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# EFFECT OF THE ANGLE OF IMPACT OF AN ABRASIVE SOIL MASS ON STEEL WEAR INTENSITY

# WPŁYW KĄTA ODDZIAŁYWANIA GLEBOWEJ MASY ŚCIERNEJ NA INTENSYWNOŚĆ ZUŻYCIA STALI

**Key words:** abrasive wear, abrasive soil mass, rotating bowl, Hardox Extreme steel.

**Abstract** This article presents a study into the effect of the rake angle of the working surface of a specimen made of Hardox Extreme steel on abrasive wear intensity. The study was conducted using the "rotating bowl" method in two types of an abrasive soil mass at three specimen rake angles of 0˚, 12˚, and 17˚. No significant differences in the wear intensity were observed for a heavy abrasive soil mass, while for a light abrasive soil mass, an increase in the wear intensity was observed with an increase in the rake angle, with the greatest increase in the wear intensity occurring after a change in the rake angle from 0˚ to 12˚. Increasing the rake angle from 12˚ to 17˚ resulted in no significant change in the wear intensity. In the light abrasive soil mass, non-zero specimen rake angles increased the dynamic impact of loose abrasive wheels. The appearance of the surface of specimens subjected to abrasion under these conditions indicated a high proportion of erosive wear accompanying the scratching and ridging wear.

**Słowa kluczowe:** zużycie ścierne, glebowa masa ścierna, wirująca misa, stal Hardox Extreme.

**Streszczenie** W artykule przedstawiono badanie wpływu kąta natarcia powierzchni roboczej próbki wykonanej ze stali Hardox Extreme na intensywność zużycia ściernego. Badania prowadzono metodą wirującej misy w dwóch rodzajach glebowej masy ściernej przy trzech kątach natarcia próbki 0˚, 12˚ i 17˚. Dla glebowej ciężkiej masy ściernej nie zaobserwowano istotnych różnic intensywności zużycia, Natomiast dla lekkiej glebowej masy ściernej wraz ze wzrostem kąta natarcia zaobserwowano wzrost intensywności zużycia, przy czym największy wzrost intensywności zużycia wystąpił przy zmianie kąta natarcia od 0˚ do 12˚ Zwiększanie kąta natarcia od 12˚ do 17˚ nie spowodowało istotnej zmiany intensywności zużycia. W lekkiej glebowej masie ściernej niezerowe kąty natarcia próbki powodowały zwiększone dynamiczne oddziaływanie luźnych ziaren ściernych. Wygląd powierzchni próbek zużywanych w tych warunkach wskazywał na duży udział zużycia erozyjnego towarzyszącego zużyciu przez rysowanie i bruzdowanie.

## INTRODUCTION

The issue of the wear of parts operated within an abrasive soil mass is very complex due to the multiplicity of factors affecting the wear process **[L. 1, 2, 3]**. One of the basic parameters of an abrasive soil mass is compactness, i.e. a feature indicating the strength of binding of particular soil particles. For compact abrasive soil masses, the abrasive particles may have an influence as fixed grains resulting in losses in the material due to processes typical of abrasive wear (scratching, microcutting, and ridging). In soil masses with low compactness, the wear is caused by the impact of loose abrasive particles on the surface of the material being subjected to abrasion, which results in wear through decohesion (more frequently) and fatigue **[L. 4]**. Similar phenomena occur in the case of the wear of operating parts of equipment used for the transport of bulk materials. The most frequent types of wear in the transport of bulk materials include erosion caused by directional and random impact of solid particles at various impact angles and abrasion caused by sliding and rolling particles **[L. 5]**. In the process of

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erosive wear, not only is the wear intensity affected by the properties of the material but also by the angle of impact of abrasive particles **[L. 6, 7]**.

The study **[L. 6]** found that an acute angle of impact of abrasive particles results in the greatest losses of the material subjected to abrasion. For martensitic steel, the greatest loss in the volume was noted for a glancing angle of abrasive particles equal to 45˚, and the smallest for an angle of 90˚.

