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COMPARATIVE ANALYSIS OF ABRASIVE-WEAR RESISTANCE OF BRINAR AND HARDOX STEELS

ANALIZA PORÓWNAWCZA ODPORNOŚCI NA ZUŻYWANIE ŚCIERNE STALI BRINAR I HARDOX

Key words: abrasion wear, low-alloy boron steels, dry sand-rubber wheel test, Brinar, Hardox.

Abstract: One of the most important problems encountered during operation of machine parts exposed to abrasive action is their wear. In addition, these parts often work under dynamic loads, so their satisfactory ductility is also required. A combination of these apparently opposing properties is to a large degree possible in low-alloy martensitic steels containing boron. These steels are manufactured by numerous metallurgical concerns, but their nomenclature is not standardised and they appear under names given by the manufacturers, and their specifications are available in commercial information materials only. Till now, Hardox steels have been objects of great interest but, with regard to the continuous development of materials engineering, the created material database requires regular supplementation. To that end, two grades of steels from this group, Brinar 400 and Brinar 500, were subjected to comparative analysis of their abrasive-wear resistance in relation to properties of competitive grades Hardox 400 and Hardox 500. Abrasive-wear resistance tests were carried-out in laboratory conditions using a tribotester T-07. In addition, to identify the main wear mechanisms, worn surfaces of the specimens were examined with use of a scanning electron microscope.

Słowa kluczowe: zużywanie ścierne, niskostopowe stale z borem, test odporności na zużywanie ścierne, Brinar, Hardox.

Streszczenie: Jednym z najważniejszych problemów, na jaki napotyka się podczas eksploatacji elementów maszyn narażonych na działanie masy ściernej, jest ich zużywanie. Dodatkowo elementy te pracują często w warunkach obciążeń o charakterze dynamicznym, stąd wymaga się od nich również zadowalającej ciągliwości. Połączenie tych, na pierwszy rzut oka, przeciwstawnych właściwości było w dużej mierze możliwe w niskostopowych, martenzytycznych stalach z borem. Stale te są produkowane przez wiele koncernów hutniczych, ale nazewnictwo ich nie jest znormalizowane i występują pod nazwami nadanymi im przez producentów, a dane o nich dostępne są jedynie w materiałach komercyjnych. Do tej pory intensywnie zajmowano się stalami typu Hardox, ale w związku z ciągłym rozwojem inżynierii materiałowej stworzona baza materiałowa wymaga stałych uzupełnień. W tym celu analizie porównawczej, pod względem odporności na zużywanie ścierne, poddano kolejne dwa gatunki należące do tej grupy stali – Brinar 400 i Brinar 500, których właściwości odniesiono do konkurencyjnych stali Hardox 400 i Hardox 500. Badania odporności na zużywanie ścierne tych stali zrealizowano w warunkach laboratoryjnych za pomocą tribotestera T-07. Dodatkowo, w celu zidentyfikowana głównych mechanizmów zużywania, za pomocą elektronowego mikroskopu skaningowego (SEM) zostały przeprowadzone badania wyeksploatowanych powierzchni próbek analizowanych stali.

INTRODUCTION

Abrasive wear of constructional elements is still one of the most important problems met by modern materials engineering. Costs generated by abrasive wear are related to servicing, energy consumption, down-times, and failures that could result not only in the destruction of a machine part, but also a danger to health or even the life of the people operating the machine. Down-times mean higher fixed costs related to missing depreciation and a loss of potential profits that could be gained when the machine works normally. Each industry is specific with respect to its environment. For example, the specificity of surface mining results from very large

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overall dimensions of mining machines, their masses, and atypical, individual constructional solutions. The costs related to repairs of parts of such machines must be enormous. Each machine is a prototype and must be operated even for several dozen years, so it is extremely important that the newest solutions within materials engineering are utilized here. The well-known ways of improving abrasive-wear resistance include, e.g., pad-welding with hard alloys in the areas subjected to intensive wear [**L. 1–4**].

However, operational examinations proved that, in spite of high hardness of these created surface layers and thus abrasion resistance of the material, it generally did not show satisfactory wear resistance in the conditions of dynamic loads [**L. 5–6**]. That resulted from the high non-homogeneity of structure in cross-sections of the parts and thus their diverse properties. In order to fulfil the users' requirements, it was endeavoured to find a material that would combine high abrasive-wear resistance with satisfactory shock-resistance. First steels with such properties were produced by Japanese metallurgical concern JFE EVERHARD Corporation as early as in 50s of the 20th Century [**L. 7**]. In Europe, the first steel with higher abrasive-wear resistance (Hardox 400) was manufactured in 1970 by Swedish metallurgical concern SSAB Oxelösund [**L. 8**]. Common features of the JFE steels and Hardox 400 were low carbon content, simple chemical composition, uniform structure on cross-section and high hardening capacity obtained by an addition of boron. The addition of boron is of a basic importance. Small additions of boron, in comparison to other alloying elements, significantly improve hardenability, as was already noticed in the 1930s in the case of low- and medium-carbon steels. During the next years, this element was used more and more widely to replace expensive alloying elements like nickel, molybdenum, and chromium, especially when the availability of these elements became significantly limited during WWII. In this way, a basis was created for the manufacture of low-alloyed (sometimes even called "micro-alloyed") martensitic steels containing boron, with higher abrasive-wear resistance [**L. 9**].

