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RESEARCH

Effect of Abrasive Soil Mass Grain Size on the Steel Wear Process

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A B S T R A C T

This article analyses the effect of the size of abrasive soil mass grains on the steel wearing process. The study examined Hardox 500 steel used for working parts exposed to abrasive wear. Wear tests were performed under laboratory conditions using the "spinning bowl" method. The study was carried out using natural soil abrasive mass, in which three grain size fractions were distinguished: 0.05-2 mm – sand, 2-16 mm – gravel, 0.05-16 mm – sandy gravel. Steel wearing tests were completed for each fraction as well as for their mixes. The mixes were prepared using one additional fraction with a grain size below 0.05 mm described as dust and loam. The highest wear impact was recorded for the abrasive mass of a gravel (75 %) and dust-loam (25 %) mix. The wear was higher than that obtained for 100 % gravel. The addition of dust and loam had a different effect on the wear impact of sand. A 25 % addition of dust and loam to sand significantly reduced the abrasive wear of samples in comparison to the application of 100 % sand. The abrasive mass of dust and loam resulted in the lowest mass loss of the examined steel. Based on the results obtained from the wearing process in natural abrasive masses, three types of phenomena of steel wear in soil mass could be distinguished, i.e. by micro-cutting, fatigue wear and ploughing. The type of prevailing wear for different mixes of soil fractions depends on the volumetric content of a given fraction in the composition of soil mass. The wear intensity of the experimental steel is higher in mixes of soil fractions than for the particular soil fractions.

1. INTRODUCTION

The wear impact of soil abrasive mass is a complex process in view of the variety of factors affecting its course. Depending on the interaction of the soil mass, process parameters and the properties of the working part, wearing can occur in various configurations. The most-frequently occurring wear involves loose abrasive particles hitting the surface of the worn material. For compact abrasive masses, soil particles can be treated as fixed grains causing material losses as a result of processes typical for abrasive wear [1,2]. Many authors (e.g. Zum Gahr [3], Torrance [4]) indicate in their papers the necessity of accounting for, in modelling abrasive wear, the grain size and shape of abrasive grains as significant factors in the course of the wear process.

The aspect of characteristic features of the abrasive mass in modelling abrasive wear has been emphasized by many authors [5-9]. Misra et al. [5] indicate that the wear index increases with an increase in the size of abrasive grains up to 100 μm and loses significance above this size. De Pellegrin et al. [7] claimed that depending on the size of abrasive particles used for a study of materials, the wear manner changes. However Xie et al. [8] determined a wear indicator for polishing based on abrasive grain size, hardness of an abrasive and polished material as well as the pressure on a contact point. Many of these papers refer to the aspect of fixed grain modelling (two-body abrasion).

The characteristics of the soil grain shape remain one of the major problems discussed in abrasive wear modelling. It particularly applies to describing the relationship between the shape of the abrasive participles and the intensity of wear. Abrasive particles can be classified in two ways: on the basis of their shape on the macro scale, where particles are arranged on the basis of similarity of their shape to standard shapes (such as a ball, a cone, a hyperboloid or a wedge) [6,10] and on the micro scale, by describing, for instance, their sharpness, angularity or roundness [11,12].

Abrasive soil mass is a mix of abrasive grains of varied size, shape and material origin. The material origin of soil mass has an effect on its wear properties. Woldman et al. [13] presents the varied wear effect of sand particles of varied origin and analyses the effect of grain size and shape on the wearing process.

In the analyzed literature the parameters of abrasive particles, used in the laboratory differ from those of abrasive particles, found in soil.

The tests made it possible to explain the phenomenon of abrasive wear in the presence of hard grains, which determine the process of material destruction but do not fully explain the phenomenon occurring during soil mass wear. The tests presented in this paper will allow to assess the impact of individual grain size fractions on the steel wear process and prediction of lifetime of a soil cultivation tool. The grain fractions were separated from natural soil classified as a light soil.

2. MATERIAL AND METHODS

2.1 Characteristics of the abrasive soil mass

The research was conducted in natural soil abrasive mass, in which three grain size fractions were separated:

- soil mass of the grain size from 0.05-2 mm– sand;
- soil mass of the grain size from 2-16 mm– gravel;
- soil mass of the grain size from 0.05-16 mm– sandy gravel.

The grain composition of the soil abrasive mass was determined using the sieve method, according to the [14].

In analyzing the grain size of the examined abrasive masses, it can be observed that:

– in the 0.05-2 mm abrasive mass, the prevailing grains (about 85 % in total) were those of 0.25<d<2 mm diameter. Grains of a diameter above 2 mm accounted for about 7 % of the grains;
– in the 2-16 mm abrasive mass, the majority of grains (about 65%) were those of a diameter larger than 4 mm and smaller than 16 mm. About 8% of grains had a diameter above 16 mm;
– the 0.05-16 mm abrasive mass was a mix of abrasive masses of 0.05-2 mm and 2-16 mm in a 70/30 % ratio. This mix was characterized by the highest grain size diversity among the examined masses. Most grains (about 20 %) were grains of 0.5<d<1 mm diameter.

A petrographic description of abrasive masses was carried out on the basis of PN-EN 932-3:1999 and is presented in Table 1.

Slivers of crystalline rocks are usually partially rounded, less often featuring sharp edges, and some of them (about 6 %) demonstrate traces of weathering. Sedimentary carbonate rocks are mainly compact, grey, well-rounded paleozoic limestones. About 8 % of the grains in this group are grains of weaker limestones and marl-limestones originating from the Cretaceous period. Quartz grains have the following features: mainly transparent, a matte surface, less often yellow tinted, with a prevailing group of partially and well-rounded grains, usually shining surface, less often with a matte surface.

Table 1. Petrographic description of the abrasive masses under analysis.

Grain size fraction [mm]	Content [wt.%]		
	Slivers of carbonate rocks	Slivers of crystalline rocks	Grains of quartz
8-16	44.8	40.1	15.1
4-8	49.0	39.7	11.3
2-4	51.0	40.0	9.0
1-2	35.6	39.4	25.0
0.5-1	28.9	28.6	42.5
0.25-0.5	13.5	10.1	76.4
0.125-0.25	12.1	8.8	79.1

Table 2. Shape descriptors used for evaluation of abrasive soil mass.

