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EXPERIMENTAL STUDIES ON THE INFLUENCE OF ABRASIVE MATERIALS ON THE WEAR OF HARD-WEARING STEELS

DOŚWIADCZALNE BADANIA WPŁYWU RODZAJU ŚCIERNIWA NA ZUŻYCIE STALI TRUDNOŚCIERALNYCH

Key words: wear, hard-wearing steels, mining.

Abstract The paper presents the wear properties of hard-wearing steels and structural steels used in mining and transport machines exposed to the aggressive action of the environment, which have been determined experimentally in the presence of diverse abrasive materials. The wear tests were carried out on a ring-on-ring test rig simulating the operating conditions of elements exposed to abrasive wear. The samples were subjected to tests in conditions of sliding contact, and the main destructive process was micro-cutting of the surface with loose corundum or quartz grain. In the case of the coal abrasive, only slight grinding in of the mating surfaces was observed. The loss of mass in the samples was measured as the parameter characterizing the wear. It was then used to determine the volume loss. Based on the results obtained, it was found that the wear resistance of hard-wearing steels was approximately four times higher as compared to S355J2 structural steel for the corundum and quartz abrasives. In the case of the coal abrasive, there was a relatively low wear for all of the materials examined.

Słowa kluczowe: zużycie, stale trudnościeralne, górnictwo.

Streszczenie W pracy określono doświadczalnie właściwości tribologiczne w zróżnicowanym ścierniwie hartowanych stali trudnościeralnych i stali konstrukcyjnych stosowanych w maszynach górniczych i transportowych narażonych na oddziaływanie agresywnego środowiska pracy. Badania zostały przeprowadzone na stanowisku badawczym typu ring-on-ring imitującym warunki pracy elementów narażonych na zużycie ścierne. Testowane próbki były poddane badaniom w warunkach współpracy ślizgowej, a wiodącym procesem niszczącym było mikroskrawanie powierzchni luźnym ziarnem korundowym lub kwarcowym, natomiast w przypadku ścierniwa węglowego obserwowano jedynie niewielkie dotarcie współpracujących powierzchni. Mierzonym parametrem charakteryzującym zużycie był ubytek masy rozpatrywanych próbek i na jego podstawie wyznaczono ubytek objętościowy. Na podstawie uzyskanych wyników stwierdzono ok. czterokrotnie większą odporność stali trudnościeralnych w porównaniu ze stalą konstrukcyjną S355J2 dla ścierniwa korundowego i kwarcowego. W przypadku ścierniwa węglowego stwierdzono relatywnie małe zużycie dla wszystkich rozpatrywanych materiałów.

INTRODUCTION

With respect to machines working in difficult operating conditions, special attention is currently paid to abrasive wear [**L. 1**]. This process is often responsible for premature withdrawal of machines and equipment from service. Their components, such as support elements and bodies, are built mainly of structural steels, but they are not intended for operation in conditions of an increased abrasive wear. However, as practice has shown, they often are also exposed to the action of the abrasive material as a result of improper selection of materials imposed by economic considerations. **Fig. 1A** shows a sample element of an excavated material transport system in underground mines, which was damaged by abrasive wear. Very often, worn out elements are refurbished (**Fig. 1B**); however, this process is expensive and time-consuming.

Currently, wear-resistant steels are a standard in the mining industry and are used for elements that

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are significantly exposed to abrasive wear. Many manufacturers of steel offer materials of this type, but there are differences in wear properties of individual steels. Oyala et al. [**L. 2, 3**] examined 5 types of wear-resistant steels with nominally identical hardness and found significant differences between these steels in terms of wear resistance reaching up to 50%. The steel with an addition of boron and nickel showed particularly good properties. Based on their studies, they proved that, when selecting the materials for elements exposed to wear, besides hardness, all of the chemical compositions and the microstructure were important factors. Wear properties of the wear-resistant hardened steels were further analysed in [**L. 4, 5, 6, 7**].

Proper selection of materials for machines and equipment requires knowledge of the destruction mechanisms that cause premature loss of durability [**L. 8**]. In this paper, the author presents studies on the impact of the type of mineral abrasive on the mechanism of abrasive wear of typical steels used for components of mining machines.

