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Observation of the Amount of Wear and the Microstructure of Hardfacing Layers after the Test of Resistance to Abrasive Wear

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The article deals with the evaluation of the amount of wear of the base material and selected hardfacing materials intended for tools for wood processing in forestry after a test of resistance to abrasive wear in laboratory conditions. The values of average weight loss W_h[g] and relative resistance to abrasive wear Ψ_h[-] were determined by calculation. The topography of the surface after the track of the rubber disc and the abrasive of the testing device was evaluated with a confocal microscope. The depth of the disc track P_t[μm;mm] was also evaluated with a confocal microscope. The state of the samples surface after the test, as well as the overall structure and mixing of the hardwearing material with the base material was evaluated by light microscopy. A touch roughness meter was used to determine the profile of the track surface after the test. Based on the results, we can recommend certain hardfacing materials for practice. Their abrasive resistance and thus also the loss of material during the work load could ensure a longer service life of the tool.

Keywords: Wear, Microstructure, Confocal microscopy, Hardfacing, Abrasion

1 Introduction

The work of environmental modification tools during forest cultivation is characterized by a high load in an inhomogeneous working environment. This environment is mainly wood, of different composition, hardness and diameter [1,2,3,4]. The second important component of this environment is the soil. On its surface there are rocks and minerals of different sizes, hardness and origin, unpredictably and irregularly distributed. The high revolutions of the rotor of the adapter of the base machine, on which the tools are stored, the uneven load of individual tools, in connection with the storage on the rotor, also contribute to their early wear, which affects their duration of use in operation [2,4,5]. Hardfacing, as one of the possibilities of renovating surfaces and increasing its service life, can be defined as deposition welding [6]. In a metallurgical process, the base material is melted at high temperatures. At the same time, a suitable hardfacing material (welding consumables) is melted and added to the melting bath. The result of welding is a homogeneous metal or alloy layer. A protective layer with the required properties can be created with the coating created in this way, such as resistance to corrosion, thermal stress, abrasive and adhesive wear, cavitation, erosion, abrasion and other adverse factors [6,7,8,10,11].

Several authors, e.g. [5,8,9,11] theoretically wrote in their research papers about the influence of factors on abrasive wear of materials. These are the effects of mechanical properties, structure, chemical elements and the influence of the abrasive.

When evaluating metal materials resistant to abrasive wear, we encounter two types of structures. They are heterogeneous structures, consisting of several structural components (formed by combinations of ferrite, pearlite, carbides, borides, carboborides, etc.) and homogeneous structures. They are formed by a single structural component (e.g. austenitic) [11,12,13].

Hardfacing consumables materials represent a wide range of alloys based on Fe, Ni, Co with the addition of carbide-forming elements (Cr, W, Mo, V, Ti, Nb), or other alloys (B, Si, etc.). Electrodes with a high chromium content are often they are used for their low cost and good resistance to particle wear. More expensive alloys that contain carbide-forming elements such as W, V and Nb combine the high hardness of the carbide phases with the toughness of the metal matrix. Carbides, due to their high hardness, represent obstacles against the penetration of hard particles. The metal matrix must resist the scoring effect of the particles and at the same time prevent the carbides from breaking out. Relatively soft but tough alloys are sometimes used in the combined action of abrasion and impacts. This group of weld alloys includes austenitic manganese steels, ledeburitic materials, martensitic alloys, ferritic-carbiditic and high-alloy steels hardenable in air [4,6,9,10,11,14].

During hardfacing process, the hardfacing consumables material is melted and at the same time the surface layers of the base material are melted. In the transition area, their mixing occurs and thus the chemical composition and microstructure change. Therefore, multi-layer hardfacing are mostly used, when the necessary chemical composition and suitable properties of the hardfaces are achieved in the second or third layer. An intermediate layer can be used before welding the hard weld [9,12,13]. Its task is to ensure a good connection with the base material. The formation of hydrogen-induced weld breaks (cracks) in preheated parts is prevented. The consequences of welding stresses are minimized and the influence of mixing is limited. Peeling off of subsequent hard layers is prevented and possible cracks from spreading into the base material, which arise in the hard deposit, are prevented [9,13]. By creating several layers, we achieve a several-fold reduction in the economic burden of renovating parts or the consumption of energy and basic material [4,12].

Confocal microscopes are currently one of the basic tools of biological, medical and materials research. They can display two-dimensional so-called optical sections of the sample placed at any depth or a three-dimensional image of sample in the form of a three-dimensional grid of points. Unlike a classic microscope, a confocal microscope displays the image in layers and can thus create a three-dimensional image of the object being examined. It contains three laser units, which enables simultaneous monitoring of three colour components in one preparation [15,16,17]. At the same time, since the measurement is non-contact, it can replace the evaluation of the surface profile of the samples with a contact roughness meter [18].

2 Introduction

Using light microscopy, as reported by the authors [1,2,19], the structure was observed on a sample taken from the body of a worn tool. We can state that it is a ferritic-pearlitic structure, the state of the material - without heat treatment. Figure 1 shows significant local deformation of the surface layer to a depth of approx. 0.20 mm on the body of the tool. Here the critical value of the mechanical stress was reached, generating the plastic flow of the material. This causes its gradual material loss from the surface. Cyclic repetition of the plastic deformation of the tool under conditions of abrasion leads to a decrease of the material over time and thus to a loss of its functionality.