Shape descriptor	Description of the parameter (descriptor)
Area	Area of the projection of the particle on the surface
Perimeter	The length of the outside boundary of the particle on the surface
Aspect Ratio (AR)	Calculated as the relation of the major axis to the minor axis of the ellipse fitted to the grain. This parameter describes elongation of the particles, assuming a value of 1 for ball-shaped particles. The higher is the value of the descriptor, the more elongated is the particle.
Round	Calculated from the following relation: $\boldsymbol{round = 4\frac{Area}{\pi \times [Major\ Axis]^2}}$
Solidity	Calculated from the following relation $\boldsymbol{solid. = \frac{Area}{Convex\ Area}}$ where *Convex area* – the area of the convex hull. *Convex hull* - replaces a polygon of freehand selection with its convex hull, which can be thought of as a rubber band wrapped tightly around the points that define the particle The more solid the particle, the closer the value of the descriptor to 1. For a 5-pointed star, it amounts to 0.50

The shape of soil mass grains was evaluated using the image analysis method. With this aim in view, photographs of scattered grains were taken, which were then subjected to morphological transformations, binarization and segmentation. The analysis of grains in the obtained images was carried out with ImageJ software and the evaluation of grain shape was performed using the shape descriptors listed in Table 2.

Frequency histograms for AR, round and solidity descriptors for individual fractions of the soil abrasive mass are presented in Figs. 1-6.

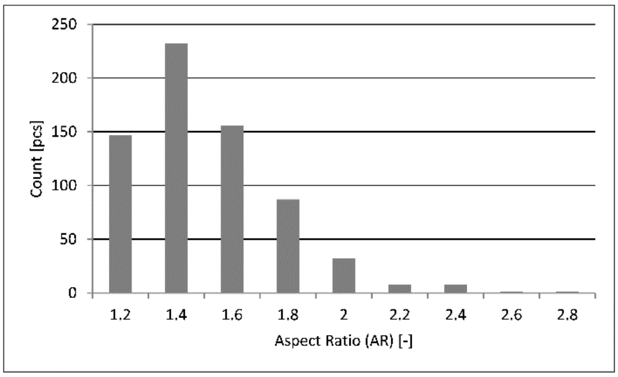

Fig. 1. Histogram of the value of the AR descriptor for abrasive mass of the grain size from 2-16 mm.

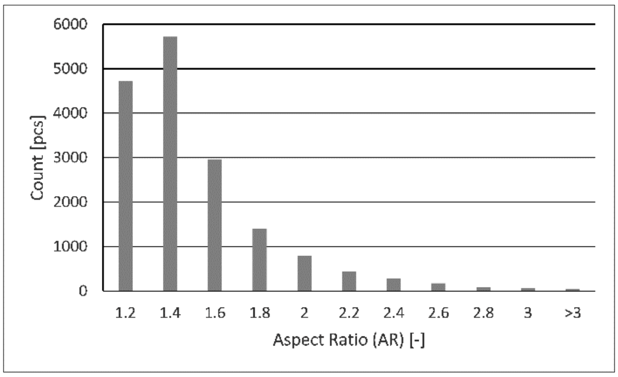

Fig. 2. Histogram of the value of the AR descriptor for abrasive mass of the grain size from 0-2 mm.

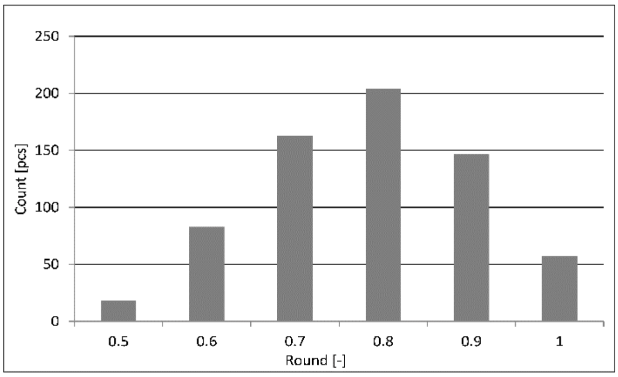

Fig. 3. Histogram of the Round descriptor for an abrasive mass of the grain size from 2-16 mm.

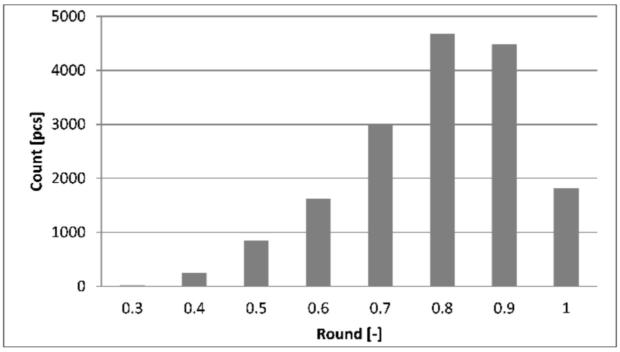

Fig. 4. Histogram of the Round descriptor for an abrasive mass of the grain size from 0-2 mm.

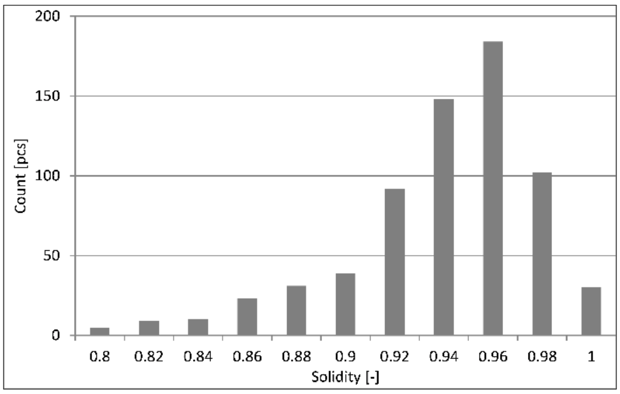

Fig. 5. Histogram of the Solidity parameter for an abrasive mass of the grain size from 2-16 mm.