The dynamic response of a soil mass subjected to processing on operating parts of machines is the main factor determining the efficiency of working process and wearability of tools. The interaction between tools for soil processing and the soil is particularly interesting in designing and operating these tools **[L. 8]**. The angle of the impact of a soil mass on the surface of an operating part is closely related to the forces exerted by abrasive grains on the tool. The forces exerted at the metal-soil interface are determined using the following formula:

$$\tau = C_a + \sigma_n \tan \delta \qquad (1)$$

where $C_a$ is the adhesive force at the soil-metal interface, $\sigma_n$ is a normal stress, and δ is the external friction angle at the soil-tool interface.

Numerous studies have been devoted to the effects of the rake angle of a soil-processing tool on the working process. For example, one study **[L. 8]** researched the effect of the rake angle of an agricultural tool on the course of the working process in terms of its efficiency and energy inputs. Other studies, e.g., **[L. 9, 10]**, concerned the effect of the rake angle of tools processing the soil on the displacement of the soil and the breakdown of its structure. On the other hand, a review of the literature on the subject revealed no publications addressing the effect of the rake angle of a tool processing an abrasive soil mass on its wear intensity. A study into the effect of a load on the intensity of wear of Hardox Extreme steel **[L. 11]** demonstrated that the value of wear increased with an increase in the load, with higher values noted for the light soil mass than for the heavy soil mass.

The aim of the study is to determine the effect of the angle of the impact of an abrasive soil mass on the intensity of the wear of abrasion-resistant steel.

## TEST MATERIALS

The testing was conducted on specimens made of Hardox Extreme steel, which is resistant to abrasive wear and used for applications with maximally high requirements regarding abrasion resistance.

To avoid changes in the structure of the material, the specimens were cut out using water jet cutting technology. The specimens were cut out from a 10 mm thick sheet metal plate and no finishing, e.g., grinding, was applied. The surface condition of the thus obtained specimens was like the one from the manufacturer of the material.

The chemical composition of Hardox Extreme steel according to the manufacturer's declaration and own tests is presented in **Table 1**.

**Table 1. Chemical composition of Hardox Extreme steel**
Tabela 1. Skład chemiczny stali Hardox Extreme

| | C | Si | Mn | P | S | Cr | Ni | Mo | B | V | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Selected chemical element [% by weight] | | | | | | | | | | |
| Manufacturer's Data | Max. 0.47 | Max. 0.50 | Max. 1.40 | Max. 0.015 | Max. 0.01 | Max. 1.20 | Max. 2.50 | Max. 0.80 | Max. 0.005 | - | - |
| Own tests | 0.47 | 0.17 | 0.52 | 0.009 | 0.008 | 0.84 | 2.19 | 0.15 | 0.002 | 0.009 | 0.62 |

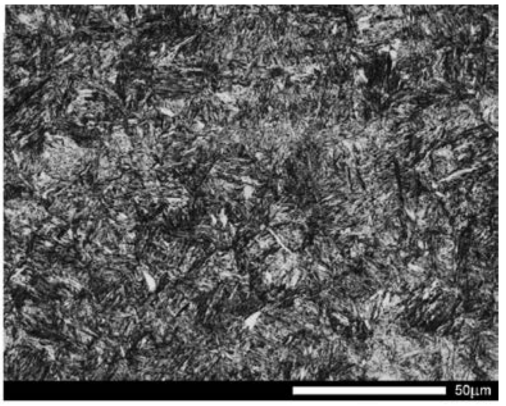


**Fig. 1. Micro-structure of Hardox Extreme steel**
Rys. 1. Mikrostruktura stali Hardox Extreme

Hardness of the specimen materials was 625±10 HBW according to PN-EN ISO 6506.

The structure of Hardox Extreme steel as delivered was characterised by a micro-structure of fine-grained strip martensite (**Fig. 1**). In addition, the orientation of the structure resulted from the hot rolling metal sheet production technology.

