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EFFECT OF EXTERNAL LOAD ON THE PROCESS OF STEEL CONSUMPTION IN A SOIL MASS

WPŁYW OBCIĄŻENIA NA ZUŻYCIE W MASIE ŚCIERNEJ STALI HARDOX EXTREME W ZRÓŻNICOWANYCH RODZAJACH GLEB

Key words: steels resistant to abrasive wear, external load, structural and mechanical properties, Hardox Extreme.

Abstract This paper presents the results of a study on the effect of external load on the course and intensity of Hardox Extreme hardness steel wear in sandy soil. The research was conducted under laboratory conditions using a rotating bowl machine. The abrasive was composed of two types of soil: light and medium. External pressure applied to the sample surface had the following values: 13.08, 39.24, and 65.04 [kPa]. On the basis of the results from the analysis of variance, a significant effect of external load on the values of wear on a differentiated level for particular soil masses was found. The analysis of friction surfaces complements the study. Furrows and micro-cuts prevail in the wearing process, and their intensity depends on the cohesion force between the soil grains.

Słowa kluczowe: zużycia w masie glebowej, obciążenie zewnętrzne, właściwości konstrukcyjne stali, Hardox Extreme.

Streszczenie W pracy przedstawiono wyniki badań wpływu obciążenia zewnętrznego na przebieg i intensywność zużywania stali trudnościeralnej Hardox Extreme w glebowej masie ściernej. Badania przeprowadzono w warunkach laboratoryjnych, wykorzystując maszynę typu „wirująca misa". Masę ścierną stanowiły dwa rodzaje gleby: lekka i średnia. Zastosowano nacisk zewnętrzny na powierzchnię próbki o wartościach: 13,08; 39,24; 65,04 **[**kPa**]**. Na podstawie wyników z analizy wariancji stwierdzono istotny wpływ obciążenia zewnętrznego na wartości zużycia w stopniu zróżnicowanym dla poszczególnych mas glebowych. Badania uzupełnia analiza wyników uzyskanych po zużyciu powierzchni tarcia. W procesie zużywania dominuje bruzdowanie oraz mikroskrawanie, których intensywność oddziaływania uzależniona jest od siły kohezji pomiędzy ziarnami glebowymi.

INTRODUCTION

The effect of load on wear characteristics has been quite extensively described with reference to structural materials such as steels, cast irons, or polymers. These models have been developed with the assumption that the material is treated as a continuous medium **[L. 1]**. Depending on the type of the wearing process, numerous analytical models have been formulated, and the usefulness of many practical solutions is commonly known. For abrasive wear, which generally includes wear in soil masses, models that are most frequently applied include those transformed to the form following the Holm–Archard model. The usefulness of these models has been demonstrated, among others, in conditions where micro-cutting and wear with fixed abrasive and corrosion-mechanical wear prevail **[L. 2]**.

The issue of the effect of load on the wear of working elements is quite different in a soil mass. It is treated as a mechanical and chemical mixture of solid, gas, and liquid phases. The interactions between individual phases are more complex than in the case of homogenous materials. In this case, the state of stress is determined not only by the current external load, but also by the load in the historical perspective. A temporary state of stress in the soil mass occurs as a result of changes in stress components occurring in the past. The knowledge of the current stress status and the history of its occurrence make it possible to classify the soils into the following categories **[L. 3]**:

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- Consolidated, in which the current value of the vertical stress component is equal to its maximum value from the past; and,
- Pre-consolidated, in which the current value of the vertical stress component is lower than its maximum value from the past.