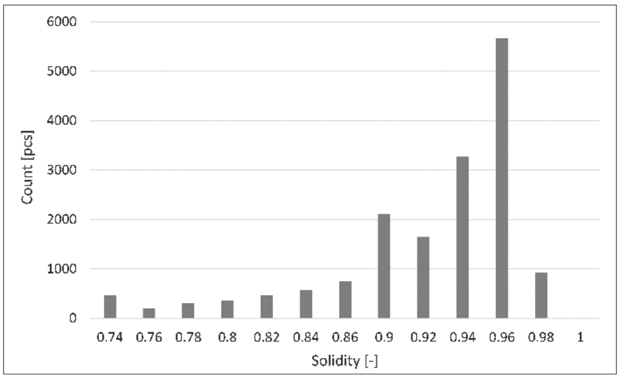

Fig. 6. Histogram of the Solidity parameter for an abrasive mass of the grain size from 0-2 mm.

The obtained values of grain shape indicate that the geometries of grains in the masses under analysis are characterized by similar values (Table 3). The average values for the elongation indicator AR for both masses is 1.4. These values demonstrate that the grains are not too elongated and that they also consist mostly of particles with a regular shape – the average value of the Round descriptor is 0.74 and 0.73 – and solid – the average value of the solidity descriptor is 0.91 and 0.93. Because the abrasive mass of the grain size from 0.05-16 mm is a mix of 0.05-2 mm and 2-16 mm abrasive masses, the shape of grains in this mix corresponds to the shape of grains of the component masses.

Because the values of shape parameters in the abrasive mass are characterized by similar values, the analysis of the results obtained from wear tests only took into consideration the value of abrasive grains defined as screenings obtained from the sieve analysis.

2.2 Research material

The tests were carried out on Hardox 500 steel used for working parts exposed to abrasive wear. Friction tests were performed under laboratory conditions using the "spinning bowl" method [14]. Steel samples were taken in the form of 30x25x10 mm cuboids using methods ensuring that their structure remained unchanged. The method of water jet cutting with water and an abrasive substance was used for cutting the samples. The finishing of samples to the required surface roughness was carried out using a surface grinder.

The measurement of hardness and the metallographic evaluation of the top layer structure were performed using:

- a HV-10D Vickers hardness tester according to PN-EN ISO 6507-1:2006 the load of the indenter applied: 98 N, loading time 10 s;
- light microscopy, using a Neophot 52 microscope coupled to a Visitron Systems digital camera;
- scanning electron microscopy and microanalysis of chemical composition, carried out using a JEOL JSM – 5800 LV scanning microscope coupled to an Oxford LINK ISIS – 300 X-ray microanalysis system.

Table 3. List of average values of shape descriptors of abrasive mass grains.

	Aspect Ratio AR [-]		Roundness [-]		Solidity [-]	
Abrasive mass	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
0.05- 2 mm	1.41	0.34	0.74	0.14	0.91	0.06
2-16 mm	1.41	0.25	0.73	0.12	0.93	0.04

The examined steel has the microstructure of tempered martensite created during a diffusionless transformation with high cooling rate of austenite. The result of the occurring transformation is martensite, being a supersaturated solution of carbon in α iron (Fig. 7).

The chemical composition determined by X-ray spectroscopy was as follows: %C–0.3529, %Si–0.70, %Mn–1.60, %Cr–1.0, %Ni–0.50, %Mo–0.60, %B–0.004.

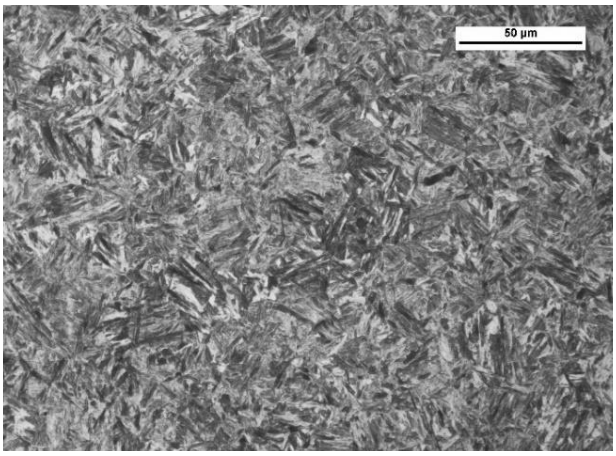

Fig. 7. Hardox 500 steel – microstructure of martensite. Etched with 3 % HNO_3 (Mi1Fe), light microscopy.

According to Stachowiak [15] and Wiliams [16], significant properties of particles affecting the abrasive wear are size, shape and hardness. Zum Gahr [17] demonstrated that when the relation of hardness of the abrasive grains to the hardness of worn surface exceeds 1.2, a further increase in the abrasive agent hardness does not affect the intensity of abrasive wear at constant parameters of the wearing process.

In the examined abrasive masses, the hardest material is silica (SiO_2) with a hardness of about 1100 HV. The relation of hardness between the abrasive material and the steel used (450 HV) is 2.44, which is a value higher than the threshold value of 1.2. Therefore, the hardness of the abrasive agent is not taken into account in the study, considering only the size of abrasive particles.

2.3 Wear testing methods

The abrasive wear resistance test of the analysed steel grades was performed using the "spinning bowl" method, using an MZWM–1 device (Fig. 8). During the tests, each sample travelled a total sliding distance of 10 000 m, at the average speed of 1.7 m/s under a normal load 49 N. The sample was weighed every 1 000 m using a laboratory weighing scale accurate to 0.0001 g.

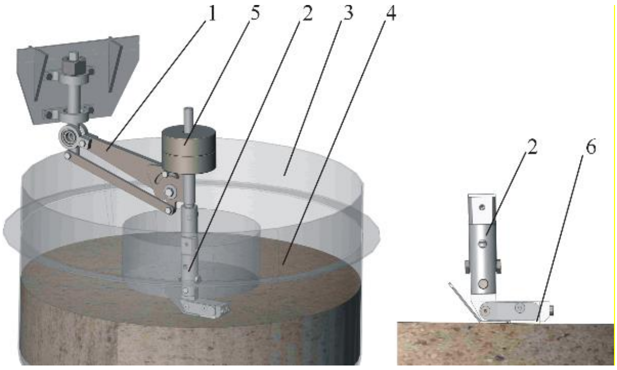

Fig. 8. Laboratory wearing station of the "spinning bowl" type; 1-swingarm, 2-specimen holder, 3-bowl, 4-soil mass, 5-weight, 6-specimen.

