Annals of Warsaw University of Life Sciences – SGGW
Forestry and Wood Technology № 122. 2023: 57-66
(Ann. WULS - SGGW, For. and Wood Technol. 122, 2023: 57-66)
Received: 29.03.23 / Accepted: 28.04.23 / Published: 30.06.23

The regeneration of the tools to cellulose cutting using electric arc surfacing method

SVITLANA ROMANIUK[1], MAREK BARLAK[1], JACEK WILKOWSKI[2]

[1] Plasma/Ion Beam Technology Division, Material Physics Department, National Centre for Nuclear Research Świerk, 7 Andrzeja Sołtana St., 05-400 Otwock, Poland

[2] Department of Mechanical Processing of Wood, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences, 159 Nowoursynowska St., 02-776 Warsaw, Poland

Abstract: *The regeneration of the tools to cellulose cutting using electric arc surfacing method*. The paper presents the laboratory results of the regeneration of the tools to cellulose cutting, using electric arc surfacing method. Three types of regenerating material was used in the rod electrodes form. Additionally, each material was applied with additional non-magnetic powder in the coating. Finally, the layer with the highest microhardness was covered with a ZrN coating in the Arc PVD process. The relative wear coefficient, the friction moment, the friction coefficient, the width of friction track and the microhardness were measured. The SEM observations and EDS investigations were applied for the studies of the microstructure of investigated materials. The best results were obtained for the regeneration using regenerating material, marked as "T-590 + powder", with ZrN coating.

Keywords: integrated technology, electric arc surfacing, nanostructured coating, modification, hardening, wear resistance

INTRODUCTION

The tools wear and damage during the cutting processes, also a soft materials. The high cost of the tools made of high-carbon alloyed steels necessitates the search for new methods of the strengthening and also the restoring of their working surfaces, therefore the development and improvement of technologies, which can extend the tool lifetime and enhance its properties is a very important problem. Currently, there are a various methods for forming alloyed wear-resistant coatings on the working surfaces of the tools. The welding technologies are widely used for the restoration of parts [Pradeep et al., 2010], however, the traditional welding method does not provide the required level of wear resistance. More effective restoration technology is the welding with the addition of various hard refractory powder particles [Wnag and Li, 2010], like oxides [Wang and Gou, 2016], carbides [Wang et al., 2000; Wang et al., 2005], carbo-nitrides and borides [Liu et al., 2013]. The introduction of modifying particles changes the material microstructure and its mechanical properties. Sometimes, the using of the expensive material additives is not economically efficient, therefore the applying of the secondary materials is needed [Skoblo et al., 2021]. The authors [Skobnlo et al. 2019] obtained a positive result when using a non-magnetic modifying powder for surfacing the working tool of agricultural machines (cultivator blade). The addition of a non-magnetic modifying powder to the coating increases the wear resistance by 1.3-fold compared to the surfacing layer applied solely with electrode T-620. Furthermore, it improves the wear resistance by 2 times compared to the original material of the cultivator blade. The addition of a non-magnetic modifying powder during surfacing with wire Св-08Г2С results in a 74% increase in wear resistance. When using wire ER321 with added powder, the wear resistance increases by 28% [Rybalko and Markov, 2012]. Using a magnetic modifying powder during surfacing with electrode Э46 increases the wear resistance of the surface layer by 25% [Skoblo et al., 2020].

An individual approach is required in each case, to ensure specific consumer properties when restoring specific parts, depending on the chemical composition of the part and the operating conditions.

This paper presents the laboratory results of the regeneration of NC11 steel tools to cellulose cutting. The tools were regenerated using electric arc surfacing method, using three kinds of the electrode materials, each without and with the powder particles.

MATERIALS AND METHODS

The investigation were provided using NC11 steel tools, with the dimensions of 6×25×195 mm^3, presented in Fig. 1, used in the food industry to the cutting of cellulose, used to the candy wrappers. There tools were intended for the Italian production machine of MC Automations company, type MC1DT-T (Fig. 2).

