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EFFECT OF ABRASIVE PARTICLE SHAPE ON TWO-BODY ABRASIVE WEAR OF STEEL

WPŁYW KSZTAŁTU CZĄSTEK ŚCIERNYCH NA ZUŻYWANIE STALI W SKOJARZENIU DWÓCH CIAŁ

Key words: two-body abrasive wear, abrasive particle shape, Hardox Extreme steel.

Abstract: This paper presents the results of Hardox Extreme steel wear rate testing using an abrasive mass of varying grain shapes. The tests were conducted by the ASTM G65 method using crushed and natural sand with a grain-size distribution of 0.05–2 mm, obtained from a gravel pit. The abrasive materials used in the tests differed in grain shape, while the particle-size distribution was similar. The test results show that the wear rate in crushed sand is four times higher than that in natural sand, which is attributable to the shape of grains and the geometry of their edges.

Słowa kluczowe: zużycie ścierne w skojarzeniu dwóch ciał, kształt cząstek ściernych, stal Hardox Extreme.

Streszczenie: W pracy przedstawiono badania intensywności zużywania stali Hardox Extreme w masie ściernej o zróżnicowanym kształcie ziaren. Badania przeprowadzono metodą ASTM G65 z użyciem piasku łamanego i płukanego o uziarnieniu 0.05–2 mm pozyskanego z kopalni kruszywa. Zastosowane w badaniach materiały ścierne różniły się kształtem ziaren. Uziarnienie pod względem wielkości ziaren było podobne. Uzyskane wyniki badań wskazują, iż intensywność zużycia w piasku łamanym jest czterokrotnie wyższa niż w płukanym, co ma związek z kształtem ziaren i geometrią ich krawędzi.

INTRODUCTION

Abrasive wear is a problem which invariably affects many industrial applications such as mining, agricultural and mineral processing equipment. This commonly occurring wear mechanism is associated with severe material losses resulting in a considerable increase in industrial operating costs. The process of material removal takes place when hard abrasive particles indent the material surface and move against it **[L. 1, 2, 3]**. In this context, the properties of abrasive particles play a crucial role in influencing the volume of material loss **[L. 4, 5, 6, 7, 8, 9]**.

The impact of abrasive particles and the mechanism of material removal are determined by the grain size and morphology. The literature indicates that both the shape (e.g., rounded or sharp edges) and the size of abrasive grains affect the way that material is removed. Rounded or multilateral particles can cause progressive abrasion, while sharp edges of abrasive particles can easily cut the material **[L. 10, 11, 12]**. This can ultimately lead to a difference in the mechanism of material surface destruction.

Abrasive particles can be classified in two ways: based on their shape on the macro scale, where particles are arranged according to the similarity of their shape to standard shapes (such as a ball, a cone, a hyperboloid or a wedge) **[L. 13, 14]** and on the micro-scale, by describing, for instance, their sharpness, angularity or roundness **[L. 15, 16]**.

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Abrasive soil mass is a mix of abrasive grains of different sizes, shapes and material origin. The material origin of soil mass affects its wear properties. Woldman et al. **[L 17]** present different wear effects of sand particles of various origins, and analyses the effect of grain size and shape on the wearing process.

This article is focused on the effect of abrasive particle geometrical properties on the process of material removal during the abrasion process.

EXPERIMENTAL MATERIALS

The tests were conducted on specimens made of low-alloyed boron steel designed for applications with strict abrasion-resistance requirements.

To avoid changes in the material structure, the specimens were cut out using the high-energy waterjet cutting method. The surface of the test specimens was ground. Tests were conducted on rectangular specimens with dimensions of 30x25x10 mm. The chemical composition of Hardox Extreme steel according to the manufacturer's declaration and our own tests, is presented in **Table 1**.

The average hardness of the specimen material was 625±10 HBW according to PN-EN ISO 6506 **[L. 19]**. The structure of Extreme steel as delivered was characterised by a micro-structure of fine-grained strip martensite **(Fig. 1)**. In addition, the structure orientation resulting from the hot rolling technology of metal sheet production was observed.