## RESEARCH METHODOLOGY

Rectangular specimens with dimensions of 30 x 25 x 10 mm were subjected to testing. The bowl of the machine was filled with a natural abrasive soil mass equivalent to a dry soil with grain-size distribution equivalent to the following, in accordance with PN-EN ISO 14668-2(2004):

– Light soil: clay: 1.27%; silt: 26.39%; sand: 72.34%,
– Heavy soil: clay: 3.75%; silt: 43.55%; sand: 52.70%.

Grain-size distribution of the soil masses was determined using a Mastersizer 2000 laser particle analyser. The testing for the intensity of wear was conducted under laboratory conditions using the "rotating bowl" method (**Fig. 2**) **[L. 2]**. The test stand was equipped with elements mixing and packing the abrasive mass, and the rake angle could be controlled using the specimen holder.

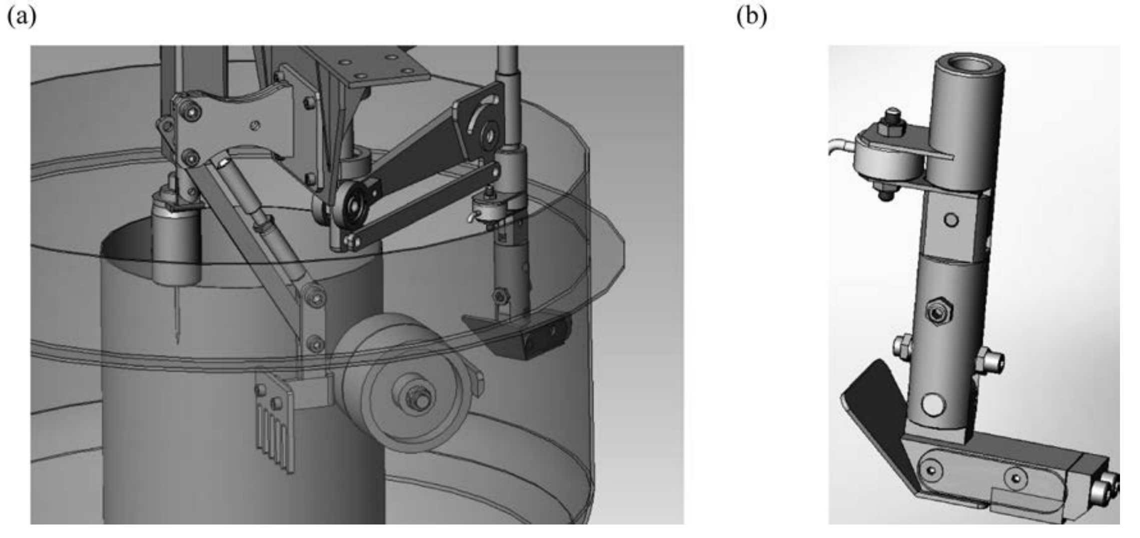


**Fig. 2. Test stand. Test section (a), specimen holder (b)**
Rys. 2. Stanowisko badawcze. Sekcja badawcza (a), uchwyt próbki (b)

In the testing, three various specimen rake angles of 0˚, 12˚, and 17˚ were applied. The rake angle was set using a pre-prepared template (**Fig. 3**). Given the design parameters, there was no possibility for setting a rake angle of more than 17˚.

**Fig. 3. A method of setting the specimen rake angle**
Rys. 3. Sposób ustawiania kata natarcia próbki

During the testing, the following friction parameters were adopted: velocity of 1.67 m/s, friction distance of 20,000 m, and vertical load on the specimen of 49 N. The moisture content of the soil mass was maintained within the range corresponding to a moist soil (15–20%). Test runs were repeated five times for each type of a soil mass and for each angle. The total friction distance for particular test runs was 20,000 m.

The mass wear was measured every 2,000 m using laboratory scales.

The mass wear was calculated using the following formula:

$$Z_w = m_w - m_i \tag{2}$$

where

$m_w$ – initial weight of the specimen prior to the testing for wear [g];
$m_i$ – weight of the specimen after having covered a specified friction distance [g].