Figure 1. The cutting tool used in the investigation

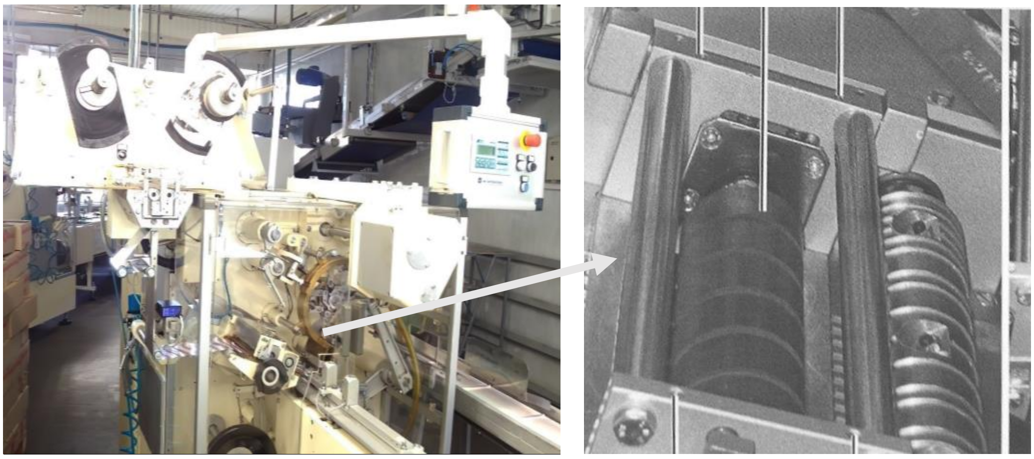

Figure 2. The view of MC1DT-T type MC Automations company machine [the author's own photographs]

The equivalent grades of the used NC11 steel are presented in Table 1. The chemical composition of the tool material was determined in our preliminary investigations, using Metavision-1008i optical spectrometer (Metal Power company). The results of this determination are presented in Table 2.

The above described tools worked e.g. on the production line in the confectionery factory in Kharkiv, in the set of 20 pieces, simultaneously. Each tool had 4 edges, used one at a time. The unit cost of the tool, before Russo-Ukrainian war was about 150 USD. Due to the relatively high price, the tools regeneration was attempted, when the wear was about 5 mm per the edge. The regeneration processes were performed at Petro Vasylenko Kharkiv National Technical University of Agriculture Ministry of Education and Science of Ukraine in Kharkiv, using the electric arc surfacing method. The estimated regeneration cost was about 20 USD per piece.

Three types of the regenerating materials in the rod electrodes form were used in the regeneration process. The chemical composition of these electrodes is presented in Table 3.

Table 1. The equivalent grades of NC11 steel [11]

Country	Standard	Steel grade
United States of America		D3, T30403, T30404
Germany	DIN, WNr	1.2060, 1.2080, X210Cr12, X210CrW12
Japan	JIS	SKD1
France	AFNOR	X200CM2, X200Cr12, Z200C12
Great Britain	BS	2080, BD3
European Union	EN	1.2080, X210Cr12, X21Cr12
Italy	UNI	X205Cr12KU
Spain	UNE	F.5212, X120Cr12, X210CM2, X210Cr12
China	GB	Cr12
Sweden	SS	2312
Poland	PN	NC11
Czechia	CSN	19436

Table 2. The chemical composition of the NC11 tools used in the investigations

Element	C	Si	Mn	Cr	Fe	P	Mo	Other (e.g. Ti, Cu, V)
Concentration (wt.%)	2.2	0.4	0.35	12.12	84.8	0.01	0.12	<0.1

Table 3. The chemical composition of the rod electrodes used to the regeneration

Electrode type	Element (wt.%)								
	C	Si	Mn	Cr	Ni	Nb	B	S	P
T-590	2.9-3.5	2-2.5	1-1.5	22-27	-	-	0.5-1.5	0.035	0.04
CL-11	0.05-0.12	<1.3	1-2.5	18-22	8-10.5	0.7-1.3	-	0.02	0.03
ANO-21	0.1	0.3	0.6	-	-	-	-	0.04	0.045

Additionally, all above presented regenerating materials were modified using the powder, in the coating form. The non-magnetic powder of the detonation charge, obtained from the disposal of ammunition was used as a modifier of recovery coatings (secondary material). The entire modifying powder was divided into five parts for detailed chemical analysis. Afterward, it was thoroughly mixed and fully utilized as a modifier during surfacing. The even distribution of the powder in the modifying layer was monitored using an electron microscope with EDS analysis. The chemical composition of the applied powder was determined using Genius 5000XRF Spectrometer and shown in Table 4.