Table 1. Chemical composition of Hardox Extreme steel [L. 18]
Tabela 1. Skład chemiczny stali Hardox Extreme **[L. 18]**

	C	Si	Mn	P	S	Cr	Ni	Mo	B	V	Cu
	Selected chemical element [% by weight]										
Manufac. 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

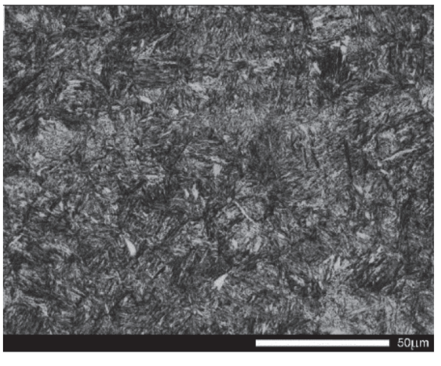

Fig. 1. Hardox Extreme steel micro-structure. Etched with 3% HNO_3
Rys. 1. Mikrostruktura stali Hardox Extreme. Trawiono 3%HNO_3

ABRASION

The study was conducted using sand with a grain size of 0.05–2 mm. Two types of sand were used: natural sand and crushed sand. Natural sand is naturally found and extracted in gravel pits, while crushed sand is manufactured by crushing rock, quarry stones, or larger aggregate pieces into sand-size particles. The sand for testing was obtained from a gravel pit near Olsztyn. The grain composition of the sand was determined by the sieve method according to PN-EN 933-1:2012 **[L. 20]**. Both types of sand contained a similar proportion of grains with a size of 0.5–1 mm (approx. 20%). Natural sand contained 8% more grains with a size of 0.25–0.5 mm, and 4% fewer grains with a size of 0.1–0.25 mm than crushed sand. Crushed sand contained two times more grains of the 0.05–0.1 fraction than natural sand. The results of an analysis of the tested abrasive grain composition are presented in **Fig. 2**.

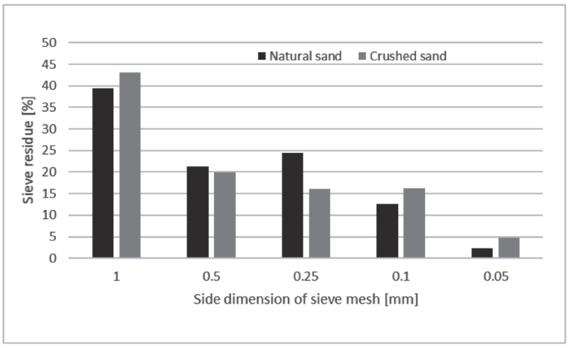

Fig. 2. Grain composition of the abrasives
Rys. 2. Zawartość frakcji uziarnienia w ścierniwie

In both sand types used, the grains with a size larger than 1 mm, which accounted for approx. 39% of the natural sand weight and approx. 43% of the crushed sand weight, were dominant.

The geometrical parameters of the sand grains were assessed by the method of image analysis based on photographs taken with an optical microscope Keyence VHX7000 while using its software. **Figure 3** presents the appearance of both natural and crushed sand grains of a fraction >1 mm.

The geometrical features of sand fraction grains were determined based on computer image analysis, whose results are provided in **Tab. 2**.

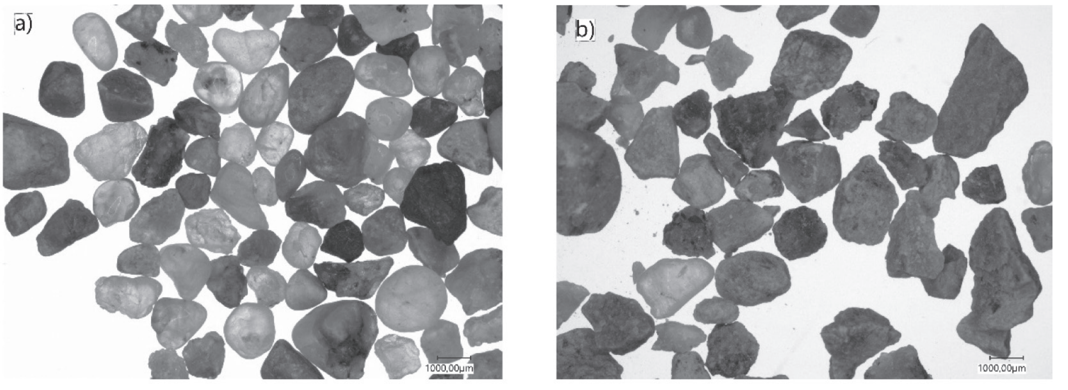

Fig. 3. Grains of natural sand (a) and crushed sand (b) used in laboratory tests (grain fraction >1 mm)
Rys. 3. Ziarna piasku płukanego (a) i łamanego (b) użytego w badaniach (frakcja uziarnienia >1mm)