Nowadays, there are many materials with their properties similar to those of Hardox steel [**L. 1**]. With use of advanced manufacturing processes, contemporary low- and medium-carbon steels reach very good mechanical properties, having at the same time moderate prices. Properties of these steels are decided by their structures obtained after a determined thermal or thermo-mechanical treatment. In order to obtain high mechanical properties and good abrasive-wear resistance, a typical heat treatment of these steels is quenching and low-temperature tempering. However, it happens that these steels are delivered by the manufacturers in various conditions, sometimes with no hardening, with a suggestion that thermal treatment should be performed by the buyer. Data concerning these materials are mainly of a commercial nature and are rarely confirmed by independent studies and their nomenclature is not standardised. In practice, manufacturers' commercial names are used. This can hamper the evaluation of these steels as replacement materials of not only traditionally used materials, but also of the Swedish Hardox steels. With so rich an offer of this type of materials, it seems strange that, e.g., Polish users of low-alloyed, high-strength steels with high abrasive-wear resistance most often use the Swedish Hardox steels, which may not be economically grounded. This results, of course, from a very good advertisement campaign of the Swedish concern, but also from a small number of studies of other similar steels. It should be emphasised that previously performed comprehensive studies of Hardox steels proved their extremely high tribological properties [**L. 6, 10–16**].

However, in order that the users could intentionally select a material suitable for their applications, they should be able to compare various steel grades within one material group. With respect to this necessity, the steels Brinar 400 and Brinar 500 manufactured by Ilsenburger Grobblech GmbH, a part of the group Salzgitter AG, were used as base examined materials in this research. According to the manufacturer's data, Brinar 400 and Brinar 500 are low-alloyed boron-containing martensitic steels with higher abrasive-wear resistance. Tribological properties of these steels were subjected to comparative analysis against the Hardox 400 and Hardox 500 steels.

The applied method of testing abrasive-wear resistance needs a comment. In the researches of abrasive-wear resistance of this group of steels, the problem of representing impact loads that occur during the operation of machine parts often appeared. However, in the research presented here, the tests were performed by means of a tribotester T-07 that does not consider impact loads. Nevertheless, as showed by numerous examinations, the T-07 tester is perfectly suitable for comparative evaluation of the materials belonging to one structural group and the obtained results of laboratory tests, and thus the created ranking of the materials are later reflected in service conditions [**L. 17–19**].

MATERIALS AND METHODOLOGY

The tests were carried-out on specimens cut-out from plates 8–12 mm thick, delivered directly by the manufacturer of Brinar and Hardox steels. Selected mechanical properties (based on the manufacturer's data) are given in **Table 1**.

Chemical analyses were made spectrally using a glow discharge emission analyser GDS500A Leco, with the parameters: U = 1250 V, I = 45 mA, argon. The obtained results are arithmetic averages of five measurements.

Brinell hardness measurements of the specimens were made acc. to EN ISO 6506-1:2014-12, using

Table 1. Mechanical properties of analysed steels [L. 20–23]: MD – manufacturer's data, OR – own results

Tabela 1. Właściwości mechaniczne analizowanych stali [**L. 20–23**]: MD – dane producenta, OR – badania własne

Steel grade	**$R_{p0.2}$** [MPa]	**R_m** [MPa]	**A_5** [%]	**KCV_{-20}** [J/cm^2]	**Hardness HBW**	
	MD	MD	MD	MD	MD	OR
Brinar 400	900	1200	12	33	340–440	410 ±6
Hardox 400	1000	1250	10	75	370–430	402 ±6
Brinar 500	1350	1500	8	25	480	465 ±2
Hardox 500	1300	1550	10	50	470–530	504 ±5

a hardness tester ZWICK ZHU 187.5 with a ball ∅2.5 mm of sintered carbides, under the load of 1875 kG acting for 15 s. Measurements were made on the specimens previously subjected to the evaluation of microstructures in their core areas.

Microstructural examinations were carried-out after etching with a 3% solution of HNO3 acc. to PN-H-04503:1961. Light microscopy examinations were made using an optical microscope Nikon Eclipse MA200. Images of microstructures were recorded using a digital camera Nikon DS-Fi2 with NIS Elements software. Additional observations of microstructures were carried-out on a scanning electron microscope Joel JSM-6610A at accelerating voltage 20 kV. Observations were performed in material contrast using SE detectors.

Examinations of abrasive-wear resistance were performed using a T-07 tester, with loose abrasive material acc. to GOST 23.208-79, under constant load F = 44 N (ΔF = 0.25 N). The T-07 tester was designed in the Institute for Sustainable Technologies – National Research Institute in Radom. The difference between the tester T-07 and the tribotester described in the international standard ASTM G65 consists in the way of locating the examined material. In T-07, the specimen is placed horizontally, and in the tribotester described in ASTM it is placed vertically. During examination, specimens 30 × 30 × 3 mm made of the research and the reference materials are subjected to wear with abrasive particles introduced to the friction contact zone in identical working conditions, i.e. speed and load. As abrasive material, aloxite No. 90 acc. to ISO 8486-2:1998 was used, and the reference specimen was made of steel C45 in normalized condition. The duration of the test was selected correspondingly to the material hardness and was equal to 30 minutes (1800 revolutions of the roll). The layout of the tester is shown in **Fig. 1**.

