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Article

Research of Resistance of Selected Materials to Abrasive Wear to Increase the Ploughshare Lifetime

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Abstract: Road maintenance and cleaning in winter are performed with ploughshares. Due to the fact that the layer of snow and ice that is removed from the road surface contains various hard impurities, ploughshares are exposed to high intensity abrasive wear. This article deals with the resistance to abrasive wear of originally used ploughshare materials and the materials that were designed as a suitable modification of the ploughshare to increase its service life. The chemical composition of materials used to manufacture ploughshare components is unknown. For this reason, they were analyzed with an ARL 4460 spectrometer, which was used to analyze the element content. The main part of the research was focused on the abrasion resistance test, which was performed according to the GOST 23.208-79 standard. Based on the chemical analysis, it was found that the basic body of the ploughshare was made of S355J2G3 steel, and the raking blade material was made of 37MnSi5 steel. The original material (steel S355J2G3) of the ploughshare body as a reference standard was compared to steel HARDOX 450. Furthermore, a sample made of the original material of the raking blade (steel 37MnSi5) was used as a reference standard, the properties of which were compared to the newly designed OK 84.58 and UTP 690 hardfacing materials. The parametric test method of statistical hypotheses was also used to process and evaluate the weight losses of the selected materials.

Keywords: abrasive wear; wear resistance; ploughshare; hardfacing materials; hypothesis testing

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1. Introduction

Forest roads are important in terms of making forests accessible for heavy machinery and timber transportation. Therefore, it is necessary to maintain these roads both in summer and winter. It is necessary to remove a layer of snow or ice from the road surface in the winter time. Snow is removed from the road using a snow ploughshare. Since the removed layer of snow contains various hard impurities, the ploughshares are exposed to high—and especially abrasive—wear and their replacement is relatively economical. Therefore, it is necessary to look for ways to increase their service life and examine their resistance to abrasive wear.

Wear is one of the main factors affecting the performance and lifetime of the components of various mechanisms [1]. Abrasive wear is one of the dominant and common tribological wear processes [2–4] leading to expensive costs for repairing worn mechanisms and replacing spare parts [1]. This wear is characterized by a reduction in the volume of the material and a change in its shape, causing a decrease in work efficiency [5]. Wear caused by shocks and abrasion by hard abrasive particles is a major problem in many industries, especially in agriculture, forestry, mining, mineral processing, etc. [6,7].

Abrasive wear occurs when a hard rough surface slides across a softer surface; in this case, wear is defined as damage to a solid surface that generally involves the progressive loss of material and is due to relative motion between that surface and a contacting substance or substances.

The material from grooves is usually removed in the form of loose particles [8–10]. The material resistance against abrasive wear is higher with higher hardness [5,11].

This type of wear is caused by sharp particles that slide or flow over the metal surface at different speeds and pressures, grinding the material from the surface like small cutting tools. The harder the particles and the sharper their shapes, then the more intense the abrasion is. Typical cases of abrasive wear are encountered in earthworks, material transportation and agricultural equipment [12,13].

During abrasive wear, the material is removed from the surface when the stress in it reaches a critical value. This local fracture stress can be achieved by one or more abrasive particles coming into contact with the tool surface. Material that is not removed in this way can be deformed due to abrasion as well as impact [14,15].

One of the very effective measures to increase wear resistance is to protect functional surfaces with a suitable coating material [16]. Hardfacing is a commonly used method to improve the surface properties of agricultural tools, mining components and soil preparation equipment, among others [17]. The alloy is applied to the surface of the base material (usually on low-carbon or medium-carbon steels) by hardfacing in order to increase the hardness and wear resistance without a significant loss in the ductility and toughness of the base material [16,17].

Important factors that determine the resistance to abrasive wear include the hardness, size, shape and intensity of the particles; as well as the hardness, shape, size and number of hard phases and their distribution in the parent metal. Wear resistance increases with the increasing hardness of hard structural components (carbides, borides, etc.) and with their increasing share in the structure [9,12].

The main components of Fe-based alloys are chromium, molybdenum and boron, which make Fe-based alloys resistant to wear. Wang et al. studied the microstructure, hardness and wear resistance of Fe-based alloys by adding the elements ferrotitanium (Fe–Ti), ferromolybdenum (Fe–Mo), ferrovanadium (Fe–V) and graphite, which were applied by the arc welding process. The results showed that the hardness and resistance of the hardfacing metal layer increase with an increasing proportion of Fe-Ti, Fe-V, Fe-Mo and graphite. Their amounts must be controlled in the range of 8–10% graphite, 12–15% Fe-Ti, 10–12% Fe-V and 2–4% Fe-Mo. However, cracks begin to form in the layer of hardfacing metal if the amount of Fe-Mo is more than 5% [18,19].

Xu et al. studied the effect of the carbide type on the resistance to abrasive wear at different sizes and abrasive particle loads. The results showed that M_6C carbides showed higher resistance to wear by fine abrasive particles compared to M_2C [20].

During impact wear, the material is exposed to impact and high pressure, due to which it deforms or locally breaks—it can even crack. Due to the relatively high working speeds of ploughshare vehicles, it is necessary to protect the ploughshare from the effects of the impact of the ploughshare hitting with a solid obstacle, e.g., ice and abrasion by mineral particles, gravel and stones [9,12].

For this reason, it is necessary to pay attention to the possibilities of increasing the life of the blades and examine their resistance to abrasive wear, which was also the main goal of the authors' long-term research.

Based on the experience and study of already published outputs in the field, the authors tried to bring new solutions to the issue [16,21]. To the best of the authors' knowledge, no relevant studies have yet been published that compare the resistance of a selected combination of materials (37MnSi5, S355JG3 and HARDOX 450 steels, as well as OK 84.58 and UTP 690 hardfacing materials) to abrasive wear. The achieved results will be contributing and applicable not only to ploughshares, construction machines and forest manipulators, but can also be used in the mechanical engineering, civil and mining industries.

2. Materials and Methods

The ploughshare (Figure 1), the resistance of which to abrasive wear is the subject of our research, is a commonly used tool for modifying forest roads during wintertime. The ploughshare works in a heterogeneous environment, coming into contact with the road and thus with snow, stones, mineral particles, gravel, sand, etc. First, the raking blade comes into contact with the road. It is stressed by the impact of the first contact with the road and with corrosion and abrasion during the raking. In addition, the rest part of the ploughshare is also stressed because the accumulated snow, together with sand and gravel, creates a force on the ploughshare body from the point of pick-up until it is pushed to the side of the road. As a result, wear occurs due to abrasion and corrosion not only on the raking blade but on the entire working part of the ploughshare (weldment).