A

B

Fig. 1. Elements of hard coal transport systems, A – a view of damage caused by abrasive wear, B – a view of the conveyor trough after the refurbishment process

Rys. 1. Elementy systemów transportu węgla kamiennego, A – widok uszkodzeń spowodowanych zużyciem ściernym, B – widok rynny przenośnika po procesie regeneracji

EXPERIMENTAL DETAILS

Characteristics of the materials tested

As a part of this study, tribological properties of 2 groups of construction materials were analysed:

– Martensitic wear-resistant steels (designated as WRSteel_400 and WRSteel_500), and
– Rolled structural steels (designated as STEEL_700MC in the state after a thermomechanical treatment and typical S355J2 steel in the normalized state).

Table 1 presents the values of the maximum strength TS for the materials examined and the measured value of the surface hardness H. The measurement uncertainty for both values was determined for the confidence level of 0.95 and the degrees of freedom f = 3. The relative uncertainty of measurement was less than 5% for all of the cases considered.

Figure 2 shows the microstructure of all considered steels. For both WRS_400 and WRS_500 wear-resistant steels, the predominant phase of the microstructure is martensite. In addition, residual austenite also occurs. In the case of steels with a higher hardness (WRS_500), the share of austenite is lower.

The structure of the STEEL_700MC steel consists of a mix of fragmented ferrite and pearlite. The grains are characterized by a deformation associated with the process of thermomechanical treatment. The S355J2 steel is also composed of ferrite and pearlite; however, the predominance of the first phase is observed. The microstructure is characterized by distinct grain banding and deformation resulting from the rolling process.

Table 1. Mechanical properties of the tested steels

Tabela 1. Właściwości mechaniczne rozpatrywanych stali

Mechanical Properties	Tensile Strength TS, MPa	Hardness H, HRC
WRSteel_400	1250	43
WRSteel_500	1600	51
STEEL_700MC	850	23
S355J2	520	21

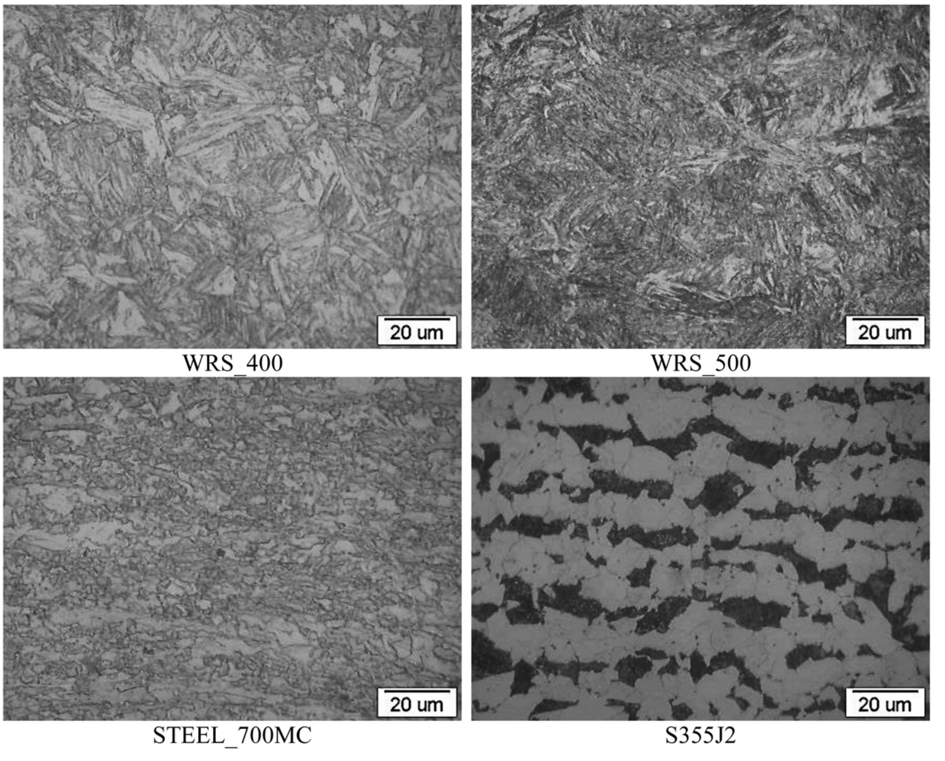


Fig. 2. Microstructure of tested steels
Rys. 2. Mikrostruktura rozpatrywanych stali

Test rig and methodology

For testing the wear of the samples of the materials in question, a ring-on-ring test rig was used (**Fig. 3**), which was described in detail in [**L. 9, 10**]. The main friction pair consists of two ring-shaped samples, between which an abrasive material is located.

