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ANALYSIS OF WEAR AND TEAR OF WORKING ELEMENTS WITH A REPLACEABLE CUTTING EDGE IN AN ABRASIVE SOIL MASS

ANALIZA ZUŻYWANIA ELEMENTÓW ROBOCZYCH Z WYMIENNYM OSTRZEM SKRAWAJĄCYM W GLEBOWEJ MASIE ŚCIERNEJ

Key words: ploughshare, wear, hardfaced layer, multi-dimensional analyses.

Abstract This paper presents an analysis of the wear and tear process of different technological solutions of plough blades with a replaceable cutting edge. The experiment was conducted under natural operating conditions. Workpieces made of B27, Hardox 500, and Hardox 500 with padding weld, and two types of boron steel with non-hardfaced and hardfaced cutting edges were tested. The analyses of chemical composition and microstructure were performed using light microscopy and scanning electron microscopy methods.

Operational research included the measurement of mass changes and geometry in the characteristic points of the plough blades.

Based on the results obtained, it was found that the components made of Hardox 500 steel with padding welding were more durable than component without the padding layer. In contrast, the weight loss intensity was similar for all the examined materials.

Słowa kluczowe: lemiesz płużny, zużycie, warstwa napawana, analizy wielowymiarowe.

Streszczenie W pracy przedstawiono analizę procesu zużywania różnych rozwiązań technologicznych lemieszy płużnych z wymiennym ostrzem skrawającym. Eksperyment przeprowadzono w warunkach naturalnej eksploatacji. Badaniom poddano elementy robocze wykonane ze stali B27, Hardox 500, Hardox 500 z napoiną oraz dwóch rodzajów stali borowej z nienapawaną i napawaną krawędzią skrawającą. Analizie poddano skład chemiczny i mikrostrukturę z wykorzystaniem metod mikroskopii świetlnej, metod elektronowej mikroskopii skaningowej .

Badania eksploatacyjne obejmowały pomiar zmian masy oraz geometrii w charakterystycznych punktach lemiesza płużnego.

Na podstawie uzyskanych wyników stwierdzono, że elementy wykonane ze stali Hardox 500 z napoiną charakteryzowały się większą trwałością niż elementy nienapawane. Natomiast intensywność zużycia masowego jest zbliżona dla wszystkich badanych materiałów.

INTRODUCTION

The operation of working elements in an abrasive soil mass is accompanied by the process of abrasive wear **[L. 1]**. It consists in the movement of loose or fixed abrasive in relation to the working surface. The largest group of tools exposed to the most intense unit and total wear in an abrasive soil mass includes ploughshares **[L. 2]**. The course and intensity of their wear depends on the following:

- The properties of the soil processed (moisture content, compactness, pH and grain size distribution);
- The type of the impact of the working element on the soil; and,
- Design and technological solutions concerning the working element.

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Users of working elements expect the manufacturers to provide design solutions that offer high durability at low prices **[L. 3, 4]**. Therefore, the materials of the working elements of tools for treating an abrasive soil mass should demonstrate high abrasive wear, as well as impact performance. Regarding the materials, medium carbon low alloyed steels are most frequently used for elements exposed to wear and local impact. In zones of the highest abrasive wear, hardfacing is also applied. This solution offers one of the methods to increase the durability of machine parts exposed to the effect of the abrasive environment. Abrasive wear resistance can be increased by the application of welding methods, making it possible to modify the chemical composition of the base material by introducing additional components increasing the resistance to abrasive wear as well as the change in hardness and microstructure of the material. However, it requires the application of advanced welding methods and hardfacing electrodes of complex chemical compositions **[L. 5]**. Therefore, low-alloyed, high performance steels with a post-martensitic structure, resistant to abrasive wear, are currently becoming increasingly more popular **[L. 6]**. They demonstrate uniform structural and resistance properties over the entire cross-section of steel products, resulting from a properly-selected chemical composition and specialist thermo-mechanical rolling procedures.

One of new design solutions intended for increasing durability is the use of a replaceable cutting edge (chisel) in ploughshares. Both sides of the edge can be used and, at the same time, its durability is much lower than the durability of the ploughshare. During the lifetime of the ploughshare, between two and three cutting edges are used, depending on environmental conditions. The user has to choose a design solution and a construction material of which the working element is made. This problem can be solved by adjustment of design and material solutions to the environmental conditions. Due to the multitude of factors determining wear and tear processes in the soil mass, in order to choose the most favourable construction and technological solution, it is important to use one of the multidimensional statistical analysis methods **[L. 7]**. Cluster analysis is aimed at distinguishing homogeneous subsets of objects of the examined elements. Clustering methods are applied when *a priori* hypotheses are not available, and the research is still in the exploration phase. Since the groups (clusters) of objects are found based on variables characteristic for the analysed objects, an important element of cluster analysis to properly select the variables used for distinguishing coherent groups of objects.

The aim of the paper is to analyse the wear and tear of different technological solutions concerning ploughshares with a replaceable cutting edge using the cluster analysis method.

RESEARCH MATERIAL

The research was carried out on landside ploughs with a replaceable cutting edge, made of low-alloyed carbon steels, non-hardfaced (**Fig. 1**), and hardfaced (**Fig. 2**).