Mass loss was calculated from the formula:

$$Z_w = m_0 - m_x , \qquad (1)$$

where:
m_0 – initial weight of the sample;
m_x – sample weight after sliding distance x.

After the end of tests, the unit wear was calculated by the mass wear to the friction distance and the sample surface, according to the following formula:

$$Z_j = \frac{Z_w}{S}\ \left[\frac{g}{km}\right] , \qquad (2)$$

where:
Z_w – mass loss after 10 000 m [g],
S – total sliding distance [km].

During the tests, the moisture content of abrasive masses was maintained at the level of moist soil, e.g. 9-12 %. The soil pH was maintained in the range of 6.3-6.9 pH.

3. RESULTS AND DISCUSSION

3.1 Analysis of wear

The course of the mass loss Z_w of the samples worn in abrasive masses of various grain sizes is presented in Figs. 9-11.

For abrasive masses of the grain size from 0-2 and 0-16 mm, the wear after 10 000 m was about 0.4125 g. For the sample examined in the abrasive mass of the grain size from 2-16 mm, the mass loss after the same distance was 0.5475 g. The course of wear for abrasive masses containing only abrasive grains above 2 mm deviates from the course of wear in other abrasive masses. In the abrasive mass containing only large grains, a sudden growth of wear can be observed after a friction distance of 2 000 m (Fig. 10). During the further friction process, the course of wear is stabilized.

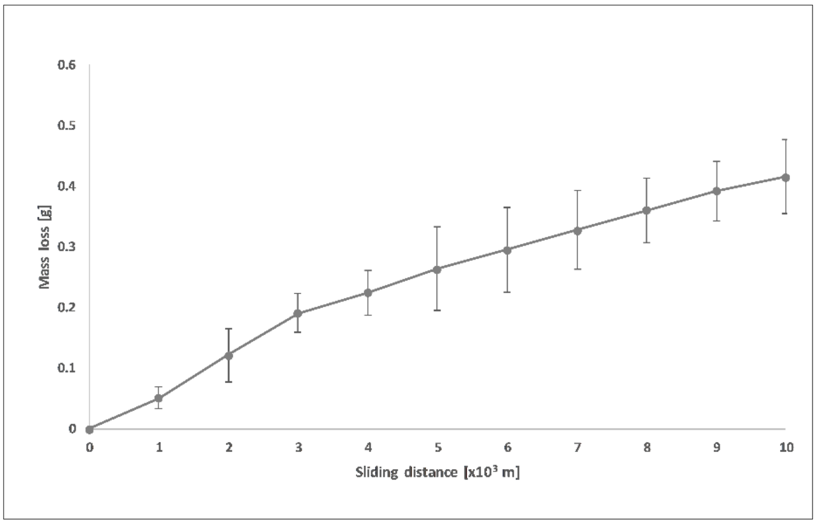

Fig. 9. Mass loss of Hardox 500 steel in 0.05-2 mm grain size abrasive mass (error bars – standard deviation).

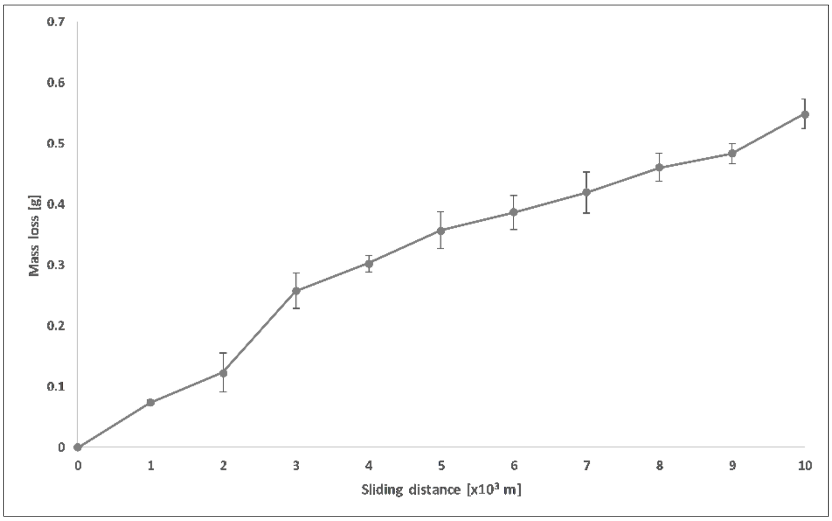

Fig. 10. Mass loss of Hardox 500 steel in 2-16 mm grain size abrasive mass (error bars – standard deviation).

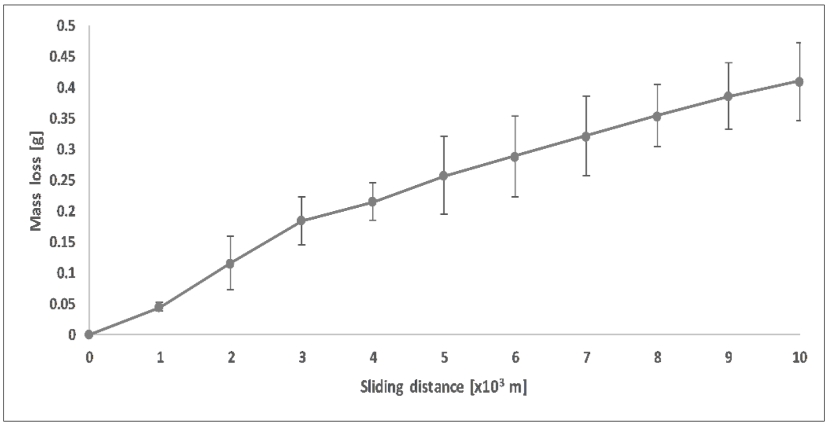

Fig. 11. Mass loss of Hardox 500 steel in 0.05-16 mm grain size abrasive mass (error bars – standard deviation).

A variance analysis of the mass loss was carried out to determine the statistical significance of the established relationships of surface layer wear. For each type of soil, a null hypothesis was assumed concerning a lack of significant differences between the wear values after the friction distance of 10 000 m and an alternative hypothesis about the occurrence of significant differences. If the null hypothesis was rejected in favour of an alternative hypothesis, Duncan's test was applied in order to distinguish uniform groups (Table 4).

