INVESTIGATION OF OPERATIONAL PARAMETERS OF COATINGS FOR REBUILDING WORN-OUT CAST-IRON PARTS OF SELF-PROPELLED AGRICULTURAL MACHINES
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ИЗСЛЕДВАНЕ НА ЕКСПЛОАТАЦИОННИ ПАРАМЕТРИ НА ПОКРИТИЯ ЗА ВЪЗСТАНОВЯВАНЕ НА ИЗНОСЕНИ ЧУГУНЕНИ ДЕТАЙЛИ ОТ САМОХОДНИ ЗЕМЕДЕЛСКИ МАШИНИ

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DOI: https:// doi.org/10.35633/inmateh-62-17

Keywords: *operational parameters, coatings for rebuilding, cast iron parts, agricultural machines*

ABSTRACT
This paper presents investigation of some operational parameters of coatings for rebuilding, deposited on worn-out cast-iron parts of self-propelled agricultural machines. The coatings have been realized by applying a combined technology comprising deposition of electrochemical coating of non-ferrous metal and subsequently deposition of welding coating. The parameters for deposition of the electrochemical coatings and the parameters for deposition of the welding coatings have been presented. The results of the investigation of the following coatings’ operational parameters are presented: removed material in friction process, friction torque, micro-hardness and roughness. Based on the results obtained, the relative wear resistance of the coatings has been calculated.

РЕЗЮМЕ
В публикацията е разгледано изследване на някои експлоатационни параметри на възстановителни покрития, нанесени върху износени чугунени детайли от самоходни земеделски машини. Възстановителните покрития са реализирани чрез прилагане на комбинирана технология, включваща нанасяне на електрохимично покритие от цветен метал и последващо нанасяне на наваръчно покритие. Представени са параметрите за нанасяне на електрохимичните покрития и параметрите за нанасяне на наваръчните покрития. Представени са резултатите от изследване на следните експлоатационните параметри на покритията: големина на износване при процеса на триене, момент на триене, микротвърдост и грапавост. На база на получените резултати е изчислена относителната износоустойчивост на възстановителните покрития.

INTRODUCTION
In the agricultural machinery cast iron parts are wide spread. They are structural parts - cylindrical blocks, cylindrical sleeves, housings, plates, shells, caps, etc. (*Souza T. et al, 2014; Vasilev T. et al, 2012*) as well as dynamically and heavily loaded parts - camshafts, crankshafts, gears, worm wheels, flywheels, belt pulleys, valves, sprockets, brake drums, clutch discs, etc. (*Mallikarjuna V. et al, 2014; Song L., 2015; Vasilev T. et al, 2012*).

The cast iron material is suitable for casting complex shape parts. The density of cast iron is lower than the steel’s density. On the other hand, the cast iron parts have high damping capacity under dynamic loads which leads to less accumulation of mechanical stresses (*Golovin S., 2012; Vasilev T. et al, 2012*).

The loss of metal of the parts’ surfaces limits the reliability and serviceability of the agricultural machines (*Popovych P. et al, 2017*).

The rebuilding of worn-out parts increases their resource, and saves money for buying spare parts, and also ensures positive environmental effect. The rebuilding of worn-out parts from agricultural machinery has a positive impact in terms of reducing the production costs in agriculture (*Lorencowicz E., Uziak J., 2015*).

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One of the most common methods for rebuilding machine parts is by applying welding coating on the worn surface (*Afanasyev V. et al, 2018; Kenchi Reddy K., Jayadeva C., 2012; Vasilev T. et al, 2012*). There are a number of difficulties in the deposition of welding coatings on cast iron parts due to certain reasons related to the structure and properties of the cast iron material (*Dametew A., 2015; Vasilev T. et al, 2012; Zuk M. et al, 2017*).

The investigation of the tribological parameters of the rebuilt machine parts allows to determine their wear resistance comparing to non-rebuilt parts. The results obtained from the tribological investigations can be used to optimize the processes of worn-out parts rebuilding (*Nikolov M., Kangalov P., 2014; Nikolov M. et al, 2015; Nikolov M. et al, 2015; Todorov I., Nikolov M., 2014*).

The experimental investigations in the current research are based on specific methodology related to similar studies (*Kadikyanov G., et al, 2010; Nikolov M., Kangalov P., 2014; Nikolov M. et al, 2016; Nikolov M. et al, 2015; Nikolov M. et al, 2015; Todorov I., Nikolov M., 2014*).