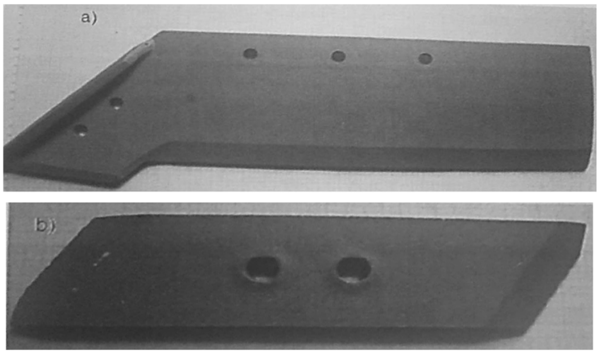

Fig. 1. Work element view: a) landside ploughshare, b) cutting blade (chisel)
Rys. 1. Widok elementu roboczego: a) dziobowy lemiesz płużny, b) ostrze skrawające (dłuto)

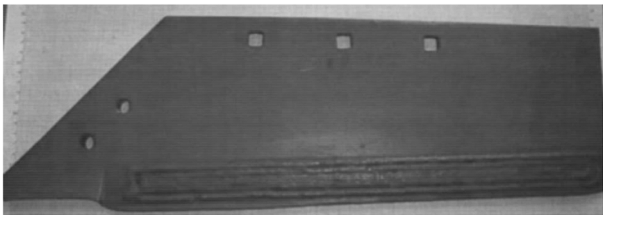

Fig. 2. View of ploughshare with a padding layer applied
Rys. 2. Widok lemiesza płużnego z nałożoną warstwą napoiny

Working elements were made of the following steels: Hardox 500, Hardox 500 surfaced with Fidur 10/65, B27 electrode, steel marked by the supplier as Unirol and Unirol with a stellite padding weld layer applied without grade specification. Chemical compositions and selected structural properties of the examined materials are presented in **Table 1** and in **Figs. 3–9.**

To carry out the research, samples of all analysed steels were collected from the examined working elements, applying a method ensuring the invariability of their structure. The method of water jet cutting with water and an abrasive substance was used for cutting the samples. The chemical composition was analysed by a spectral method using a glow discharge atomic emission spectrometer GDS500A manufactured by LECO. During the analyses, the following parameters were applied: U = 1250 V, I = 45 mA, argon. The results obtained were the arithmetic mean of at least five measurements. Observations of the microstructure were performed using a light microscope (LM) Nikon Eclipse MA200 coupled with a digital camera Nikon DS-Fi2 and using NIS Elements software. Observations

Table 1. Chemical composition of tested materials on the basis of own tests [BW] and on the basis of manufacturer data [DP]

Tabela 1. Skład chemiczny badanych materiałów na podstawie badań własnych [BW] oraz danych producenta [DP]

Material		C	Mn	Si	P	S	Cr	Ni	Mo	B	HRC
		Selected chemical element [% by weight]									
B27	DP	≤0.32	≤1.50	≤0.40	≤0.020	≤0.015	≤0.60	–	–	0.0008 –0.0050	49
	BW	0.28	1.26	0.23	0.009	0.006	0.32	0.05	0.007	0.002	48
Hardox 500	DP	≤0.27	≤1.60	≤0.50	≤0.025	≤0.010	≤1.20	≤0.25	≤0.25	≤0.005	49–53
	BW	0.29	1.05	0.23	0.006	0.000	0.96	0.05	0.017	0.001	52
Hardox 500 + padding weld	DP	4.50	0.50	0.70	–	–	34.0	–	–	–	62–64
	BW	–	–	–	–	–	–	–	–	–	62
Unirol	BW	0.33	1.21	0.29	0.021	0.008	0.31	0.06	0.016	0.002	48
Unirol + padding weld	BW	–	–	–	–	–	–	–	–	–	45

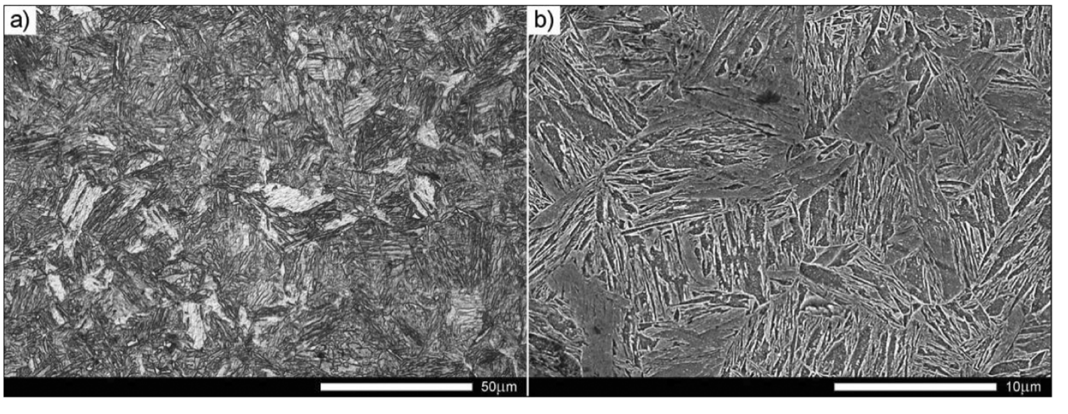

Fig. 3. Image of microstructure of B27 steel at different magnification scale: a) light microscopy, b) SEM. Structure of fine quartz martensite hardening with few bainitic areas. Mi1Fe etched