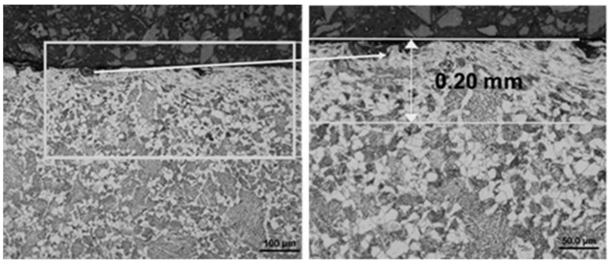

Fig. 1 *Plastic deformation on the back surface of a tool for processing wood mass [19]*

For research on increasing the service life of tools for wood processing in forestry, hardfacing materials were selected, which with their chemical composition as well as the created structure can ensure better resistance to abrasive wear and shock loads [8,11,17,21]. The following tests and analyses were used in the experiment:

- testing the material's resistance to abrasive wear;
- microscopic analysis by light microscopy (LM);
- evaluation of the surface profile with the confocal microscope/profilometer;
- evaluation of the surface profile with the contact roughness meter.

The tool is made of steel 16MnCr5, (Wr.Nr. 1.7131, STN 14 220). It is a structural low-alloy, low-carbon cementitious chromium-manganese steel. It is well forming under heat. After soft annealing, it is also forming when cold. It is easily machinable and weldable. It is used for the production of various machine parts and is suitable for cementation with the achievement of high strength in the core. The chemical composition of steel 16MnCr5 is C 0.16%, Mn 1.25%, Si 0.27%, Cr 0.95%, the balance Fe.

E520 RB VÚZ, Bratislava - electrode suitable for applying layers' resistant to strong abrasive wear even at elevated temperatures (mining harvesters, earthmoving and agricultural machines). The electrode is characterized by good operational properties, good ignition, stability and arc burning. It has good layering and spread of weld metal. It forms a ledeburitic structure with the presence of chromium carbides. The chemical composition of the electrode is C 3.50%, Mn 0.80%, Si 0.80%, Cr 25%, V 1.3%, the rest Fe. The diameter of the electrode used was 2.5mm.

RD 571 VÚZ, Bratislava - filled rod, intended for manual welding of tungsten carbide layers. It is a special welding material formed by WC carbides in a steel matrix. It is intended for surfaces extremely stressed by abrasion and impacts (jaws of earthmoving machines, functional parts of kneading equipment, etc.). It has good operational properties, but the putting weld beads is difficult. It requires a certain skill of the welder. The chemical composition is C 0.10%, Mn 0.50%, Si 0.80%, Cr 5.0%, Ni 15.0%, B 0.3%, W_2C 60%, the rest Fe. The diameter of the used filled bar was 3.2mm.

LNM 420FM Lincoln Electric - hardfacing wire creates layers with a ferritic-martensitic structure that is highly resistant to abrasion, impact and corrosion. It can be used for hardfacing working parts of agricultural equipment, rollers of conveyors, earthmoving machines, etc. It has excellent operational properties, namely good holding of the arc, good connection of layers, good spreading of beads. The chemical composition is C 0.50%, Mn 0.40%, Si 3.00%, Cr 9.00%, the rest Fe. The diameter of the hardfacing wire was 1.2mm.

E DUR 600 Elektrode Jesenice - basic hardfacing electrode intended for parts exposed to wear by abrasion (earthmoving machines, furrow knives, parts of mills, sealing surfaces, etc.). It forms a ledeburitic structure with a low C and Cr content. It has excellent operational properties - good arc ignition, good arc stability and burning, good layering and spread of weld metal. Chemical composition C 0.50%, Cr 8.5%, W 0.5%, the rest Fe. The diameter of the electrode used was 2.5mm.

WEARTRODE 62 (OK 84.84) ESAB Slovakia - basic hardfacing electrode contains weld metal with a high content of fine carbides in a martensitic matrix. In addition to resistance to abrasive wear, it has excellent impact resistance. It is used for rock processing equipment, hammers, knives, excavator teeth, etc. It has significantly worse operational characteristics - more difficult ignition of the arc, stability of arc burning, difficult deposition of layers of hardfacing beads, poor spreading of welding beads. It requires a certain skill of the welder. Chemical composition C 3.00%, Mn 0.30%, Si 2.00%, Cr 6.30%, V 5.00% Ti 4.80%, the rest Fe. The diameter of the used electrode was 2.5mm.

Even though the wear analysis of the tool for crushing unwanted growth showed the need to ensure a structure more resistant to abrasive wear than the structure of the tool body to a depth of approx. 0.20 mm (Fig. 1), where only one layer would be sufficient, the hardfacing material was applied in two layers. The first layer should fulfill the function of an intermediate layer, which should ensure a good connection with the base material, minimize the consequences of welding stresses, prevent flanking of the second layer and prevent the spread of possible cracks arising in the hardfacing into the base material [9,13].