The aim of the paper is to determine some operational parameters of coatings deposited on specimens. The investigation is needed for selection of the most appropriate coating in rebuilding process of worn-out cast-iron parts of self-propelled agricultural machines.

MATERIALS AND METHODS

OBJECT OF INVESTIGATION AND METHODOLOGY

Object of investigation

The objects of investigation are two types of coatings for rebuilding, realized by a combined technology applied on cast iron specimens. This technology involves the deposition of a transient electrochemical coating of non-ferrous metal (nickel and/or copper) and subsequent deposition of a welding coating. The welding coating has been realized by a process of automatic arc welding in a carbon dioxide protective medium using low-carbon steel thin wire. The reason for applying the non-ferrous metal transition coating is to improve the welding properties of the cast iron in order to realize a welding coating with sufficient parameters, as well as to provide stress relaxation, i.e. to prevent cracks. The rebuilt surfaces are in friction process with sliding bearings in the conditions of liquid, semi-liquid and boundary friction (*Vasilev T. et al, 2012*).

Table 1 presents the parameters of deposited transient electrochemical coatings. The treated specimens are called coating “A” and coating “B”.

Table 1

Parameters of the transient electrochemical coatings

Coating for rebuilding	Type of transient electrochemical coating	Thickness of the electrochemical coating $h_{el.chemical\ coating}$, [mm]
coating “A”	Cu	0.3
coating “B”	Ni + Cu	total thickness 0.2 (0.1 – Ni; 0.1 – Cu)

Table 2 presents the parameters of the welding deposition process for the investigated coatings for rebuilding.

Table 2

Welding deposition parameters

Coating for rebuilding	d_{wire} [mm]	l_{wire} [mm]	$\dot{V}_{CO_2}$ [l/min]	n [min^{-1}]	S_{weld} [mm/min^{-1}]	V_{wire} [m/min]	V_{weld} [m/min]	U_{weld} [V]	$I_{weld.}$ [A]
coating “A”	1	15	20	0.79	4.50	2.60	0.12	23	90
coating “B”	0.8	12	20	0.79	5.30	6.35	0.12	25	90

The parameters in the table are as follows: d_{wire} – welding wire diameter, mm; l_{wire} – length of the welding wire out of contact nozzle, mm; $\dot{V}_{CO_2}$ – volume flow rate of the carbon dioxide, l/min; n – rotational speed of the cylindrical specimen, min^{-1}; $S_{weld.}$ – step of welding deposition, mm/min^{-1}; V_{wire} – welding wire feed rate, m/min; $V_{weld.}$ – welding deposition speed, m/min; $U_{weld.}$ – welding deposition voltage, V; $I_{weld.}$ – welding deposition current, A.

Methodology for determination of the operational parameters

The investigated operational parameters can be divided into three types: tribological parameters (removed material in friction process and friction torque), mechanical parameter (micro-hardness), and micro-geometric parameter (roughness).

Figure 1 presents the experimental installation for investigation of liquid friction processes. The physical model of the friction pair “shaft–sliding bearing” is the pair "roll–sector" with corresponding parameters of geometric and physical similarity (Figure 2).

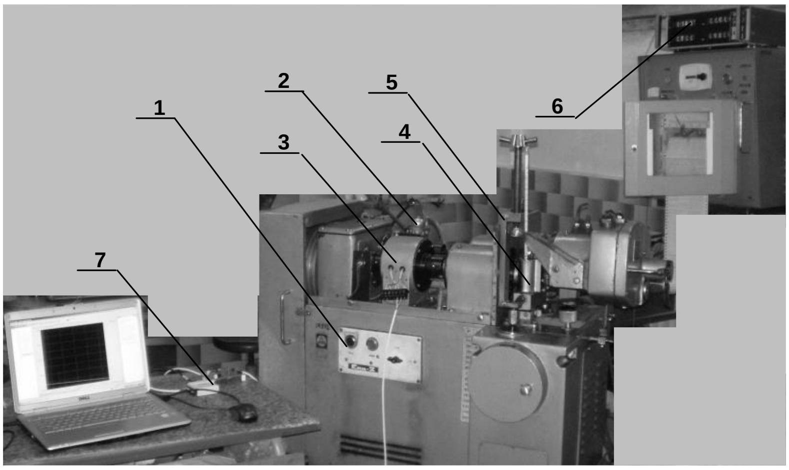

Fig. 1 - Experimental installation:
1 – tribometer for tribological investigations; 2 – oil mixing system; 3 – friction torque sensor; 4 – water-cooled chamber; 5 – loading mechanism; 6 – electronic recording system; 7 – electronic board of "National Instruments"