According to the superposition principle, the total stress within the soil is the sum of the primary stress (from the soil mass) and the stress from the external load. The application of load results in a reduction of the soil volume as a result of its compaction. It depends on the type and the value of the load and on soil properties. The change in value can be permanent or impermanent. Permanent strains emerge as a result of movement or crumbling of soil particles. Impermanent (elastic) strains of soil consist in the reduction of the soil volume as a result of elastic properties of solid particles and bound water, as well as a consequence of reducing the volume of air closed in pores. Reduction of load causes the reverse phenomenon – increasing the soil volume, i.e. expansion, resulting from the disappearance of elastic strains. If the stress is re-applied, the soil will consolidate again **[L. 4]**. The basic indicators specifying soil susceptibility to compaction include the threshold stress of the soil, which is the measure of natural soil resistance to strains. It reflects the history of the effect of loads on bonds created between water particles and solid phase particles. After exceeding the threshold stress values, natural bonds are destroyed and the process of chaotic movement of particles begins **[L. 5, 6]**. The effect of pressure under field conditions on the wear of soil treatment elements has been presented in Kostecki **[L. 7, 8]**. Those studies show that an increased load results in an increase in wear from two to four times, depending on the type of the examined structural material. Those studies were carried out in field conditions, where the soil load on the working element surface is a resultant of the primary load and the external load, characterized by high randomness. Therefore, the results presented are only of utilitarian value for given environmental conditions. On the other hand, laboratory tests performed in natural soil conditions can ensure the stability of the load process and guarantee that only the normal load is applied **[L. 9]**.

The aim of the paper is to analyse the effect of external load on the process of steel wear in varied soil conditions.

RESEARCH MATERIAL

Hardox Extreme steel is a material described as high-strength abrasion-resistant martensitic-grade steel. This steel is manufactured by a Swedish steelworks, SSAB, using thermo-mechanical rolling with AccuRollTech technology, according to the EN 10 029 standard. As a result of this process, sheets up to 2.000 mm wide and up to 14.630 mm long are produced. The range of available sheet thickness ranges from 8 to 19 mm. Hardox Extreme steels are supplied by the manufacturer in thermally-treated conditions, i.e. after hardening and/or hardening and low tempering. It is not recommended to carry out additional thermal treatment procedures. According to the manufacturer's data, this results in a high level of hardness of this steel, reaching 700 HBW. **Table 1** presents the basic chemical properties and hardness values of Hardox Extreme steel in the supplied condition, while **Figure 1** demonstrates a sample microstructure of this steel. On the basis of the research conducted, it can be claimed that the content of all analysed chemical elements in the examined steel is much lower than the value provided by the manufacturer. The exception is the coal content, which was consistent with information materials for the investigated case, amounting to 0.47% by weight. Based on the long-term experience of the authors of this paper with regard to the low-alloyed abrasion resistant martensitic steels, it can be claimed that significant divergences in chemical compositions result from a varied range of available Hardox Extreme sheet thickness values and from the assumed level of hardness over the entire cross-section of the sheet. Steels in this material group are characterized by a nickel addition of up to 2.50% to reduce the austenitising temperature and reduce the temperature of transition into the brittle state. Additionally, the share of carbide-forming elements, such as Cr, Mo, Ti, and B, promotes a delay of diffusion changes in these steels, and therefore, increases their hardenability.

Tabela 1. Selected properties of Hardox Extreme based on the manufacturer's data [DP] and own tests [BW]
Tabela 1. Wybrane własności stali Hardox Extreme na podstawie danych producenta [DP] oraz badań własnych [BW]

	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	B	HBW
	Selected chemical element [% by weight]											
DP	Max 0.47	Max 1.40	Max 0.50	Max 0.015	Max 0.010	Max 1.20	Max 2.50	Max 0.80	–	–	Max 0.005	650–700
BW	0.47	0.52	0.17	0.009	0.008	0.84	2.19	0.15	0.009	0.62	0.002	625±11