Figure 1. The arrow ploughshare [22].

The basic dimensions of the currently used steel raking blades and their geometry, symmetrically placed in the shape of an arrow on the front part of the tractors, are shown in Figure 2. The values of these basic dimensions, declared by the manufacturer [23], are listed in Table 1.

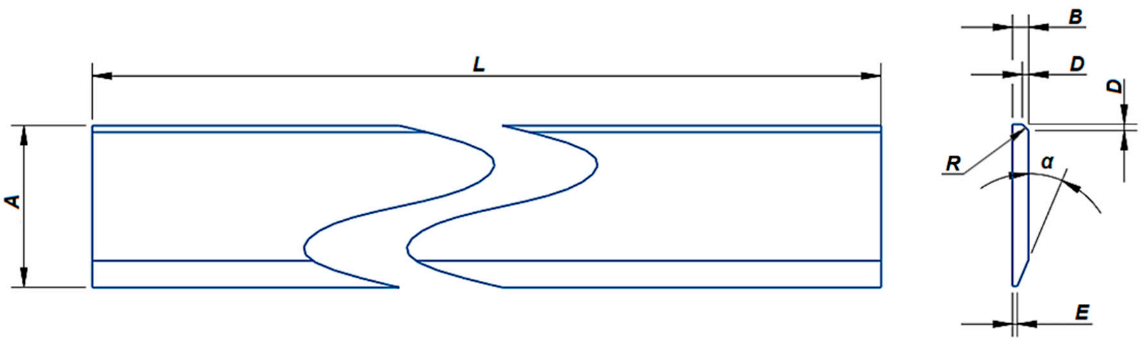


Figure 2. Basic dimension of steel raking blade.

Table 1. Basic dimension of steel raking blade [23].

A (mm)	*B* (mm)	*α* (°)	*R/D* (mm)	*E* (mm)	*L* (mm)
80–400	12–50	20.2–24	R3/5–12	3–28	6000–6300

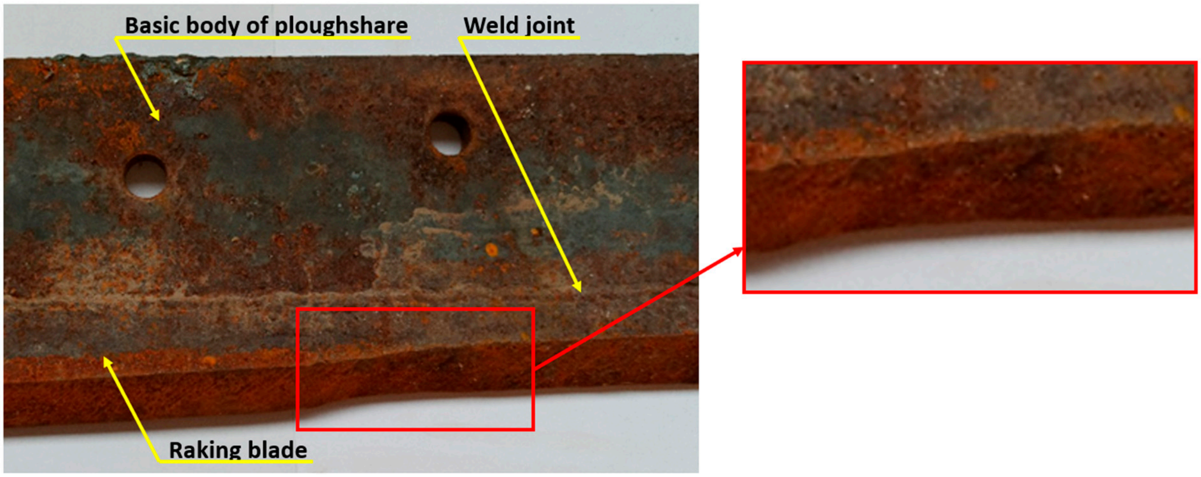
2.1. Materials of Research Samples

The raking blades of the ploughshares can be attached to the ploughshare body (to the base material of the ploughshare) in two ways:

- Threaded joint;
- Welded joint.

Due to the rapid wear of the ploughshare and the need for its frequent replacement, the operator of such ploughshares initiated research that would have increased their lifetime and ensured greater efficiency in the use of funds spent on their purchase and replacement.

For the ploughshare that was the subject of the research, the raking blade was attached by a weld, so it can be said that the ploughshare consisted of 3 main parts, namely the basic ploughshare body, the raking blade and the weld (Figure 3a). There is a detail of the raking blade which is that its significant damage due to the heterogeneity of the working environment is visible in Figure 3b.



(**a**) (**b**)

Figure 3. Part of the discarded ploughshare: (**a**)—main parts of the ploughshare; and (**b**)—detail of a raking blade).

The chemical composition of materials used to manufacture ploughshare components is unknown. From this concern, their elemental analyses were carried out using ARL 4460 spectrometer. The results of the chemical analysis of the individual parts of the originally used ploughshare are shown in Table 2.

Table 2. Chemical composition of the individual parts of the original ploughshare.

Element	C	Mn	Si	Cr	Ni	Cu	Mo	P	S	Fe
Basic body of the ploughshare (wt.%)	0.2	1.4	0.3	0.04	0.055	0.16	<0.01	<0.005	<0.15	balance
Base weld metal (wt.%)	0.06	1.3	0.55	-	-	-	-	-	-	balance
Raking blade (wt.%)	0.33	1.24	1.36	-	-	0.04	0.178	0.017	<0.15	balance

Based on the performed chemical analysis, it is possible to state that:

- The basic body of the ploughshare was made of S355J2G3 steel. It is the steel of the usual quality for low temperatures with guaranteed weldability. It is used in parts of equipment operating at temperatures up to −50 °C made of sheet metal with a guaranteed value of notch toughness up to −50 °C. The yield strength is *Rm* = 355 MPa and the ultimate tensile strength is *Re* = 470–610 MPa [24]. The chemical composition of the tested steel, according to the data from the material sheet, is shown in Table 3;
- The base weld metal—an electrode for general use, suitable for welding carbon and low-alloy steels—was used for welding the basic ploughshare body with a raking blade. The weld metal of the electrode is tough and resistant to cracking [14];
- The raking blade was made of 37MnSi5 material (Wr. Nr. 1.5122). It is manganese-silicon steel suitable for tempering. It is used on medium-stressed machine parts and particularly wear-resistant road vehicle parts, e.g., shafts, axles, connecting rods,

levers, bolts, etc. The ultimate tensile strength of 37MnSi5 steel is Rm = max. The 760 MPa and hardness 217 HBW [25]. The chemical composition of the tested steel, according to the data from the material sheet, is shown in Table 3.