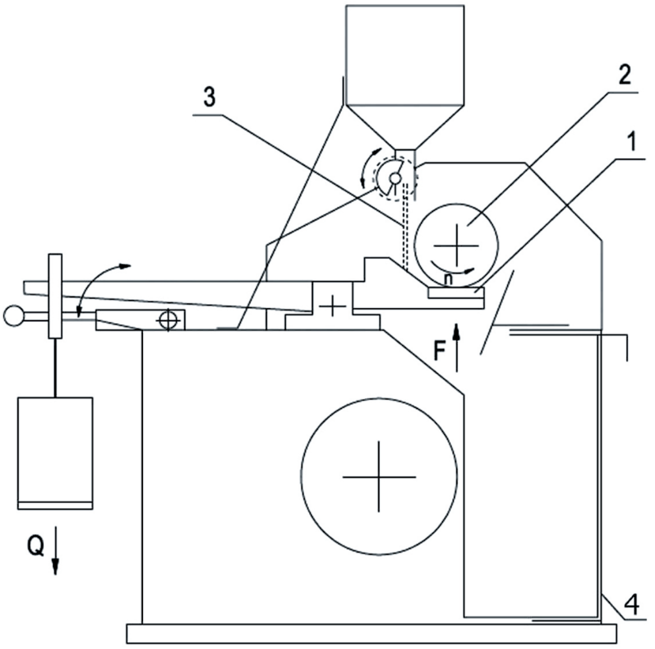

Fig. 1. Layout of tribotester T-07: 1 – examined specimen, 2 – counter-specimen, 3 – container with abrasive material, 4 – container for used abrasive material

Rys. 1. Schemat tribotestera T-07: 1 – próbka badanego materiału, 2 – przeciwpróbka, 3 – zasobnik ze ścierniwem, 4 – zasobnik na zużyte ścierniwo

Abrasive wear of the specimens was determined by the gravimetric method. The specimen was weighed on a laboratory balance with accuracy ±0.0001 g. In addition, abraded surfaces were subjected to SEM observations in order to determine dominating wear mechanisms. The final result of the examination was determining relative abrasive-wear resistance in relation to the reference specimen. The so defined abrasive-wear resistance index Kb was determined from the following relationship:

$$K_b = \frac{Z_{ww}\rho_b N_b}{Z_{wb}\rho_w N_w} \qquad (1)$$

where K_b – relative abrasive-wear resistance index,
Z_{ww} – weight wear of the reference specimen [g],
Z_{wb} – weight wear of the examined specimen [g],
N_w – number of roll revolutions for the reference specimen,
N_b – number of roll revolutions for the examined specimen,
ρ_w, ρ_b – material densities of the reference and the examined specimens, respectively [g/cm^3].

RESULTS

It can be said on the basis of chemical analyses (see **Table 2**) that, generally, the concentration of carbon in the examined materials ranges within 0.17–0.30%. Hardenability of the examined steels was obtained by introducing alloying elements like manganese, chromium, nickel, molybdenum and, in particular, boron. It is common for all these steels that concentration of boron (0.0008–0.0023%) is higher than the alloying range. Up to 0.25% of nickel is added in order to lower the temperatures of austenitizing and of ductile–brittle transition. An exception is Brinar 400, in that 0.45% of nickel significantly exceeds the alloying concentration. It is worth emphasising that nickel content in Brinar 400 is not declared by its manufacturer. The strongly carbide-forming elements Cr, Mo, and Ti delay diffusion transformations, which results in the higher hardening capacity of the steel. In order to intensify this effect, chromium and molybdenum are often used jointly. The addition of molybdenum is the more important, because chromium (and at its presence also nickel and manganese) increases susceptibility to temper brittleness. In this connection, higher concentrations of molybdenum in steel make its tempering treatment possible. Moreover, additions of aluminium and titanium in the examined steels fix nitrogen and counteract austenite grain coarsening during high-temperature processes like welding. One more feature characteristic for the examined steels is a reduced concentration of noxious impurities of sulphur (0.001–0.002%) and phosphorus (0.007–0.015%).

Table 2. Chemical composition of the examined steels [L. 20–23]: MD – manufacturer's data, OR – own results
Tabela 2. Skład chemiczny analizowanych stali [**L. 20–23**]: MD – dane producenta, OR – badania własne

Element [%]	**Brinar 400**		**Hardox 400**		**Brinar 500**		**Hardox 500**	
	MD	OR	MD	OR	MD	OR	MD	OR
C	≤ 0.18	0.20	≤ 0.15	0.17	≤ 0.28	0.30	≤ 0.27	0.21
Mn	≤ 2.00	1.13	≤ 1.60	1.00	≤ 1.50	0.97	≤ 1.60	0.73
Si	≤ 0.50	0.23	≤ 0.70	0.37	≤ 0.80	0.60	≤ 0.70	0.31
P	≤ 0.015	0.012	≤ 0.025	0.010	≤ 0.020	0.015	≤ 0.025	0.007
S	≤ 0.005	0.001	≤ 0.010	0.002	≤ 0.005	0.001	≤ 0.010	0.002
Cr	≤ 1.55	0.61	≤ 0.50	0.22	≤ 1.50	0.87	≤ 1.00	0.56
Ni	-	0.45	≤ 0.25	0.05	-	0.04	≤ 0.25	0.05
Mo	≤ 0.60	0.31	≤ 0.25	0.01	≤ 0.40	0.20	≤ 0.25	0.01
V	-	0.040	≤ 0.004	0.004	-	0.005	≤ 0.004	0.005
Cu	-	0.025	-	0.006	-	0.020	-	0.004
Al	≤ 0.10	0.071	-	0.035	≤ 0.10	0.038	-	0.057
Ti	-	0.005	-	0.020	-	0.007	-	0.003
Nb	-	0.013	-	0.010	-	0.000	-	0.005
Co	-	0.012	-	0.010	-	0.013	-	0.009
B	≤ 0.005	0.0023	-	0.0016	-	0.0008	-	0.0008
Pb	-	0.003	-	0.003	-	0.002	-	0.003