It was found that no statistically significant differences occurred between the wear in an abrasive mass of the grain size from 0.05-2 and 0.05-16 mm, while the wear in these masses differed significantly from the wear in the mass of the grain size from 2-16 mm. Different forms of wear are visible on the surface, which is the projection of the wear volumes of examined steel (Figs. 12-17).

Table 4. Results of variance analysis.

Group No.	Duncan's test; variable - wear, Uniform groups, alpha = 0.05			
	Grain size [mm]	Average mass loss after 10 km sliding distance [g]	1	2
3	0.05-16	0.4098	****	
1	0.05-2	0.4157	****	
2	2-16	0.5488		****

**** - reflects a statistically significant difference p<0.05 between abrasive mases*

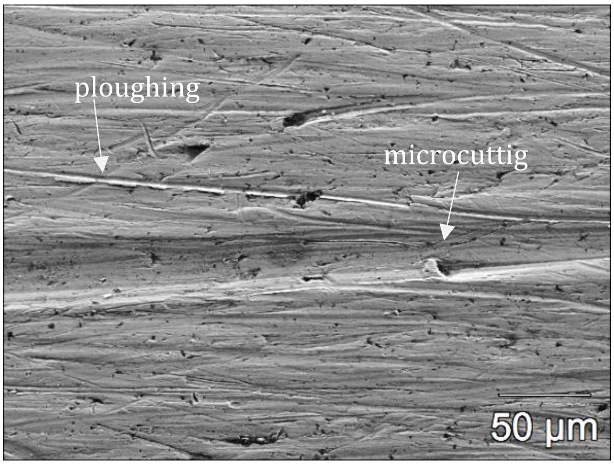

Fig. 12. Surface of the sample worn in the 0.05-2 mm (100 % sand) grain size abrasive mass,

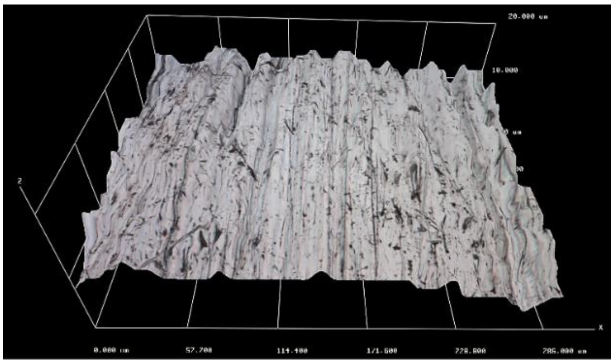

Fig. 13. 3D model of the surface of the sample worn in the 0.05-2 mm grain size abrasive mass.

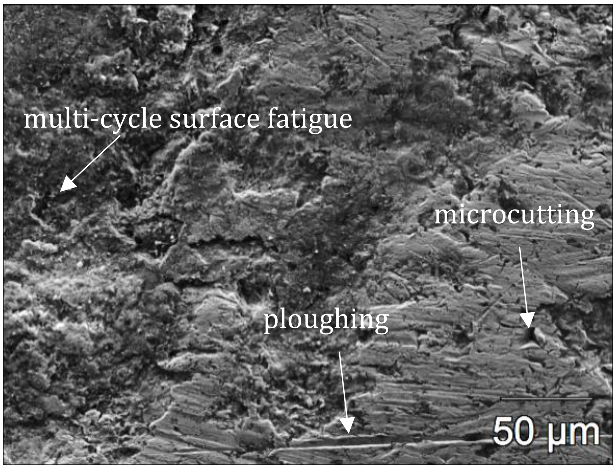

Fig. 14. Surface of the sample worn in the 2-16 mm (100 % gravel) grain size abrasive mass.

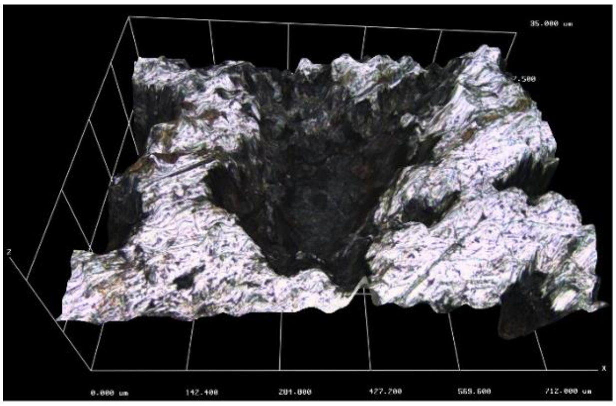

Fig. 15. 3D model of the surface of the sample worn in the 2-16 mm grain size abrasive mass.

The surface of the sample worn in the 0.05-2 mm grain size abrasive mass shows visible marks formed by microcutting and ploughing resulting from the sliding behaviour of abrasive particles (Figs. 12 and 13). Despite a slight elongation of abrasive particles, they had limited possibilities of rolling on the sample surface. A reduction in the degree of freedom of abrasive grains resulted from the forces of cohesion between numerous small abrasive grains. The loading of the sample also favoured the fixing of abrasive grains in the abrasive mass.

In the 2-16 mm grain size abrasive mass the absence of finer abrasive grains resulted in in the big grains being loosely distributed and passing over the surface of the sample and affecting it by blasting. Such a type of impact caused local surface fatigue and material particles to chip off (Figs. 14 and 15). A sudden increase in the wear value demonstrated in Fig. 10, indicates that chipping off occurred after about 2 km of the friction distance.

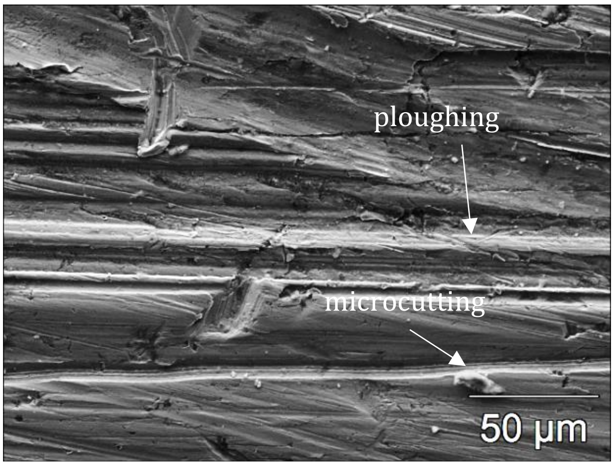

Fig. 16. Surface of a sample worn in the 0-16 mm grain size abrasive mass.