## STUDY RESULTS

The course of wear of Hardox Extreme steel in the light and heavy soil mass at the specified specimen rake angle is presented in **Figs. 4** and **5**.

The data presented in **Fig. 4** show that, for the light abrasive soil mass, there is a clear relationship between the specimen rake angle and the wear intensity. For a rake angle equal to zero, the weight loss, after having covered a distance of 20 km was 0.5 g for the angle of 12˚, amounted to 3 g. An increase in the rake angle to 17˚ resulted in an increase in mass wear to 3.35 g.

For the heavy abrasive soil mass (**Fig. 5**), a change in the rake angle from 0˚ to 12˚ increased the mass wear from 1.92 g to 2.78 g after having covered the friction distance of 20 km. Further increasing in the rake angle to 17˚ slightly increased the wear to 2.97 g.

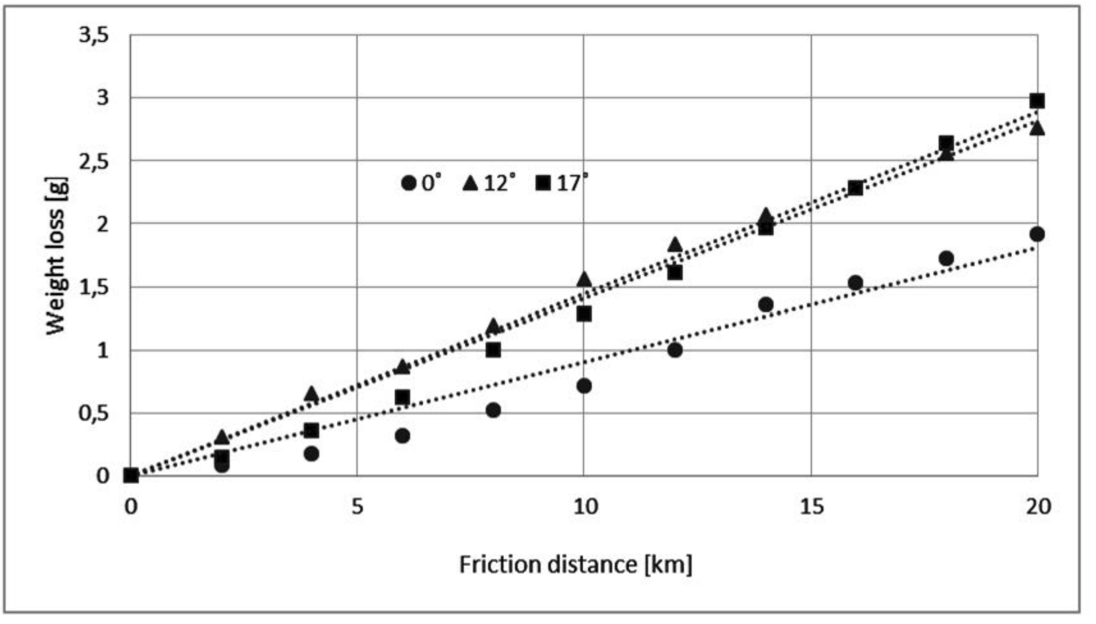


**Fig. 4. The course of mass wear of Hardox Extreme steel in the light abrasive soil mass for the specified specimen rake angles**

Rys. 4. Przebieg zużycia masowego stali Hardox Extreme w lekkiej glebowej masie ściernej dla ustalonych kątów natarcia próbki