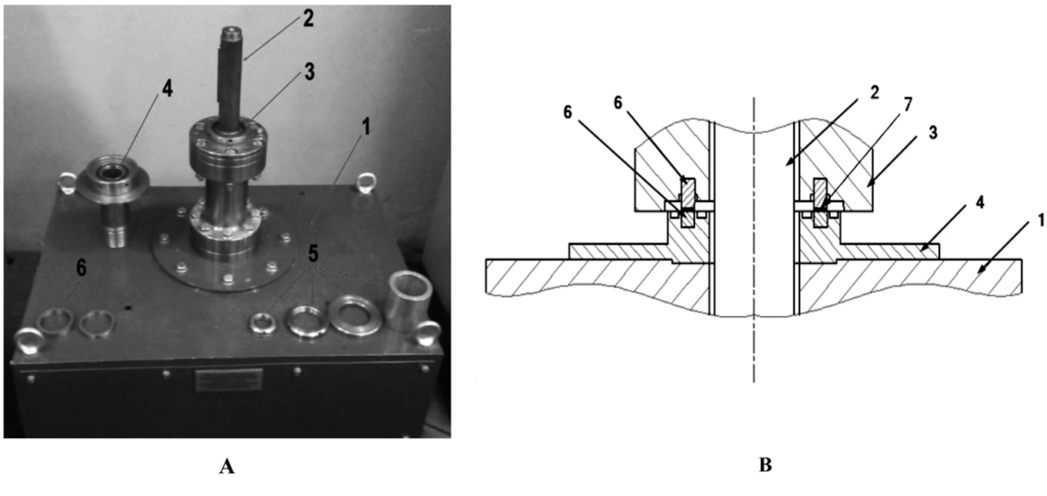


Fig. 3. The design of the test rig: A – view of the test rig, B – diagram showing the manner of fixing the samples: designations: 1 – body of the test rig with a motor, 2 – drive shaft, 3 – upper sample holder, 4 – lower sample holder, 5 – fastening elements, 6 – test samples, 7 – abrasive
Rys. 3. Stanowisko badawcze; A – widok stanowiska, B – schemat zamocowania próbek; oznaczenia: 1 – korpus stanowiska wraz z silnikiem, 2 – wał napędowy, 3 – górny uchwyt próbki, 4 – dolny uchwyt próbki, 5 – elementy mocujące, 6 – próbki badawcze, 7 – ścierniwo

During the tests, grains of corundum, quartz sand, and coal with an ash content of 28% were used as abrasive materials. They were added in an amount of 1 cm^3 between the mating samples. Each abrasive material had grains with a diameter below 50 µm.

A characteristic feature of the test conducted on this test rig is a constant presence of the abrasive between the samples as well as the presence of crushed grains and wear products originating from the damaged surface.

This situation corresponds with many cases of the actual wear of machine components. When conducting the tests, an observation was made that hard abrasive grains were completely crushed during the test cycle.

The research methodology assumed that, after each 10-minute wear cycle, the samples will be cleaned and weighed and fresh corundum abrasive will be added. The test for 1 selected abrasive consisted of eight 10-minute cycles. Each test was repeated 3 times. The basic parameters characterizing the wear test are presented in **Table 2**.

The wear parameter to be determined was defined by Formula (1):

$$u_M = (m_{pd0} - m_{pdt}) + (m_{pg0} - m_{pgt}) \tag{1}$$

where

m_{pd0} – mass of the lower sample before starting the test, g,
m_{pdt} – final mass of the lower sample, g,
m_{pg0} – mass of the upper sample before starting the test, g,
m_{pgt} – final mass of the upper sample, g,
u – loss of the mass of samples, g.

The uncertainty of the determination of the mass wear was specified for the confidence level of 0.95 and the degrees of freedom f = 4. The relative uncertainty of measurement was less than 1% for all of the cases considered.

Table 2. Basic parameters of the wear tests
Tabela 2. Podstawowe parametry testu zużyciowego

Unit preasure σ, MPa	0.031	0.062	0.094
Peripheral speed v, m/s	0.29		
Time of testing, min	8×10		
Friction distance, m	1520		

Values of the RWR (Relative Wear Resistance) coefficient [**L. 11**] were determined using the following dependence (2):

$$RWR = \frac{\text{Weight loss of sample of reference material}}{\text{Weight loss of sample}} \tag{2}$$

Typical S355J2 steel was adopted as the reference material.