The preparation of the samples and the actual testing of the material's resistance to wear was carried out according to GOST 23.208-79 standard [20]. The essence of the method consists in comparing the loss of the tested material and the loss of the standard material under the same test conditions. For testing, samples (30x30x6mm) (Fig. 2a) were prepared according to the mentioned standard, cut with an abrasive water jet (AWJM), then milled and ground on a planar magnetic grinder.

Before the test, each sample was weighed on a KERN analytical balance, e=0.1mg. The sample was placed in the testing device, the feed of the abrasive was started, the rubber disc was pressed against the sample. After rotating the disk 1000 times, the sample was selected and weighed. This cycle was repeated 5 times. Each time, after traveling a distance of 153.3m (767.75m in total), the sample was weighed to determine the weight loss. Sample weights and W_h[g] weight loss values were calculated.

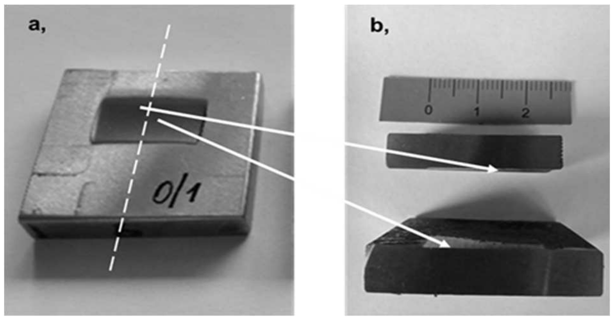

Fig. 2 *Sample after test of resistance to abrasive wear (a,); sample after cutting for observe the track (b,)*

After testing the resistance of the material against abrasive wear, an analysis of the track created by the rubber disc from the abrasive wear test was performed (Fig. 2b). All samples were cut by abrasive water jet (AWJ) in the direction parallel to the track to observe track depth as well as surface topography (Fig. 3).

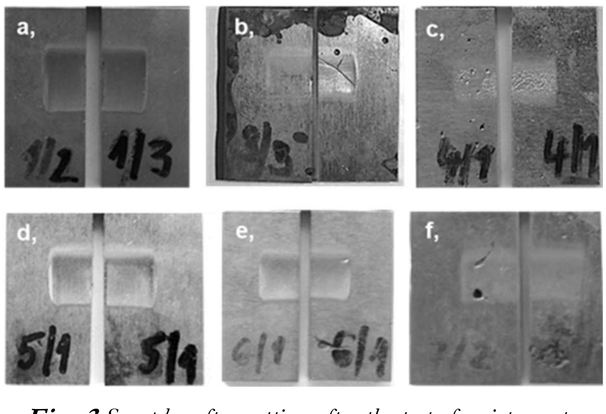

Fig. 3 *Samples after cutting after the test of resistance to abrasive wear; a, 16MnCr5; b, E520 RB; c, RD 571; d, LNM 420FM; e, E DUR 600; f, WEARTRODE 62*

Nital etchant (2% solution of HNO_3 in ethyl alcohol) was used for etching, inducing the microstructure of the base material and Cor etchant (120 ml CH_3COOH, 20 ml HCl, 3 g picric acid, 144 ml CH_3OH) was used for etching of the hardfacing layers.

For analysis purposes, an Olympus CX71 inverze light optical metallographic microscope with an Olympus DP12 camera was used to evaluate the microstructure of the samples. A Neox Plu confocal microscope/3D optical profilometer with Nikon lenses was used for non-contact measurement of surfaces (area analysis) and cross-sectional profiles obtained from traces after wear tests. A contact roughness meter Mitutoyo SJ 210 was used to evaluate the surface profile in the track on the samples.

3 Results and discussion

In tab. 1 shows the values of the average weight loss W_h[g] after the travelled track R[m] and the relative resistance to abrasive wear Ψ_h[-] of all observed samples of hardfaces as well as the base material 16MnCr5. The reference values with which the measured and calculated values of the weld samples are compared are the values of the base material.

Tab. 1 *Values of average weight loss W_h and relative resistance to abrasive wear Ψ_h*

Parameters	16MnCr5	E520 RB	RD 571	LNM 420FM	E DUR 600	WEARTRODE 62
W_h[g]	0.0996	0.0152	0.0181	0.0538	0.0359	0.0177
Ψ_h[-]	1	6.1040	5.1747	1.6355	2.6907	5.4201

In Table 2, the values of the depth of the P_t disk track in µm, as it was recorded by the confocal microscope, are written. At the same time, the value in mm is also indicated. This is because of a realistic imaging when compared to the loss of material on the tool.

Tab. 2 *Track depth values P_t*

Parameter	16MnCr5	E520 RB	RD 571	LNM 420FM	E DUR 600	WEARTRODE 62
P_t [µm; mm]	424; 0.424	120; 0.12	103; 0.103	271; 0.271	201; 0.201	121; 0.121

In Fig. 4 are graphs that show the values of the loss W_h[g] (Fig. 4a) and the calculated relative resistance to abrasive wear Ψ_h[-] (Fig. 4b) of individual hardfacing materials in comparison with the base material.

