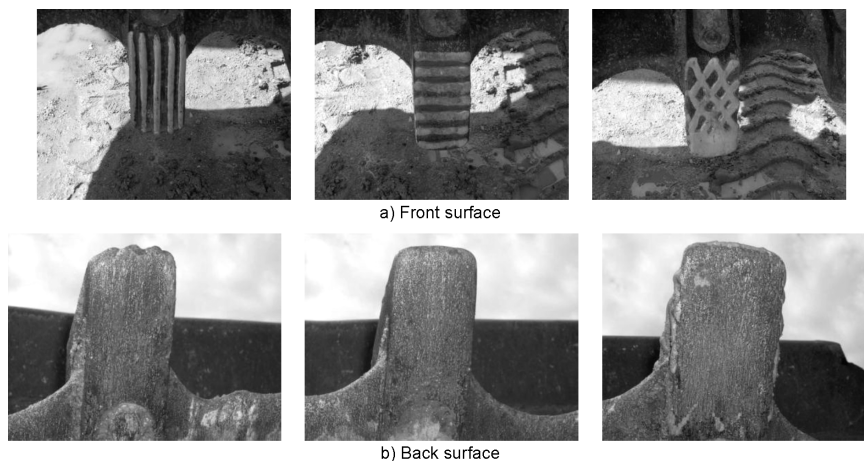


Figure 12: Hardfaced teeth after 3200 h of operation: a) front surface, b) back surface

Slika 12: Zob s trdim navarom po 3200 h dela: a) zgornja površina, b) spodnja površina

Table 4: Results of mass measurements before and after the teeth were put into operation for 3200 h**Tabela 4:** Merjenje mase zob pred 3200 h dela in po njem

Tooth type	New (non-hardfaced) teeth			Hardfaced teeth with the layers deposited*			New (non-hardfaced) teeth		
Tooth number	1	2	3	4	5	6	7	8	9
Tooth mass before the operation, kg	8.60	8.58	8.62	9.02	9.05	9.62	8.67	8.60	8.64
Tooth mass after the operation, kg	7.75	7.72	7.84	8.80	8.65	9.22	7.62	7.74	7.82
Mass loss, kg	0.85	0.86	0.78	0.22	0.50	0.40	0.95	0.86	0.82
Mass-loss percentage, %	9.88	10.02	11.09	2.44	5.46	4.16	11.08	10.00	9.49

*Tooth #4 hardfaced vertically; tooth #5 hardfaced horizontally; tooth #6 hardfaced in a honeycomb structure

three-layer hardfacing (with an interlayer) was chosen. Hardfaced layers were deposited at the front and back sides – vertically over a tooth (**Figure 9a**), horizontally across a tooth (**Figure 9b**) or in a honeycomb pattern (**Figure 9c**). The width of the hardfaced layers was from 10 mm to 12 mm and the height was about 4 mm. Then, the hardfaced teeth were installed onto the central part of the bucket with the most intensive abrasive wear (**Figure 10a**, teeth 4, 5 and 6). The end teeth mounted on both sides were new (1, 2, 3 and 7, 8, 9).

The wear area was monitored and inspected after 360 h (**Figures 10a to 10c**), after 1600 h (**Figures 11a and 11b**) and finally after 3200 h of operation (**Figures 12a and 12b**)^{5,8}.

5 DISCUSSION

The teeth mass was measured before they were installed. After the teeth were used under real operating conditions for about 3200 hours, they were dismounted and their mass was measured again (**Table 4**). **Figure 13** gives the diagrams of mass losses for the new (non-hardfaced) and hardfaced teeth.

The examination of the damaged-tooth geometries and the measurements of the material depth in the wedge parts of the teeth revealed that the wear degree of the

lower (back) surfaces was about 3 times higher than that of the upper (front) surfaces of the teeth. This can be ascribed to the friction of the back surfaces in contact with the abrasive material^{5,8}.