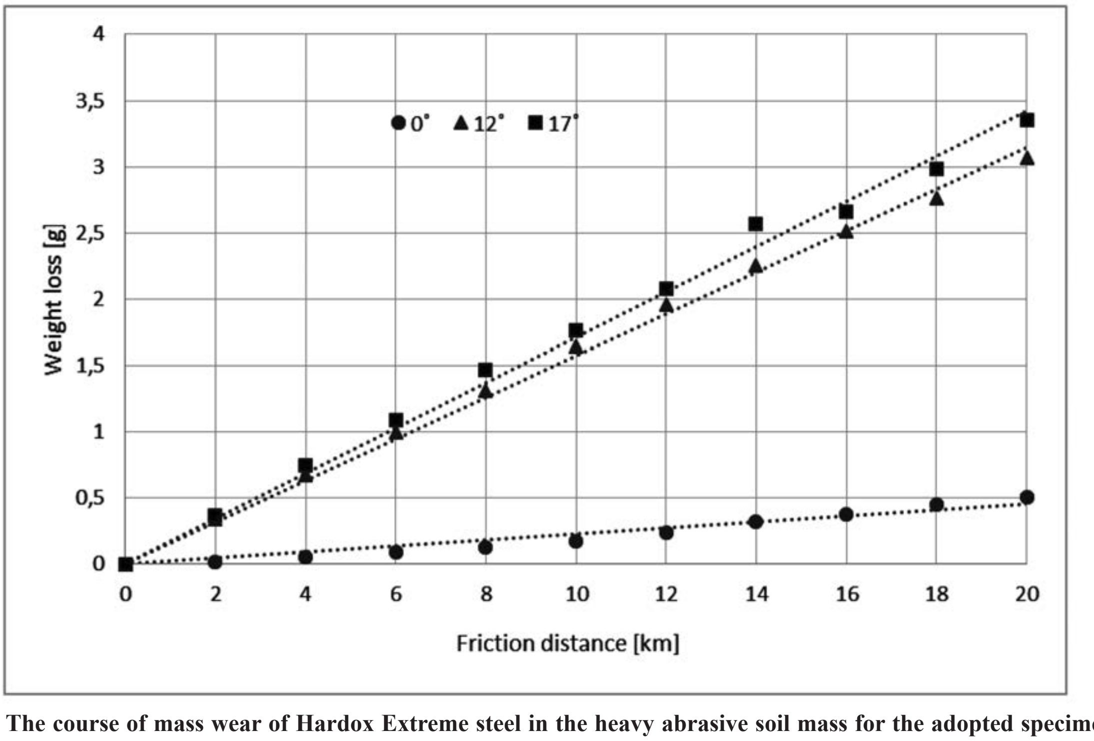


**Fig. 5. The course of mass wear of Hardox Extreme steel in the heavy abrasive soil mass for the adopted specimen rake angles**

Rys. 5. Przebieg zużycia masowego stali Hardox Extreme w ciężkiej glebowej masie ściernej dla ustalonych kątów natarcia próbki

In order to determine whether the existing differences in the value of mass wear of specimens subjected to abrasion at various angles and in various soils were statistically significant, one-way analysis of variance (ANOVA) and Duncan's tests were applied to select homogeneous groups. Statistical analysis results in the form of selected homogeneous groups are presented in **Table 2**.

**Table 2. Statistical analysis results – selected homogeneous groups for light and heavy soil mass**
Tabela 2. Wyniki analizy statystycznej – wyłonione grupy jednorodne dla masy glebowej lekkiej i ciężkiej

| Homogeneous groups – light soil mass | | | | |
|---|---|---|---|---|
| | Duncan test; Homogeneous groups, alpha = 0.05000<br>Error: Intergroup MS = 0.76111, df = 30,000 | | | |
| Subclass No | Angle | Average wear | 1 | 2 |
| 1 | Angle of 0˚ | 0.212391 | | **** |
| 2 | Angle of 12˚ | 1.590933 | **** | |
| 3 | Angle of 17˚ | 1.733132 | **** | |
| | | | | |
| Homogeneous groups – heavy soil mass | | | | |
| | Duncan test; Homogeneous groups, alpha = .05000<br>Error: Intergroup MS = .80146, df = 30,000 | | | |
| Subclass No | Angle | Average wear | 1 | 2 |
| 1 | Angle of 0˚ | 0.850539 | **** | |
| 2 | Angle of 12˚ | 1.356605 | **** | |
| 3 | Angle of 17˚ | 1.464680 | **** | |

The statistical analysis shows no significant differences in the values of mass wear of Hardox Extreme steel in the light soil mass following a change in the rake angle from 12˚ to 17˚, while the difference in the values of the mass wear was significant following a change in the rake angle from 0˚ to 12˚. On the other hand, in the heavy abrasive soil mass, the statistical analysis showed no significant differences in the value of wear for specimens subjected to abrasion at various rake angles.