Table 2. Geometrical parameters of sand grains used for the tests
Tabela 2. Parametry geometryczne ziaren piasku użytego do badań

Shape parameter	Grain composition [mm]	Crushed sand	Natural sand
Area [µm²]	>1	1 939 341	1 786 489
	0.5<1	619 511	436 087
	0.25<0.5	119 805	142 503
	0.1<0.25	20 802	37 662
	0.05<0.1	8 025	20 802
Perimeter [µm]	>1	5 670.651	5 276.432
	0.5<1	3 337.251	2 547.205
	0.25<0.5	1 381.557	1 463.521
	0.1<0.25	636.228	735.504
	0.05<0.1	348.333	636.228
Horizontal Feret [µm]	>1	1 616.990	1 542.829
	0.5<1	945.823	752.4073
	0.25<0.5	399.562	440.355
	0.1<0.25	173.551	216.272
	0.05<0.1	106.704	173.551
Vertical Feret [µm]	>1	1 652.013	1 571.226
	0.5<1	939.684	765.211
	0.25<0.5	403.315	435.093
	0.1<0.25	171.473	216.412
	0.05<0.1	106.289	171.473
Circularity [-]	>1	0.723	0.760
	0.5<1	0.676	0.779
	0.25<0.5	0.734	0.784
	0.1<0.25	0.608	0.790
	0.05<0.1	0.809	0.608

For the description of the shape and size of fractions of the abrasive material tested, the coefficients that enable the description of their varying structure were selected. Based on the obtained values of the determined coefficients, the shapes of the grains of particular sand fractions used in the experiment were characterised. This allowed their dimensions to be determined and the grains to be differentiated between the two types of abrasive material.

The grains of the fraction 0.05, for crushed sand are characterised by a limited shape, which results from the values of the circumference determined (approx. 348 µm). However, as follows from the highest noted value of the circularity coefficient, these grains are characterised by the most regular shape among all the fractions of test materials. A microscopic analysis of grains of this fraction enables the conclusion that the edges of these grains are corrugated.

Based on the analysis of the Feret diameter values, it can be concluded that for crushed sand grains of the fractions of 0.05–1 and 0.1–0.25 mm, similar values were noted, which means that they have a similar, regular shape. On the other hand, the visual analysis for the other fractions indicated that these grains have irregular, sharp edges. Grains of the other fractions are more slender and elongated, as indicated by the considerable differences between the vertical and horizontal Feret diameter values. The greatest differences in these parameters' values were noted in crushed sand for the grain-size fractions of 0.5–1 and >1 mm.

The varied shape of the grains found in crushed sand is indicated by the varied values of the circularity coefficient. As follows from the analysis of its values, grains of the 0.1–0.25 mm are characterised by the most irregular shape, which is different from a circular shape. The second highest value was noted for the fraction of 0.5–1 mm which, compared to the smallest fraction grains, was 1.2 times lower. For the next two fractions (0.25 mm and >1 mm), these values are similar.

The analysis of the shape parameters for the natural sand fractions indicates that these grains are characterised by a smaller surface than that for crushed sand. Moreover, the fractions >1 and 0.5–1 mm are smaller, which results from the determined circumference. Grains of the other three fractions have circumference values greater than those for crushed sand grains. Based on the similar values of the vertical and horizontal Feret diameter values, it can be concluded that grains of all fractions are characterised by a regular shape. However, a microscopic analysis of particles shows that these grains have rounded edges.

In comparing the values of the coefficient describing the circularity of the objects found in a particular type of abrasive material, it must be concluded that the natural sand fractions, except the grains of a size of 0.05–1 mm, for which a lower coefficient value was noted, have a much more regular shape. These differences are even greater than 1.2 times.

EXPERIMENTAL PROCEDURE

The wear tests were performed using an ASTM G65 abrasion tester **[L. 21]**. This test simulates low stress sliding abrasion, which is typical of soil engaging tools. A schematic diagram of the test rig can be seen in **Figure 4**. During testing, the examined specimens were exposed to the influence of the abrasive. The abrasive was stored in a hopper and fed into the contact zone through a nozzle **[L. 21]**.