Microstructures of the examined steels are shown in **Figs. 2** and **3**. The structures of fine-lath martensite are typical for low-carbon steels. Moreover, grain boundaries of former austenite and, within these boundaries, clear features of martensite packing are visible. Sizes of martensite laths are similar and thus differences in properties of these steels result mostly from various carbon concentrations, and not from grain refinement.

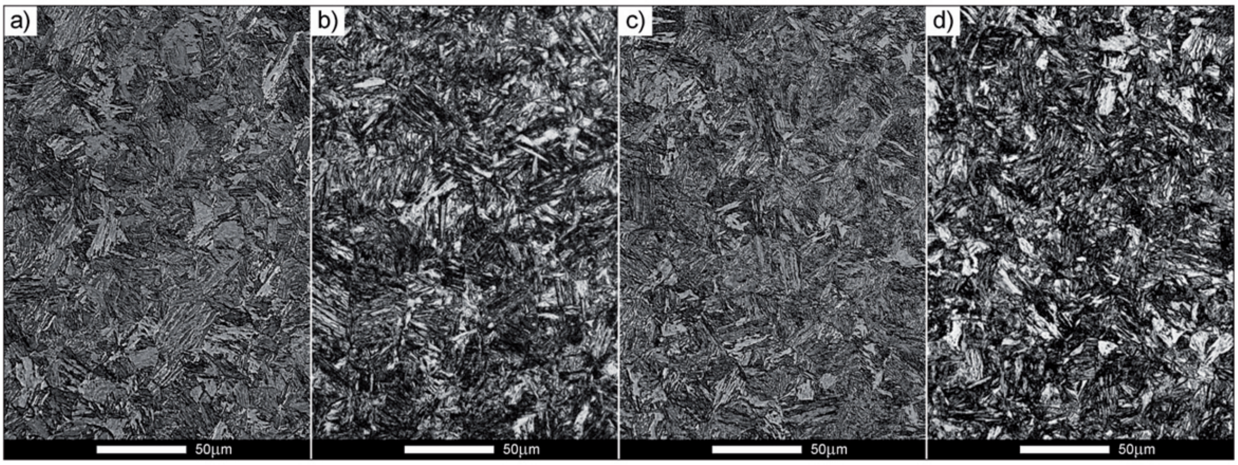

Fig. 2. Microstructures of examined steels: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. Light microscopy, etched with 3% HNO_3

Rys. 2. Obrazy mikrostruktur analizowanych stali: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. Mikroskopia świetlna, stan trawiony 3% HNO_3

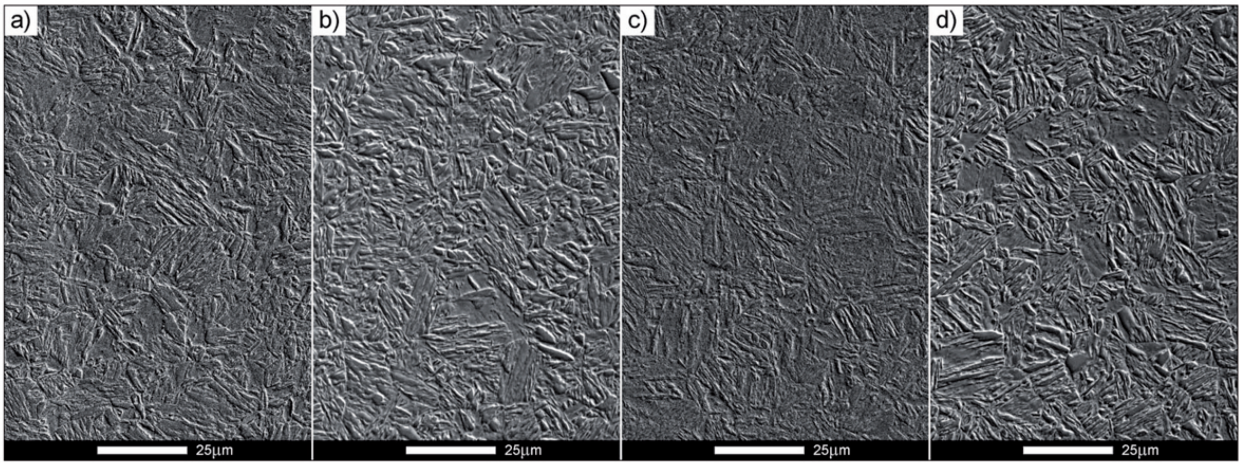

Fig. 3. Magnified images of microstructures of examined steels shown in Fig. 2: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, etched with 3% HNO_3

Rys. 3. Powiększone obrazy mikrostruktur badanych stali pokazanych na **Rys. 2**: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, stan trawiony 3% HNO_3

Values of abrasive-wear resistance index are given in **Fig. 4**. The highest abrasive-wear resistance is shown by Hardox 500 (hardness 504 HBW) and the lowest is shown by Brinar 400 (hardness 410 HBW), while the abrasive-wear resistance index of Brinar 400 is ca. 15% lower. However, abrasive-wear resistance of Brinar 400 is slightly lower than that of Hardox 400 (hardness 406 HBW). In turn, Brinar 500 (hardness 465 HBW) shows almost 8% lower abrasive-wear resistance than Hardox 500. It should be stressed that the hardness of Brinar 500 is lower than that of Hardox 500. So, it should be generally acknowledged that, in this comparison, Hardox steels appear slightly better and the obtained results for the grades Hardox 400 and Brinar 400 are similar.