**Figure 6** shows a comparison of the intensity of wear of Hardox Extreme steel for the adopted rake angles in the soil masses under study.

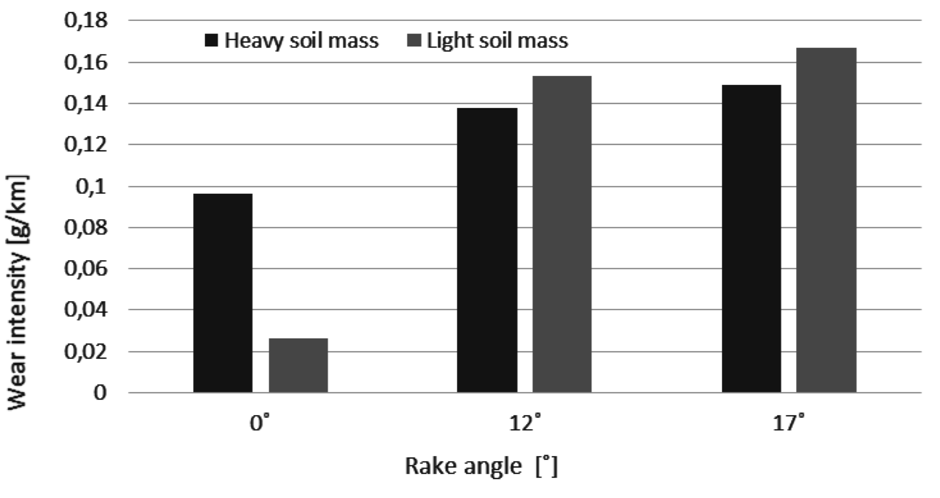


**Fig. 6. A comparison of the intensity of wear of Hardox Extreme steel depending on the rake angle in the abrasive soil masses under study**
Rys. 6. Porównanie intensywności zużycia stali Hardox Extreme w zależności od kąta natarcia w badanych glebowych masach ściernych

For the rake angle of 0˚, the intensity of wear in the heavy abrasive soil mass is 3.6 times higher than in the light soil mass. For the rake angles equal to 12˚ and 17˚, a higher intensity of wear was observed for the light soil mass. The intensity of wear in the light soil was higher by 10% for the angle of 12˚, and by 12% for the angle of 17˚, compared to the intensity of wear in the heavy soil at the same rake angles. In the heavy soil mass, the high content of binding fractions (clays) strengthens the abrasive grains of sand, which results in wear through microcutting and ridging. On the other hand, in the light abrasive soil mass, the wear process proceeds as a result of the dynamic impact of loose abrasive grains, which resembles erosive wear. For the rake angle of 0˚, the impact on the specimen surface is mainly exerted by tangential components of the forces generated by the movement of abrasive particles. For the compacted grains (heavy soils), these forces cause intense abrasion (**Fig. 7a**), while for loose grains, they cause rolling onto the surface of the specimen, which results in smaller losses in the material (**Fig. 7b**). With rake angles higher than zero, the dynamics of the interaction of loose abrasive grains results in higher values of normal components of the forces affecting the surface. On the surface of a specimen subjected to abrasion in the light soil mass (an angle of 12˚), signs of these interactions can be noted in the form of deformations and scratches caused by impacts of abrasive grains (**Fig. 8b)**. The surface of a specimen subjected to abrasion in the heavy soil mass at the same rake angle reveals no such signs (**Fig 8a**).