The ploughshare that was the subject of the research worked for 6–8 weeks. After this time, the raking blade of the ploughshare was worn and unusable. The frequent replacement of the raking blades caused economic and technical problems. Due to the fact that the currently used ploughshare was functionally usable only for a short time and did not meet the requirements for the lifetime of this type of product, it was necessary to design a new solution that improved the situation. Based on the authors' own research and practical experience, as well as on the results described in the professional and scientific literature presented in the Introduction, the following options are suggested to increase the lifetime of the ploughshare and thus increase its resistance to abrasive wear (Figure 4):

(a) Change of ploughshare material for HARDOX 450 material;
(b) Application of the OK 84.58 hardfacing material to the exposed surfaces of the functional parts of the ploughshare;
(c) Application of the UTP 690 hardfacing material to exposed areas of functional parts of the ploughshare.

The first alternative solution was the idea of replacing the original ploughshare with one compact body made of HARDOX material, replacing all three parts of the ploughshare: the ploughshare body, the weld metal, and the raking blade. HARDOX steels are produced in several designs. HARDOX sheets are considered a worldwide standard in the field of abrasion-resistant steel due to their unique combination of hardness and toughness. The hardness of this steel ranges from 400 HBW to 600 HBW. It is available in the form of sheet metal in thicknesses from 0.7 mm to 160 mm but also in the form of tubes and rods [9,26]. HARDOX 450 material is an abrasion-resistant steel with excellent construction properties. The hardness of this steel is 450 HBW, and the yield strength is Re = 1100–1300 MPa. HARDOX 450 material is a well flexible material that has guaranteed weldability. It provides good abrasion resistance and thus a longer lifetime. It has better wear resistance [27], higher load capacity, and a longer lifetime compared to ordinary steel with the same hardness. It is used in various components and constructions that are subject to wear [9,27,28]. The chemical composition of HARDOX 450 material is shown in Table 3.

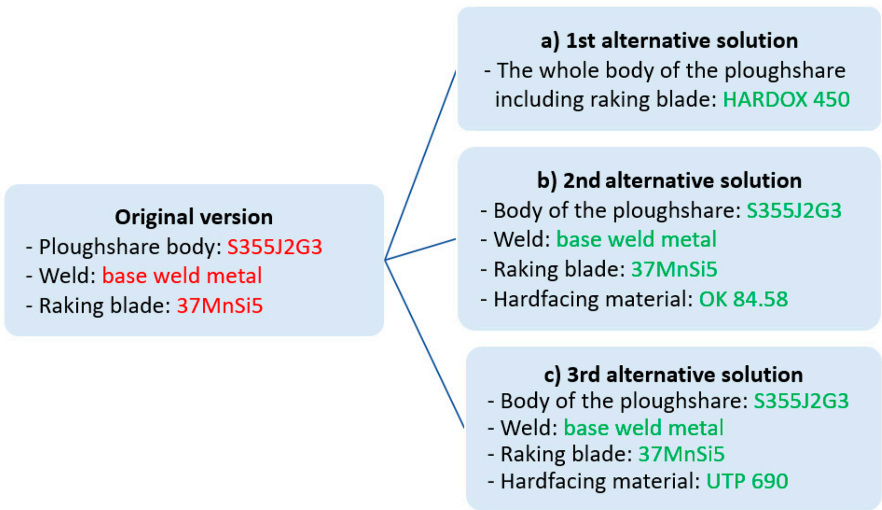


Figure 4. Suggested research solutions regarding the current state.

The second alternative solution was to apply a new layer in the form of a hardfacing material to the original 37MnSi5 steel of the raking blade part (see Figure 4). Such a sample with OK 84.58 hardfacing material (Figure 5a) was prepared in the company ŽOS Zvolen, a.s. in a single layer by certified welders. The electrode was dried for 2 h at 200 °C without preheating the sample. The applied hardfacing voltage was U = 21.5 V and the hardfacing current was I = 140 A. The stated parameters were chosen according to the experience of experts from the company.

(**a**) (**b**)

Figure 5. Sample with hardfacing materials; (**a**) OK 84.58; and (**b**) UTP 690.

The OK 84.58 electrode is a high-yield electrode for hardfacing functional surfaces resistant to wear under simultaneous shock stress with the required partial corrosion resistance, used, e.g., for parts of agricultural and forestry machines, mixers, transport equipment, etc. It forms a martensitic structure after hardfacing. It is possible to treat hardfacing materials by grinding [29,30]. The chemical composition of the OK 84.58 electrode is shown in Table 3.

The sample with hardfacing material UTP 690 (Figure 5b), prepared in the company ŽOS Zvolen, a.s. by certified welders, was used as the third alternative solution (see Figure 4). The hardfacing layer was applied to the original 37MnSi5 material of the raking blade part. The electrode was dried for 2 h at 300 °C with the preheating of the sample to 230 °C. The applied hardfacing voltage was U = 21.5 V, and the hardfacing current was I = 105 A. In this case, the parameters were also designed according to the experience of the experts from the company.

The UTP 690 electrode is used for the repair and production of cutting tools, especially for the restoration of cutting edges and work surfaces. The coating is highly resistant to friction, compression and impact even at elevated temperatures up to 550 °C [31]. Using this electrode, it is also possible to produce new tools by hardfacing on carbon and low-alloyed base steels [31]. This forms a martensitic structure after hardfacing [16]. The chemical composition of the UTP 690 electrode is shown in Table 3.

Table 3. Chemical composition of S355J2G3 [24], 37MnSi5 [25], HARDOX 450 [27] steels and OK 84.58 [29] and UTP 690 [31] hardfacing materials according to the datasheets.

Material	Element (wt.%)														
	C	Mn	Si	Cr	Ni	Cu	Cr+Ni+Cu	Ti	P	Mo	B	S	V	W	Fe
S355J2G3	max. 0.20	max. 1.40	max. 0.55	max. 0.30	max. 0.30	max. 0.30	max. 0.70	max. 0.20	max. 0.03	-	-	max. 0.03	-	-	balance
37MnSi5	0.33–0.41	1.10–1.40	1.10–1.40	-	-	-	-	-	max. 0.035	-	-	max. 0.035	-	-	balance
HARDOX 450	max. 0.23	max. 1.60	max. 0.5	max. 1.20	max. 0.25	-	-	-	max. 0.025	max. 0.25	max. 0.005	max. 0.010	-	-	balance
OK 84.58	0.67	0.70	0.7	10.40	-	-	-	-	-	-	-	-	-	-	balance
UTP 690	0.90	0.50	0.80	4.50	-	-	-	-	-	-	-	-	1.20	2.00	balance

All samples, both standard (S355J2G3 and 37MnSi5) and reference ones (HARDOX, OK 84.58 and UTP 690), were prepared according to the GOST 23.208-79 standard by abrasive water jet cutting technology (AWJM), machined by milling and ground by a magnetic surface grinder for obtaining dimensions 30 mm × 30 mm × 10 mm and surface roughness

Ra = 0.4 µm (Figure 6). OTTAWA SiO_2 silica sand with a grain size of 0.1–0.3 mm was used as an abrasive material [31]. The hardness corresponds to the hardness value according to Vickers 500 HV and Rockwell 54 HRC.