Rys. 3. Obraz mikrostruktury stali B27 w różnej skali powiększenia: a) mikroskopia świetlna, b) SEM. Struktura drobnolistwowego martenzytu hartowania z nielicznymi obszarami bainitycznymi. Trawiono Mi1Fe

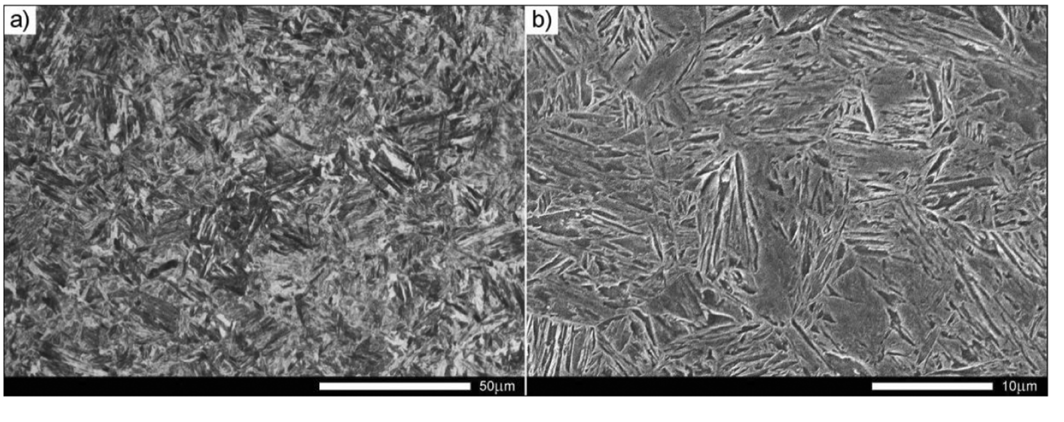

Fig. 4. Hardox 500 microstructure image at different magnification scale: a) light microscopy, b) SEM. Structure of tempered hard martensite with few areas of tempered martensite. Mi1Fe etched

Rys. 4. Obraz mikrostruktury stali Hardox 500 w różnej skali powiększenia: a) mikroskopia świetlna, b) SEM. Struktura drobnolistwowego martenzytu hartowania z nielicznymi obszarami martenzytu odpuszczonego. Trawiono Mi1Fe

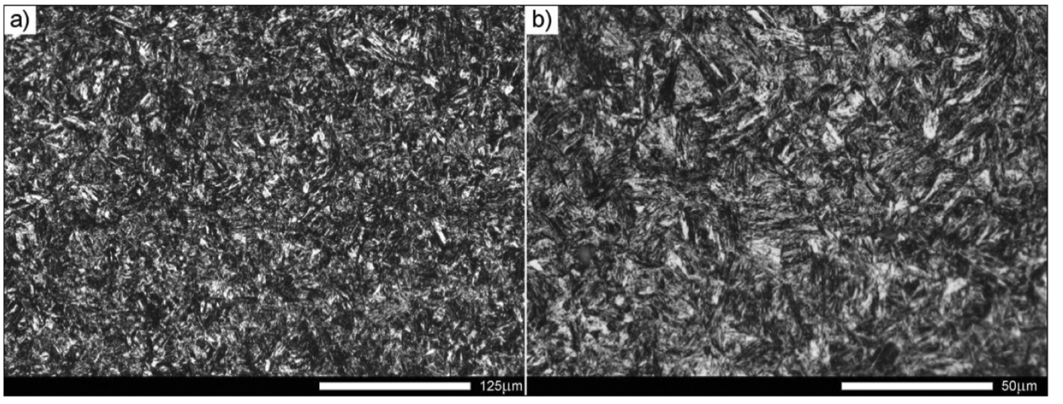

Fig. 5. Unirol steel microstructure image at different zoom ratios. Structure of quenching martensite with areas of tempered martensite. Light microscopy, Mi1Fe etched

Rys. 5. Obraz mikrostruktury stali Unirol w różnej skali powiększenia. Struktura martenzytu hartowania z obszarami martenzytu odpuszczonego. Mikroskopia świetlna, trawiono Mi1Fe

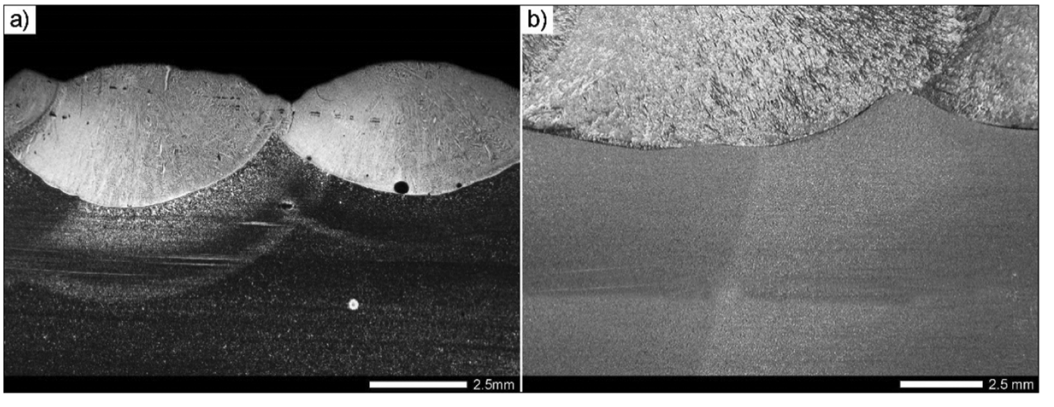

Fig. 6. Macroscopic images of welded layers: a) Unirol steel, b) Hardox steel 500. Light microscopy, etched with Mi1Fe and electrolytic chromic acid