RESULTS AND DISCUSSION

Figure 4 shows sample plots of the wear as a function of the duration of the tests obtained for all materials and abrasives under consideration. **Table 3** shows values of the RWR coefficient.

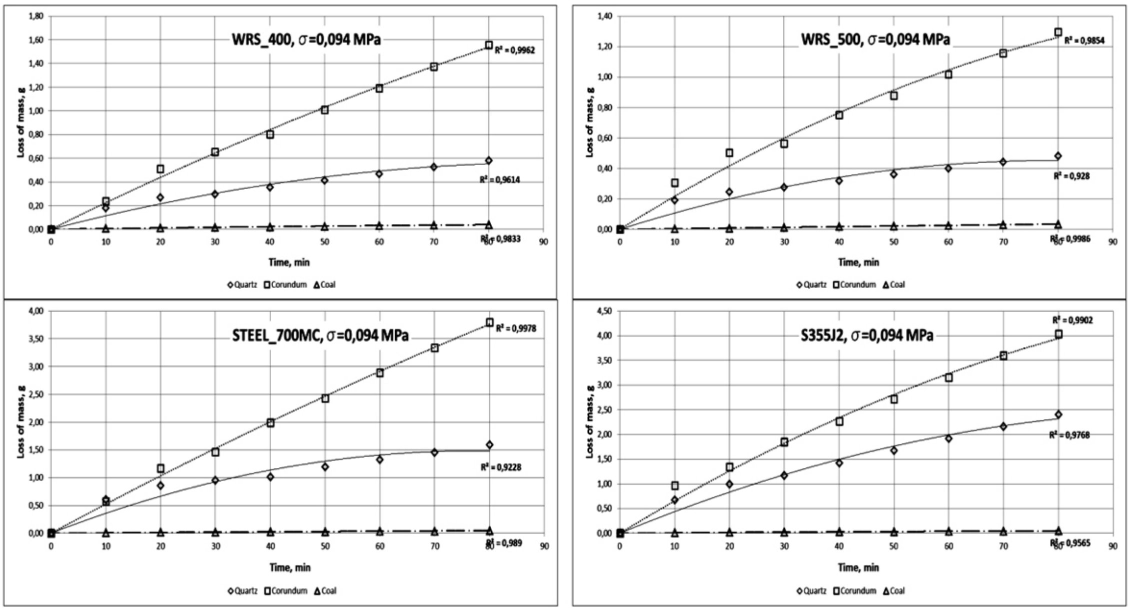


Fig. 4. Plots of the mass wear u_M as a function of time, determined for corundum, quartz and coal abrasives (stress σ = 0.094 MPa)

Rys. 4. Przebiegi zużycia masowego u_M w funkcji czasu wyznaczone dla ścierniwa korundowego, kwarcowego i węgla (naprężenie σ = 0,094 MPa)

Table 3. Values of the total RWR coefficient for the materials examined
Tabela 3. Wartości względnej odporności na zużycie RWR wyznaczone dla rozpatrywanych materiałów

RWR	0.031 MPa	0.062 MPa	0.094 MPa
Corundum			
WRSteel_400	3.875	3.131	2.593
WRSteel_500	3.972	3.235	3.119
STEEL_700MC	1.192	1.149	1.064
S355J2	1	1	1
Quartz			
WRSteel_400	3.098	3.825	4.148
WRSteel_500	3.996	4.541	4.866
STEEL_700MC	1.661	1.585	1.513
S355J2	1	1	1
Coal			
WRSteel_400	1.253	1.175	1.225
WRSteel_500	1.541	1.459	1.440
STEEL_700MC	0.995	1.014	1.043
S355J2	1	1	1

Plots of the wear in conditions of the presence of corundum and quartz abrasives show that the materials in question have distinctly differentiated tribological properties. The martensitic wear-resistant steel with a hardness of 500 HB (WRS_500) had the lowest values of wear. The steel designated as WRS_400 had slightly worse tribological properties. The structural steels (S355J2 and STEEL_700MC) had a significantly worse resistance to abrasive wear. This can be easily seen on the basis of the RWR coefficient, which, for the combination of wear-resistant steels and the corundum and quartz abrasives, ranged between 2.7 and 4 (depending on the load).