The greatest resistance to the abrasive wear (loading of crushed stone material) was exhibited by the teeth with the hardfaced layers applied vertically, followed by the teeth with the hardfaced layers deposited in a honeycomb structure, while the teeth with the horizontal hardfaced layers showed the least wear resistance. The best hardfacing patterns for the other conditions of the abrasive wear require a further investigation^{5,8}.

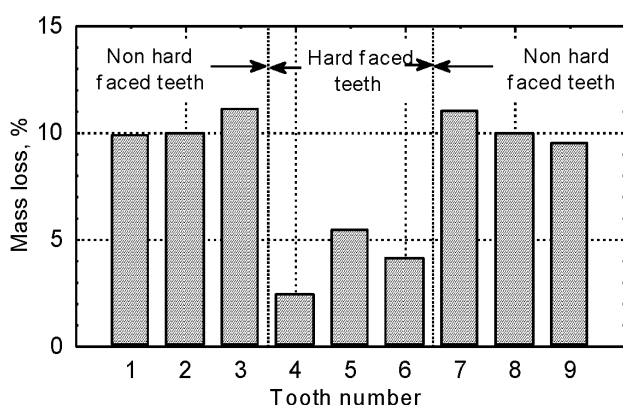
On the basis of the knowledge acquired in practice and from the literature, the criterion for a worn-tooth replacement was established, stating that teeth should be replaced after 6400 h of operation (two seasons) or when the mass loss is about 20 %^{5,8,16,17}. Considering the last rows of **Table 4** and **Figure 13**, one can notice that the hardfaced teeth were worn significantly less than the new ones, by about 2 to 4 times. Thus, one can conclude that the expected service life of the hardfaced teeth would be 2–4 times longer than the service life of the non-hardfaced teeth, depending on the applied hardfacing method.

The techno-economic analysis^{4,5,7,15,16} showed that the production and reparatory hardfacing of the working parts of construction machinery is cost-effective. Especially the production hardfacing of parts was studied in detail. Taking into consideration the costs for repair, the costs for new parts and the service life, it can be concluded that the savings reach up to 225 %, while for the repair hardfacing, they reach up to, or even exceed, 300 %^{5,8}.

6 CONCLUSION

Through the experimental investigations of the hardness and microstructure of hardfaced-layer characteristic zones, as well as tribological investigations of hardfaced layers, the optimum hardfacing technology was determined.

Based on these models and other experimental investigations, as well as the tests of real parts in operating conditions, it was concluded that the optimum produc-

**Figure 13:** Diagram of mass losses for the non-hardfaced and hardfaced teeth**Slika 13:** Prikaz izgube mase za neobdelane in trdo navarjene zobe

tion-hardfacing technology should consist of the following steps:

- Proper selection of the filler material (the right type of electrodes);
- Selection of the hardfacing parameters (welding current, voltage, welding speed, input heat);
- Number and order of deposited layers;
- Direction of the hardfaced-layer deposition;
- Thermal treatment prior to hardfacing (preheating) or deposition of a buffer interlayer.

The right choice of the hardfacing technology and its proper application ensure numerous advantages and benefits over the installation of new non-hardfaced parts. Hardfacing extends the service life by two to four times, increases productivity, shortens downtime, reduces the inventory of spare parts, i.e., reduces the production costs in general.

Although hardfacing represents an almost unique process, requiring the technology to be modified for each particular part, the general procedure applicable to similar parts of construction, mining and agricultural machineries has been determined in this paper. This technology can be applied to both manufacturing new teeth (or parts in general) and repairing the worn ones. The techno-economic benefits are the same.

It has also been shown that the choice of the hardfacing technology is closely related to the complex procedure of hardfaced-layer quality control. This means that this type of work can be performed only in specialized facilities with adequate equipment and skilled staff. In other words, successful hardfacing can be performed only by expert teams specialized in the technical system maintenance.

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