Rys. 6. Makroskopowe obrazy warstw napawanych: a) stal Unirol, b) stal Hardox 500. Mikroskopia świetlna, trawiono Mi1Fe oraz elektrolitycznie kwasem chromowym

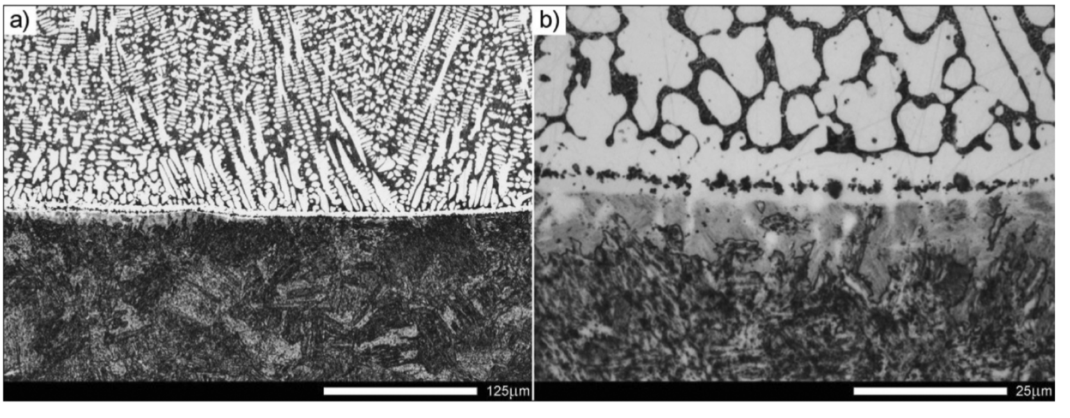

Fig. 7. Image of the microstructure of the Unirol steel melt infusion zone shown in Fig. 8a: a) general view of the melt zone without significant cracks and discontinuities; b) enlarged fragment of the melt zone with visible microstructure changes. In the transition zone, a visible "continuous" bar of solid solution (ferrite alloy) with tempered martensite areas on the side of the backing material (bottom) is visible. Light microscopy, etched with Mi1Fe and electrolytic chromic acid

Rys. 7. Obraz mikrostruktury strefy wtopienia warstwy napawanej stali Unirol pokazanej na **Rys. 8a**: a) ogólny widok strefy wtopienia bez wyraźnych pęknięć i nieciągłości, b) powiększony fragment strefy wtopienia z uwidocznionymi zmianami mikrostruktury. W strefie przejściowej widoczny jasny „pasek" ciągłego roztworu stałego (ferryt stopowy) z obszarami martenzytu hartowania po stronie materiału podkładki (u dołu). Mikroskopia świetlna, trawiono Mi1Fe oraz elektrolitycznie kwasem chromowym

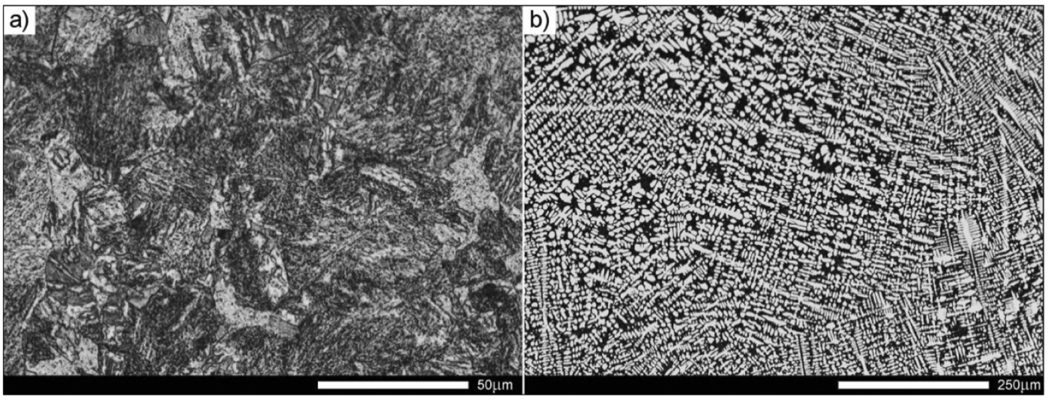

Fig. 8. An enlarged image of the microstructure of the Unirol coated steel layer shown in Fig. 8a: a) the material of the backing in the heat–affected zone – the structure of tempering sorbent with hardened martensite areas; b) the liner material – the ledeburite structure with primary chromium carbide. Light microscopy, etched with Mi1Fe and electrolytic chromic acid

Rys. 8. Powiększony obraz mikrostruktury warstwy napawanej stali Unirol pokazanej na **Rys. 8a**: a) materiał podkładki w strefie wpływu ciepła – struktura sorbitu odpuszczania z obszarami martenzytu hartowania, b) materiał napoiny – struktura ledeburytu z pierwotnymi węglikami chromu. Mikroskopia świetlna, trawiono Mi1Fe oraz elektrolitycznie kwasem chromowym