Additionally, it was determined that the powder contains 2.87-4.5 wt.% carbon (nano- and dispersed diamonds, with a small fraction, up to 0.3% graphite), using a chemical method.

The restored layer with the highest microhardness was additionally covered with a ZrN coating with the thickness of 4.5 μm, formed in the Arc PVD process (vacuum-arc method using RF discharge) [Taran et al., 2018], to further enhance the wear resistance of the layers formed on the tools.

The cross-sections of all manufactured regeneration layers (without and with the powder) were investigated using SEM microscopy for the magnifications of 80-10000× and for the acceleration voltage of 15 kV. EDS method was used to the determination of chemical compositions of the ones, for the magnifications of 80-1500× and for the acceleration voltage of 15 kV.

Table 4. The chemical composition of the modifying powder

Element (wt.%)	Measurement number					Average
	1	2	3	4	5	
Mg	-	66.826	-	-	-	13.37
Al	-	28.464	-	-	-	5.69
Si	-	1.945	-	-	-	0.39
Ti	20.185	-	-	11.014	9.963	8.23
V	8.155	-	-	-	-	1.63
Cr	1.17	-	-	0.659	0.544	0.47
Mn	0.856	0.035	-	0.462	0.435	0.36
Fe	6.231	0.461	4.91	9.614	10.884	6.42
Ni	0.005	-	-	0.205	0.177	0.08
Cu	7.807	1.45	9.147	25.005	23.087	13.3
Zn	-	0.819	4.632	11.362	12.61	5.88
Y	2.583	-	-	0.723	0.773	0.82
Zr	0.236	-	-	-	-	0.05
Mo	0.44	-	-	0.176	0.129	0.15
Sn	5.483	-	71.187	4.515	3.698	16.98
Hf	2.904	-	-	-	-	0.58
Ta	0.411	-	-	-	-	0.08
W	4.237	-	-	-	-	0.85
Pb	39.239	-	8.128	30.385	34.67	22.48
Bi	0.058	-	-	-	-	0.01
Ag	-	-	0.395	0.083	-	0.1
Sb	-	-	1.601	2.091	-	0.74
Co	-	-	-	1.122	1.09	0.44
Cd	-	-	-	2.584	1.94	0.9

Dry friction tests were carried out using ball-on-disc method on SMT-1 type machine. Sample loading was performed at 10 N and the duration of each stage was 5 minutes. At the same time, the coefficient of friction was fixed at each stage. The rotation frequency of the roller (countersample, counter specimen material) was 50 min^{-1}. The roller was made from LH15 steel. This steel composition is presented in Table 5.

Table 5. The chemical composition of the roller

C	Cr	Si	Mn	Ni	Cu
0.95-1.05	1.3-1.65	0.17-0.37	0.2-0.4	to 0.3	to 0.25

The wear coefficient of all regeneration layers was defined by the weight. Except that, the roller wear was determined.

The microhardness of NC11 steel and all obtained layers were determined using Vickers method for the load of 0.5 N, before and after the wear tests.

RESULTS AND DISCUSSION

The determined optimal amount of modifying powder relative to the electrode fraction was 5-7 wt.% [Romaniuk, 2019]. This limitation was due to the presence of oxides in the powder. Too much powder content was the reason to the formation of the voids and the gas bubbles, during the surfacing process. The example cross-section microstructure of the modifying layer with the defects is presented in Fig. 3.