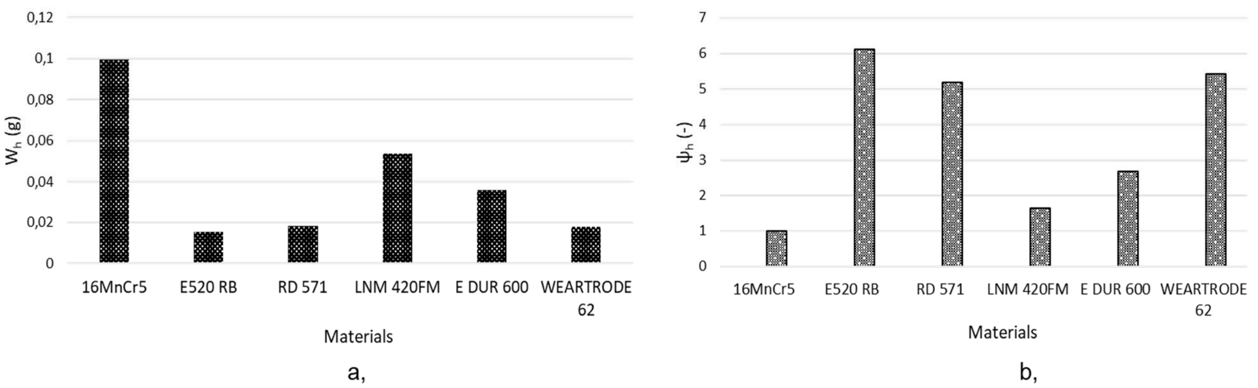

Fig. 4 *Graphs of the comparison of monitored parameters obtained by the test of resistance to abrasive wear*

Fig. 5 shows a graph comparing the depth of track P_t[mm] after the rubber disc from the test of resistance to abrasive wear and the total weight loss W_h[g] from the material after this test.

The profile and depth of the track on the sample after the abrasive wear test was observed with a confocal microscope. Figure 6a shows the profiles and trace depth of the base material with a ferritic-pearlitic structure of 16MnCr5, P_t=0.424mm, and a hardfacing electrode E520 RB, with a ledeburitic structure with the presence of Cr carbides, P_t=0.120mm (Fig. 6b).

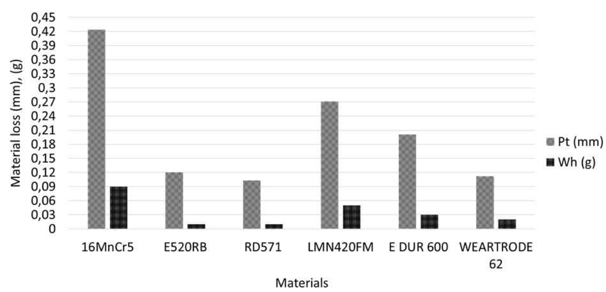

Fig. 5 *Comparison of trace depth P_t[mm] and total weight loss W_h[g] from the material*

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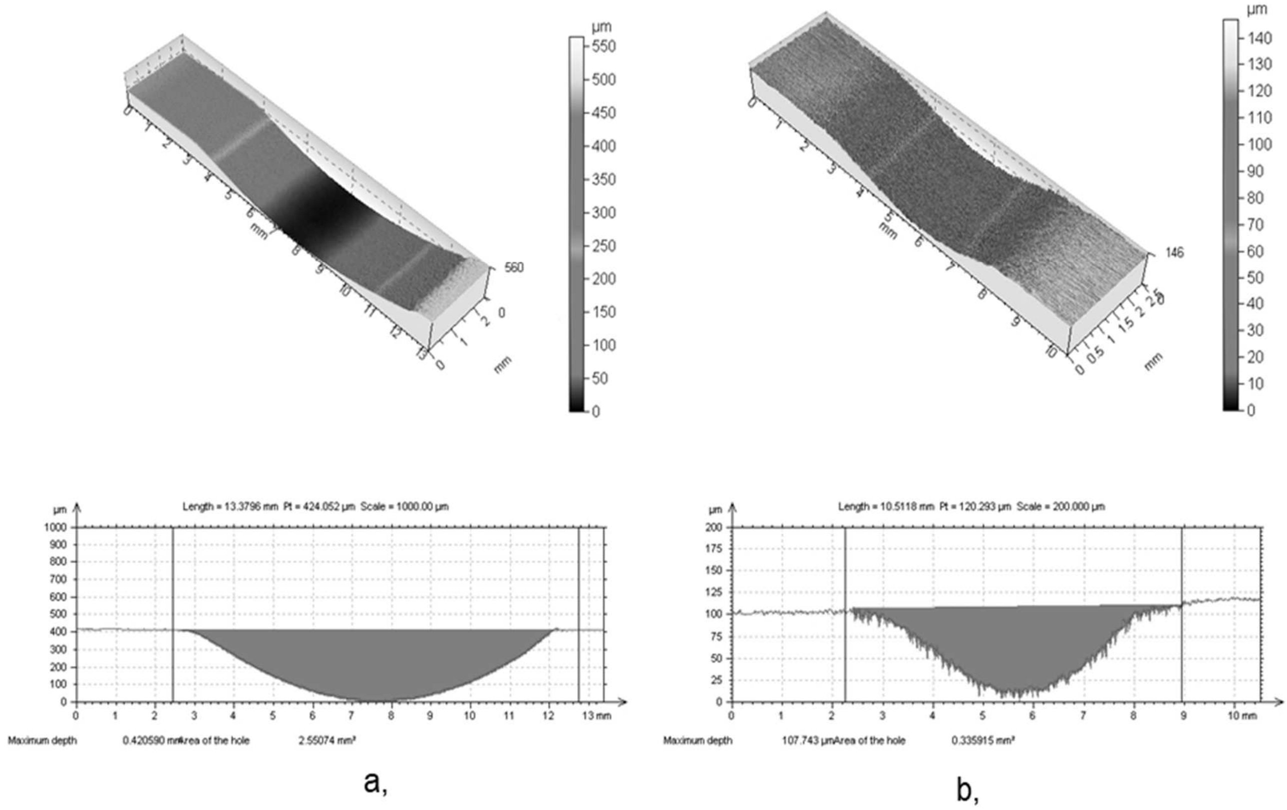