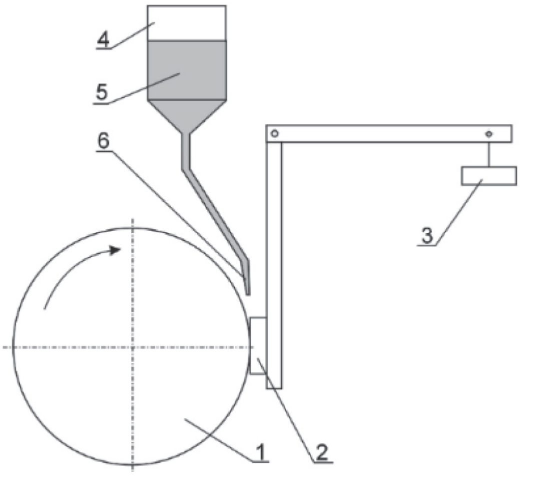

Fig. 4. Schematic diagram of the ASTM G65 abrasion test rig: 1 – rubber wheel, 2 – test specimen, 3 – weight, 4 – hopper, 5 – abrasive, 6 – nozzle

Rys. 4. Schemat stanowiska do badania zużycia metodą ASTM G65: 1 – koło gumowe, 2 – badana próbka, 3 – obciążenie, 4 – zasobnik, 5 – ścierniwo, 6 – dysza

Tests were carried out under modified conditions with a sample load of 73.6 N, a rotational velocity of the wheel of 150 min^{-1}, a sand flow rate of 350 g/min and the number the revolutions of the rubber wheel was 2000, which corresponded to the total sliding distance of 2000 m. Before and after testing, each test specimen was cleaned with ethanol and dried. Weight loss was determined by weighing the specimens before and after the tests with an analytical balance (RADWAG AS160. R2, 0.0001 g). Each test was repeated five times.

Weight loss was calculated from the following formula:

$$Z_w = m_0 - m_1, \quad (1)$$

where:
m_0 – initial specimen weight;
m_1 – specimen weight after wear test.

RESULTS AND DISCUSSION

Figure 5 shows the weight loss in specimens subjected to wear in natural and crushed sand.

The testing results indicate that crushed sand causes a four-times greater loss in the weight of the tested steel. To assess the wear process, an analysis of the test specimen surfaces was conducted. On the surface of the specimens subjected to wear in natural sand **(Fig. 6)**, wide scratches and ridges can be seen, which were caused by the impact of the greatest abrasive grains being moved across the specimen surface.

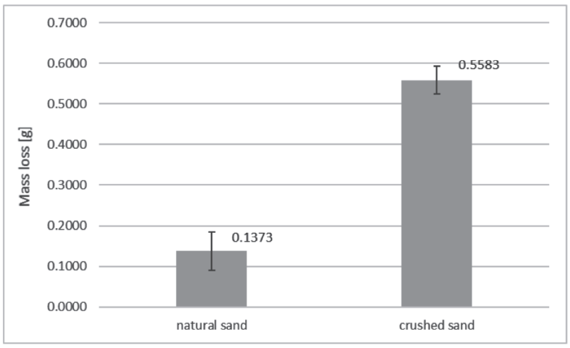

Fig. 5. Mass loss of steel worn in two types of sand
Rys. 5. Zużycie masowe stali ścieranej w dwóch rodzajach piasku

A considerable number of dents caused by grains being rolled across the surface were also observed. The shape of these dents was regular and similar to the sand grain shape. The traces of microcutting by the sharp-edged grains of small fractions can also be seen.

Similar effects of destruction can be seen on the surface of the steel subjected to wear in crushed sand **(Fig. 7)**. However, in this case, the resulting scratches are narrower. In crushed sand, the rolling of grains across the surface occurs as well, but due to the sharp edges of crushed sand grains, the resulting dents are deeper and have sharp edges.

Measurements of ridges and dents on the specimen surface (**Figs. 6c** and **7c)** indicate that grains with rounded edges cause the formation of scratches on the material surface, which are wider than those for sharp-edged grains.