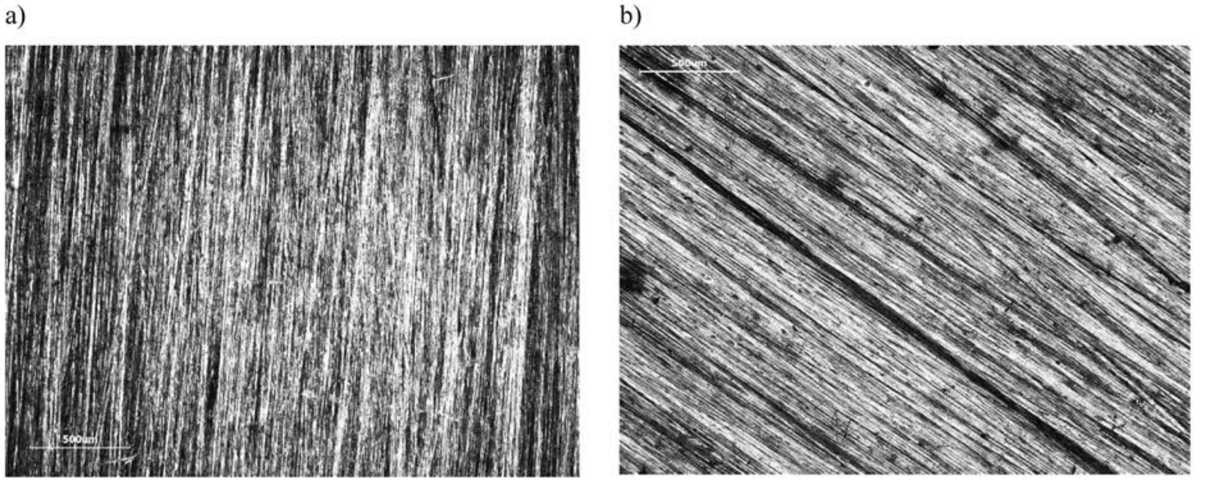


**Fig. 7. The view of the surface of Hardox Extreme steel subjected to abrasion in the heavy (a) and light (b) abrasive soil mass with a rake angle of 0˚**

Rys. 7. Widok powierzchni stali Hardox Extreme zużywanej w ciężkiej (a) i lekkiej (b) glebowej masie ściernej z kątem natarcia 0˚

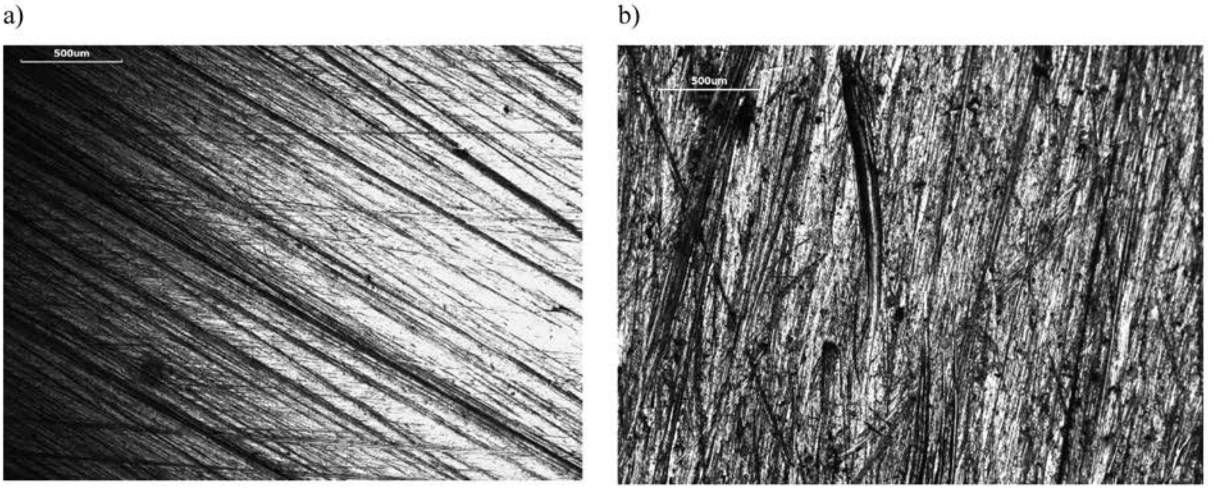


**Fig. 8. The view of the surface of Hardox Extreme steel subjected to abrasion in the heavy (a) and light (b) abrasive soil mass with a rake angle of 12˚**