The obtained results show a clear correlation between the abrasive-wear resistance and hardness of the examined steels, see **Fig. 5**. Therefore, for comparative analysis of martensitic steels, hardness

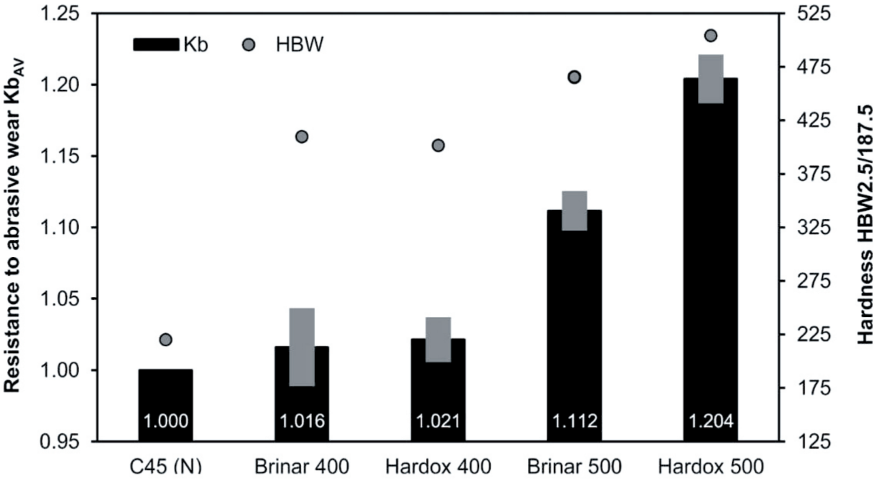

Fig. 4. Average values of abrasive-wear resistance indices K_b and hardness of examined steels
Rys. 4. Średnie wartości wskaźników odporności na zużywanie ścierne K_b oraz twardości badanych stali

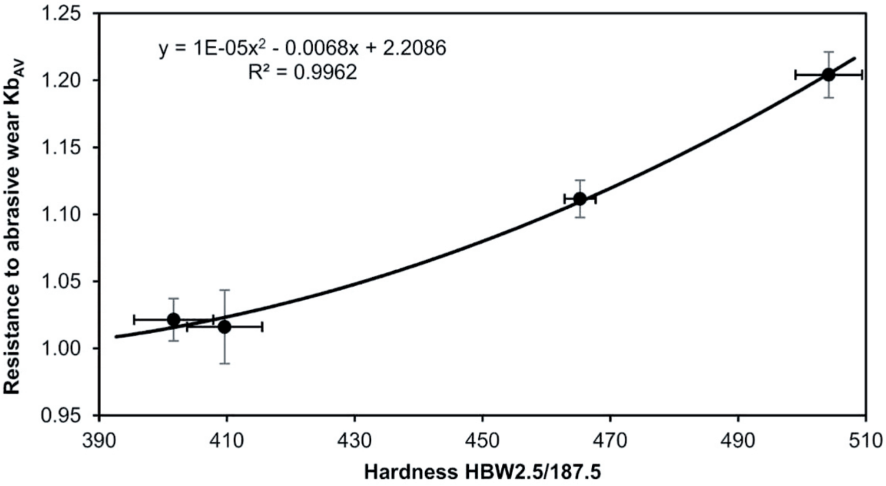

Fig. 5. Relation between relative abrasive-wear resistance index K_b and hardness (HBW) of the examined steel
Rys. 5. Zależność między względnym wskaźnikiem odporności na zużywanie ścierne K_b a twardością (HBW) analizowanych stali

values can be accepted as preliminary criteria of their abrasive-wear resistance. Why the analysed martensitic steels showed an advantage of a few percentage points only over normalized steel C45 being the reference material acc. to GOST 23.208-79 should be considered. Many authors indicate that, in the case of ferritic (and also ferritic-pearlitic) thermally untreated steels, the dominating mechanism of wear is microridging that can cause smaller material losses than microcutting [**L. 24–27**]. This is why, beside the analysed steels Brinar and Hardox, images of reference steel surface are also shown in **Figs. 6** to **9**. Wear mechanisms in the reference material were identified and compared with those in the steels Brinar and Hardox, which should make it possible to confirm the previous suppositions concerning the slightly higher abrasive-wear resistance of martensitic steels in comparison to ferritic-pearlitic steels.