Crushed sand grains in the contact zone behave in two ways. Grains moving across the surface assume an orientation in line with the direction of movement while gouging deep scratches. However, other grains assume an orientation perpendicular to the direction of movement. In this position, they are being rolled across the surface, causing the formation of dents running transverse to the

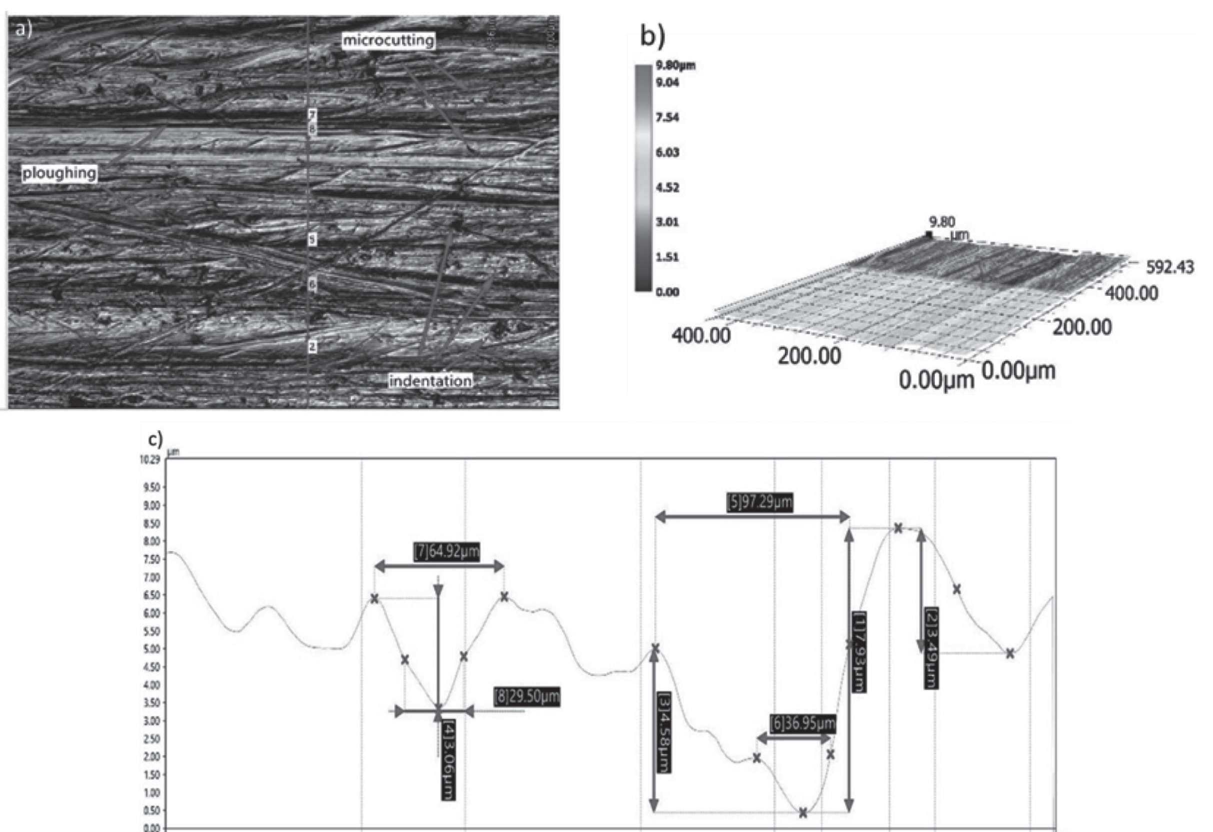

Fig. 6. Analysis of the steel surfaces subjected to wear in natural sand: a) appearance of the surface, b) 3D model of the surface, c) outline of the profile transverse to the direction of the abrasive particle movement
Rys. 6. Analiza powierzchni stali zużywanej w piasku płukanym: a) widok powierzchni, b) model 3D powierzchni, c) zarys profilu poprzecznego do kierunku ruchu cząstek ściernych