Rys. 8. Widok powierzchni stali Hardox Extreme zużywanej w ciężkiej (a) i lekkiej (b) glebowej masie ściernej z kątem natarcia 12˚

Clay and silty components in the heavy soil mass combined with the moisture content exhibit high adhesion and cause the adhesive bond of the abrasive mass with the inclined surface of the specimen. The inclination of the specimen surface decreases the values of the tangential forces which do not "clean" the specimen surface. In such a situation, on the front part of the specimen surface, a sort of a protective layer is generated from the adhering soil, which results in only a part of the specimen surface being exposed to the intense dynamic impact of abrasive grains, which can be seen on the surface of the specimen (**Fig. 9**).

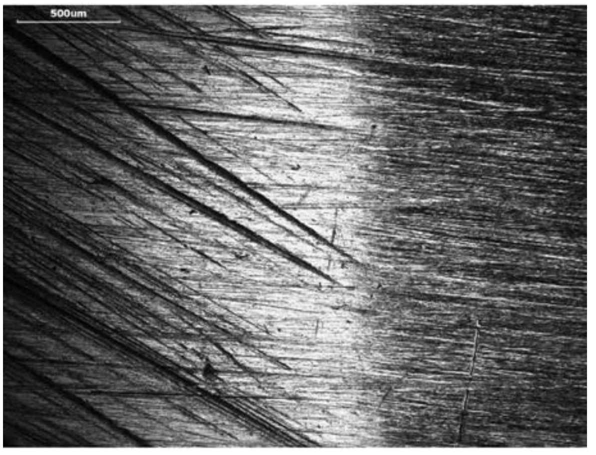


**Fig. 9. A view of the surface of a specimen subjected to abrasion in the heavy soil mass; a visible boundary between surfaces with different intensities of abrasive grain impact**

Rys. 9. Widok powierzchni próbki zużywanej w ciężkiej masie glebowej widoczna granica pomiędzy powierzchniami o różnej intensywności oddziaływania ziaren ściernych

## SUMMARY

With a zero angle of impact of the abrasive soil mass on specimens made of Hardox Extreme steel, it was noted that the intensity of their wear within the heavy abrasive mass is 3.6 times higher than that in the light soil mass. For the angles of 12 and 17 degrees, a higher wear intensity was observed in the light soil.

The statistical analysis revealed no significant changes in the mass wear for specimens subjected to abrasion in the heavy abrasive soil mass at a rake angle of 0˚, 12˚, and 17˚. Therefore, it can be concluded that, for the heavy abrasive soil mass, no effect was observed of the rake angle on the abrasive wear of Hardox Extreme steel.

On the other hand, for the wear of Hardox Extreme steel in the light abrasive mass, the rake angle of the specimen affects the wear value. Increasing it from 0˚ to 12˚ resulted in a significant change to the mass wear value. A further increase in the rake angle to 17˚ resulted in no significant change in the wear value.

A different effect of the angle of impact of abrasive soil masses with different properties on the wear of Hardox Extreme steel is associated with the adherence of the soil mass. The heavy abrasive soil mass adheres to the specimen's surface and limits the area of the surface exposed to the dynamic impact of abrasive particles. Due to the low content of silt fractions and silts in the light abrasive mass, the phenomenon is limited. On the other hand, greater dynamics of the movement of abrasive particles, which are not bound with a sort of binder, i.e. the clays, occur in the abrasive soil mass.

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