Surfaces of the specimens subjected to abrasive wear show relatively developed topography and make it possible to identify the main, dominating mechanisms of abrasive wear. Surfaces of both Brinar and Hardox steels are similar, even if these steels show different values of abrasive-wear resistance indices. This indicates the occurrence of similar mechanisms of abrasive wear. Small differences can be seen on the surface of Hardox 400 only, where more small scratches oriented at various angles are visible (**Figs. 6b** and **7b**). In other steels, scratches and grooves are mostly parallel to the direction in that loose abrasive material moves on the specimen surface. There are few scratches oriented

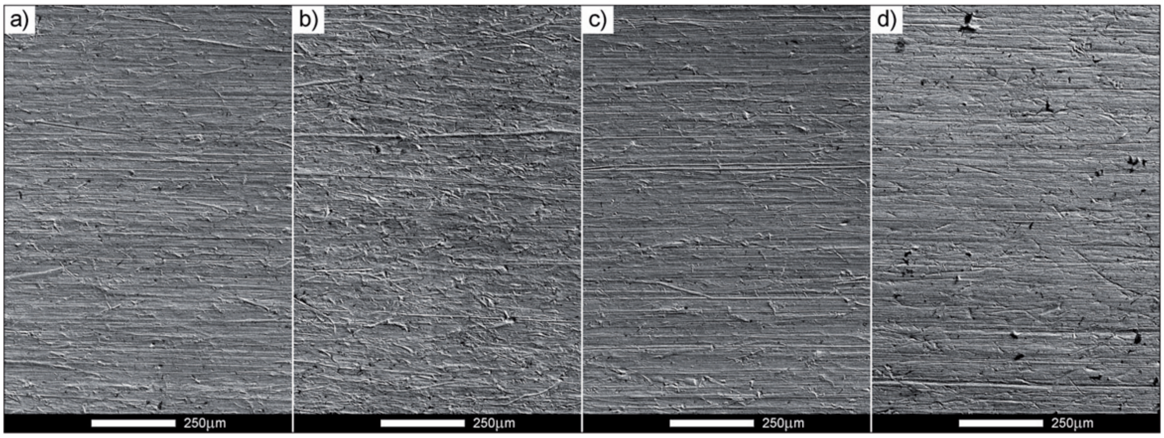

Fig. 6. Surfaces of steel specimens after abrasive-wear testing: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, unetched

Rys. 6. Obrazy powierzchni próbek badanych stali po procesie zużywania ściernego: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, stan nietrawiony

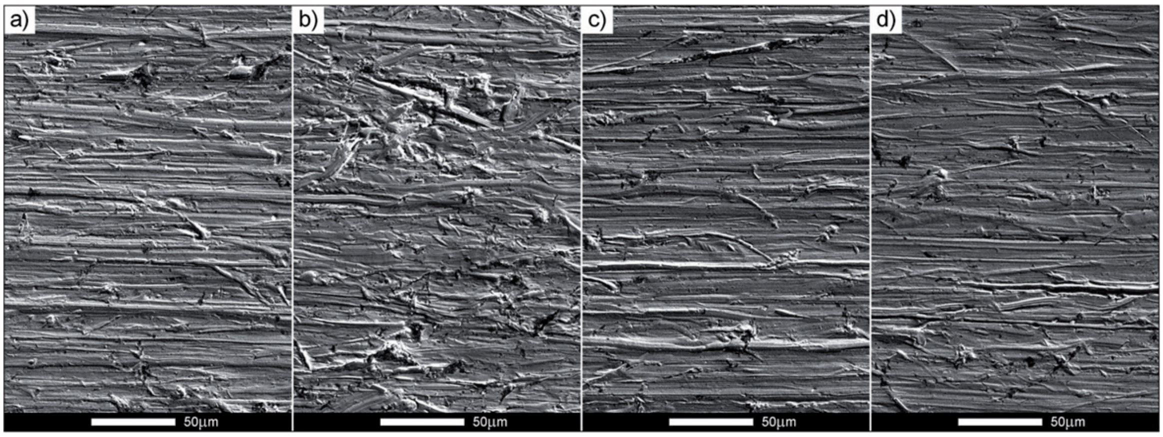

Fig. 7. Magnified images of surfaces shown in Fig. 6: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, unetched

Rys. 7. Powiększone obrazy powierzchni próbek pokazanych na **Rys. 6**: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, stan nietrawiony

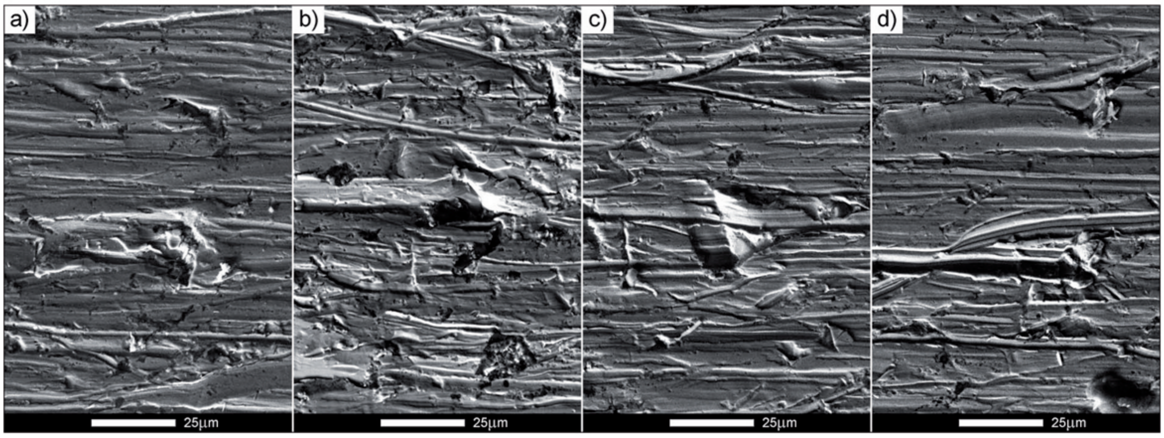

Fig. 8. Magnified images of surfaces shown in Fig. 7: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, unetched