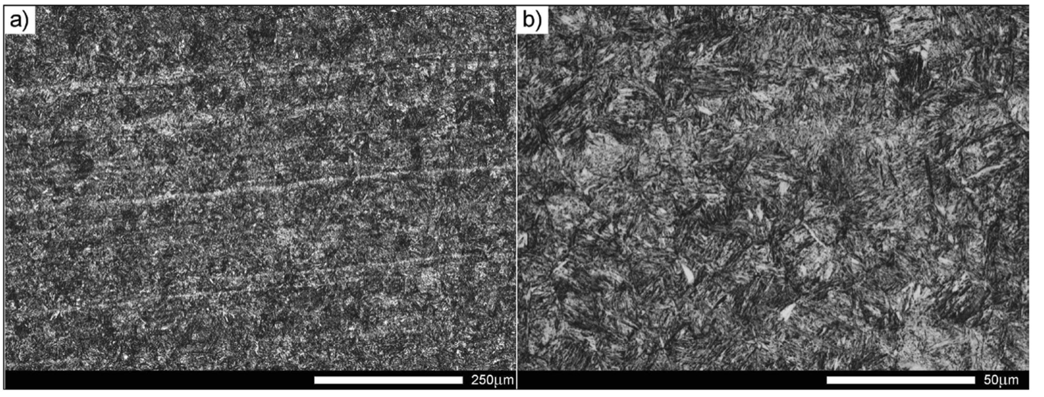

Fig. 1. Image of the microstructure of Hardox Extreme steel in the state of delivery: a) and b) the same material at a different magnification scale. Light microscopy, Mi1Fe etched

Rys. 1. Obraz mikrostruktury stali Hardox Extreme w stanie dostarczenia: a) i b) ten sam materiał w różnej skali powiększenia. Mikroskopia świetlna, trawiono Mi1Fe

Additionally, micro-additions of aluminium and titanium (not specified in the chemical compositions provided by the manufacturer) bind nitrogen and prevent austenite grain growth during the heat treatment. A characteristic feature often emphasized for Hardox Extreme steel is reduced sulphur (0.009%) and phosphorus (0.008%) contents.

In terms of structure, Hardox Extreme steel in the supplied state is characterized by a tempered fine lath martensitic microstructure with areas of acicular martensite **(Fig. 1)**. Additionally, features of structure banding, resulting directly from the hot rolling process can be clearly observed **(Fig. 1a)**. Inside martensitic laths, very scarce separations of carbide phases can be seen **(Fig. 1b)**.

RESEARCH METHOD

The research was conducted on 30 cuboid-shaped samples cut from the Hardox Extreme steel sheet, 30 x 25 x 10 mm. Five samples were tested for each set load. The tests were carried out in two types of abrasive masses. Since the primary load was removed from the masses before the tests, they demonstrated the features of the pre-consolidated mass. The grain size distribution, determined with a Mastersizer 2000 laser particle size analyser, was as follows (PTG 2008 classification):

Medium soil: loam: 3.75% dust: 43.55% sand: 52.70% – sandy soil;

Light soil: loam: 1.27% dust: 26.39% sand: 72.35% – loamy sand.

The tests were conducted on a rotating bowl machine designed for wear tests. The structure of the machine is based on the self-supporting frame to which working units are mounted **(Fig. 2)**. Research samples are mounted on two independent sections fixed on a detached wishbone suspension. The stem of the rocker is equipped with a special stem enabling the use of weights to add extra load to the sample. During the tests, three values of unit pressure were applied, i.e. 13.08, 39.24, and 65.04 kPa. The abrasive mass, in order to eliminate preliminary stresses, was shaken and evened out by two loosening mechanisms mounted on rocker bases.

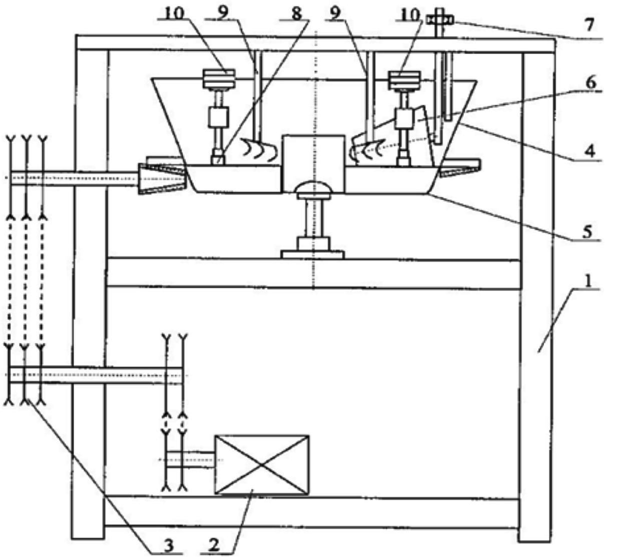

Fig. 2. Landfill test bench: 1 – frame, 2 – engine, 3 – belt transmission, 4 – bowl, 5 – soil, 6 – kneaders, 7 – roller clamp, 8 – sample holder, 9 – loosening fork 10 – sample weights