Fig. 6 *Profile and track depth on samples of material a, 16MnCr5 and b, E520 RB*

Figure 7a shows the profiles and depth of the track of the hardfacing material - filled rod RD 571, intended for manual hardfacing of tungsten-carbide layers, P_t=0.103mm and hardfacing wire with ferritic-martensitic structure LNM 420FM, P_t=0.271mm (Fig. 7b).

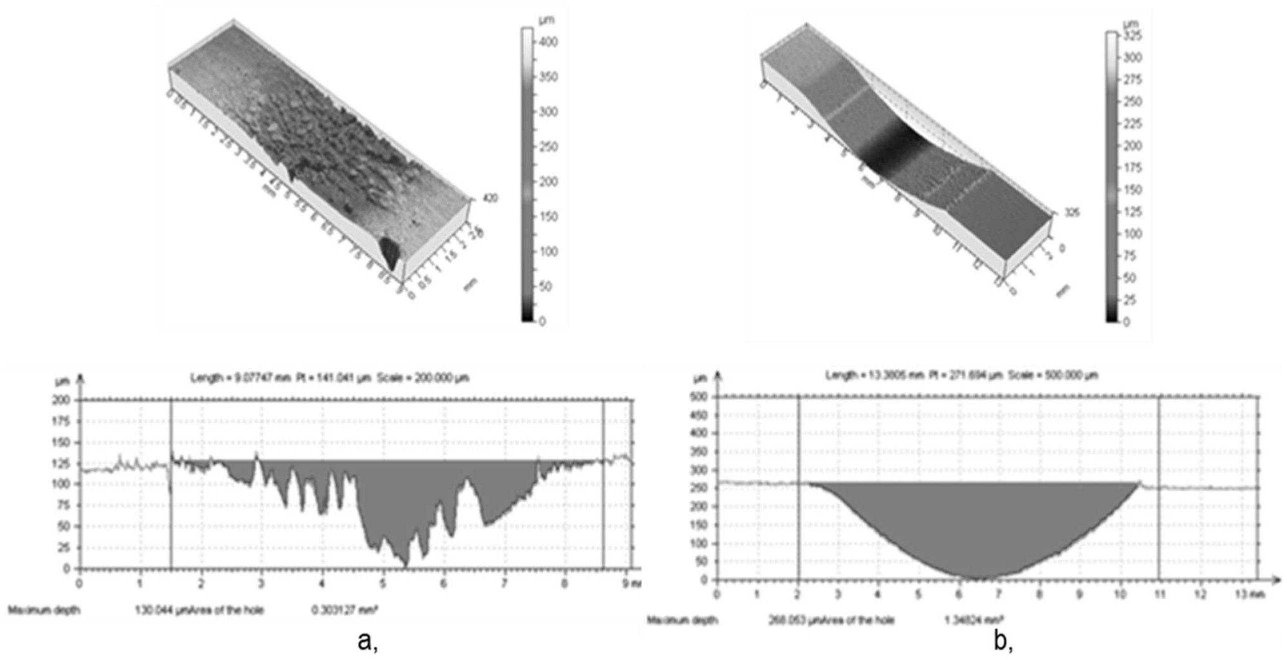

Fig. 7 *Profile and depth of track on a sample a, RD 571 and b, LNM 420FM*

The E DUR 600, a basic hardfacing electrode with a ledeburite structure, P_t=0.201mm and WEARTRODE 62, which is a basic hardafacing electrode and contains a high content of weld metal of fine carbides in a martensitic matrix with a track depth of P_t=0.121mm have the profile and trace depth recorded in Figure 8a, 8b.

