Łukasz KONAT[*], **Jerzy NAPIÓRKOWSKI**[**], **Beata BIAŁOBRZESKA**[*]

STRUCTURAL PROPERTIES AND ABRASIVE-WEAR RESISTANCE OF BRINAR 400 AND BRINAR 500 STEELS

WŁAŚCIWOŚCI STRUKTURALNE I ODPORNOŚĆ NA ZUŻYWANIE ŚCIERNE STALI BRINAR 400 I BRINAR 500

Key words: steels resistant to abrasive wear, structural and mechanical properties, Brinar steel, abrasive soil mass.

Abstract In the paper, microstructures and the examination results of abrasive-wear resistance of steel grades Brinar 400 and Brinar 500 are presented. It was found on the grounds of light and electron scanning microscopy that these steels are characterised by subtle differences in microstructures, influencing their mechanical and usable properties. In as-delivered condition, the steels have fine-grained structure with post-martensitic orientation, containing few particles of carbide phases. Such microstructures of Brinar steels and the performed chemical analyses indicate that their properties are formed during specialised operations of thermo-mechanical rolling. Generally, it can be said that the examined steels were designed according to the accepted standards of material engineering, related to low-alloy, high-strength, and abrasive-wear resistant martensitic steels. According to the above, the obtained results of structural examinations of Brinar 400 and Brinar 500 steels were referred to real abrasive-wear indices obtained by the spinning bowl method with use of various abrasive soil masses. The tests carried-out in light soil (loamy sand), medium soil (sandy loam), and in heavy soil (loam), as well as hardness measurements showed strict dependence of abrasive-wear indices on microstructures and the heat-treatment condition of the examined steels. Examination results of abrasive-wear resistance of Brinar steels were compared with those of steel 38GSA in normalised conditions.

Słowa kluczowe: stale odporne na zużywanie ścierne, własności strukturalne i mechaniczne, stal Brinar, glebowa masa ścierna.

Streszczenie W pracy przedstawiono budowę strukturalną oraz wyniki badań odporności na zużywanie ścierne stali Brinar 400 i Brinar 500. Na podstawie przeprowadzonych metodami mikroskopii świetlnej i skaningowej badań wykazano, że stale te cechują się subtelną różnicą w budowie strukturalnej rzutującą na ich charakterystyki wytrzymałościowe i użytkowe. W stanie dostarczenia rozpatrywane stale charakteryzują się drobnoziarnistą strukturą o orientacji pomartenzytycznej z nielicznymi wydzieleniami faz węglikowych. Powyższy typ budowy strukturalnej stali Brinar oraz przeprowadzone analizy spektralne składu chemicznego wskazują, iż ich właściwości kształtowane są w toku specjalistycznych zabiegów termomechanicznego walcowania. Ogólnie rzecz biorąc, można stwierdzić, że badane stale zostały zaprojektowane zgodnie z przyjętymi kanonami inżynierii materiałowej odnośnie do niskostopowych, wysokowytrzymałych stali martenzytycznych odpornych na zużywanie ścierne. Zgodnie z powyższym uzyskane wyniki badań strukturalnych stali Brinar 400 i Brinar 500 odniesiono do rzeczywistych wskaźników odporności na zużycie ścierne uzyskanych metodą „wirującej misy” z wykorzystaniem zróżnicowanych glebowych mas ściernych. Zrealizowane badania w glebie lekkiej (piasek gliniasty), glebie średniej (glina lekka) oraz glebie ciężkiej (glina zwykła), a także przeprowadzone pomiary twardości wykazały ścisłą zależność uzyskanych wskaźników odporności na zużywanie ścierne od budowy fazowej oraz od stanu obróbki cieplnej badanych stali. Wyniki badań odporności na zużywanie ścierne stali Brinar odniesiono porównawczo do stali 38GSA w stanie normalizowanym.

---

[*] Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, e-mail: lukasz.konat@pwr.edu.pl.
[**] University of Warmia and Mazury in Olsztyn, Michała Oczapowskiego 2, 10-719 Olsztyn, Poland, e-mail: napj@uwm.edu.pl.