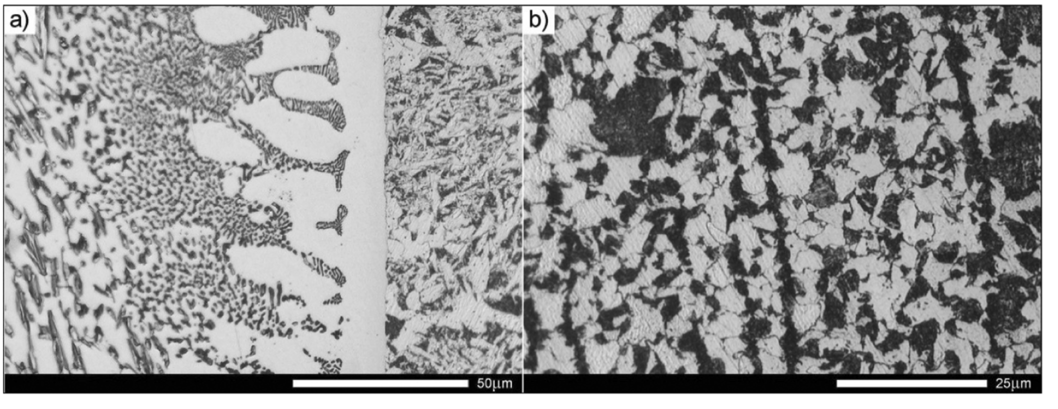

Fig. 9. Magnified image of microstructure of Hardox 500 hardcoat layer shown in Fig. 8b: a) melting zone consisting of alloy strip ferrite, b) backing material in heat affected zone – structure of unequal ferrite grain with fine perlite pearl and few areas of martensitic hardening. Light microscopy, etched with Mi1Fe and electrolytic chromic acid

Rys. 9. Powiększony obraz mikrostruktury warstwy napawanej stali Hardox 500 pokazanej na **Rys. 8b**: a) strefa wtopienia składająca się w „paska" ferrytu stopowego, b) materiał podkładki w strefie wpływu ciepła – struktura nierównowagowych ziaren ferrytu z drobnodyspersyjnym perlitem i nielicznymi obszarami martenzytu hartowania. Mikroskopia świetlna, trawiono Mi1Fe oraz elektrolitycznie kwasem chromowym

using the light microscopy methods were carried out with a 100–1000 zoom. The examination of the microstructure with the application of a larger zoom ratio and microanalyses of the chemical composition were carried out using a (SEM) Jeol JSM-5800LV electron scanning microscope coupled with an Oxford Link ISIS-300 X-ray micro-analyser. An accelerating voltage of 20 and 25 kV was applied, as well as contrast materials using SE and BSE detectors. Hardness measurements of the examined samples were taken with a Zwick ZHU 187,5 universal hardness tester, using the Brinell and Rockwell method with 1875/1500/600 kgf test loads, according to PN-EN ISO 6506-1:2014-12 and PN-EN ISO 6508-1:2016-10 norms. Measurements were carried out on samples subject to previous evaluation of the microstructure in the area of their roots. The hardness indicators obtained were mean values obtained from at least five measurements.

B27, Hardox 500 and Unirol steels provided for tests demonstrated very similar properties, both as regards their chemical and structural features. The conducted chemical analyses (**Table 1**) indicated that all materials under analysis are low-alloyed steels resistant to abrasive wear with boron. The chemical compositions of those materials were selected based on the possibility of obtaining a homogenous martensitic structure (the same level of hardness) over the entire cross-section of the sheet, regardless of its thickness. Consequently, in these steels, the actual amounts of alloy additions are most often slightly lower than the value specified by their manufacturers. Such elements as chromium, nickel, manganese, molybdenum, and boron are introduced to those steels in order to obtain their high hardening capacity. Nickel is added to lower the temperature during the austenitising heat treatment, as well as to reduce the temperature of transition into a brittle state. Additionally, those steels are characterized by a reduced content of harmful admixtures in the form of sulphur and phosphorus. Conducted structural examinations of those steels demonstrated that, in the state in which they are supplied, they feature similar, in terms of morphology, structures of fine lath martensite (resulting from carbon content) with scarce areas of tempered martensite (**Figs. 5–7**). The convergence of structural features was additionally confirmed by the fact that those steels reached similar levels of hardness (**Table 1**).

Padded layers of Unirol and Hardox 500 steels also revealed a very similar structural composition, particularly in the material of the padding weld and the fusion zone. Areas of hardfaced materials demonstrated a ledeburite structure with the separation of original chromium carbides. It can be also added that, in both cases of the examined layers, the presence of single interseam discontinuities was recorded, as well as the presence of numerous gas bubbles. The last remark refers mostly to Unirol steel (**Figs. 8a** and **9b**). Apart from the chemical composition the observed property of this padding layer can contribute to a significantly lower hardness level (45 HRC) in comparison to Hardox 500 steel (62 HRC). In the fusion zones, both padding welds demonstrated a structure composed of a continuous "strip" of alloy ferrite with dendritic branches of the solid solution with local discontinuities (**Fig. 9**). As in the previous case, numerous pores can be observed in the zone where the layer weld is fused into the backing material of the Unirol steel (**Fig. 9b**), which can additionally result in lowering the abrasive resistance by the padded layer crumbling. Additionally, in this material, in the strip directly adjoining the fusion zone (at the contact point with alloy ferrite), a continuous area of martensitic structure can be observed, resulting from a high cooling rate during the hardfacing, or a insufficient degree of preliminary heating of the backing material before hardfacing.