Rys. 2. Stanowisko do badania zużycia w glebie: 1 – rama, 2 – silnik, 3 – przekładnia pasowa, 4 – misa, 5 – gleba, 6 – rolki ugniatające, 7 – docisk rolki, 8 – uchwyt z próbką, 9 – widełki spulchniające, 10 – obciążniki próbki.

During the tests, a slightly acid reaction of soil, pH 6.4–6.8, was ensured. The pH value was measured by the electrometric method with the EpH-117/118 pH-meter manufactured by Alsmeer-Holland. Moisture content of the soil was determined using the drying method through the measurement of the solid phase dried at 105°C. The following formula was used for analytical determination of moisture content:

$$W = \frac{m_1 - m_2}{m_2 - m_n} \times 100\% \quad (1)$$

where
W – moisture content [%],
m_1 – soil sample weight before drying [g],
m_2 – sample weight after drying [g],
m_n – sample container weight [g].

The tests were conducted in an abrasive mass whose parameters corresponded to moist soil 12%–14%. The set friction path of the sample was 10.000 m at 1.66 m/s. Each time after the sample covered 2.000 m, its weight loss was measured. The weight loss of the sample was measured on a laboratory balance with 0.0001 g accuracy. Samples before the tests were subject to smooth sanding, ensuring R_a = 0.22–0.28 μm along the friction surface and 0.32–0.42 μm in the perpendicular plane. Each weight measurement was preceded by washing the sample in an ultrasound bath. Weight loss was determined from the following relation:

$$Z_{pw} = m_w - m_i \text{ [g]} \quad (2)$$

where
m_w – initial weight of the sample before the friction test [g],
m_i – sample weight after the friction path s [g].

To determine the significance of wear differences in relation to the load applied, a variance analysis was carried out. A null hypothesis of the lack of differences between the values of wear was assumed, as well as an alternative hypothesis about differences in wear. Duncan's test was used to distinguish homogenous groups.

Metalwork tests were carried out using a HUVITZ HRM-300 microscope.

ANALYSIS OF THE OBTAINED RESULTS

The results obtained in the tests are presented in **Figures 3** and **4**. To determine the effect of the load on the significance of the examined steel wear in the soil abrasive soil, a variance analysis was applied**.** For each load value, a null hypothesis was assumed about the lack of differences between the values of wear after the friction path of 10.000 m and an alternative hypothesis H1 concerning the occurrence of significant differences in wear. Based on the results of statistical analysis **(Tables 2, 3)**, it can be claimed that the applied load significantly affects the wear of Hardox Extreme steel, both in light and medium soil.

It was observed that, regardless of the type of soil mass, the intensity of wear increases along with an increase in the unit pressure and reaches higher values in light soil. For a pressure of 13.09 kPa, weight loss was obtained at the level of 0.2931 g in light soil and 0.2498 g in medium soil. At 39.24 kPa pressure, a weight loss was obtained with the value of 0.5069 g and 0.3667 g, and the load of the material with pressure of 65.04 kPa resulted in 0.7380 g and 0.5826 g weigh loss for light and medium soil, respectively. Wear intensity in light abrasive mass was from 1.17 to 1.38 times higher than in medium soil for individual pressure values. The highest wear of Hardox Extreme steel was recorded for the load of 65.04 kPa both in light and medium soil, and the lowest was for the load of 13.08. It was 2.5 times lower in light soil and twice lower in medium soil.