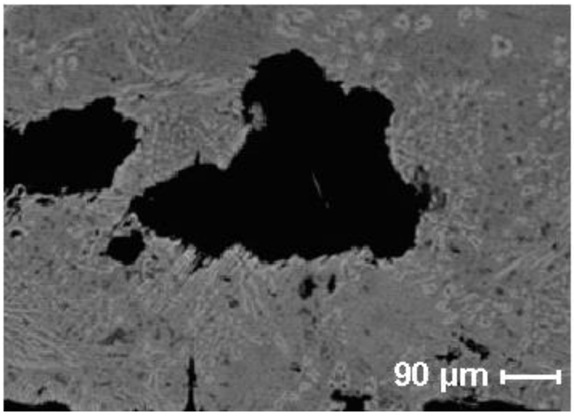

Figure 3. The microstructure of the surfacing layer with electrode T-590 and the addition of modifying powder exceeding 10 wt.%

It was observed that, the powder presence leads usually to obtain more stable and proper microstructures of the formed layers, e.g. without the cracks. Probably, the powder presence lowers the temperature of the liquid bath and reduces the cooling rate of the liquid metal and as a results the brittleness of the transition zone. Additionally, the powder addition reduces the width of the transition layer about 2-3-fold.

The example crack of the microstructure obtained using CL-11 electrode without the powder is presented in Fig. 4.

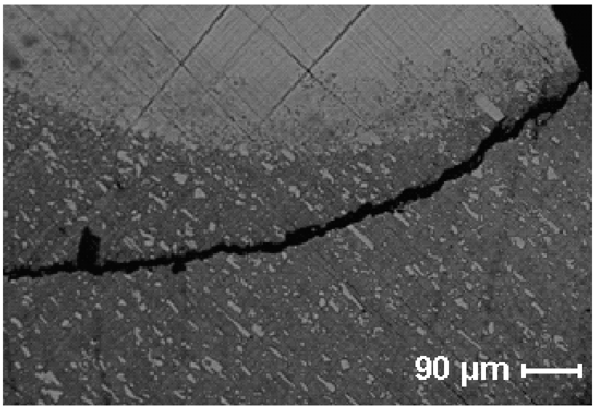

Figure 4. The microstructure of the repaired component after surfacing with electrode CL-11 without modifying powder

The proposed technology provides to the increasing of the wear resistance and the microhardness.

Table 6 shows the relative values of the wear coefficients for the formed layers and for LH15 steel roller, used in the tests. The change of the weight in the test was determined relatively for each material pair, i.e. for the formed layer and the roller. For example, when the loss of the layer weight was 1.5 unit, the loss of roller weight was 1.8 unit, for "ANO-21 + powder" modification type.

We can see, that the relative wear resistance was practically the same for "T-590 + powder", "ANO-21" and "ANO-21 + powder" modification types. A large difference in weight loss was observed in "T-590" case, in favour of the layer, and in "CL-11 + powder" case, in favour of the roller.

Table 6. The relative values of the wear coefficient for the tested material pairs

Modification type	Relative wear coefficients	
	Layer	Roller
T-590	0	-1
CL-11	-1	-1.5
ANO-21	-1	-1
T-590 + powder	0	0
CL-11 + powder	-2	0
ANO-21 + powder	-1.5	-1.8

Table 7 shows the average values of others tribological properties of the formed layers, like the friction moment, the friction coefficient and the width of the friction track. The values of the friction moment are in the range from 1 Nm for “CL-11” case to 3.5 Nm for “T-590” case. The friction coefficient values are from 0.09 for “CL-11” case to 0.31 for “T-590” case. The width of friction track values are from 0.59 mm for “CL-11” case to 1.1 mm for “ANO-21” case. It is worth noting, that the smallest values of all tribological parameters were obtained for “CL-11” modification type, and one of the greatest values, for “T-590”, “T-590 + powder” and “ANO-21 + powder” modification types.

Table 7. The tribological parameters values of the modified layers

Modification type	Friction moment (Nm)	Friction coefficient	Width of friction track (mm)
T-590	3.5	0.31	0.75
CL-11	1	0.09	0.59
ANO-21	1.5	0.13	1.1
T-590 + powder	3	0.27	0.88
CL-11 + powder	1.5	0.13	0.79
ANO-21 + powder	2.5	0.22	0.85

The level of the microhardness, before and after wear tests is an important indicator for evaluating the effectiveness of the restoration and strengthening process. In this case, wear tests were conducted under conditions similar to the real-life operation of the tools. The results of the microhardness measurements before and after the wear tests for all modification types are presented in Fig. 5.