INTRODUCTION

The currently built and operated large engineering objects, as well as other facilities used in heavy industry (e.g. in rock raw material mining), are the constructions in that the introduction of material changes, on one hand, is extremely difficult and requires mature decisions and, on the other hand, is often a necessary and indispensable undertaking. This results mostly from economic aspects of the given problem and also from the environmental strategy. From the material viewpoint, low-alloy medium-carbon steels are most often used for parts exposed to abrasive wear and high pressures. In the zones of the most intensive abrasive wear, the use of pad-welded layers is also common. This solution is expected to increase the durability of machine parts subjected to abrasive wear. However, this requires the use of advanced welding techniques and electrodes for pad welding with complex chemical compositions, which increases the costs of manufacture and the operation of the machines. Therefore, approximately since the mid-1970s, low-alloy high-strength abrasive-wear resistant steels with post-martensitic structure have been more and more popular. These steels are characterised by uniform structural and mechanical properties on the entire cross-sections of metallurgical products, resulting from precisely selected chemical compositions, and specialised operations of thermo-mechanical rolling. In these materials, strong pressure is also put on the weldability criterion. Significant reduction of the CEV index of most grades of low-alloy abrasive-wear resistant steels is realised by micro-additions of niobium, molybdenum, titanium, and boron. These elements make it possible to move phase transition curves towards longer times, create very hard and stable carbides, nitrides, and carbonitrides, also hampering austenite grain coarsening during heat treatment operations. In addition, the reduced concentration of phosphorus and sulphur decreases the ductile-brittle transition temperature, allowing clear plastic features and satisfactory impact strength to be maintained at negative Celsius temperatures (even at -40°C). It should be emphasised that, with regard to relatively limited application areas of these materials, their evaluation criteria belong rather to qualitative than to quantitative ones. It results from previous investigations of the Authors that, for a given metallic material with the declared above-mentioned features, there is no unequivocal criterion of usability for a specific constructional application. From the viewpoint of a potential user of these metallic materials, no proper characteristics have been developed of their behaviour in various working conditions in a function of welding parameters, heat treatability, ladle chemical analysis, or even mechanical properties. Most of available data related to the concerned group of materials are of advertising nature and make no ground for unequivocal evaluation of their usable properties. Thus, in the Authors' opinion, it is necessary to accept a suitable strategy of laboratory testing of low-alloy abrasive-wear resistant steels, which would make it possible to correlate their selected microstructural and mechanical properties with real wear resistance indices. Such a laboratory strategy has been implemented at Wrocław University of Technology for several years in co-operation with the Department of Building and Operation of Vehicles and Machines of *University* of Warmia and Mazury in Olsztyn. It is mostly related to a qualitative description of the behaviour of selected material groups in the environment of soil abrasive mass, as well as in the environment of mining coal and rock raw materials **[L. 1–15]**. This strategy strives for linking the indices characterising abrasive-wear resistance of the material with its structural properties, on the grounds of numerous results of metallographic, chemical, and mechanical examinations. In this connection, the examination results of Brinar steels presented in this paper only make up part of the research strategy related to the selected steels classified as abrasive-wear resistant steels.

MATERIAL AND METHODOLOGY

Abrasive-wear resistance tests were carried-out by the spinning bowl method on two grades of steels delivered by Ilsenburger Grobblech GmbH, i.e. Brinar 400 and Brinar 500. According to the manufacturer **[L. 16–17]**, these steels are defined as abrasive-wear resistant steels, water-quenched, and tempered.

Brinar 400 steel is delivered in form of sheets up to 80 mm thick. Its hardness in as-delivered condition is 360–440 HB. According to catalogue data, this steel can be subjected to removal machining and to cold working. Minimum bend radius of sheets is equal to triple sheet thickness for both longitudinal and transverse directions. In order to maintain the declared usable properties, it is not recommended to heat it above 250°C. Plastic hot forming of these sheets is also possible. The recommended temperature range for this process is 850–1000°C, with intermediate heat-treatment operations adequate for the required mechanical properties. Moreover, the Brinar 400 steel can be subjected to gas cutting and welding (with all the available methods). Sheets over 30 mm thick do not require preheating, but preheating to 100–175°C is recommended for sheets 30–80 mm thick.

Brinar 500 steel is available in form of sheets up to 60 mm thick. Its typical hardness in as-delivered condition is 480 HB. This steel can be processed by removal machining and by cold working. Minimum bend radii are equal to seven times sheet thickness for the transverse direction and to ten times sheet thickness for the longitudinal direction. Hot forming of this steel is not recommended. However, it can be subjected to gas cutting and welding with all the available methods. Sheets below 10 mm thick do not require preheating, but preheating to 100–175°C is recommended for sheets

10–60 mm thick. In order to maintain the declared high hardness, it is not recommended to heat Brinar 500 above 250°C.