Rys. 8. Powiększone obrazy powierzchni próbek pokazanych na **Rys. 7**: a) Brinar 400, b) Hardox 400, c) Brinar 500, d) Hardox 500. SEM, stan nietrawiony crosswise; however, some crosswise cracks and losses of significant material volumes can be observed. On this basis, it was found that the dominating mechanism of abrasive wear in the examined steels is microcutting and, to a lesser degree, microridging. These mechanisms are typical for martensitic steels. Moreover, plastic deformations of material surface were found, caused by actions of abrasive particles. The particles hitting against steel surface at a large angle clearly remove a significant material volume and cause its plastic deformation at the edge of the created crater, see **Figs. 8b** to **8d**. This can result in significant material losses. The reason is that, under repeated impacts of abrasive particles, the material gathered at the crater edge can be easily separated from the surface as a result of fatigue processes. On the other hand, the particles hitting against the surface at a smaller angle cause the creation of deep grooves with no craters. Moreover, fragments of abrasive particles are still present in some craters, but no typical features of adhesive mechanisms can be found, since, except craters, scratches and grooves are free from abrasive material.

On the surface of the specimen made of normalized steel C45 (**Fig. 9**), scratches and grooves are not parallel to the direction in that loose abrasive material moves on the specimen surface, see **Figs. 9a** and **9b**. The created grooves are deep, with abrasive material in some of them. Plastic deformations during ridging and the dominating fatigue mechanism are clearly visible. Therefore, in relation to qualitative evaluation, the mechanism dominating in martensitic steels causes their uniform, predictable wear. However, in ferritic-pearlitic steels, this is excluded by the domination of the fatigue mechanisms. As was already mentioned, the T-07 tester serves for comparative analysis of steels belonging to one structurally similar group, and quantitative analysis must be always complemented with qualitative analysis of the surfaces subjected to abrasion.

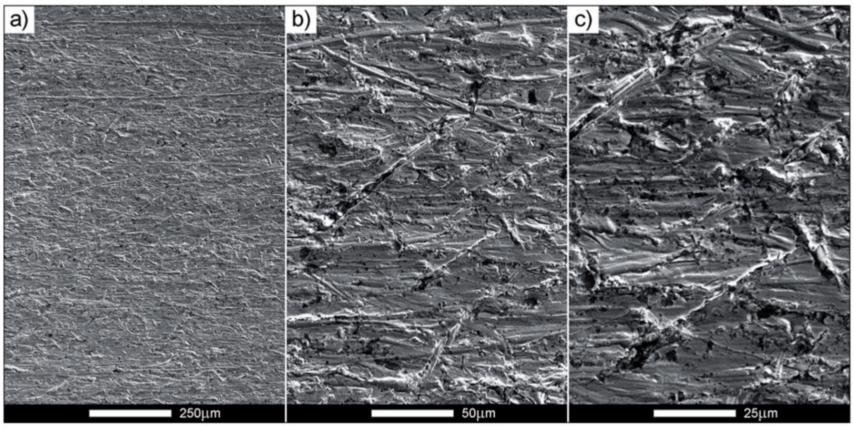

Fig. 9. Surfaces of C45 specimens after abrasive-wear testing at various magnifications. SEM, unetched

Rys. 9. Obrazy powierzchni próbek ze stali C45 po procesie zużywania ściernego w różnej skali powiększenia. SEM, stan nietrawiony

SUMMARY

Spectral chemical analyses of the examined steels show that concentrations of carbon range within 0.17–0.30%. The hardening capacity of these steels was obtained by additions of alloying elements like manganese, chromium, nickel, molybdenum and, especially, boron. Moreover, the presence of other elements not specified in manufacturer's information materials was found. A common feature of all the examined steels was the alloying concentration of boron (0.0008–0.0023%) and the reduced concentration of noxious impurities like sulphur (0.001–0.002%) and phosphorus (0.007–0.015%).

With respect to microstructure, it was shown that the examined steels are characterised by structures of fine-lath tempered martensite, typical for low-carbon steels. Martensite laths are of similar sizes; therefore, differences in properties of the steels result mostly from various carbon concentrations and not from various microstructure refinement degrees.

The tests showed that steel Hardox 500 is characterised by the highest relative abrasive-wear resistance index (1.2014). Values of these indices for Hardox 400 (1.021) and Brinar 400 (1.016) are ca. 15% lower and for Brinar 500 (1.112) – ca. 8% lower. Moreover, on the basis of the obtained results, a clear correlation was found between the abrasive wear and the hardness of the steels. Steels with lower hardness are characterised by lower resistance to abrasive wear. Therefore, in the case of martensitic steels, hardness can be accepted as a preliminary criterion at comparative analysis of abrasive-wear resistance.

In the case of the examined steels, microcutting was identified as the main mechanism of abrasive wear and, to a lesser degree, microridging. Abrasive particles hitting at a large angle against steel surface clearly removed a significant material volume and caused its plastic deformation at the crater edge, which finally resulted in significant material losses. In turn, the particles hitting at a smaller angle created deep grooves without forming craters. The mechanisms observed in the examined steels are typical for steels with martensitic structures.