A decreasing of the hardness level was observed after the wear tests for all samples. This may be related to the removing of a finer non-magnetic fraction contributed to the formation of secondary structures, observed on the friction surface of the formed layers (not shown here).

The maximum level of microhardness both before and after wear tests was obtained for the layer formed using “T-590 + powder” electrode, while the observed decreasing of the microhardness for the both “ANO-21” cases, may be related to the observed non-homogeneity of the obtained layers (not shown here).

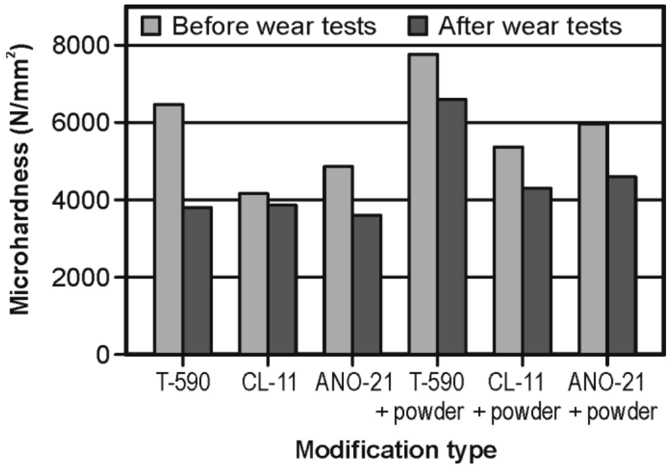

Figure 5. The level of the microhardness, before and after the wear tests

The next presented results are for the investigations of “T-590 + powder” layer, additionally covered with ZrN coating. Table 8 presents the relative values of the wear coefficients for material pair, i.e. “NC11 steel + “T-590 + powder” + ZrN” case and for LH15 steel roller, used in the tests (like in Table 6). Additionally, the results obtained for the material pair with the substrate material (NC11 steel) and for the material pair with the substrate material with ZrN coating, are presented for the comparison.

We can see a different change of the mass for each case, i.e. the weight growth of the substrate material and the weight loss of the roller in NC11 steel case, the weight loss of both materials in the case of NC11 steel covered with ZrN and finally, the loss mass of NC11 steel + “T-590 + powder” + ZrN case and the weight growth of the roller. This tendency and the obtained values are difficult to explain at this stage of investigations.

Table 8. The relative values of the wear coefficient for the tested material pairs

Modification type	Relative wear coefficient	
	Material	Roller
NC11 steel	+1	-1
NC11 steel + ZrN	-0,8	-1
NC11 steel + “T-590 + powder” + ZrN	-0,4	+0,5

Table 9 shows the average values of others tribological properties of the formed layers, like the friction moment, the friction coefficient and the width of the friction track for “NC11 steel + “T-590 + powder” + ZrN” case. Also, the results obtained for the material pair with the substrate material (NC11 steel) and for the material pair with the substrate material with ZrN coating, are presented for the comparison.

It is seen that all obtained values are the smallest for third case (NC11 steel + “T-590 + powder” + ZrN), e.g. the friction track value is only 0.07 Nm, which is 6-fold smaller in the comparison with the original tool material (NC11 steel) and about 5.3-fold smaller in the comparison with NC11 steel covered with ZrN coating.

Table 9. The tribological parameters of the modified layers with ZrN coating

Modification type	Friction moment (Nm)	Friction coefficient	Width of friction track (mm)
NC11 steel	0.42	3	0.27
NC11 steel + ZrN	0.37	2	0.2
NC11 steel + “T-590 + powder” + ZrN	0.07	1.5	0.13

Fig. 6 shows the results of SEM observations (for the magnification of 300×) and EDS measurements (for the magnification of 500×) of the surface of the layer with ZrN coating, after the wear resistance tests. A less distinct surface structurization was observed, with the zones of the compression (darker areas) and the stress relief (Fig. 6, left). The friction boundary was undulating, with heterogeneous wear of the coating (Fig. 6, right). The results of EDS measurements for three different regions, marked in Fig. 6b are presented in Table 10. It is seen, the absence of the selected elements, like nitrogen, oxygen and zirconium in the zone of the compression and the silicon introduction to this zone, probably from roller material.