In the zone of heat impact, on the other hand, the structure of both backing materials demonstrated quite significant differences. Unirol steel in this zone is characterized with a tempered sorbite structure, while, in Hardox 500, a structure of unbalanced ferrite grains was recorded, with partially irregular, quasi-eutectoid streaks.

RESEARCH METHODS

Operational tests were conducted on a farm from mid-July to the beginning of November 2016. Ploughshares were mounted on a Unia Grudziądz TUR 4+1 five-furrow patch plough with a breaking bolt as the overload protection device. The plough was aggregated with a Valtra N121 tractor. Ploughing was carried out on stubble, after previous post-harvest treatment with a disc harrow. The ploughing depth was about 0.20–0.25 m, with a speed range of 6–8 km·h^{-1}. Before starting the tests and every day, measurements of the value of properties typical for changes in the geometry and weight of the ploughshares and chisels were made. Measurement points for the ploughshare are presented in **Fig. 10** and for the cutting edge in **Fig. 11**.

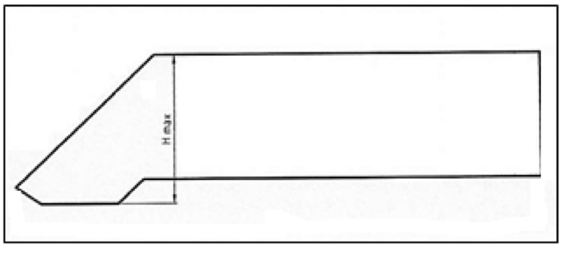

Fig. 10. Measuring the size of wear of the ploughshare. H_{max} – max. width
Rys. 10. Pomiarowe wielkości zużycia lemiesza. H_{max} – max szerokość

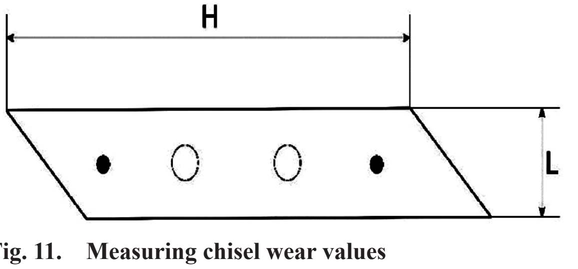

Fig. 11. Measuring chisel wear values
Rys. 11. Pomiarowe wielkości zużycia dłuta

The weight of the elements was measured using a technical balance with accuracy of ±5 g, while chisels were weighed using a balance with accuracy of ±1 g. The length and the width were determined using a calliper with an accuracy of ±0.02 mm.

Soil graining was determined using a laser particle size analyser, Mastersizer 2000 (PTG 2008 classification). The tests were conducted in coarse grain loamy sand **(Tab. 2)** with a moisture content by mass ranging from 11% to 13%.

The tests were stopped at the moment when the weakest blade, i.e. Unirol + padding layer, reached the threshold state.

Table 2. Grain size distribution of the soil
Tabela 2. Skład granulometryczny gleby

Grain size distribution of soil – fraction share (%)			
loam	***dust***		***sand***
<0.002 mm	**0.002––0.020 mm**	**0.020––0.050 mm**	**0.050––2.000 mm**
1.31	9.47	11.22	78.00

In order to identify sets of similar materials, a cluster analysis was performed that classified the objects into groups. The agglomeration method was used, through which hierarchically-arranged clusters are obtained, which can be demonstrated in a tree form (dendrogram), presenting the distance between the grouped objects.

ANALYSIS OF RESEARCH RESULTS

The results of the tests measuring the value of weight and geometric wear of the examined materials in the function of ploughed area are presented in **Figs. 12–16**.

The highest value of weight loss was found for ploughshares made of Unirol steel, and the lowest was for ploughshares made of B27 steel. For weight loss in chisels, the highest value was observed for the chisel made of Unirol steel with a padding layer and the lowest, just like in case of ploughshares, was for B27 steel.

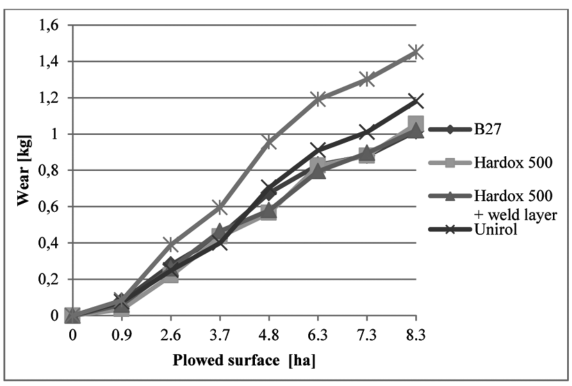

Fig. 12. The course of weight loss in ploughshares
Rys. 12. Przebieg zużycia masowego lemieszy