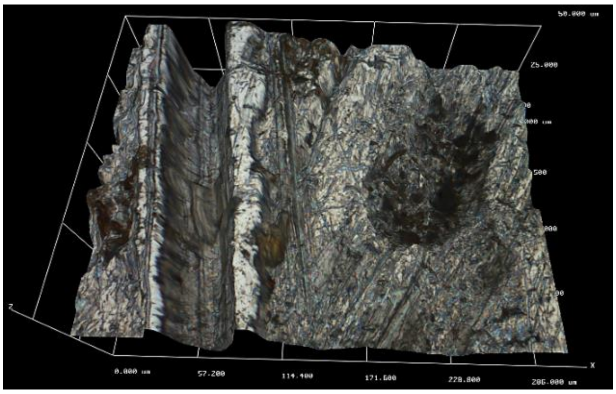

Fig. 17. 3D model of the surface of a sample worn in the 0-16 mm grain size abrasive mass.

In the 0-16 mm grain size abrasive mass containing both large and small grains, the phenomenon of material fatigue is not that clear (Figs. 16 and 17). This can be explained by the fact that lower abrasive particles, penetrating into spaces between large particles, wedge them in place and reduce the possibility of their rolling over the surface. In this case, wear through the fixed grains occurs, which is seen as scratches and furrows on the material surface. Slight traces of fatigue wear are also visible.

To precisely describe the wearing phenomena in varied soil masses, particles of the grain size below 0.05 mm were introduced (dust and loam). The results of Hardox 500 steel wear in the prepared abrasive masses are presented in Fig. 18.

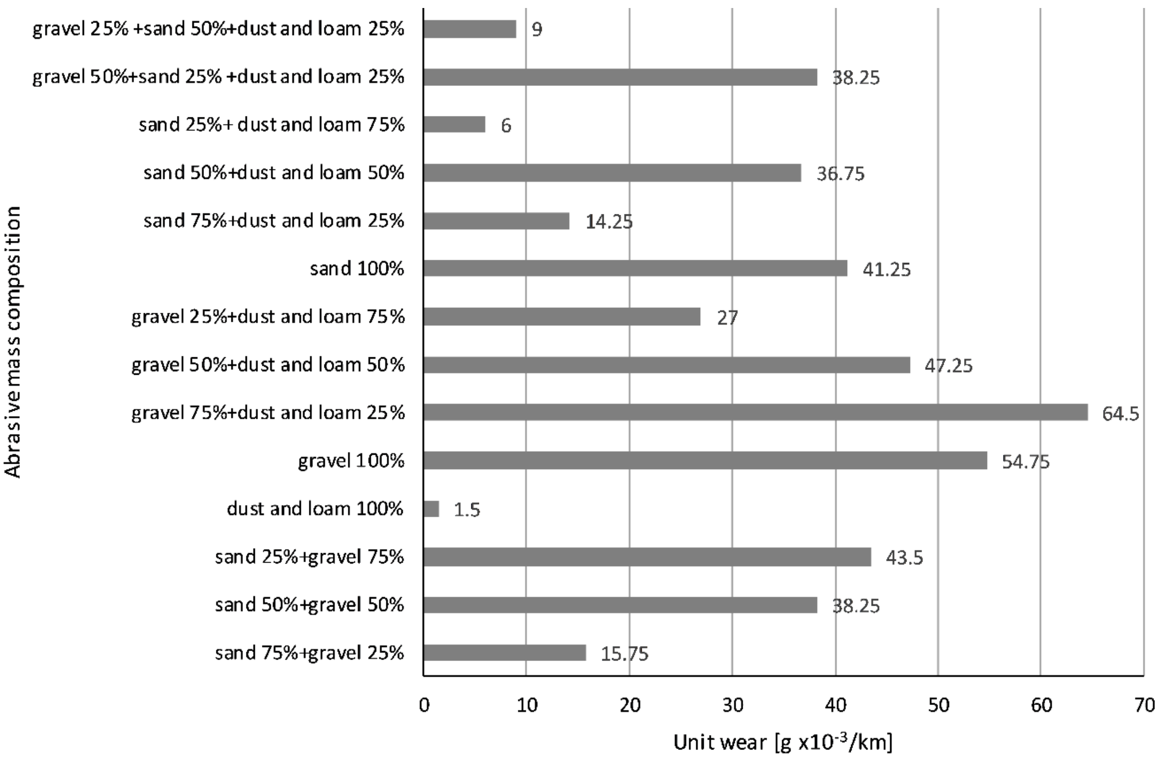

Fig. 18. Unit wear of Hardox 500 steel in various abrasive masses.

Table 5. Statistical analysis results – the identified homogeneous groups for various mixtures of abrasive mass.

Duncan's test; variable - wear, Uniform groups, alpha = 0.05														
Abrasive soil mass composition	Average unit wear value [g*10^{-3}/km]	1	2	3	4	5	6	7	8	9	10	11	12	13
dust and loam 100%	1.50	****												
sand 25%+ dust and loam 75%	6.00		****											
gravel 25% +sand 50%+dust and loam 25%	9.00			****										
sand 75%+dust and loam 25%	14.25				****									
sand 75%+gravel 25%	15.75					****								
gravel 25%+dust and loam 75%	27.00						****							
sand 50%+dust and loam 50%	36.75							****						
gravel 50%+sand 25% +dust and loam 25%	38.25								****					
sand 50%+gravel 50%	38.26								****					
sand 100%	41.25									****				
sand 25%+gravel 75%	43.50										****			
gravel 50%+dust and loam 50%	47.26											****		
gravel 100%	54.76												****	
gravel 75%+dust and loam 25%	64.50													****

**** - reflects a statistically significant difference $p<0.05$ between abrasive mases*

The highest wear impact was demonstrated by the abrasive mass specified as a mix of gravel (75 %) with dust and loam (25 %). Its wear impact was higher than for 100 % gravel. An increase in the share of dust and loam in this abrasive mass reduced its wearing impact. For abrasive mass containing 25 % gravel and 75 % dust and loam, its abrasive impact was 2.38 times lower than in mixes consisting of 75 % gravel and 25 % dust and loam.