As a reference material for the examined Brinar steels, hot-worked and normalized steel 38GSA was used. This was dictated by numerous references to the results of previous research works related to abrasive wear in abrasive soil mass.

For examinations, samples of all the analysed steels were taken from the sheets, using the methods guaranteeing their unchanged microstructures. Specimens were cut-out with high-energy stream of water with abrasive material or by spark erosion in distilled water. Finishing to the required roughness was carried-out by grinding and polishing.

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

Microstructural observations at magnification between 100 and 1000 times were performed using an optical microscope Nikon Eclipse MA200 coupled with a digital camera Nikon DS-Fi2 with NIS Elements software. Observations at larger magnifications and chemical microanalyses were performed using a scanning electron microscope Joel JSM-6610A. Accelerating voltage 20 kV and material contrast using SE detectors were applied.

Brinell hardness measurements of the specimens were made acc. to EN ISO 6506-1:2014-12, using a hardness tester ZWICK ZHU 187.5 with a ball of sintered carbides dia. 2.5 mm, under the load of 1875 kG acting for 15 s. Measurements were made on the specimens previously subjected to microstructure observations in their core areas. The obtained hardness values were arithmetic averages of at least five measurements.

Abrasive-wear resistance tests were carried-out by the spinning bowl method using a MZWM–1 device **[L. 6]**. The general layout and view of the device are shown in Fig. 1. The tests were performed on cuboidal specimens 30x25x10 mm, 18 specimens from each of the steel grade. During the tests, two specimens were placed in the machine, one of each of the analysed materials. Each specimen travelled a friction distance of 20000 m at approximately 1.7 m/s. Masses of the specimens previously cleaned in an ultrasonic washer were measured every 2000 m on laboratory scales with accuracy to 0.0001 g. At each stage of testing, the soil mass was replaced with a new mass and initial weights of the specimens were determined. Characteristics of abrasive soil mass are given in **Table 1**. The granulometric composition of soil was determined using a laser particle size meter Mastersizer 2000+Hydro. Soil moisture was determined by weighing the solid phase after drying at 105°C. The examinations were performed with use of a wet abrasive mass.

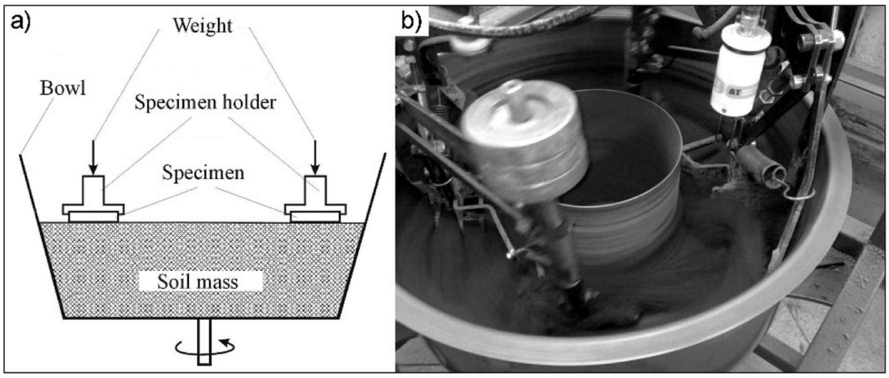

Fig. 1. "Spinning bowl" laboratory test stand [L. 18]: a) general layout and main operating elements; b) fragment of the device during operation

Rys. 1. Laboratoryjne stanowisko zużyciowe typu „wirująca misa" **[L. 18]**: a) ogólny schemat urządzenia z oznaczeniem głównych elementów wykonawczych; b) fragment urządzenia w czasie jego pracy

Table 1. Characteristics of abrasive soil mass

Tabela 1. Charakterystyka glebowej masy ściernej

Soil type	**Granulometric group**	**Fraction content [%]**			**Actual moisture [wt%]**
		Sand 2.00–0.05 mm	Dust 0.050–0.002 mm	Silt < 0.002 mm	
LIGHT	Loamy sand	82.7	8.4	8.9	10–12
MEDIUM	Sandy loam	58.3	22.5	19.2	11–13
HEAVY	Loam	38.0	35.7	26.3	12–15

RESULTS

Table 2 presents the results of spectral chemical analyses and selected mechanical properties of the examined steels. **Figures 2–4** show representative as-delivered microstructures of the steels Brinar 400 and Brinar 500. The issues related to properties of the steel 38GSA in as-delivered condition were previously considered by the authors **[L. 18–19]**, so this information is omitted in this paper.