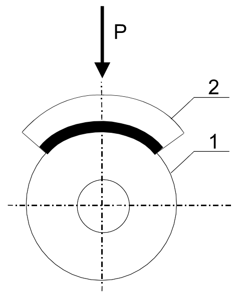

Fig. 2 - Physical model of the friction pair
1 – roll; 2 – sector

The tribometer for tribological investigations is equipped with additional devices, which have ensured: continuous mixing of the oil; cooling the chamber with oil to maintain a constant temperature; measuring the rotation speed of the roll (the friction path travelled) and duration of the experiment.

The friction pair has been loaded by a spring and a worm gear, by counting the divisions of the graduated flywheel.

The friction torque between the roll and the sector has been measured by an inductive sensor positioned between the reducer and the machine spindle. At the output of the inductive sensor for the friction torque, two electrical voltages have been obtained. The difference between the two voltages increases by increasing of the friction torque. To measure the output of the sensor and convert it into units for friction torque (N.cm), an USB electronic circuit board of „National Instruments” and the "LABVIEW" software have been used. The friction torque data has been continuously recorded during the experiment and visualized on the PC screen in digital or graphical form.

The rotational speed of the roll has been measured by electronic system, which receives the signal from another inductive sensor mounted between the reducer and the friction torque sensor.

The friction process between the roll and the sector has been implemented in an oil chamber with volume of 0.15 l. The chamber is water-cooled. The oil is being stirred by air fed from a three-way tap located in the bottom of the chamber. For temperature control in the chamber is used a thermostat.

The parameters of friction and wear of the investigated specimens have been determined by liquid friction conditions in engine oil environment. The oil is with standard parameters and used in the breaking-in process of the internal combustion engines from agricultural machinery.

Figure 3 presents the variation of the friction torque in breaking-in and wear processes, in conditions of stepless loading.

The amount of material removed from the friction elements (roll and sector) during the wear process has been determined by the weighing method. Analytical weighing scale with accuracy of 0.05 mg has been used. The specimens have been cleaned with gasoline, dried and weighted before and after each fixing to the tester.

The roughness of the roll and the sector has been determined before and after each experiment of breaking-in and wear processes. The roughness parameter R_a in different planes and sections has been measured with roughness meter.

The micro-hardness of the surfaces has been measured with hardness meter. The measurements have been implemented with loading by weight of 100 g for the roll, and 50 g for the sector respectively.