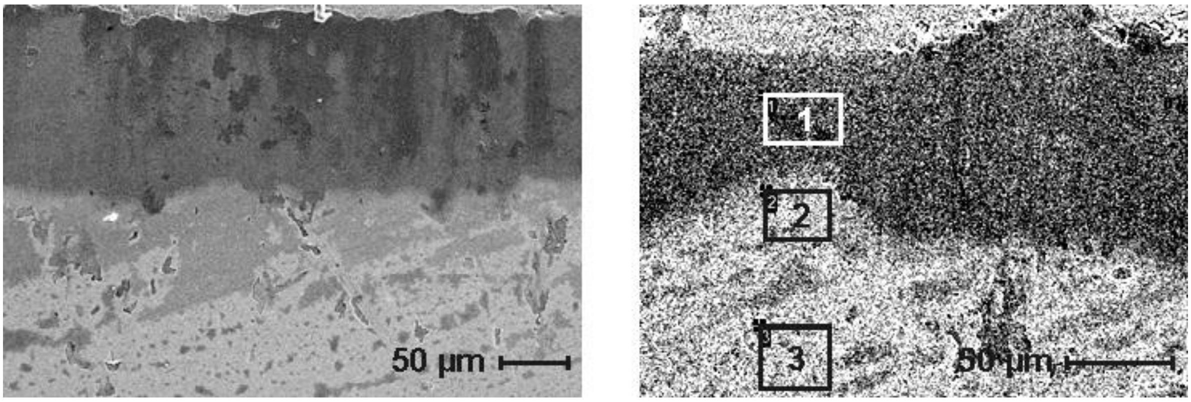

Figure 6. SEM image of a surface with ZrN coating after the wear tests (left) and EDS image once (right)

Table 10. The contents (in wt.%) of components on the restored surface with ZrN coating after wear resistance tests (Fig. 6, right)

Measurement region	C	N	O	Si	Cr	Fe	Zr
1	5.56	-	-	1.48	23.65	69.31	-
2	6.21	13.45	2.92	-	4.94	12.68	59.8
3	6.26	12.32	2.45	-	3.57	5.69	69.72

An increase of the microhardness of “NC11 steel + “T-590 + powder” + ZrN” material by 32.7%. was observed after wear tests.

The comparison of the obtained data with the best results of the using the modifying powder, presented in Refs [7-10] shows a significant reduction (by 34.6%) in microhardness during friction [8]. Additionally, the use of the "T-590 + non-magnetic modifying powder" electrode on NC11 steel allowed for reproducible results and relatively low (15.38%) decrease in microhardness value. Furthermore, the result of our new approach (additional ZrN layer) was a 2.5-fold increase in tool wear resistance.

CONCLUSIONS

Based on the results of the research, the following conclusions can be drawn:

- the tribological indicators, like the friction moment, the friction coefficient or the width of the friction track were the best for the sample without the powder, i.e.“CL-11” modification type,
- the tool regeneration using the materials with the additional powder was more effective in the comparison with the regeneration using the same materials without the powder,
- the optimal content of the used powder was about 5-7 wt.%, for this content the formation of the voids and the gas bubbles is not observed,
- probably, the increasing of the microhardess of the regenerating layers is a results of the formation of secondary structures in the formed layers,

- the using additional ZrN coating leads to an increase in the durability of regenerating material, several times.

The presented investigation were realized in the laboratory environment. The planned tests in the factory conditions and an economic analysis in relation to the use of new/regenerated tools have been destroyed as a result of the outbreak of the Russo-Ukrainian war.

ACKNOWLEDGMENTS

The authors wish to thank Mr. T. Maltsev for the tribological measurements and Mr. A. Taran for ZrN coating deposition.