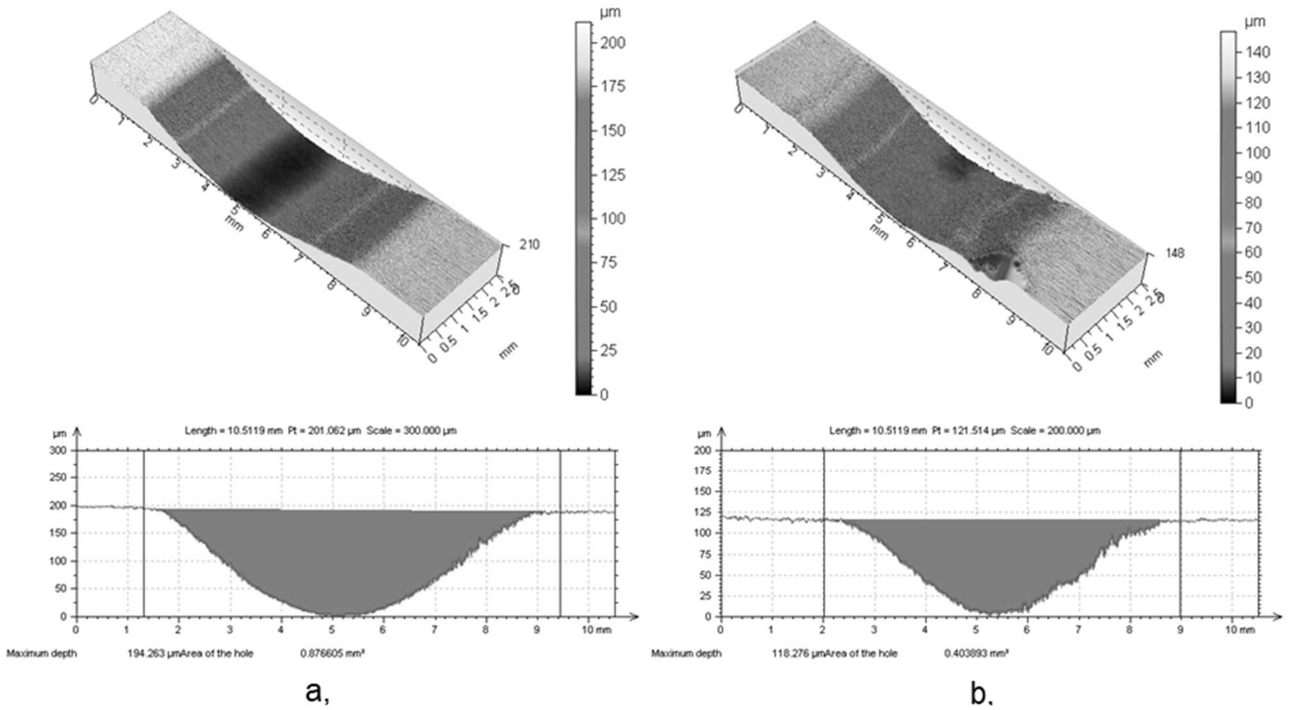

Fig. 8 *Profile and depth of track on samples a, E DUR 600 and b, WEARTRODE 62*

Figure 9 shows the microstructures of the surfaces of the base material and hardwearing materials after the test of resistance to abrasive wear. The microstructures of the weld zones of the base and hardfacing material are also shown in the pictures.