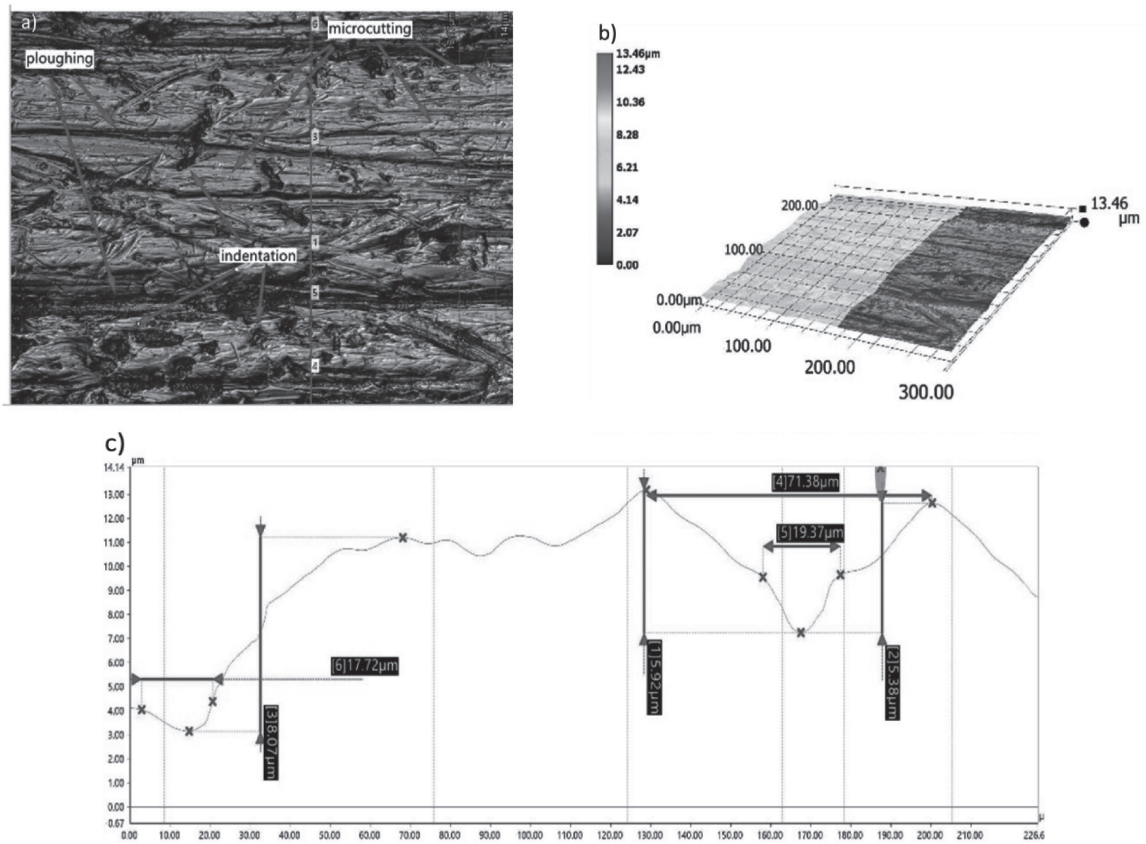

Fig. 7. Analysis of the steel surfaces subjected to wear in crushed sand: a) appearance of the surface, b) 3D model of the surface, c) outline of the profile transverse to the direction of the abrasive particle movement

Rys. 7. Analiza powierzchni stali zużywanej w piasku łamanym, a) widok powierzchni, b) model 3D powierzchni, c) zarys profilu poprzecznego do kierunku ruchu cząstek ściernych

ridging direction. The traces of micro-cutting, visible on the surface of the specimens subjected to wear in both types of abrasive material, are caused by sharp-edged grains of small fractions, found in both natural and crushed sand. However, micro-cutting is more intense for the specimens subjected to wear in crushed sand, which is linked to the considerable proportion of sharp-edged grains in this type of sand.

CONCLUSIONS

1. The sands used in the study had a similar particle-size distribution. The differences concerned the grain shape. In crushed sand, they were characterised by a lower regularity of the shape (circularity) and sharp edges, as compared to the natural sand grains.
2. Crushed sand grains caused a four times greater loss in the weight of steel than natural sand grains. In the process of steel wear in both abrasive materials, wear by ridging and micro-cutting was observed, which is typical of abrasive wear of two bodies. Moreover, traces of abrasive particles rolling across the material surface can be seen in the form of dents.
3. Grains with an irregular shape and soft edges caused the gouging of scratches with greater width and smaller depth compared to sharp-edged grains. The impact of feed forces in the contact zone affected the arrangement of irregularly shaped grains. Grains moving across the specimen surface assumed a position in line with the direction of movement and smaller grains with more degrees of freedom arranged themselves transversely to the direction of movement and were rolled, thus creating dents in the surface. In view of the above, it can be concluded that the wear pattern is not only determined by the grain shape but also by their number of degrees of freedom in the contact zone, which can be linked to the difference in grain size in the abrasive material.

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