REFERENCES

1. CHOO S.H., KIM C.K., EUH K., LEE S., JUNG J.Y., AHN S., 2000: Correlation of microstructure with the wear resistance and fracture toughness of hardfacing alloys reinforced with complex carbides, Metallurgical and Materials Transactions A no 31; 3041-3052
http://www.splav-kharkov.com/mat_start.php?name_id=264
2. LIU D., LIU R., WEI Y., MA Y., ZHU K., 2013: Microstructure and wear properties of Fe–15Cr–2.5Ti–2C–xB wt% hardfacing alloys, Applied Surface Science no 271; 253-259
3. PRADEEP G.R.C., RAMESH A., DURGA PRASAD B., 2010: A review paper on hardfacing processes and materials, International Journal of Engineering, Science and Technology no 2; 6507-6510
4. ROMANIUK S., 2019: Development of technological process for restoring the surface of tools made of high-carbon alloy steel, Bulletin of the National Technical University “KhPI”, Series: Innovative technologies and equipment handling materials in mechanical engineering and metallurgy no 26; 47-51
5. RYBALKO I., MARKOV O., 2022: Modification of the restored layer of wear parts during surfacing, Proceedings of the International scientific and technical conference "Strength and durability of modern materials and constructions; 166-167, in Ukrainian
6. SKOBLO T.S., NANKA O.V., KUSKOV YU.M., SAYCHUK O.V., ROMANCHENKO V.M., ROMANYUK S.P., RYIBALKO I.M., MARKOV O.V., SAMSONOV YU.V., MALTSEV T.V., 2021: A new way of getting the charge with diamond fraction, Nanosistemi, Nanomateriali, Nanotehnologii no 19; 23-33
7. SKOBLO T.S., RYIBALKO I.M., TIHONOV A.V., MALTSEV T.V., 2019: Improving the wear resistance of hoe blades by modifying of restoration coatings, Problems of Tribology no 94; 27-32
8. SKOBLO T.S., SIDASHENKO A.I., ROMANYUK S.P. GONCHARENKO A.A., OMEL’CHENKO L.V., BANTKOVSKII V.A., 2020: Specific features of structure formation in the course of modification of the coatings on products made of dispersion-hardened steels. Materials Science no 55; 884-891
9. TARAN A., GARKUSHA I., TARAN V., MURATOV R., STARIKOV V., BATURIN A., SKOBLO T., ROMANIUK S., MAMALIS A.G., 2018: Structure and properties of nanostructured ZrN coatings obtained by vacuum-arc evaporation using RF discharge, Nanotechnology Perceptions no 14; 167-178

10. WANG Q.B., LI X.Y., 2010: Effects of Nb, V, and W on microstructure and abrasion resistance of Fe-Cr-C hardfacing alloys, Welding Journal no 89; 133-139
11. WANG X.H., ZOU Z.D., QU S.Y., SONg S.L., 2005: Microstructure and wear properties of Fe-based hardfacing coating reinforced by TiC particles, Journal of Materials Processing Technology no 168; 89-94
12. WANG Y., GOU J., CHU R., ZHEN D., LIU S., 2016: The effect of nano-additives containing rare earth oxides on sliding wear behavior of high chromium cast iron hardfacing alloys, Tribology International no 103, 102-112

Streszczenie: *Regeneracja narzędzi do cięcia celulozy metodą napawania łukowego*. W pracy przedstawiono laboratoryjne wyniki regeneracji narzędzi do cięcia celulozy, regenerowane metodą napawania łukiem elektrycznym. Zastosowano trzy rodzaje materiałów regenerujących w postaci elektrod prętowych. Dodatkowo, do materiałów regenerujących dodawano niemagnetyczny proszek w postaci otuliny. Warstwę o największej mikrotwardości pokryto jeszcze powłoką ZrN, w procesie Arc PVD. Zmierzono względny współczynnik zużycia, moment tarcia, współczynnik tarcia, szerokość toru tarcia oraz mikrotwardość. Do badań mikrostruktury badanych materiałów wykorzystano obserwacje SEM oraz badania EDS. Najlepsze wyniki uzyskano dla regeneracji przy użyciu materiału regenerującego oznaczonego jako „T-590 + proszek” z powłoką ZrN.

Corresponding author:
Svitlana Romaniuk
7 Andrzeja Sołtana St.
05-400 Otwock, Poland
Svitlana.Romaniuk@ncbj.gov.pl
(22) 273 16 22