In the case of the coal abrasive, the impact of an increased surface hardness on a reduction of the mass wear was observed, but the differences between the determined wear values for individual steels were slight. The RWR coefficient for both wear-resistant steels ranges between 1.18 and 1.54. For wear-resistant steels and hard abrasives (quartz and corundum), the predominant mechanism of abrasive wear was micro-cutting (schematically shown in **Fig. 5A**), while, in the case of structural steels, micro-cutting or micro-ridging (schematically shown in **Fig. 5B**) accompanied by fatigue damage. In the case of the coal abrasive, the predominant mechanism responsible for damage to the

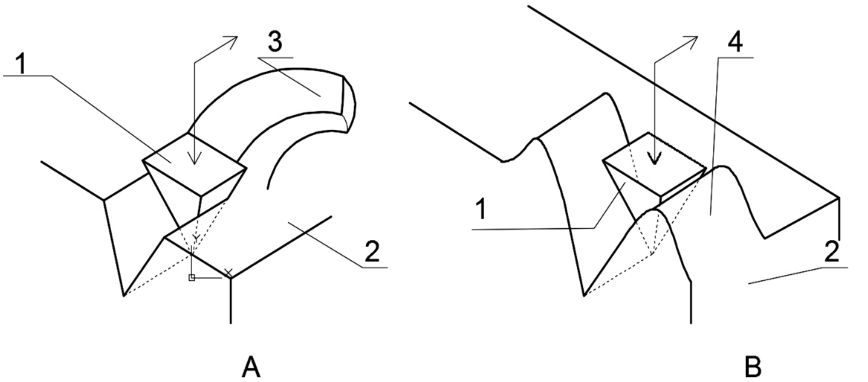


Fig. 5. Schematic presentation of elementary mechanisms of abrasive wear: A) micro-scratching, B) micro-ridging; designations: 1 – abrasive particle, 2 – surface subject to wear, 3 – separated cut, 4 – ridge (based on [L. 12])
Rys. 5. Schematyczne przedstawienie elementarnych mechanizmów zużycia ściernego, A) mikrorysowanie, B) mikrobruzdowanie; oznaczenia: 1 – cząstka ścierniwa, 2 – powierzchnia zużywana, 3 – oddzielony skraw, 4 – bruzda (na podstawie [**L. 12**])

surfaces was low-cycle fatigue. The mechanism of this form of wear is explained schematically in **Fig. 6**. The above mentioned destruction mechanisms can be clearly seen in the views showing the microstructure of the sample cross-section and mating surfaces – **Figures 7–11**.

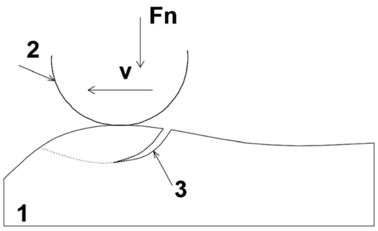
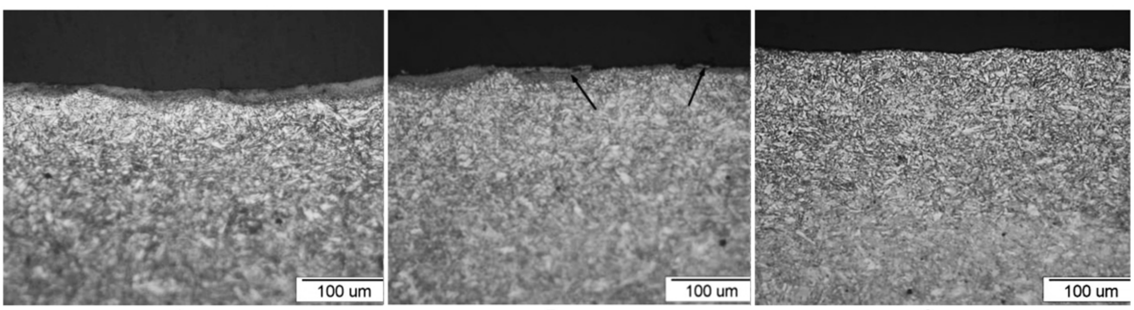


Fig. 6. Schematic presentation of the cyclical action of surface roughness resulting in low-cycle fatigue; designations: 1 – base, 2 – roughness projection, 3 – crack, *v* – sliding velocity, F_n – pressure force (based on [L. 13])