Chemical analyses of the Brinar steels showed real concentrations of selected alloying elements lower than those announced by the manufacturer. An exception can be the concentration of carbon, where slight exceeding of the declared maximum concentration was noted in both materials **(Table 2)**. Moreover, the presence of elements not listed in manufacturer's specification was found in all the analysed cases. These elements include mainly nickel (not specified for Brinar 400) and also micro-additions of copper, titanium, cobalt and, in the case of Brinar 500, also boron.

Generally, excluding 38GSA, the concentration of carbon in the examined Brinar steels ranges within 0.20 to 0.30%. From the viewpoint of hardenability and the declared hardness levels, these values seem to be insufficient. This is why the following alloying additions and micro-additions are introduced to these steels: manganese, chromium, nickel (Brinar 400 only), molybdenum, titanium, and boron.

The strongly carbide-forming elements Cr, Mo, and Ti impede diffusion transformations, at the same time increasing hardening capacity. Chromium and molybdenum are applied jointly, because chromium is likely to increase the susceptibility of steel to temper brittleness. Micro-additions of aluminium and titanium bond nitrogen and counteract grain coarsening during austenitization being a part of heat treatment. Nickel in Brinar 400 is added in order to decrease the temperatures of austenitizing and of ductile-brittle transition. A characteristic feature of the examined steels is also the reduced concentration of harmful impurities.

Table 2. Chemical compositions and selected mechanical properties of steels on the grounds of the authors' results and manufacturer's data [L. 16–17, 18–20]

Tabela 2. Składy chemiczne i wybrane właściwości mechaniczne badanych stali na podstawie badań własnych oraz danych producenta **[L. 16–17, 18–20]**

Element [wt%]	38GSA		BRINAR 400		BRINAR 500	
	OR – own results; MD – manufacturer's data					
	OR[1]	MD[2]	OR[3]	MD[3]	OR[3]	MD[3]
C	0.38	0.34–0.42	0.20	≤ 0.18	0.30	≤ 0.28
Mn	0.97	0.70–1.10	1.13	≤ 2.00	0.97	≤ 1.50
Si	0.90	0.80–1.10	0.23	≤ 0.50	0.60	≤ 0.80
P	0.011	≤ 0.035	0.012	≤ 0.015	0.015	≤ 0.020
S	0.007	≤ 0.040	0.001	≤ 0.005	0.001	≤ 0.005
Cr	0.05	≤ 0.30	0.61	≤ 1.55	0.87	≤ 1.50
Ni	0.08	≤ 0.30	0.45	-	0.04	-
Mo	0.02	-	0.31	≤ 0.60	0.20	≤ 0.40
Cu	0.25	≤ 0.30	0.03	-	0.02	-
Al	0.02	0.02–0.06*	0.07	≤ 0.10	0.04	≤ 0.10
Ti	0.002	0.03–0.06*	0.005	-	0.007	-
Co	0.01	-	0.01	-	0.01	-
B	-	-	0.0023	≤ 0.005	0.0008	-
HBW	272 ±7	440	412 ±2	360–440	472 ±4	480
R_e [MPa]	-	1200	-	1100	-	1350
R_m [MPa]	-	1500	-	1300	-	1500
A_5 [%]	-	8	-	8	-	8
KCV_{-20} [J/cm^2]	-	30**	-	25	-	25

[1] Normalized; [2] quenched (870–900°C/water) and tempered (200–250°C in air or oil); [3] as-delivered;
* If jointly: Al+Ti ≥ 0.03 wt%; **KCU_{+20}

Microscopic examinations of both grades of Brinar steels in as-delivered condition showed similar microstructures of lath hardening martensite, see **Figs. 2–4**. The microstructure morphology of Brinar 400 **(Figs. 2a–4a)** was of block nature with relatively small variability of crystallographic orientation within the created packages. However, in Brinar 500 **(Figs. 2b–4b)**, a much more random variability of crystallographic orientation of martensite blocks within the created packages and within grains of former austenite was found.

It can be said that the above-mentioned difference results mostly from slightly different carbon concentrations in both steels. Moreover, not too many particles of carbide phases were observed in both materials, which indicate low-temperature tempering of these steels or even the omission of tempering at heat treatment.