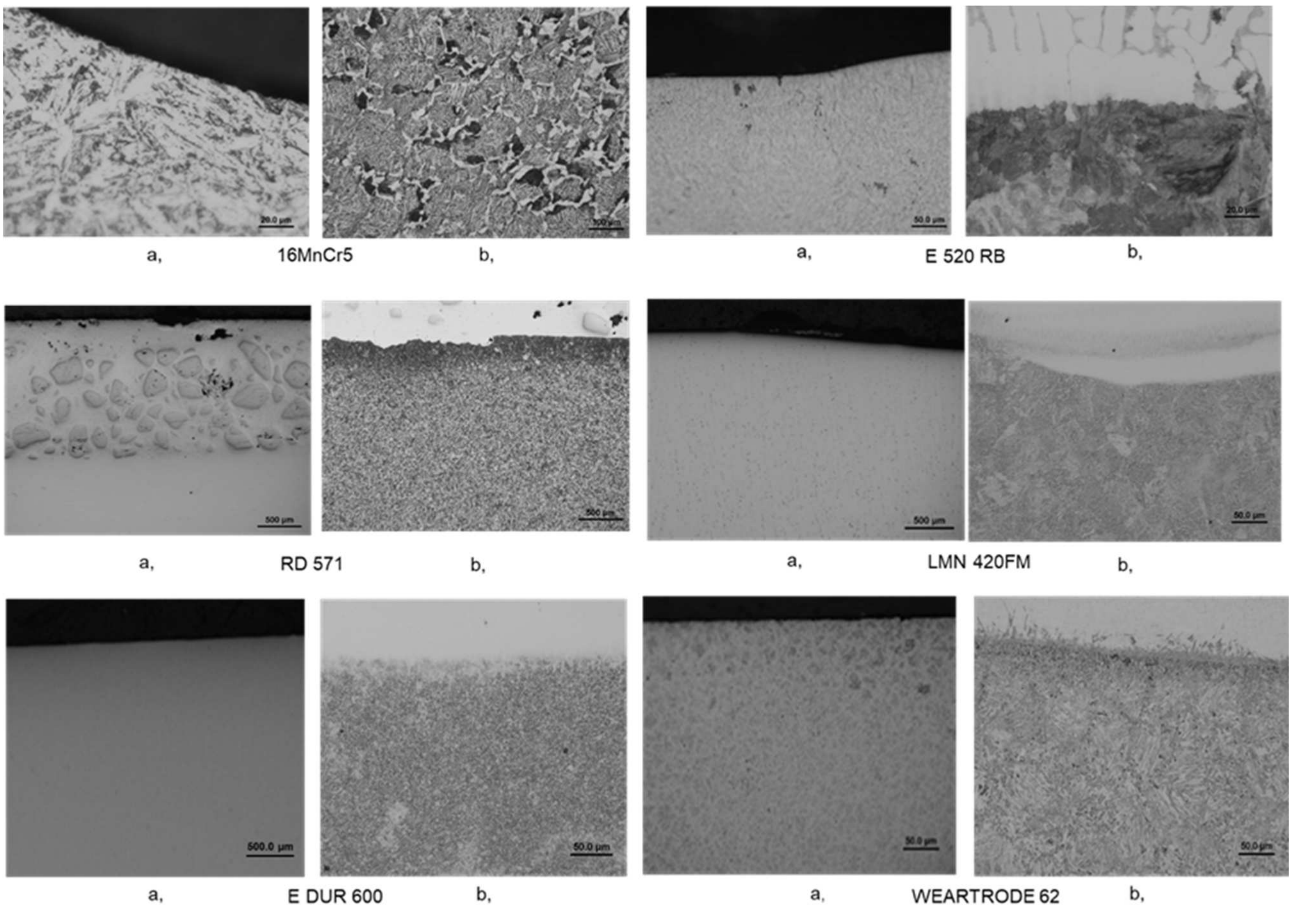

Fig. 9 *Surface of samples (track in section) after abrasive wear test (a,); microstructure in the sample core (b,) (LM; Nital 2%, Cor)*

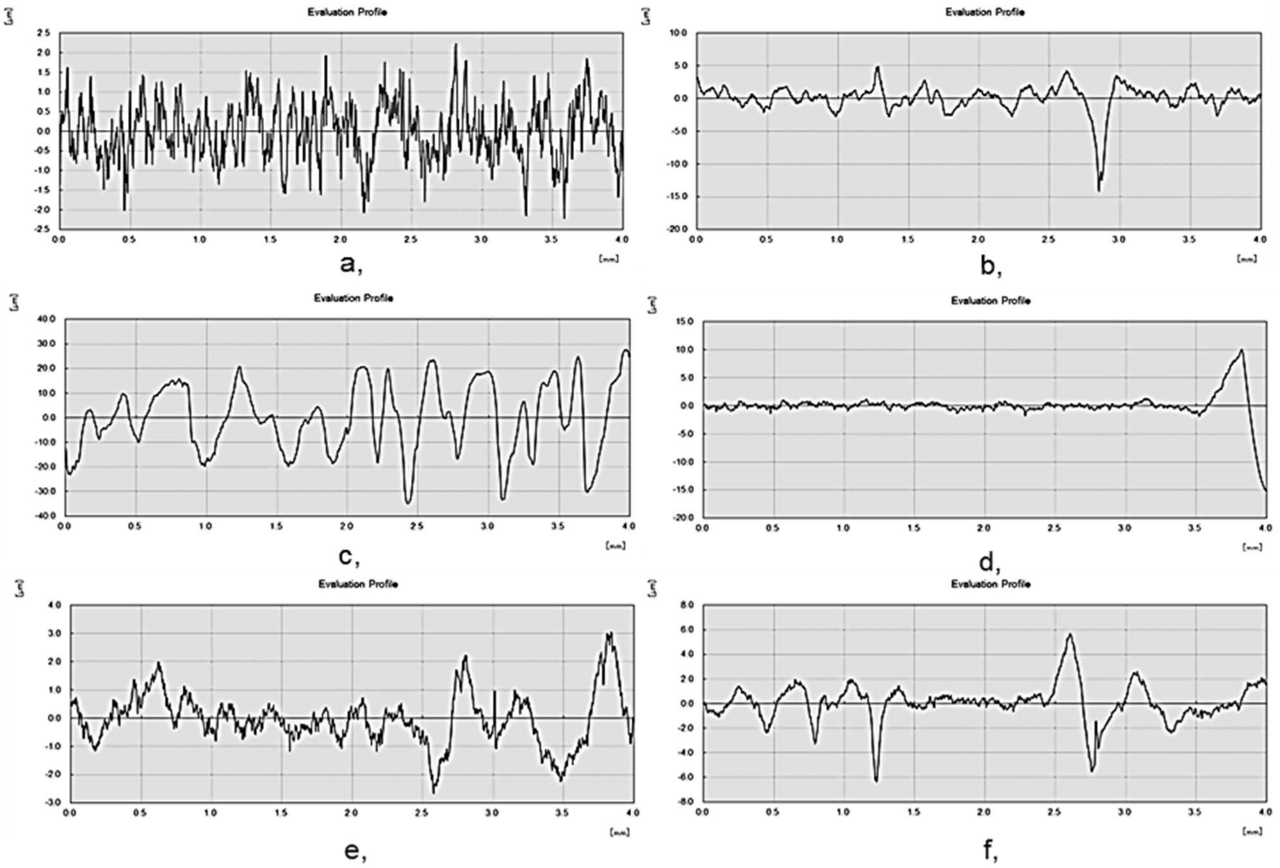

Fig. 10 *Profile of the surface of the materials evaluated with the contact roughness meter*

According to the character of the work of the tool, which works in a heterogeneous environment, with individual fractions of several centimetres in size (wood mass, minerals of different hardness and size, soil, etc.), the roughness values in the track, measured after the test of resistance to abrasive wear, have not for praxis high value. However, an evaluation of the surface profile after this test was carried out using the contact roughness meter. In Fig. 10 shows the evaluated profiles of the surfaces of all six samples: a, 16MnCr5; b, E520 RB; c, RD 571; d, LNM 420FM; e, E DUR 600; f, WEARTRODE 62.