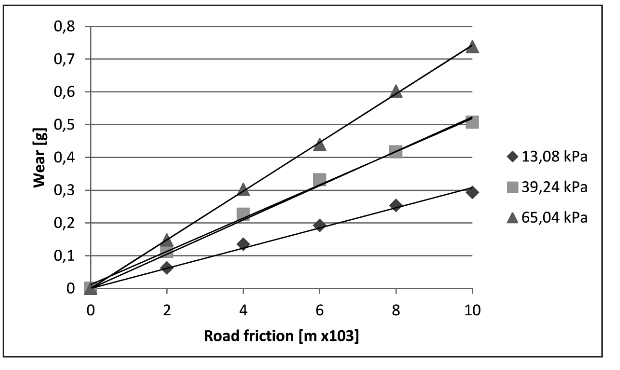

Fig. 3. Dependence of Hardox Extreme steel consumption in light soil mass from an external load
Rys. 3. Zależność zużycia stali Hardox Extreme w lekkiej masie glebowej od obciążenia zewnętrznego

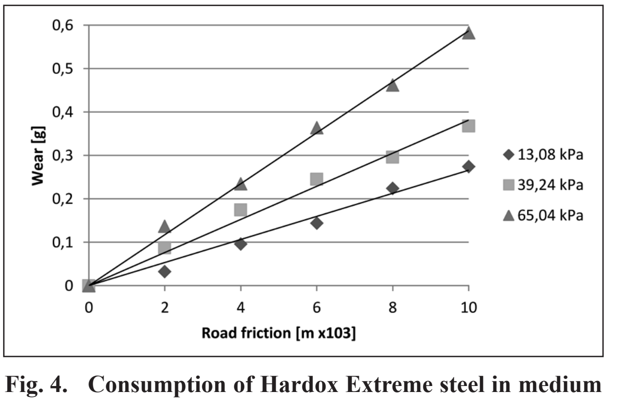

Fig. 4. Consumption of Hardox Extreme steel in medium soil mass from an external load
Rys. 4. Zależność zużycia stali Hardox Extreme w średniej masie glebowej od obciążenia zewnętrznego

Based on the results of the statistical analysis, it can be claimed that the applied load has a significant effect on Hardox Extreme steel wear in both light and medium soil.

Table 2 presents the results of the variance analysis concerning the effect of load on wear of the examined materials in light soil. Based on this, post-hoc tests were carried out in which three homogenous groups were distinguished. A similar procedure was applied in an analysis of medium soil. The results of variance analysis are presented in **Tab. 3**, in which significant differences were recorded in wear between the load of 39.24 kPa and 65.04 kPa. Based on those results, two homogenous groups were distinguished. The first group was made of the 13.08 kPa and 39.24 kPa load values and the other of the 65.04 kPa load applied.

Table 2. Variation analysis results in the light soil
Tabela 2. Wyniki analizy wariancji w glebie lekkiej

Subclass No.	Duncan test; intergroup MS = .03815, df = 87.000			
	Load	{1} 0.15582	{2} 0.26547	{3} 0.37165
1	13.08		0.032500	0.000119
2	39.24	0.032500		0.038219
3	65.04	0.000119	0.038219	

Table 3. Variation analysis results in medium soil
Tabela 3. Wyniki analizy wariancji w glebie średniej

Subclass No.	Duncan's test; variable Approximate probability for *post hoc* tests Error: intergroup MS = .02492, df = 81.000			
	Load	{1} .11849	{2} .19511	{3} .29660
1	13.08		0.074711	0.000148
2	39.24	0.074711		0.019153
3	65.04	0.000148	0.019153	

In order to examine the effect of a given load value on the significance of wear of the examined steel, an analysis was carried out to compare the load applied for two soil types (**Tab. 4**). For the loads of 13.09 kPa and 39.24 kPa, no statistically significant differences were found, while they were observed for the 65.04 kPa load.