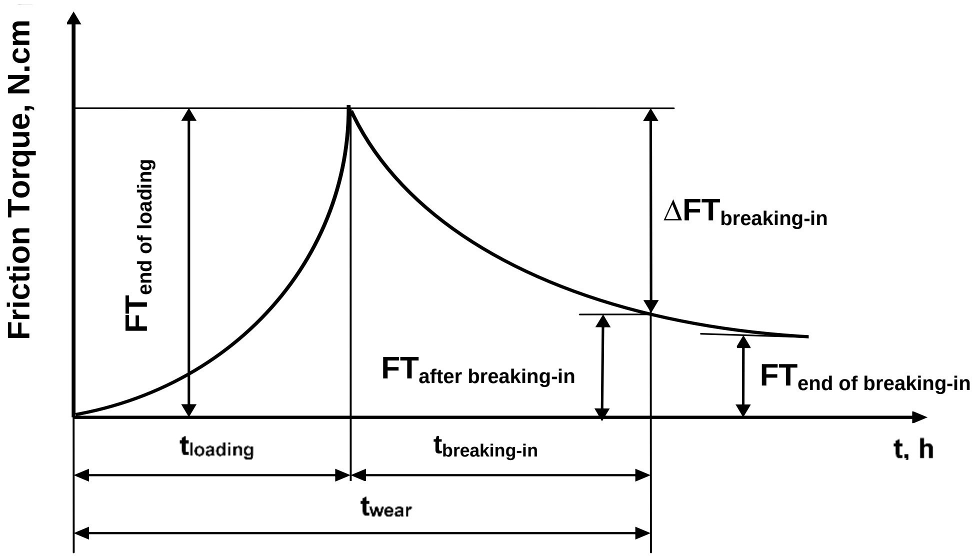

Fig. 3 - Variation of the friction torque in breaking-in and wear processes

$FT_{end\ of\ loading}$ – friction torque at the end of the loading; $FT_{after\ breaking\text{-}in}$ – friction torque after the breaking-in process; $\Delta FT_{breaking\text{-}in}$ – friction torque during the breaking-in process; $FT_{end\ of\ breaking\text{-}in}$ – friction torque at the end of breaking-in process; $t_{loading}$ – loading period; $t_{breaking\text{-}in}$ – breaking-in period; t_{wear} – wear period

The specimens are two types sectors and rolls. The sectors for the friction pair are with steel base on which a bearing lining with a thickness of 0.1 ÷ 0.5 mm in radius has been deposited (Figure 4). Respectively, the material of investigated rolls is ferrite-pearlite grey cast iron (Figure 5).

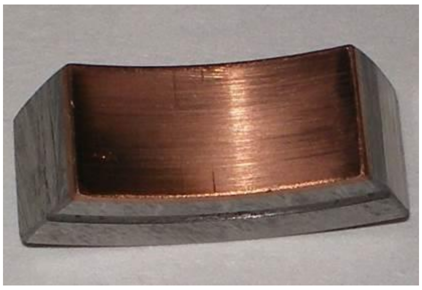

Fig. 4 - Sector for investigation of coatings for rebuilding

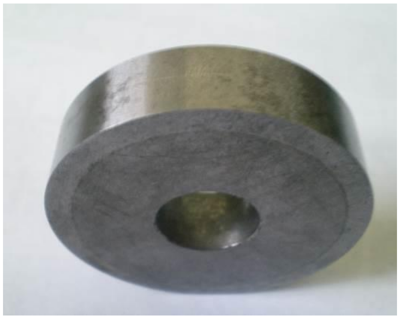

Fig. 5 - Roll with deposited coating for rebuilding

The friction pair has been loaded up uniformly. The loading parameters are: loading speed – 1 MPa/min, loading duration – 5 minutes, and a value of load – 100 daN, as the accuracy of the loading mechanism is 1 daN. The applied load of 100 daN provides a pressure of 5 MPa between the roll and the sector. This pressure value is close to the boundary conditions and can be applied for different types of materials and coatings without fretting of the surfaces.

The rolls' rotation speed is 540 min^{-1}, the roll diameter is 50 mm. At these conditions the wear of specimens is measurable. The calculated parameters for these conditions are: a sliding speed – 1.41 m/s, and a tribological characteristic PV = 7.05 MPa/s. These values have been accepted in accordance to the admissible load limits of the sliding bearings.

During the experiments, the oil temperature in the low-volume chamber for friction and wear investigations, has been maintained in the range of 30 ÷ 40 °C. These temperatures are typical for the processes of agricultural machinery's engines cold starting, where the wear process is intensive.

RESULTS

Results obtained from the investigation of the wear process of the friction pair elements

Figure 6 presents the variation in the quantity of the removed material in friction process J_i of the rolls: with coating “A” (the friction surface is welding coating with transient layer of Cu), with coating “B” (the friction surface is welding coating with transient layer of Ni+Cu), and “NO” coating (the friction surface is ferrite-pearlite grey cast iron) during the investigation.

In all three types of friction surfaces of the rolls, the highest wear has been observed in the interval from the beginning to the first hour. Then the process of breaking-in between the surfaces of the friction pair is more intensive. After the second hour of the investigation, during the steady wear process, the value of J_i has decreased significantly. This is due to the cutting of most of the micro-irregularities on the friction surfaces. Generally, the highest wear in the process of investigation has been observed in the roll without deposited coating for rebuilding. The least wear has occurred in the roll, with deposited coating "B".

Figure 7 presents the variation in the quantity of the removed material in friction process of the sectors. Analogically to the rolls, the highest wear of the sectors has been observed in the first hour of the investigation. As a whole, the biggest wear has the sector involved in the friction process with the roll “NO” coating. The least wear has the sector involved in the friction pair with the roll type coating “B”.