The addition of dust and loam had a different effect on the wear impact of sand. An addition of dust and loam to the sand in the amount of 25 % and 75 % significantly reduced the abrasive wear of samples compared to 100 % sand, while an addition of dust and loam in the amount of 50 % also reduced wear, but to a much lower degree. The abrasive mass consisting of a dust and loam fraction resulted in the lowest mass loss of the examined steel.

3.2 Statistical analysis

To determine the impact of the content of individual grain size fractions on the wear value, analysis of variance was used. A null hypothesis was adopted about the lack of impact of the content of individual grain fractions on the intensity of wear of the tested materials after a 10 km sliding distance, and an alternative hypothesis about the occurrence of significant differences in wear depending on the soil fraction content. If the null hypothesis was rejected in favour of an alternative hypothesis, Duncan's test was applied in order to distinguish uniform groups (Table 5).

Based on statistical analysis, it can be concluded that there are significant differences in the value of steel wear in abrasive mixtures with different content of individual grain fractions. Abrasive mass specified as a mixture of gravel (75 %) with dust and clay (25 %) showed the largest impact on wear (Fig. 19). Its impact on wear was greater than for 100 % gravel. This can be explained by the aggregating effect of dust and silt on gravel particles. Gravel grains bonded with loam and dust have limited possibility of movement, which affects the way the surface is affected. A change in the ratio of dust and clay (50 %) to gravel (50 %) reduced the wear effect of this mixture. This is due to the reduction in the amount of large abrasive grains that are mainly in contact with the sample surface.

No statistically significant differences in the wear value were found for the mixture containing gravel 50 % + sand 25 % + dust and loam 25 % and sand 50 % + gravel 50 %. In these mixtures, the content of gravel grains is the same, and these are mainly responsible for contact with the sample surface. Abrasive grains of the sand fraction, as well as dust and loam are smaller than gravel grains and therefore fill the free spaces between them. This arrangement of small grains limits their contact with the sample surface, reducing their wear impact. The sandy fraction does not have the ability to bond the grains of the gravel fraction, therefore the wear effect of this mixture is smaller than the mixture containing 50 % gravel and 50 % dust and loam.

3.3 Samples surface analysis

Figures 19-25 present the appearance of the surface of samples worn in soil abrasive masses of various granulation.

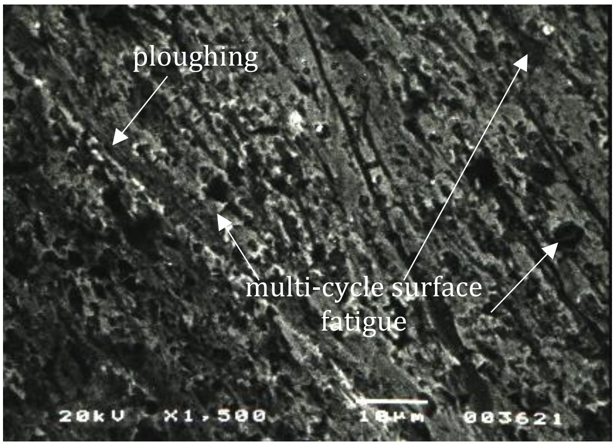

Fig. 19. Gravel 75 % + dust and loam 25 %.

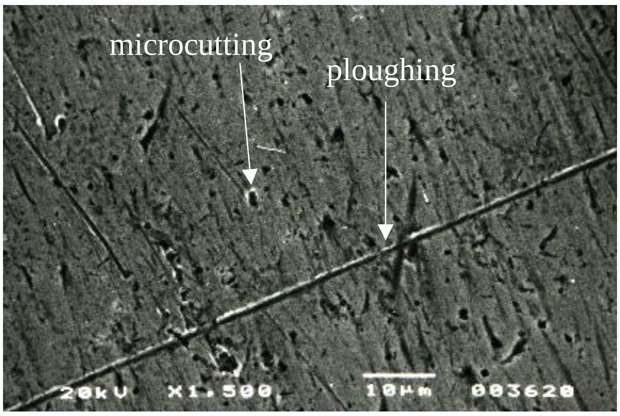

Fig. 20. Dust and loam 100 %.

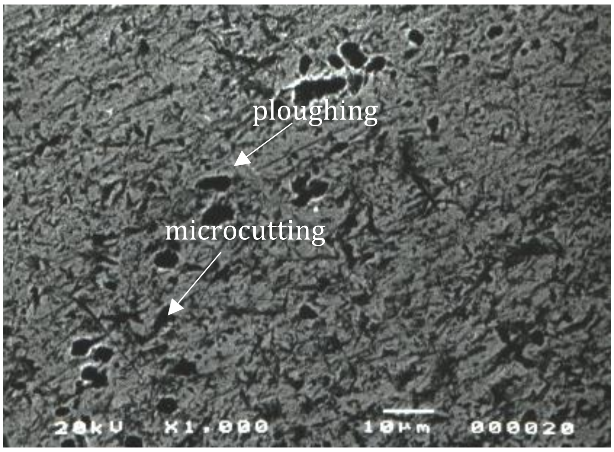

Fig. 21. Dust and loam 75 % + sand 25 %.

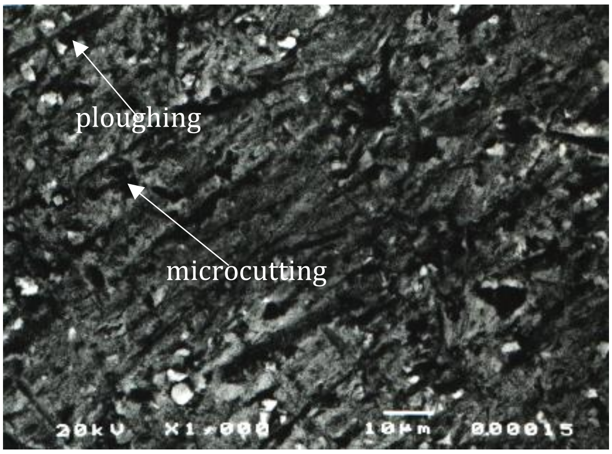

Fig. 22. Sand 50 % + dust and loam 50 %.