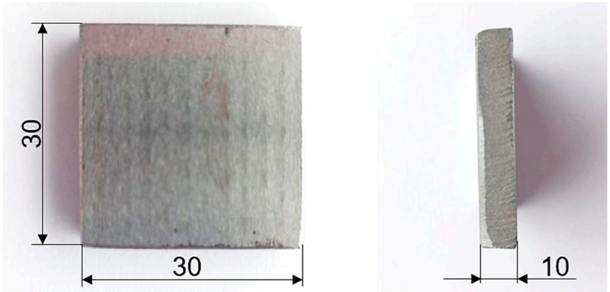


Figure 6. Sample for abrasion resistance test with marked dimensions.

2.2. Testing Methods

There are several methods for testing the wear resistance of materials. Based on the ploughshare operating environment, the method simulating its load in the laboratory conditions at the Technical Faculty of CULS in Prague was chosen. The abrasion resistance test was performed according to standard GOST 23.208-79—Ensuring wear resistance of products. The wear resistance testing of materials by friction against loosely fixed abrasive particles [32].

The principle of the method is to compare the loss of test material and the loss of standard material under the same test conditions. The abrasive material used is electrocorundum with a grain size of 100–250 µm [33] and with a maximum relative mass moisture content of 0.15%. The standard further states that when assessing wear resistance under specific wear conditions, it is permitted to use abrasive material corresponding to the material used during operation but with a maximum grain size of 1.0 mm [32].

Each test sample (standard, test sample) is weighed before the test and placed in the test equipment. Subsequently, the abrasive supply is started, and the rubber disc is pressed against the test sample. A schematic diagram of test equipment for testing the abrasive resistance of materials with a sample ready for testing is shown in Figure 7.

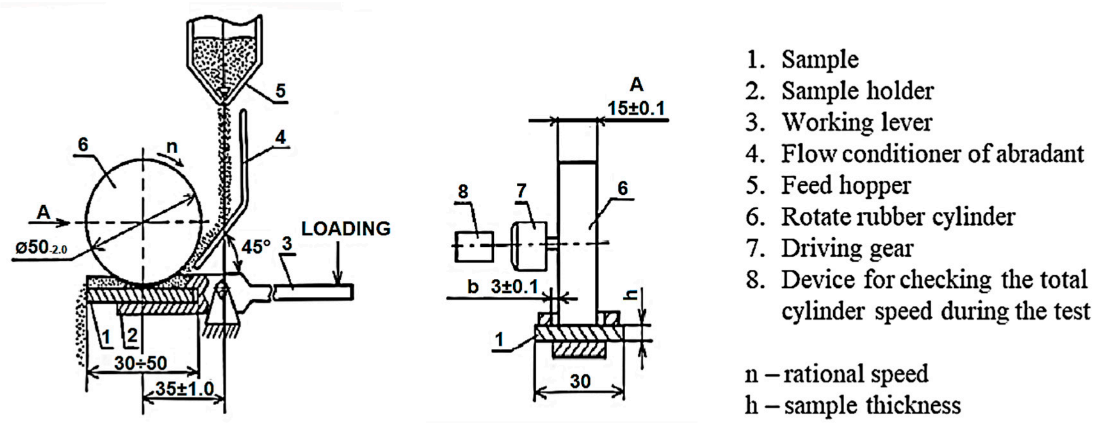
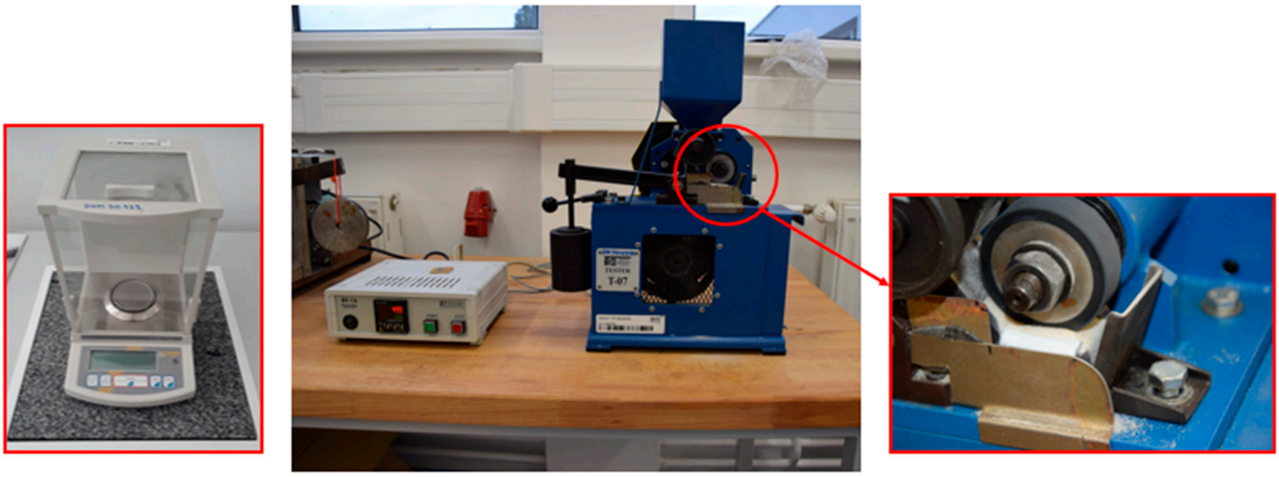


Figure 7. Scheme of the test equipment with a test sample [32].

The test equipment Tester T-07, ITC PIB Institution of Technology Radom and the BT-16 Controller (Instytut Technologii Eksploatacji, Radom, PL) used in the presented research are shown in Figure 8b,c, together with the scales (Figure 8a). Three samples were used for each material. After each cycle, the sample was weighed three times on Kern ABS analytical scales with a maximum weight of 120 g and an accuracy of g = 1.5 mg. The parameters of the test equipment and samples are shown in Table 4.