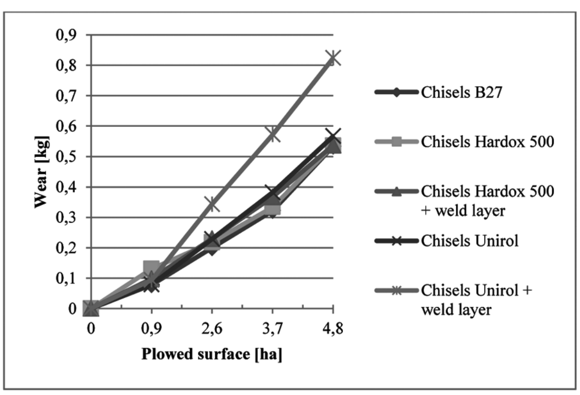

Fig. 13. The course of weight loss in chisels
Rys. 13. Przebieg zużycia masowego dłut

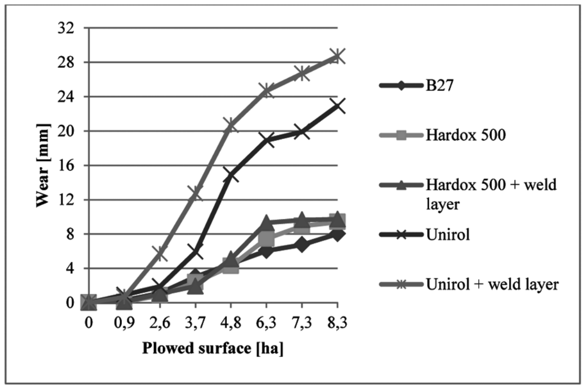

Fig. 14. Width changes in ploughshares
Rys. 14. Przebieg zmian szerokości lemiesza

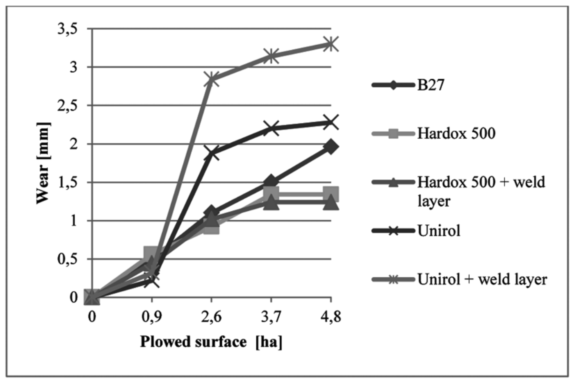

Fig. 15. Width changes in chisels
Rys. 15. Przebieg zmian szerokości dłuta

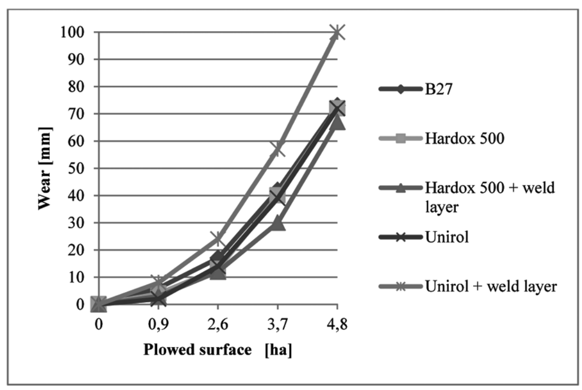

Fig. 16. Chisel length changes
Rys. 16. Przebieg zmian długości dłuta

Analysing the dependency between the geometric wear (width) of the examined materials and the ploughed area, the highest loss was found for working elements made of hard-faced Unirol steel. Among the ploughshares, the element made of B27 steel proved the most resistant to wear while, among the chisels, the element made of Hardox 500 hardfaced steel was the most resistant.

In order to obtain information on which of the materials can be considered similar, a multi-dimensional analysis–cluster analysis was carried out (**Figs. 17––20**). It was observed that, at the beginning, each material formed its own cluster. A further analysis of the dendrogram to the right demonstrated that similar materials combined into clusters. On the basis of **Fig. 17** referring to the dendrogram for clusters according to weight loss, ploughshares made of Hardox 500 and hardfaced Hardox 500 steel were most similar. For chisels (**Fig. 18)**, elements made of hardfaced Hardox 500 and Unirol steels proved the most uniform.

In the analysis of geometric wear (width), the materials forming the closest clusters, both among ploughshares and chisels, were those made of Hardox 500 and hardfaced Hardox 500 steel.