On the basis of the analyses presented in the research works carried out on the worn tool [1,2,4,19], research works published by the authors [3,7,8,12,22,23] and also theoretical knowledge [6,14,17] certain hardfacing materials were selected. Their application should create surfaces with structures that would ensure increased resistance to abrasive wear of tools and thus increase their service life.

According to the achieved results, it can be concluded that each of the selected welding materials would contribute to an increase in resistance to abrasive wear. This is evident from the values of the mass loss W_h[g] and the calculated relative resistance to abrasive wear Ψ_h[-], as well as the depth of track P_t[mm] (graphs in Fig. 4 and 5).

In their research papers [11,12,13,24], the authors state that hagrdfacing layers made by an electrode with a high Cr content and a low C content, represented by the E 520 RB electrode, have a ledeburitite type structure with a lot of carbidic phases. A high-strength but brittle deposit with high hardness of the ledeburitite matrix is formed. We can conclude that the connection between the materials is satisfactory, without the assumption of flaking or other unacceptable form of reduction of mutual cohesion (Fig. 9b, E520 RB). The depth of the trace P_t=120μm as well as the high value of ψ_h=6.1 indicate, based on the results of laboratory tests, that the hardfacing material could also prove itself in operational tests.

The special hardfacing material RD 571 has a high content of W_2C and also Ni. The WC carbides in the steel matrix can cause cracking during welding, which was also confirmed by microscopic analyses of material samples (Fig. 9a RD 571). Likewise, cracks in the coating, or through carbide grains, can cause carbides to crumble and peel off from the matrix. This can lead to stronger wear of the hard layer. Although the cracks themselves do not significantly affect the resistance to particle wear, they can initiate fracture under stress [3,6,13,14]. Although, the value of ψ_h=5.17 is high and the depth of the P_t=103μm track is low, this may not yet guarantee good abrasion resistance in operation.

The hardfacing wire LMN 420FM is a representative of the ferritic-martensitic structure and had average values of the detected coefficients. The profile depth of the track is 0.07mm greater than the expected loss of material when working in the terrain. The mixing between the layers is sufficient, without visible defects such as pores, voids and cracks (Fig. 9b, LMN 420FM). However, this hardfacing material is affordable and proven by practice for similar applications.

When evaluating the samples of the hardfacing electrode E DUR 600 tested in the experiment, we can state that a higher value of the coefficient ψ_h=2.69 was achieved in the welding and also the depth of trace P_t had a value of 201µm. Light microscopy indicates a sufficient diffusion connection of the base material with the first layer. In Fig. 9b, E DUR 600, it can be seen that the interfaces are free of pores, cracks and other defects that would reduce the quality of the connection of the individual layers and thereby reduce their cohesion. We can assume that the surface created by this hardfacing material will achieve good results even in operational tests.

The hardfacing electrode WEARTRODE 62 produces metal with a martensitic matrix, formed by fine carbides. The C content is high but the Cr content is medium. However, it is alloyed with Ti, which increases strength and refines the grain. Element V is also the alloy. This increases resistance to wear. According to the authors of the research papers [8,21,25,26], hard deposits with a basic martensitic metrix are characterized by a high resistance to abrasive wear, which is mainly due to the high hardness of the martensitic structure and deformation hardening occurs on the worn surface. Carbides, due to their high hardness, represent obstacles against the penetration of hard particles. The low value of P_t=121µm as well as the high value of ψ_h=5.42 predict a small removal of material with high resistance to wear. In Fig. 9b, WEARTRODE 62, we can observe a sharp interface by light microscopy, which indicates that the diffusion between the materials probably did not take place afterwards. The hard layer on the base material may not satisfactorily meet the requirements for increasing the resistance to the operating load of the tools under conditions of abrasion and shock loads.

We can also state that the significant correlation between the profile of the track measured by the confocal microscope and the touch roughness meter was not confirmed.

4 Conclusion

Increasing the service life of parts and tools can be done in various ways. One of them is the application of suitable structures on exposed, worn surfaces in the form of hardfacing materials. High load on tools in the form of a heterogeneous working environment and high rotor speeds of the base machine are variable factors that can unpredictably affect their service life. In order to find out whether the results of laboratory tests correlate with real results, it is necessary to verify them in practice.

By evaluating the resistance to abrasive wear, the microstructure, the quality of mixing and the cohesion of the individual layers of materials and the surface after the test of resistance to abrasive wear, as well as the overall quality of the hardfacing metals, based on the results of the laboratory tests, tests and observations, we assume that the best results in practice will be achieved by the weld materials with a ledeburitic type structure with a lot of carbidic phases, or with a ferritic-martensitic structure.

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