(a) (b) (c)

Figure 8. Abrasion resistance and weight measuring equipment (scales); (**a**)—scales; (**b**)—abrasion resistance equipment; (**c**)—detail of a driving gear with abrasive particles.

Table 4. Parameters of the test equipment.

Length of the Friction Path in One Cycle *R* (m)	153.6
Diameter of rubber cylinder *D* (mm)	48.9
Compression force *F* (N)	15.48
Cylinder revolutions in one cycle (revolutions)	1000
Abrasive material	OTTAWA silica sand

The sample is taken and weighed again after passing the track. Weight loss was calculated as a mean value based on the measurements of each sample.

The hardness coefficient K_T (-) is calculated from Equation (1) [32] as follows:

$$K_T = \frac{H}{H_a}\,(-) \tag{1}$$

where H—standard material hardness, which is the reference sample (HRC), and H_a—abrasive hardness (HRC).

The relative abrasion resistance is calculated from Equation (2) [12,32] as follows:

$$\Psi_h = \frac{W_{hE}}{W_{hPV}}\,(-) \tag{2}$$

where W_{hE}—weight loss standard (g); W_{hPV}—a weight loss of the reference sample (g).

2.3. Evaluation Methods

TESCAN VEGA3 electron microscope (Tescan Orsay Holding, a. s., Brno, CZ) was used for microscopy. The samples were etched in a solution of HNO_3 in ethyl alcohol—2% Nital and in etchant Cor (120 mL CH_3COOH, 20 mL HCl, 3 g picric acid, 144 mL CH_3OH).

The parametric test method of statistical hypotheses was chosen to verify the established hypothesis of the weight loss of materials 37MnSi5, S355JG3, HARDOX 450 and OK 84.58 and UTP 690 hardfacing materials. STATISTICA 12 software (Version number 1.0-0, StatSoft, Inc., Tulsa, OK, USA) was used to test statistical hypotheses.

The significance level of the test is chosen to be α = 0.05. It is necessary to test the equality of the variances before testing the difference between the two means. Additionally, therefore [34,35]:

$$H_0 : \sigma_1^2 = \sigma_2^2 \tag{3}$$

against

$$H_1 : \sigma_1^2 \neq \sigma_2^2 \quad (4)$$

where σ_1^2—variance of material weight loss values of standards S355J2G3, 37MnSi5; σ_2^2—variance of material weight loss values of reference samples HARDOX 450 material, OK 84.58 and UTP 690 hardfacing materials.

A test of the two means difference was then performed. The software calculates the appropriate p-level. In order to verify the hypothesis on the basis of the graph, that the average value of the weight losses of the standard material is greater or smaller than the material of the reference sample. In this case, the software-calculated p-level must be divided by 2, as the software works with two-way hypothesis testing.

If the value of the p-level is greater than α, then H_0 is not rejected, and thus the equality of the variances is confirmed. Conversely, if the p-level value is less than α, then H_0 is rejected in favor of H_1.

3. Results and Discussion

3.1. Preliminary Research

Individual materials were analyzed in terms of microstructure during the initial phase of the research. Figure 9a shows the microstructure of the standard material of 37MnSi5. The samples were etched in a solution of HNO_3 in ethyl alcohol—2% Nital. The microstructure of the material was predominantly sorbite, referring to the fact that the raking blade was heat treated-hardened and then tempered at a high temperature.

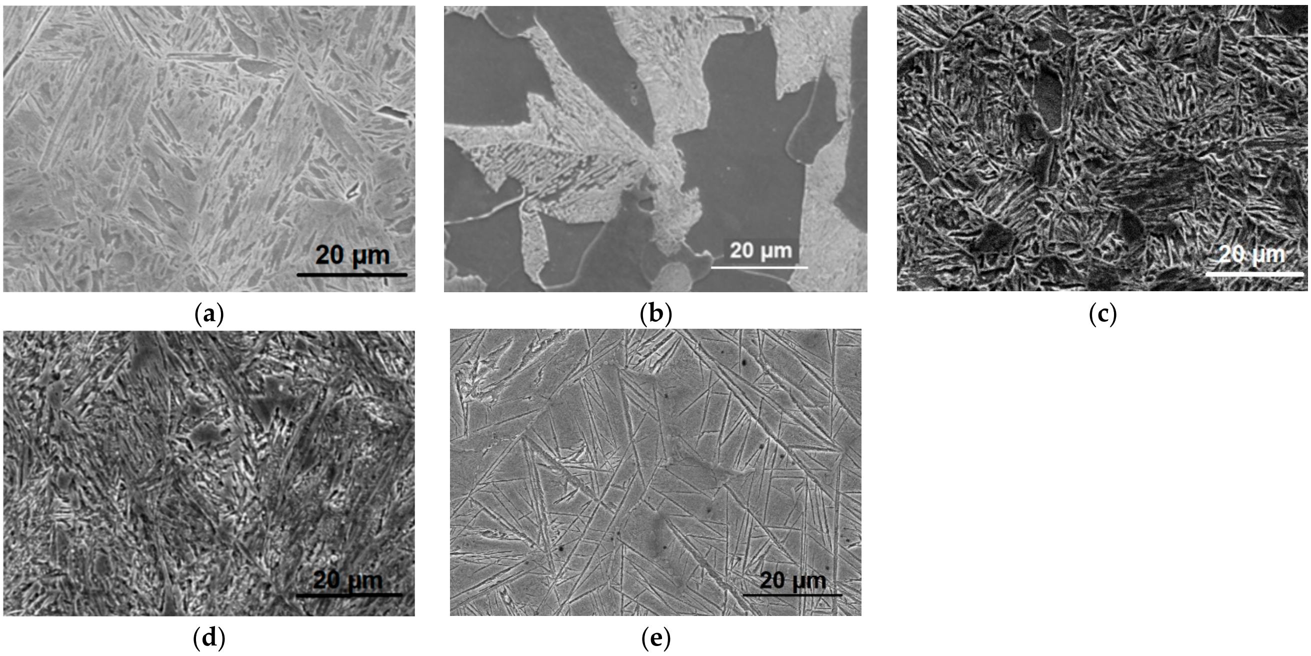


Figure 9. Microstructure of the materials; (**a**) 37MnSi5; (**b**) S355J2G3; (**c**) HARDOX 450; (**d**) hardfacing material OK 84.58; (**e**) hardfacing material UTP 690.