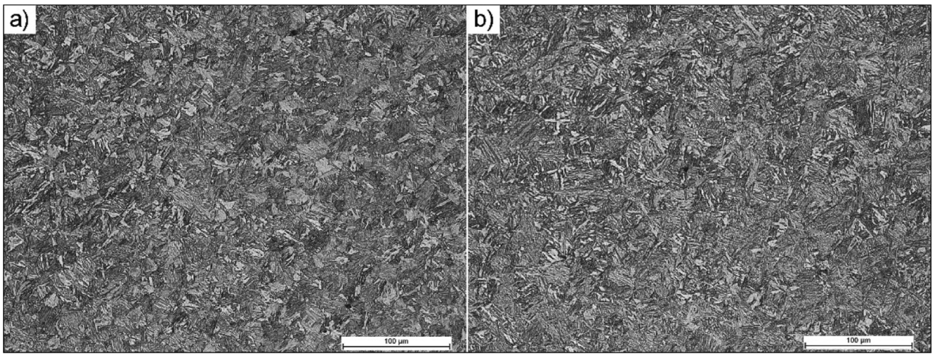

Fig. 2. Microstructures of Brinar steels as-delivered: a) Brinar 400; b) Brinar 500. Fine-grained hardening structures with no clear banding features. Etched with 2% HNO_3; LM

Rys. 2. Mikrostruktura stali Brinar w stanie dostarczenia: a) stal Brinar 400; b) stal Brinar 500. Drobnoziarniste struktury hartowania bez wyraźnych cech pasmowości. Traw. 2% HNO_3; LM

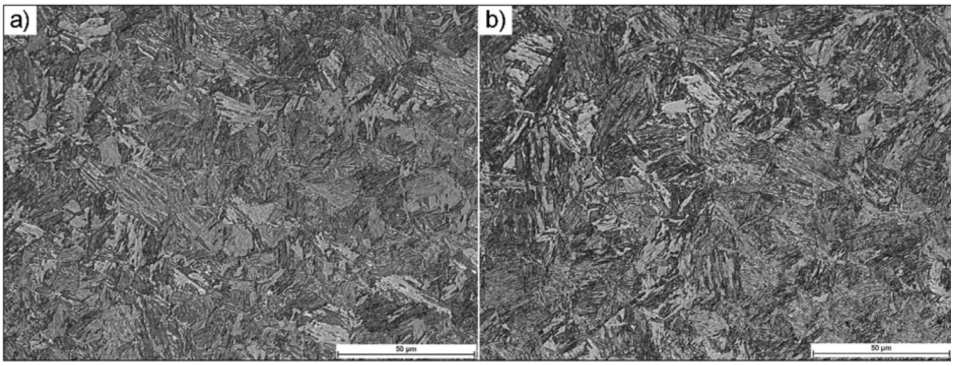

Fig. 3. Magnified images from Fig. 2. a) Brinar 400; b) Brinar 500. Morphologically similar structures of fine-lath hardening martensite. Etched with 2% HNO_3; LM

Rys. 3. Powiększony obraz mikrostruktury stali Brinar pokazanej na **Rys. 2**: a) stal Brinar 400; b) stal Brinar 500. Pod względem morfologii, zbliżone do siebie struktury drobnolistwowego martenzytu hartowania. 2% HNO_3; LM

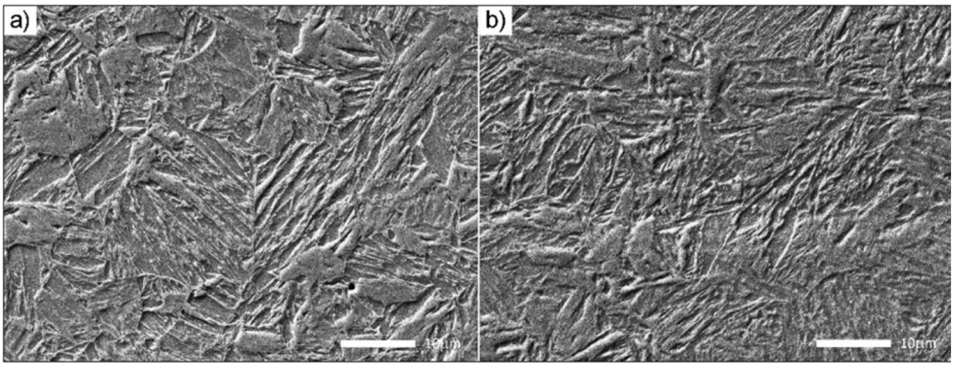

Fig. 4. Magnified images from Fig. 3. a) Brinar 400 – fine-lath hardening martensite with characteristic arrangement in form of packages; b) Brinar 500 – fine-lath hardening martensite with significantly diversified block orientation in individual packages. Etched with 2% HNO_3; SEM