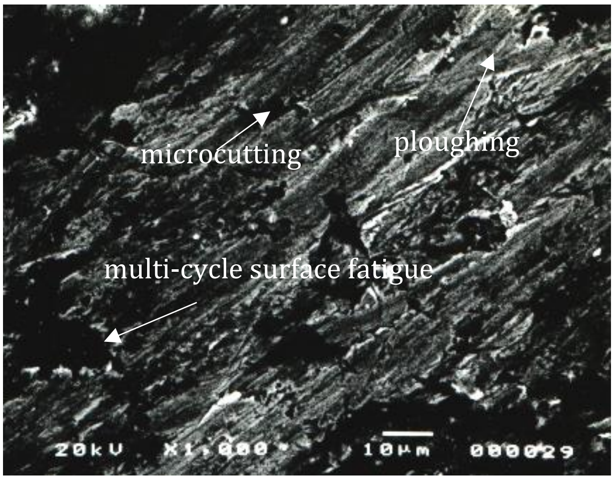

Fig. 23. Gravel 50 % + sand 25 %+dust and loam 25 %.

The content of loam and dust as well as sand fraction may mostly affect the dominant wear process. For example, by adding dust and loam in 25 % volume, more intensive wear processes occurred than in 100 % volume gravel. When used in a mixture of gravel with dust and loam (Fig. 19), there are visible signs of wear resulting from multi-cycle surface fatigue.

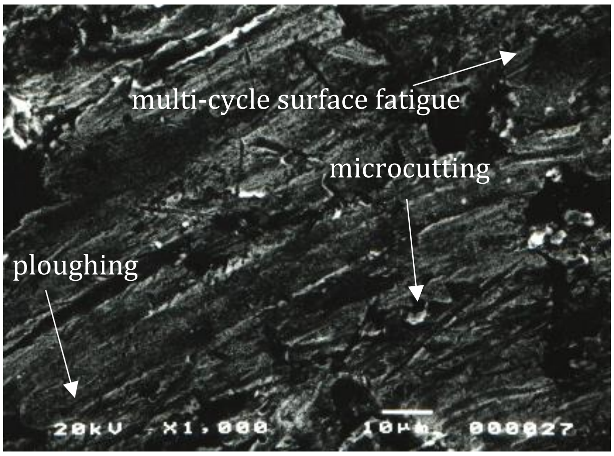

Fig. 24. Gravel 25 % + sand 50 % + dust and loam 25 %.

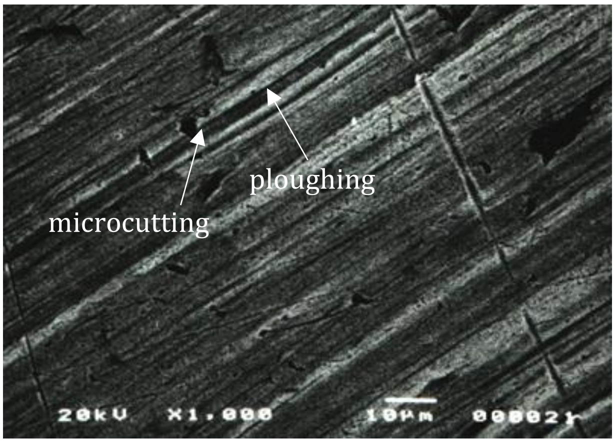

Fig. 25. Sand 75 % + dust and loam 25 %.

The signs are much smaller compared to signs obtained for wear tests in 100 % gravel (Fig. 14). The addition of dust and clay fractions to gravel reduces the fatigue wear of the sample surface, while it intensifies microcutting and ploughing processes (Fig. 19). The occurrence of these wear processes results in the largest weight loss of the sample. On the surface of the sample being worn in the 100 % dust and loam there are visible signs of wear from microcutting (Fig. 20).

In the case of the mixture of gravel and sand, as well as dust and loam, the proportion of wear by multi-cycle surface fatigue in relation to microcutting increases while the content of gravel increases (Figs. 23 and 24). On the sample surface worn in the abrasive mass without gravel the dominant wear mode is microcutting and ploughing (Fig. 25).

Analysing the surface of the examined samples worn in various abrasive masses, it can be seen that for the abrasive mass composed mainly of the gravel fraction, the prevailing processes are those of fatigue nature (Fig. 14). Addition of a dust and loam fraction results in additional occurrence of a surface ploughing and microcutting processes (Fig. 19). This type of wearing process results in the highest loss of weight of the examined samples. The abrasive mass containing 100 % sand fraction causes ploughing processes also, in addition to microcutting processes. An increase in the share of dust and loam in the abrasive mass (without gravel) up to 50 % intensifies ploughing and microcutting processes (Fig. 22) by fixing abrasive grains in abrasive mass. Further increase in the dust fraction content in the abrasive mass results in a reduction of the mass loss.

4. CONCLUSIONS

The wear intensity of the examined steel in mixes of soil fractions is generally higher than the intensity of wear in individual soil fractions. This is related to a synergetic joint impact of the entire soil mass, not of individual abrasive grains. The powdery particles (<0.05 mm) are usually grains of quartz and amorphous silica which increase the actual friction area, by limiting the number of degrees of freedom of the abrasive grains.

The abrasive masses used in the tests were dominated by abrasive grains without sharp edges. The shape of the grains was round, close to oval. The results obtained from the tests of the wearing processes in this type of natural abrasive masse made it possible to distinguish three types of phenomena of the wear of the steel in the soil mass, namely wear by micro-cutting, fatigue wear and ploughing.

In the mixtures of the soil fractions, the type of the dominant wear depends on the volume content of a given fraction in the soil mass. The multi-cycle fatigue wear increases with the increase of the gravel share in the total volume of abrasive. In the soils without a gravel fraction, the wear processes are micro-cutting and ploughing.

The sand contained in the used soil affected the wear process by ploughing. The presence of a fraction of dust and loam in the abrasive mass resulted in intensification of wearing processes. This is due to the bonding effect of the loam presence in the abrasive grains of the sand and gravel fraction. This caused the process of wear by fixed abrasive grains.

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