Figure 9b shows the microstructure of the S35J2G3 material. A ferritic-pearlitic structure was observed, with a predominance of ferrite, corresponding to the type of microstructure of structural low carbon steels. We used 2% Nital as an etchant. This part of the ploughshare is not directly exposed to abrasion in contact with the road. It is a supporting part for the raking blade connected to the base material by a weld. However, with a larger amount of material to be cleaned, this part also comes into contact with the abrasive particles but with a lower degree of attack on its surface and is thus exposed to an abrasive load. The ferritic-pearlitic structure is characterized by a low degree of abrasive resistance.

This was the reason for the idea of replacing such a weldment with one unit made of abrasion-resistant material.

Figure 9c shows the microstructure of HARDOX 450 material. The sample was etched with Cor etchant (120 mL CH_3COOH, 20 mL HCl, 3 g picric acid, 144 mL CH_3OH). The fine-grained structure corresponds to the state after heat treatment-hardening and tempering, which is stated and declared by the manufacturer in his technical sheet [27].

Figure 9d shows the microstructure of OK 84.58 hardfacing coating. The samples were also etched with Cor etchant. The microstructure corresponds to the chemical composition with a high Cr and medium C content. These elements create a precondition for the formation of carbides and intermediate phases, hardening the softer ferritic matrix. This increases the hardness and also partly the abrasion resistance while maintaining the good toughness of the material.

Figure 9e shows the microstructure of the UTP 690 hardfacing coating. Samples were also etched with Cor etchant. The microstructure of UTP 690 material is very similar to the microstructure of OK 84.58 material. The hardfacing material UTP 690, with its chemical composition represented by Cr and W, increases wear resistance and hardness. The elements V and W refine the grain, which also promotes the abrasion resistance of the material where V increases the toughness needed to balance the increased hardness with carbides C, Cr and W. Compared to OK 84.58 hardfacing material, we can observe a needle-like structure in the UTP 690 hardfacing material, which could better transfer the loads that act on it and is thus a premise for better resistance to abrasive wear.

Microstructural analyses confirmed that the choice of hardfacing materials, which due to their chemical composition, create different and more suitable structures than the analyzed structures of the original ploughshare materials, was correct. This creates the premise of better abrasion resistance and impact resistance on the ploughshare.

The hardness was measured after verifying the microstructure of the materials. Hardness is the ability of a metallic material to resist the ingress of a foreign body. Therefore, the hardness of the material is an important value providing information on the resistance of the material to abrasive wear. At the same time, hardness values are needed to calculate K_T hardness coefficients. The hardness of steel 37MnSi5, S355J2G3, HARDOX 450 and OK 84.58 and UTP 690 hardfacing materials was measured according to Vickers and Rockwell. Vickers hardness was measured according to the procedure stated in ISO 6507-1: 2018 [36] with a Vickers 432SVD hardness tester. The duration of the load was t = 15 s, and the loading force was F = 98.07 N. The Rockwell hardness was measured according to the procedure stated in ISO 6508-1: 2016 [37], with a UH250 hardness tester, and the loading force was F = 1471 N. Vickers hardness was used because it is more sensitive to small differences in material hardness. Rockwell hardness was used to better compare harder hardfacing materials. The average values of measured hardnesses obtained from ten measurements are shown in Table 5.

The measured hardness of 37MNsi5 steel (raking blade) was 538 HV0.5 and 50 HRC. The hardness of S355J2G3 steel (raking blade body) was 168 HV0.5 and 18 HRC. During its work, the ploughshare is stressed by abrasive wear not only on the raking blade but also on its supporting part. The idea of modifying the ploughshare within the meaning of changing the weldment into a solid piece of HARDOX 450 steel was based not only on removing the connecting part acting as a notch under stress, but also increasing the hardness of the new material compared to S355J2G3 material. The hardness of the HARDOX 450 material is higher compared to the S355J2G3 material, its value according to Vickers is 519HV0.5 and Rockwell is 45HRC. The aim of hardfacing additional materials to the raking blade was to increase the lifetime of the raking blade (37MnSi5) of the ploughshare. The OK 84.58 hardfacing material was the same hardness as the 37MnSi5 material, and its value was 546HV0.5 and 50 HRC. Significantly higher hardness compared to the 37MnSi5 material was achieved only by hardfacing material UTP 690, with which the hardness value was 677HV0.5 and 62 HRC. The results of the material hardness measurements predicted that the UTP 690 hardfacing material could be a suitable solution for ploughshare modification.

Table 5. Measured hardness values.

Hardness Type	37MnSi5	S355JG3	HARDOX 450	OK 84.58	UTP 690
Vickers hardness (HV 0.5)	538 ± 40	168 ± 20	519 ± 30	546 ± 40	677 ± 40
Rockwell hardness (HRC)	50 ± 2	18 ± 2	45 ± 2	50 ± 2	62 ± 2

3.2. Abrasive Wear Resistance Analysis

The abrasion resistance test was firstly performed on standard samples of 37MnSi5 and S355J2G3 materials. Subsequently, the test was also performed on reference samples made of HARDOX 450 steel and with OK 84.58 and UTP 690 hardfacing materials. In Figure 10, samples after an abrasive wear test with traces of a rubber disc are presented.

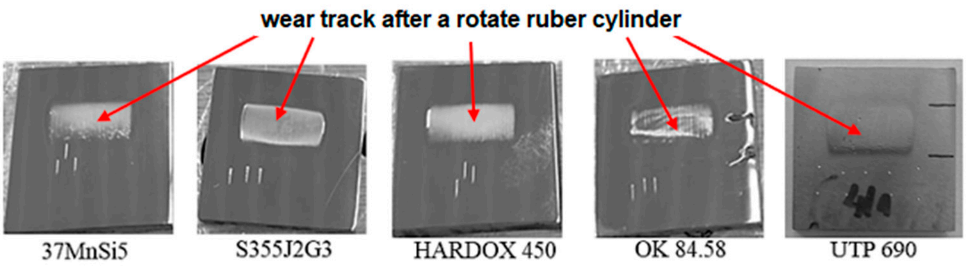


Figure 10. Samples after abrasive wear test.

For each material, three samples were used for the abrasion test. After each cycle, the sample was weighted three times on Kern ABS analytical scales, while the average values of the weight losses that were used for the next processing are shown in Table 6.

Table 6. Average weight losses of 37MnSi5, S355J2G3, HARDOX 450 steels and OK 84.58 and UTP 690 hardfacing materials.