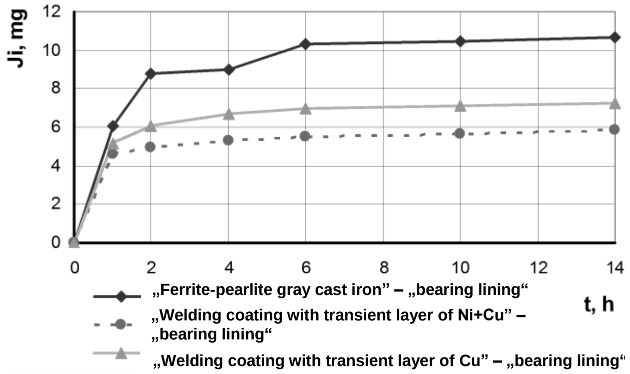

Fig. 6 - The quantity of the removed material from the rolls at different friction surfaces

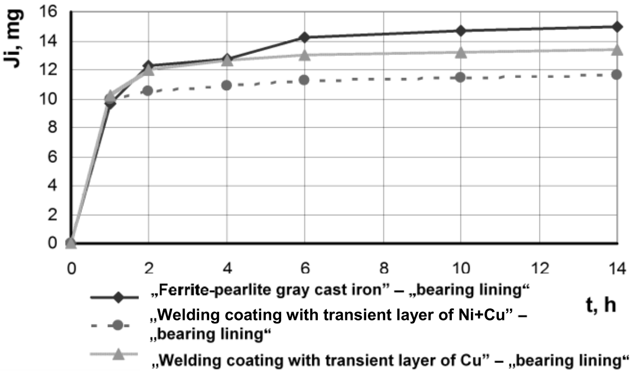

Fig. 7 - The quantity of the removed material from the sectors at different friction surfaces of the rolls

Results obtained from the investigation of the friction torque between the friction pair elements

The variation of the friction torque at the end of the loading during the investigation is presented in Figure 8. It can be seen that for all three types of rolls that the friction torque at the end of the loading has decreased during the investigation in the transition from the breaking-in process between the elements from the friction pair to the process of steady wear. The smallest value of $FT_{end\ of\ loading}$ has the pair, in which the roll has been deposited with coating „B”. Therefore, in this case the best breaking-in process with the bearing alloy deposited on the sectors has been observed.

Figure 9 presents the variation of the friction torque after the breaking-in process. Based on the results, it can be concluded that at the rolls with deposited coating for rebuilding, the friction torque after the breaking-in process has decreased. The lowest value of $FT_{after\ breaking\text{-}in}$ has been obtained at the roll deposited with coating “B”.

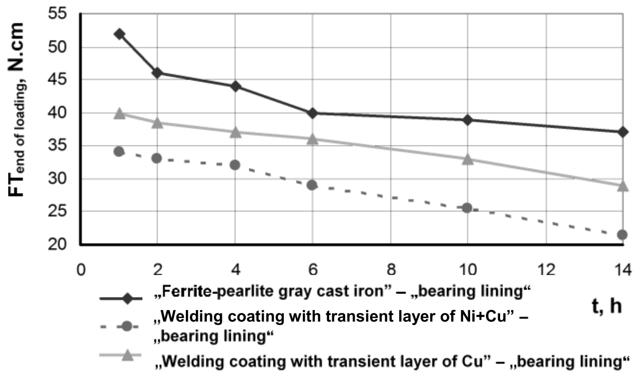

Fig. 8 - Variation of the friction torque at the end of the loading

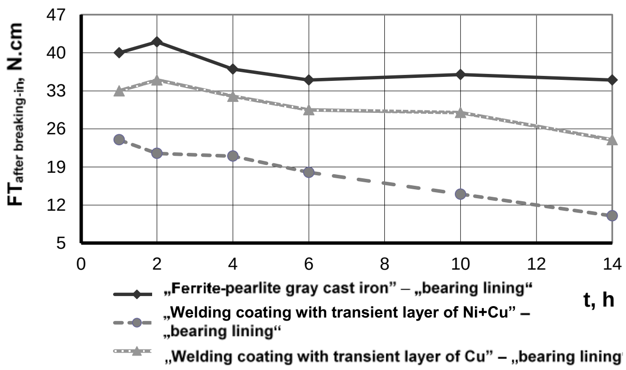

Fig. 9 - Variation of the friction torque after the breaking-in process

The variation of the friction torque at breaking-in process has been presented in Figure 10. The lowest values of the friction torque at breaking-in process have been obtained at the roll deposited with coating “A” and at the roll without deposited coating.