Table 4. Variation analysis results for a 65.04 kPa load.
Tabela 4. Wyniki analizy wariancji dla obciążenia 65,04 kPa

Subclass No.	Duncan's test; Approximate probability for *post hoc* tests Error: intergroup MS = .00087, df = 8.0000		
	Soil	{1} 0.73798	{2} 0.58258
1	Light soil		0.0002
2	Medium soil	0.0002	

A reflection of obtained wear values is the image of worn surfaces presented in **Figs. 5** and **6.** The surface appearance changes depending on the load and grain size distribution of the soil mass. On the surfaces abraded at the lowest load, the processes of scratching and local grooving can be observed. The share of wear through plastic strains (grooving) and local micro-cutting increases with the increasing loads. This process quite intensively occurs in light soil masses under the heaviest load. It is under these conditions that the largest wear values were found. With friction applied in medium soil, an increase in friction surface is observed. Increased friction resulted in larger soil compaction and, therefore, a reduction in the freedom of sand grains planted in loam

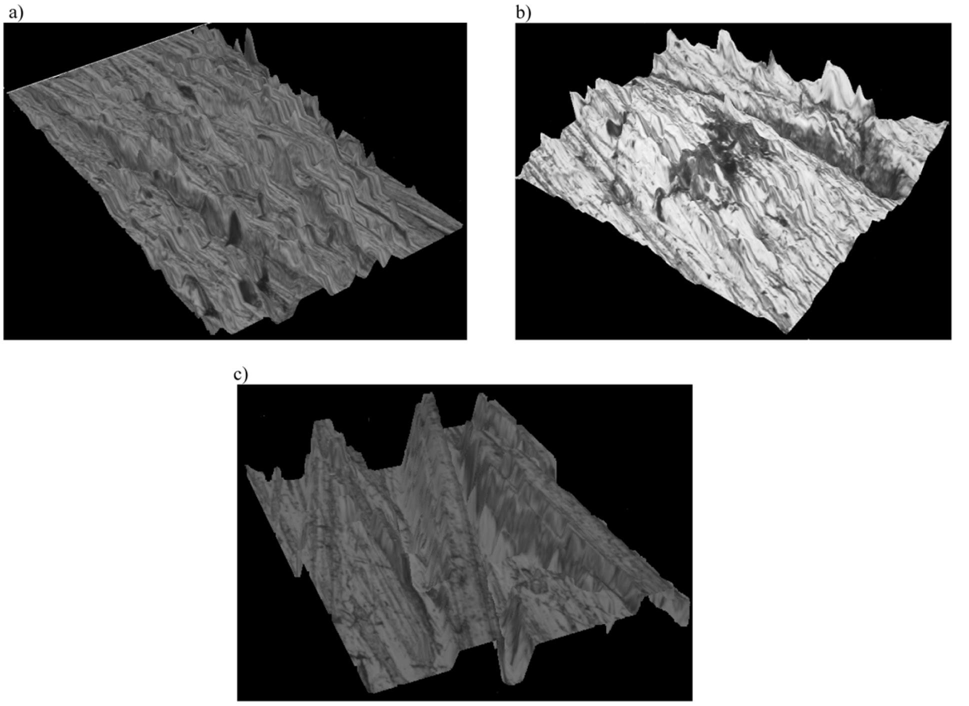

Fig. 5. Image of surface wear in light soil depending on the load: a) 13.08 kPa, b) 39.24 kPa, c) 65.04 kPa
Rys. 5. Obraz zużycia powierzchni w glebie lekkiej w zależności od obciążenia: a) 13,08 kPa, b) 39,24 kPa, c) 65,04 kPa

and silt fractions. Numerous scratches and tracing of grooving traces are visible with a much lower intensity of impact on the material than in the case of micro-cutting. The wear values found in these conditions were lower in relation to light soil, where grains were characterized by significantly lower cohesion forces. On the basis of previous research **[L. 10]**, it was found that differences in the shape of abrasive grains in individual types of soil did not significantly differ. Therefore, the course of the process of wear in the soil mass, beside the grain size distribution, was primarily determined by the external load on working elements.