Rys. 6. Schematyczne przedstawienie cyklicznego działania nierówności powierzchni przejawiające się zmęczeniem niskocyklowym; oznaczenia: 1 – podłoże, 2 – występ chropowatości, 3 – pęknięcie, *v* – prędkość ślizgania, F_n – siła nacisku (na podstawie [**L. 13**])

Figure 7 shows the microstructure of the surface layer of the WRS_500 steel after the tests with the use of three different abrasives. The predominant form of damage for quartz and corundum abrasives is micro-cutting of the surface. A similar form of damage to the wear-resistant WRS_400 steel is shown in **Figures 8B** and **8C** (cuts caused by the action of the corundum abrasive can be clearly seen in this figure). Fatigue cracks are clearly visible in **Fig. 7B** for the variant of wear in the presence of coal and in **Fig. 8A** for the lowest of the loads considered.

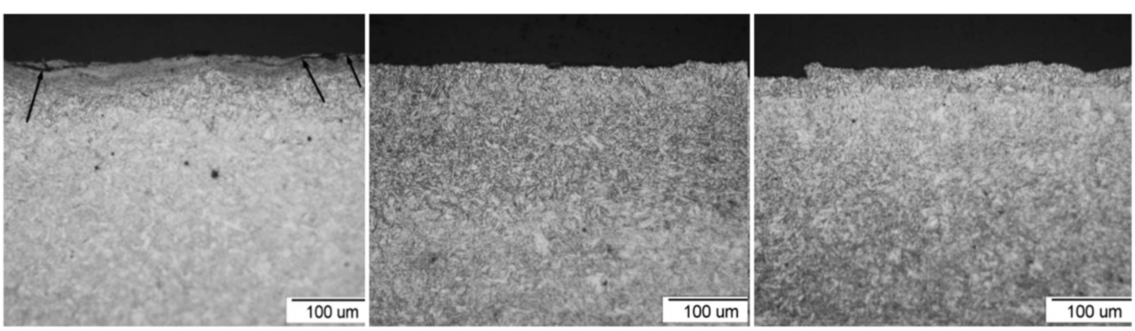
Figures 9A and **9C** show the surface of the WRS_400 steel after the wear tests in the presence of hard abrasives. In the case of the test variant with quartz abrasive, the damage zones with various degrees of surface superfinishing can be seen. This could have been caused by different sizes of broken abrasive grains. In the case of the test variant with corundum abrasive, no different degrees of surface superfinishing are observed, and only a single large surface damage to the surface can be seen, which most probably was caused by unbroken grain that was driven into the surface in the initial phase of the test. **Fig. 9B** shows the surface after the test in a relatively soft abrasive (in coal). This surface is



A B C

Fig. 7. Microstructure of the surface layer of the WRS_500 steel after the tests under the load σ = 0.061 MPa: A – for quartz sand, B – for coal, C – for corundum (the arrow indicates cracks in the surface layer)

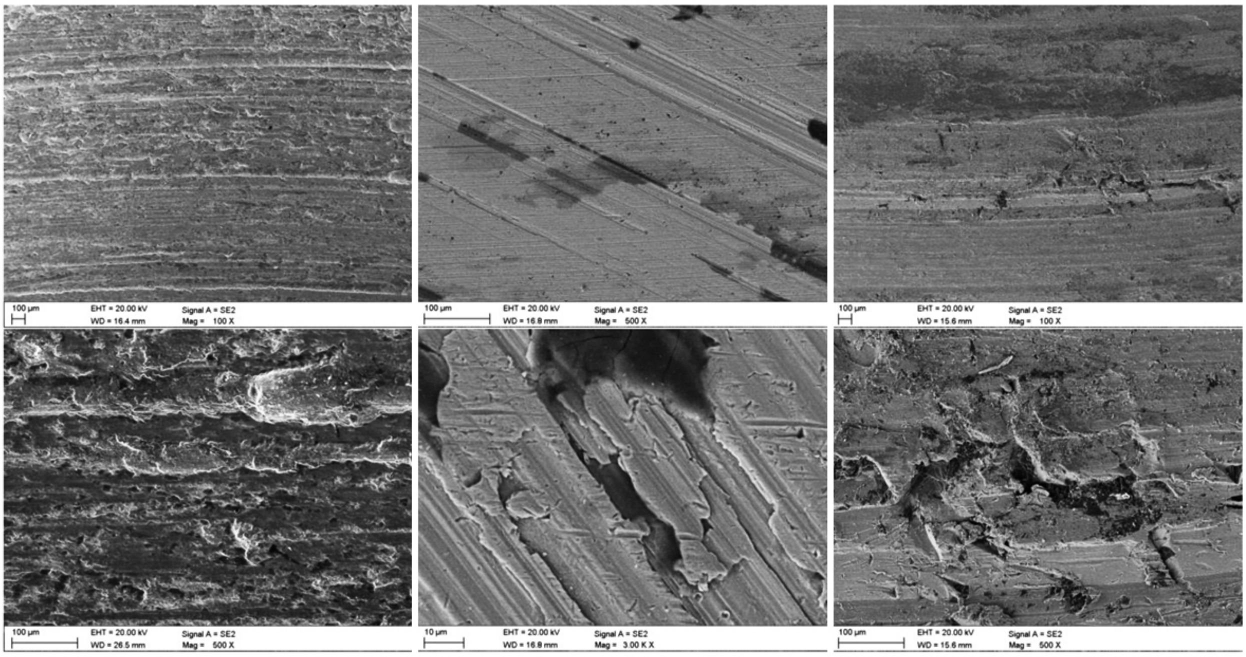
Rys. 7. Mikrostruktura warstwy wierzchniej stali WRS_500 po testach pod obciążeniem σ = 0,061 MPa: A – w piasku kwarcowym, B – w węglu, C – w korundzie (strzałką wskazano pęknięcia w warstwie wierzchniej)