The friction torque reducing during the tests is due to the smoothing of the friction surfaces’ microroughness, which reduces their direct contact.

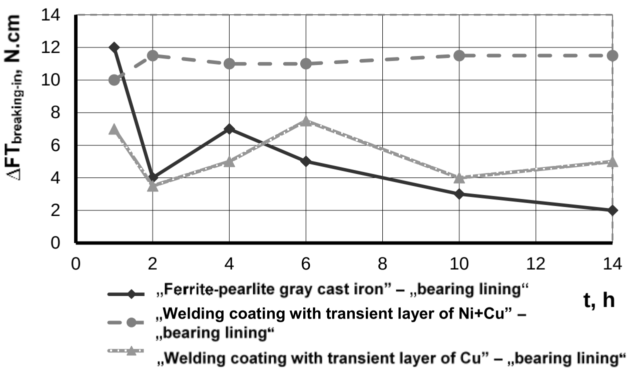

Fig.10 - Variation of the friction torque at breaking-in process

Results obtained from the investigation of the roughness of pair elements’ friction surfaces

Figure 11 presents the variation of the friction surfaces’ roughness of the rolls, during the investigation. The diagram presents that the lowest roughness has the roll with not deposited coating. The rolls with deposited coatings have almost the same roughness values.

Figure 12 presents the variation of the friction surfaces’ roughness of the sectors at different friction surfaces of the rolls. The roughness of the sectors, involved in the friction pair with the rolls with deposited coating, has decreased during the breaking-in process, to reaching almost constant value in the steady wear process.

Due the transfer of microparticles against each other surfaces the roughness increases during breaking in process. This phenomenon is typical of this process. The general tendency to reduce the roughness of the friction surfaces after breaking-in process is generated by the reduction of the height of the microroughness.

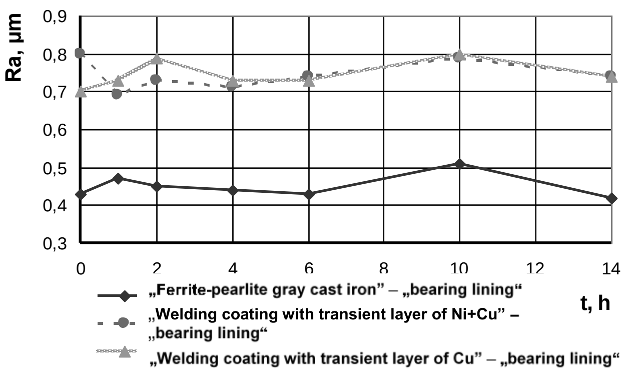

Fig. 11. Variation of the friction surfaces’ roughness of the rolls

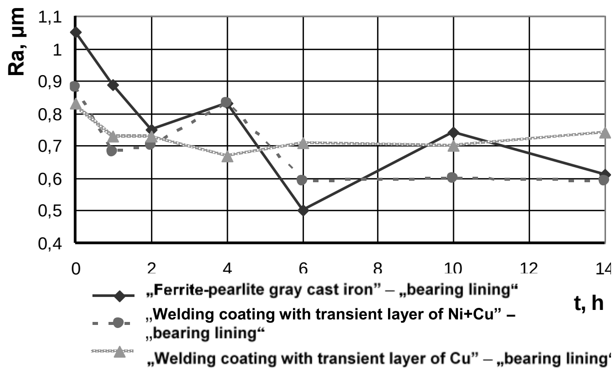

Fig. 12. Variation of the friction surfaces’ roughness of the sectors

Results from micro-hardness investigation of friction surfaces of the friction pair elements

The variation of the friction surfaces’ micro-hardness of the rolls during the investigation is presented in Figure 13. The highest micro-hardness of the friction surface has the roll deposited with coating “B”. At the three types of rolls, the micro-hardness of the friction surface has changed in wide boundaries in the breaking-in process compared to the steady wear process.

Figure 14 presents the variation of the micro-hardness of the sectors’ friction surfaces at different friction surfaces of the rolls. The micro-hardness of the friction surfaces of the sectors has changed significantly. The sector with the highest micro-hardness values is the sector with coating “A” (friction surface - welding coating with copper transient layer).