Tracked Distance R (m)	Weight Loss (g)				
	37MnSi5	S355J2G3	HARDOX 450	OK 84.58	UTP 690
153.6	0.0062	0.0158	0.0133	0.0062	0.0022
307.2	0.0088	0.0223	0.0108	0.0075	0.0009
460.8	0.0067	0.0208	0.0091	0.0078	0.0013
614.4	0.0072	0.0145	0.0077	0.0062	0.001
768.0	0.0072	0.0126	0.0066	0.0078	0.0011
921.6	0.0043	0.0197	0.0069	0.0072	0.0010
1075.2	0.0042	0.0133	0.0081	0.0072	0.0008
1228.8	0.0098	0.0141	0.0076	0.0070	0.0009
1382.4	0.0053	0.0131	0.0067	0.0050	0.0012
1536.0	0.0056	0.0118	0.0068	0.0062	0.0012
1689.6	0.0061	0.0141	0.0072	0.0053	0.0038
Average weight loss W_{hi}	0.0064	0.0157	0.0082	0.0066	0.0014

Equation (1) [16] was used to calculate the hardness coefficients K_{TE} and K_{TV} of the standard materials 37MnSi5 and S355J2G3 and reference samples HARDOX 450, OK 84.58 and UTP 690 materials. The resulting values are shown in Table 7.

Table 7. Hardness coefficient values K_T.

Sample Material	37MnSi5	S355J2G3	HARDOX 450	OK 84.58	UTP 690
Hardness coefficient K_T	0.93	0.33	0.83	0.93	1.15

If this coefficient is higher than 1, it is assumed that the material and the hardfacing material can withstand abrasive particles. It is clear from the graph that the largest value of the K_T hardness coefficient was reached by the UTP 690 hardfacing material, namely 1.15. Other steels (37MnSi5, S355J2G3, HARDOX 450) and hardfacing material (OK 84.58) reached a value of K_T inferior to 1. The S355J2G3 material of the ploughshare body reached the lowest value of K_{TE2} = 0.33 in comparison with all examined materials and the standard. Based on this result, it would also be appropriate to consider changing the base material to a HARDOX one.

The relative abrasion resistance Ψ_h was then calculated according to Equation (2) from the weight losses of W_h. The relative resistance to abrasive wear was also calculated for the S355J2G3 basic material of the ploughshare, as it is also exposed to abrasive wear during raking [8]. The resulting values are shown in Table 8.

Table 8. Relative abrasion resistance Ψ_h.

Sample Material	37MnSi5	S355J2G3	HARDOX 450	OK 84.58	UTP 690
Relative abrasion resistance Ψ_h	1	1	1.91	0.97	4.57

Materials 37MnSi5 and S355J2G3 have the value Ψ_h = 1 because they are standard materials. The relative resistance to abrasive wear is the ratio of the weight loss of the standard material to the weight loss of the material, respectively, of the reference sample. If this coefficient is higher than 1, it is assumed that the material and the hardfacing material of the reference sample can withstand abrasive wear better than the material of the standard sample. Based on the test of resistance to abrasive wear, we can state that the sample from HARDOX 450 material achieved almost twice as good results as the standard sample from S355J2G3 steel.

As the abrasion resistance increases in direct proportion to the hardness of the material [5,9] by using higher grade HARDOX abrasion resistant steel with higher hardness, we can achieve even better abrasion resistance. With OK 84.58 hardfacing material, we achieved almost the same resistance to abrasive wear as the standard sample made of 37MnSi5 material. The highest value of Ψ_h was reached by the UTP 690 hardfacing material, up to 4.5 times higher than the 37MnSi5 standard material. Based on these results, we can state that UTP 690 hardfacing material could be the most suitable for modifying the ploughshare.

Figure 11 shows the box plots with 95% confidence intervals. In the first case (Figure 11a), the weight loss values of S355J2G3 and HARDOX 450 materials were compared. It can be stated from the graph that the average values of weight loss of S355J2G3 and HARDOX 450 materials are not the same. Based on these results, it can be assumed that HARDOX 450 material will have better resistance to abrasive wear.

In the second case (Figure 11b), the values of the weight loss of 37MnSi5 material and OK 84.58 hardfacing material were compared. Based on the graph, it can be stated that the average values of the weight loss of 37MnSi5 material and OK 84.58 hardfacing material are almost the same, and thus hardfacing with such a hardfacing material on the exposed parts of the ploughshare will not significantly increase the lifetime.

In the third case, the values of mass losses of the 37MnSi5 material and UTP 690 hardfacing material were compared (Figure 11c). A comparison of the graphs clearly shows that the average values of weight loss of 37MnSi5 material and UTP 690 hardfacing material that UTP 690 hardfacing material will have better resistance to abrasive wear.