A B C

Fig. 8. Microstructure of the surface layer of the WRS_400 steel after the tests in the presence of quartz sand and at the following values of the load σ: A – 0.031 MPa, B – 0.062 MPa, C – 0.094 MPa (the arrow indicates cracks in the surface layer)

Fig. 8. Mikrostruktura warstwy wierzchniej stali WRS_400 po testach w obecności piasku kwarcowego i wartości obciążenia σ: A – 0,031 MPa, B – 0,062 MPa, C – 0,094 MPa (strzałką wskazano pęknięcia w warstwie wierzchniej)



A B C

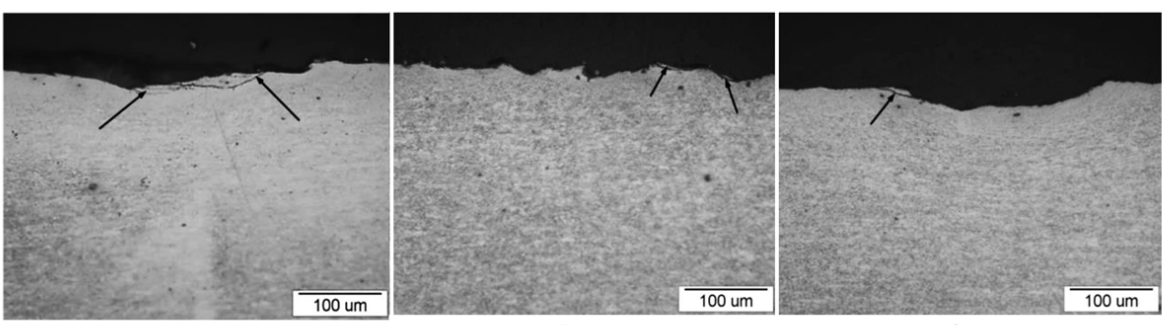
Fig. 9. A view of the surface of the WRS_400 steel after the tests under the load σ = 0.094 MPa: A – for quartz sand, B – for coal, C – for corundum (the arrow indicates cracks in the surface layer)

Rys. 9. Widok powierzchni (SEM) stali WRS_400 po testach pod obciążeniem σ = 0,094 MPa: A – w piasku kwarcowym, B – w węglu, C – w korundzie

superfinished. There are visible roughness protrusions, a partly blotted out ridge and a surface crack being formed with a shape typical of fatigue surface cracks.

A complex form of damage to the STEEL_700MC steel is shown in **Fig. 10**. In the microstructure of the surface layer of the steel subjected to wear in the presence of corundum grains and quartz sand, there are cuts caused by the action of the abrasive as well as cracks in the structure which are arranged in parallel to the surface. In the case of the steel subjected to wear in the presence of coal, surface damage in the form of cuts is visible, but probably there is also fatigue chipping of the surface.