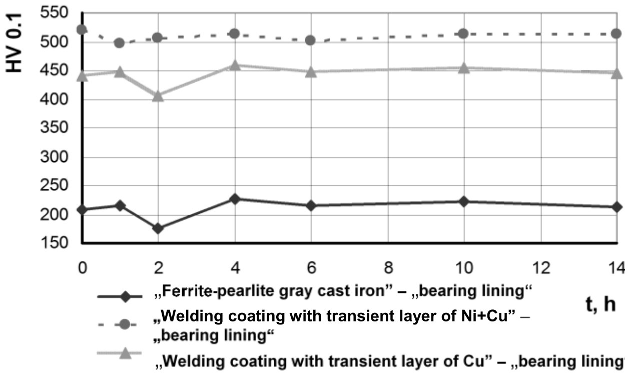

Fig. 13 - Variation of the friction surfaces' micro-hardness of the rolls

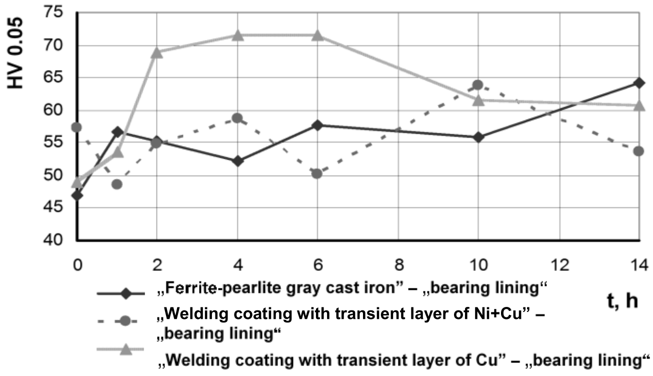

Fig. 14 - Variation of the micro-hardness of the sectors' friction surfaces

Determination of the relative wear resistance of the coatings for rebuilding

The relative wear resistance of the coatings for rebuilding has been determined by the equation:

$$\varepsilon = E/E_E \tag{1}$$

where: E is wear resistance of the friction surface of a roll with deposited coating for rebuilding, m/g;

E_E – wear resistance of the friction surface of a roll without deposited coating for rebuilding, m/g.

The wear resistance is a reciprocal parameter of the wear intensity v:

$$E = 1/V \text{ [m/g]} \tag{2}$$

The wear intensity of the friction surface, V of the rolls has been determined by the equation:

$$V = J_i/S \text{ [g/m]} \tag{3}$$

where S = 71215.2 m is the path of the friction surface of the roll, during the investigation.

Table 3 presents the values of calculated relative wear resistance of the rolls' friction surfaces.

Table 3

Relative wear resistance of the rolls' friction surfaces

Type of roll's friction surface	Micro-hardness, HV 0.1	Removed material in wear Ji [g]	Wear intensity V [g/m]	Wear resistance E [m/g]	Relative wear resistance ε
Coating "A"	472	7.25 x 10^{-3}	10.1 x 10^{-6}	99009.90	1.485
Coating "B"	525	5.83 x 10^{-3}	8.1 x 10^{-6}	123456.79	1.852
"NO" coating	232	10.70 x 10^{-3}	15 x10^{-6}	66666.67	1

Based on the results in the Table 3, it can be concluded that coating "B" is with the highest relative wear resistance. The value of the wear resistance means that the resource of the rebuilt machine part with this coating will increase 1.852 times, compared to non-rebuilt machine part.

CONCLUSIONS

The rebuilding of machine parts is a way of achieving a positive economic, environmental and social effect in many fields. The presented investigations of the coatings for rebuilding allow determining the achieved wear resistance of the rebuilt parts. It is directly related to the calculation of the savings, for not buying of spare parts.

The results from the investigations can be used to analyse the qualities of the coatings for rebuilding. Based on current results, the most appropriate coatings can be selected. On the other hand, the results can be used for optimization of the methods and technologies for rebuilding of worn-out machine parts.

Last but not least, it can be summarized that the coating "B" is better than coating "A". Coating "B" is characterized with higher micro-hardness, lower quantity of removed material in friction process, respectively higher wear resistance, less friction torque at the end of the loading process and less friction torque after the breaking-in process.

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