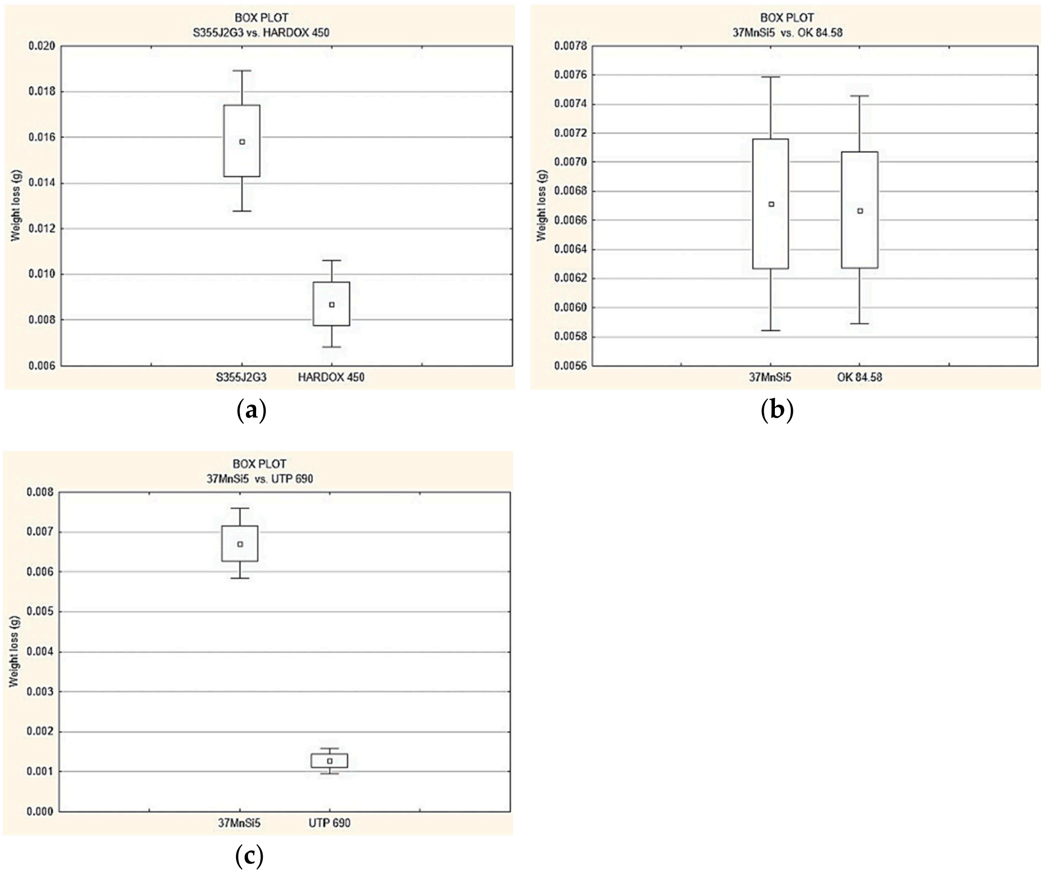


Figure 11. Box charts: (**a**) weight loss of S355J2G3 and HARDOX 450 materials; (**b**) weight loss of 37MnSi5 material and OK 84.58 hardfacing material; and (**c**) weight loss of 37MnSi5 material and UTP 690 hardfacing material.

3.3. Discussion

(a) Change of the S355J2G3 material of the supporting part of the ploughshare for the HARDOX 450 material

Based on the results, we can state that HARDOX 450 material has significantly better results compared to the S355J2G3 material of the basic ploughshare body. The hardness of HARDOX 450 material was 45 HRC, and the hardness coefficient of K_{TV1} reached the value of 0.83. The hardness of the basic body S355J2G3 material was 18 HRC, and the hardness coefficient of K_{TE2} reached the value of 0.33. These two basic data provide us with the initial information that HARDOX 450 material will better resist the abrasive particles present during the work cycle than the S355J2G3 material of the basic ploughshare body. The relative abrasion resistance Ψ_{h1} reached the value of 1.91. Based on this datum, we can say that HARDOX 450 material achieved almost twice as good results as the standard sample No. 2 made of S355J2G3 steel. In this case, it would be appropriate to verify the suitability of the higher class HARDOX material, e.g., HARDOX 550, which has higher hardness.

(b) Hardfacing on the exposed part of the raking blade with the OK 84.58 hardfacing material

Based on the results, we can state that the OK 84.58 hardfacing material achieved almost the same results in comparison with the 37MnSi5 material of the raking blade. The hardness of the raking blade 37MnSi5 material was 50 HRC, and the hardness coefficient of K_{TE1} reached the value of 0.93. The hardness of the OK 84.58 hardfacing material was 50 HRC, and the hardness coefficient of K_{TV2} reached the value of 0.93. These two basic data provide us with the initial information that the OK 84.58 hardfacing material will be worse as well as resist the abrasive particles present during the work cycle as a 37MnSi5 material. The relative resistance to abrasive wear Ψ_{h2} reached the value of 0.97. Based on this datum, we can say that the OK 84.58 hardfacing material achieved worse results by only 3% compared to the 37MnSi5 standard material of the raking blade. These elements create a precondition for the formation of carbides and intermedial phases hardening the softer ferritic matrix. This increases the hardness as well as partly the abrasion resistance while maintaining the good toughness of the material.

(c) Hardfacing on the exposed part of the raking blade with the UTP 690 hardfacing material

Based on the results, it can be stated that UTP 690 hardfacing material achieved better results compared to the 37MnSi5 material of the raking blade. The hardness of the UTP 690 hardfacing material was 62 HRC, and the hardness coefficient K_{TV3} reached the value of 1.15. These two basic data provide us with initial information that the UTP 690 hardfacing material will better withstand the abrasive particles present during the working cycle. The relative resistance to abrasive wear Ψ_{h3} reached the value of 4.57. Based on this data, we can say that the UTP 690 hardfacing material achieved more than 4.5 times better results compared to the 37MnSi5 standard material of the raking blade. In this case, we can state that the UTP 690 hardfacing material could significantly affect the lifetime of the ploughshare. The hardfacing material of the UTP 690 coating with its chemical composition represented by Cr and W increases wear resistance and hardness. The elements V and W soften the grain promoting the abrasion resistance of the material, where V increases the toughness needed to balance the increased hardness with carbides C, Cr and W. Compared to the OK 84.58 hardfacing material to transfer the loads that act on it and is, therefore, an assumption for better resistance to abrasive wear.

Based on the results, we can state that the hardness of the material strongly correlates with the resistance to abrasive wear. The hardness of HARDOX 450 was almost 2.5 times higher than S355J2G3. The relative abrasion resistance was almost twice as high for HARDOX 450 as for S355J2G3. The hardness and relative abrasion resistance of the 37MnSi5 material and the OK 84.58 hardfacing material were almost the same. Compared to the 37MnSi5 material, the UTP 690 material achieved higher hardness and higher resistance to abrasive wear.

4. Conclusions

Ploughshares are exposed to high wear, especially of the abrasive type, and their replacement is relatively economical. For this reason, it is necessary to look for ways to increase their lifetime and examine their resistance to abrasive wear.

When working with a ploughshare, it is not only the raking blade that wears rapidly but also its supporting part which the raking blade welded to. The article analyzes three ways to modify ploughshares. Based on the results, it is possible to state the following:

(a) The HARDOX 450 material achieved significantly better results compared to the basic S355J2G3 material, not only in terms of hardness and hardness coefficient K_T but also in terms of relative resistance to abrasive wear, where the coefficient Ψ_{h1} for HARDOX 450 material achieved almost twice as good results compared to the standard sample from S355J2G steel;
(b) The OK 84.58 hardfacing material achieved almost the same results compared to the 37MnSi5 original material of the raking blade and therefore does not significantly affect the lifetime of the raking blade on the ploughshares;
(c) The UTP 690 hardfacing material achieved more than 4.5 times better results than the 37MnSi5 standard material of the raking blade, so it could significantly affect the lifetime of the ploughshare. Compared to the OK 84.58 hardfacing material, we can observe a needle-like structure in the UTP 690 hardfacing material, which could better transfer the loads that act on it, and thus it is an assumption for the better resistance to abrasive wear.

Based on the results, the manufacturer of ploughshares was recommended to use HARDOX 450 material as a basic material and UTP 690 coating material hardfacing on exposed parts of functional surfaces as a suitable means of increasing the lifetime of ploughshares.

In further research, it would be appropriate to also perform a test of resistance to abrasive wear for abrasion-resistant HARDOX sheet but of a higher class, i.e., with higher hardness, e.g., HARDOX 550 material, as well as for OK 84.58 hardfacing material which would be hardfaced in several layers. Then, the most suitable adjustments would be selected and tested under real operating conditions.

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