REFERENCES

1. Buchely M.F., Gutierrez J.C., Leon L.M., Toro A., The effect of microstructure on abrasive wear of hardfacing alloys, Wear 259(1–6) (2005) 52–61.
2. Choo S.H., Kim C.K., Euh K., Lee S., Jung J.Y., Ahn S., Correlation of microstructure with the wear resistance and fracture toughness of hardfacing alloys reinforced with complex carbides, Metall. Mater. Trans. A 31(12) (2000) 3041–3052.
3. Chotěborský R., Hrabě P., Müller M., Savková J., Jirka M., Abrasive wear of high chromium Fe-Cr-C hardfacing alloys, Re. Agr. Eng. 54(4) (2008) 192–198.
4. KenchiReddy K.M., Jayadeva C.T., The Effects of Welding Processes and Microstructure on 3 Body Abrasive Wear Resistances for Hardfacing Deposits, Bonfring Int. J. Ind. Eng. Manage. Sci. 2(2) (2012) 28–34.
5. Konat Ł., Structures and properties of Hardox steels and their application possibilities in conditions of abrasive wear and dynamic loads, Ph.D. Thesis, Wrocław, 2007 (in Polish).
6. Dudziński W., Konat Ł., Pękalski G., Structural and strength characteristics of wear-resistant martensitic steels, Arch. Foundry Eng. 8(2) (2008) 21–26.
7. JFE EVERHARD. JFE-EH Series. Abrasion-Resistant Steel Plate. Information materials of JFE Steel Corporation (in Polish).
8. Hardox – Das Verschleiβblech der vielen Möglichkeiten. Wydawnictwo SSAB-Oxelösund. Materiały informacyjne huty SSAB-Oxelösund, 2002.
9. Yoon-Suk Ch., Sung-Joon K., Ik-Min P., Kwang-Woo K., In-Suk Y., Boron distribution in a low-alloy steel, Metals and Materials 3(2) (1997) 118–124.
10. Łętkowska B., Effect of heat treatment on structure and selected properties of steels B27 and 28MCB5, Ph.D Thesis, Wrocław, 2013 (in Polish).
11. Dudziński W., Konat Ł., Pękalski G., Structural and strength characteristics of wear-resistant martensitic steels, Arch. Foundry Eng. 8(2) (2008) 21–26.
12. Cegiel L., Konat Ł., Pawłowski T., Pękalski G., Hardox steels – new generation of constructional materials for surface mining machines, Węgiel Brunatny 3(56) (2006) (in Polish).
13. Dudziński W., Konat Ł., Pękalski G., Pękalska L., Structures and properties of Hardox 400 and Hardox 500 steels, Materials Engineering 3(27) (2006) 139–142 (in Polish).
14. Pękalski G., Selected material issues of surface mining machine parts exposed to abrasive wear and possibilities of using Hardox steels, Surface Mining 4/5 (47) (2005) 47–53 (in Polish).
15. Frydman S., Konat Ł., Pękalski G., Fractographic analysis of Hardox 400 and Hardox 500 steels at impact testing, Surface Mining 49(3/4) (2007) 36–47.
16. Frydman S., Konat Ł., Pękalski G., Impact and fractographic characteristics of Hardox 400 and Hardox 500 steels in normalized condition, Surface Mining 49(3/4) (2007) 48–56.
17. Białobrzeska B., Kostencki P., Abrasive wear characteristics of selected low-alloy boron steels as measured in both field experiments and laboratory tests, Wear 328–329 (2015) 149–159.
18. Swanson P.A., Comparison of laboratory and field abrasion tests, in: K.C. Ludema, Proceedings of the International Conference on Wear of Materials, ASME, NewYork, 1985, 519–525.
19. Swanson P.A., Comparison of laboratory abrasion tests and field tests of materials used in tillage equipment, in: A.W. Ruff, R.G. Bayer (Eds.), Tribology: Wear Test Selection for Design and Application, ASTM STP 1199, ASTM International, W. Conshohocken, PA, USA, 1993, 80–99.
20. http://www.ilsenburger-grobblech.de/fileadmin/mediadb/ilg/infocenter/downloads/werkstoffblaetter/Verschleissfeste_Staehle_BRINAR_400_Cr.pdf
21. http://www.ilsenburger-grobblech.de/fileadmin/mediadb/ilg/infocenter/downloads/werkstoffblaetter/verschleissfeste_staehle_brinar500.pdf
22. http://hardox400.pl/index.php/hardox400
23. http://hardox500.pl/index.php/hardox500
24. Kazemipour M., Shokrollahi H., Sharafi S., The influence of the matrix microstructure on abrasive wear resistance of heat-treated Fe–32Cr–4.5C wt% hardfacing alloy, Tribol. Lett. 39 (2010) 181–192.

25. Hokkirigawa K., Kato K., An experimental and theoretical investigation of ploughing, cutting and wedge formation during abrasive wear, Tribol. Int. 21 (1988) 51–57.
26. Sapate S.G., Selokar A., Garg N., Experimental investigation of hard faced martensitic steel under slurry abrasion conditions, Mater. Des. 31 (2010) 4001–4006.
27. Turenne S., Lavallee F., Masounave J., Matrix microstructure effect on the abrasion wear resistance of high-chromium white castiron, J. Mater. Sci. 24 (1989) 3021–3028.