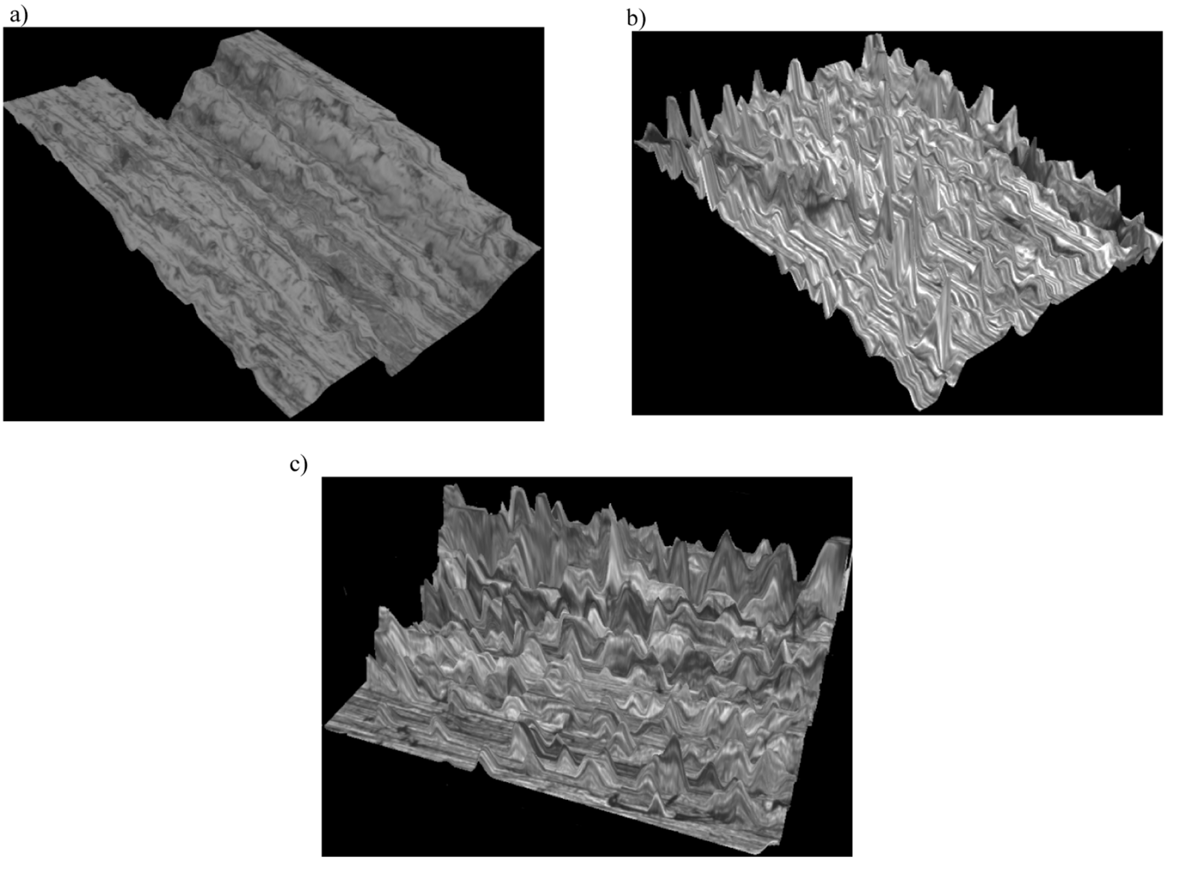

Fig. 6. Image of surface wear in light soil, depending on load. a) 13.08 kPa, b) 39.24 kPa, c) 65.04 kPa
Rys. 6. Obraz zużycia powierzchni w glebie lekkiej w zależności od obciążenia. a) 13,08 kPa, b) 39,24 kPa, c) 65,04 kPa

CONCLUSIONS

The results obtained from the research presented indicate that the external load affecting the steel surface during the friction in an abrasive soil mass has a significant effect on the wear values obtained. Along with an increase in load, wear increases. An increase in load by 53 kPa resulted an over twofold increase in wear, regardless of the soil type. Higher wear values were found for light (elastic) soil than for medium soil containing a higher share of silt and loam fractions. Depending on the external pressure, the wear in light soil was 17% to 38% higher than the wear in medium soil. This results from the fact that the content of loam and silt in moisture does not have a significant effect on the process of wear. The effect of those fractions is caused by reduced freedom of movement of sand grains, which first of all determine the intensity of wear.

In order to obtain full wear characteristics in abrasive soil masses in relation to the applied load, research should be carried out for higher pressures and for other types of soil.

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