In the case of the S355J2 steel (with the lowest surface hardness), deformations in the ferritic-pearlitic structure can be noticed in **Fig. 11**. This suggests a destruction mechanism in the form of ridging. Cracks are located at the roughness protrusions. For the variants of wear in the presence of quartz and corundum abrasives, approx. 20–30 μm under the surface, there are visible darker clusters in the form of longitudinal cracks, which may have been caused by multiple actions of the



A B C

Fig. 10. Microstructure of the surface layer of the STEEL_700MC steel after the tests under the load σ = 0.061 MPa: A – for quartz sand, B – for coal, C – for corundum (the arrow indicates cracks in the surface layer)

Rys. 10. Mikrostruktura warstwy wierzchniej stali STEEL_700MC po testach pod obciążeniem σ = 0,061 MPa: A – w piasku kwarcowym, B – w węglu, C – w korundzie (strzałką wskazano pęknięcia w warstwie wierzchniej)

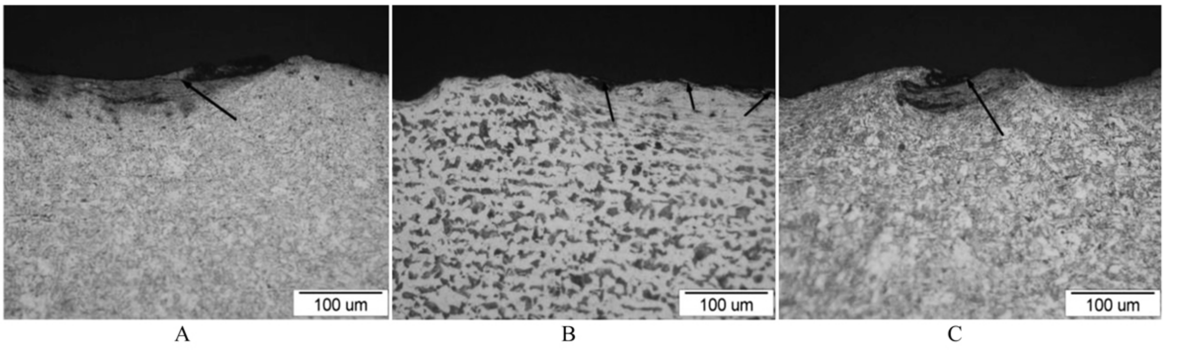


Fig. 11. Microstructure of the surface layer of the S355J2 steel after the tests under the load σ = 0.061 MPa: A – for quartz sand, B – for coal, C – for corundum (the arrow indicates cracks in the surface layer)

Rys. 11. Mikrostruktura warstwy wierzchniej stali S355J2 po testach w: A – piasku kwarcowy, B – w węglu, C – w korundzie (strzałką wskazano pęknięcia w warstwie wierzchniej)

abrasive. These places may initiate fatigue chipping of the surface.

The observations presented above prove that the operating and material factors have a decisive impact on the wear mechanism and its value. The most aggressive abrasive was corundum, and the level of its impact (cutting and ridging) was significantly higher than in the case of grains of quartz sand. The least aggressive was the action of coal. In this case, the predominant form of damage was low-cycle fatigue of roughness protrusions. This proves that a greater number of loading cycles is needed to separate the roughness protrusions. A lack of distinct cuts in the case of wear in coal may also indicate that roughness protrusions are not directly in contact with each other, but through a layer of coal, which may provide some protection against abrasive wear; nevertheless, in the course of further operation, it leads to fatigue forms of surface damage.

CONCLUSIONS

1. Among the analysed steels, martensitic wear-resistant steel with a nominal hardness of 500 HB proved to be the most resistant steel, regardless of the type of abrasive. The S355J2 structural steel appeared to be the least resistant.
2. The type of abrasive in combination with the hardness of the steel surface determines the mechanism of tribological wear.
3. In the case of martensitic steels and hard abrasives, micro-cutting is the predominant form of damage.
4. In the case of the STEEL_700MC structural steel, which was tested in corundum and quartz abrasives, there was a complex wear mechanism consisting of micro-cutting and low-cycle fatigue. In the case of the S355J2 steels, tested in the same abrasives, the cause of damage was ridging and low-cycle wear.
5. In the case of the wear tests in the presence of coal, regardless of the type of steel, fatigue chipping of the protrusions in the mating surfaces was observed.

ACKNOWLEDGEMENT

The study was carried out as a part of the project “Development of the innovative technology of conveyor chutes routes using robotic methods,” No. POIG.01.04.00-24-05-057/13.

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