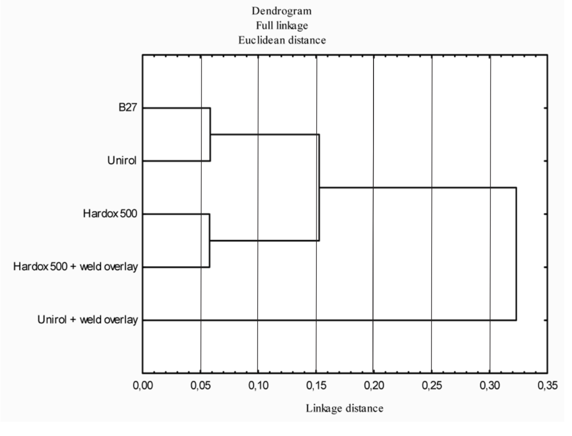

Fig. 17. Dendrogram for ploughshare clusters according to weight loss

Rys. 17. Dendrogram dla skupień lemieszy wg zużycia masowego

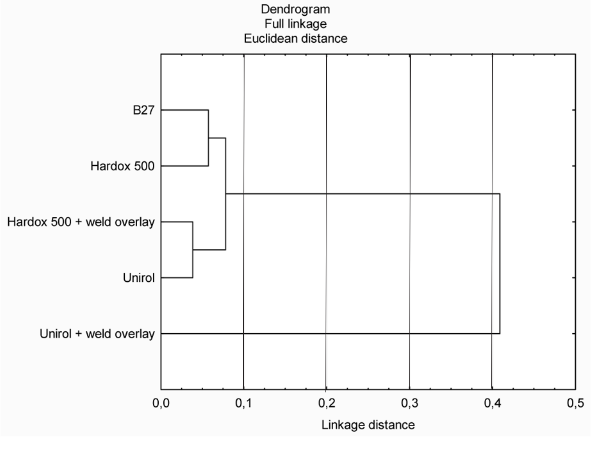

Fig. 18. Dendrogram for chisel clusters according to weight loss

Rys. 18. Dendrogram dla skupień dłut wg zużycia masowego

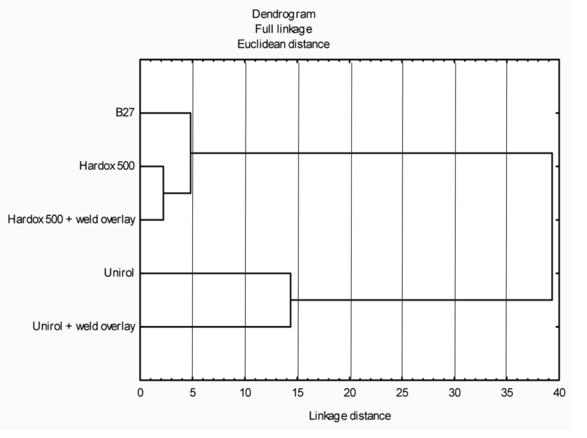

Fig. 19. Dendrogram for ploughshare clusters according to geometric wear (width)

Rys. 19. Dendrogram dla skupień lemieszy wg zużycia geometrycznego (szerokość)

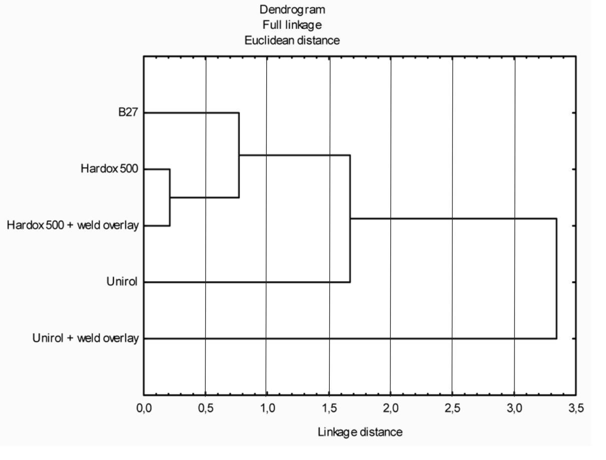

Fig. 20. Dendrogram for chisel clusters according to geometric wear (width)

Rys. 20. Dendrogram dla skupień dłut wg zużycia geometrycznego (szerokość)

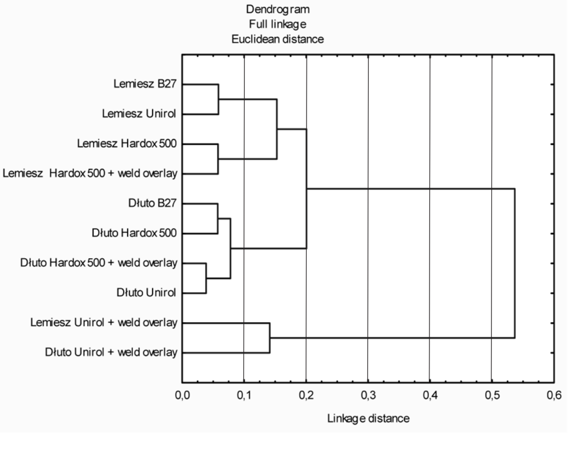

Fig. 21. Dendrogram for ploughshare and chisel clusters according to weight loss

Rys. 21. Dendrogram dla skupień lemieszy i dłut wg zużycia masowego

The cluster analysis conducted led to grouping of the examined structural materials demonstrating similar abrasive resistance. Among the examined materials, according to similar values of weight loss, the following groups of materials were distinguished (**Fig. 21**):

- B27 ploughshare, Unirol ploughshare;
- Hardox 500 ploughshare, Hardox 500 + padding layer ploughshare;
- B27 chisel, Hardox 500 chisel;
- Hardox 500 chisel + padding layer, Unirol chisel;
- Unirol + padding layer ploughshare, Unirol + padding layer chisel.

CONCLUSIONS

1. A padding layer, which was used to reinforce working elements made of Hardox 500 steel, contributed to reducing the wear intensity in comparison to other materials. For Unirol steel, a similar effect was not obtained, which could result in pores in the zone of fusing into the backing material, as well as the presence of single interseam discontinuities and gas bubbles.
2. Ploughshares and chisels made of steels containing martensite in their structure originating from various transformation forms demonstrated a similar level of wear.
3. In order to demonstrate the usefulness of grouping the materials by the applied method of multidimensional analysis in modelling the abrasive wear of working elements treating the abrasive mass, tests should be carried out for the same construction materials in various environmental conditions.

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