Rys. 4. Powiększony obraz mikrostruktury stali Brinar pokazanej na **Rys. 3**: a) stal Brinar 400 – mikrostruktura drobnolistwowego martenzytu hartowania o charakterystycznym ułożeniu w postaci pakietów; b) stal Brinar 500 – mikrostruktura drobnolistwowego martenzytu hartowania o znacznym zróżnicowaniu orientacji blokowej w poszczególnych pakietach. Traw. 2% HNO_3; SEM

Results of abrasive-wear resistance of the analysed steels are presented in **Table 3** and **Fig. 5**. Surface images of specimens after abrasive-wear tests are shown in **Figs. 6–11**. The results indicate that Brinar 500 is characterised by the highest resistance to the action of abrasive soil mass (the smallest mass loss). The advantage of this steel over the other considered grades turns out mainly in light soil (loamy sand) and heavy soil (loam). In light soil, average mass loss on a friction distance of 20000 m for Brinar 500 was smaller in comparison to Brinar 400 and 38GSA by ca. 0.11 g and ca. 3.39 g, respectively. In medium soil, a very significant advantage of Brinar 500 was found only in comparison to 38GSA in normalized condition, the difference of mass losses being ca. 1.62 g. In this soil, abrasive-wear resistance on the analysed maximum friction distance was almost identical for both Brinar grades, with a slight advantage of Brinar 400.

Table 3. Mass loss values of 38GSA and Brinar specimens on friction distance 20000 m in various abrasive soil masses

Tabela 3. Zestawienie zużycia masowego próbek stali 38GSA oraz stali Brinar na drodze tarcia 20000 m w różnych rodzajach glebowych mas ściernych

Soil mass	**38GSA**		**BRINAR 400**		**BRINAR 500**	
	Mass loss: AV – average value [g]; UV – unit value [g/km/cm^2]					
	AV	UV	AV	UV	AV	UV
LIGHT	2.4049	0.0160	0.8031	0.0054	0.6374	0.0042
MEDIUM	2.2084	0.0147	0.5805	0.0039	0.5896	0.0039
HEAVY	3.7087	0.0247	0.4307	0.0029	0.3231	0.0022

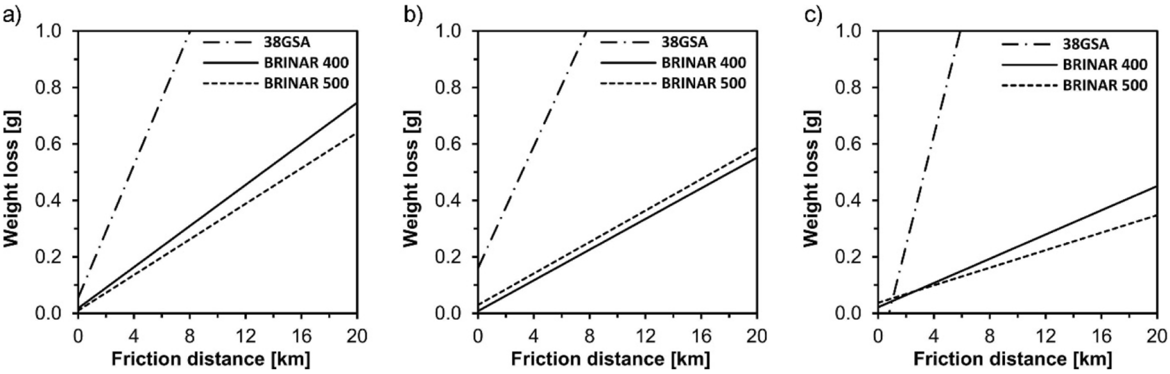

Fig. 5. Mass loss of steels in function of friction distance. Tests carried-out in soil masses: a) light, b) medium, c) heavy

Rys. 5. Ubytek masy badanych stali w funkcji drogi tarcia. Próby zrealizowane w masie glebowej: a) lekkiej, b) średniej, c) ciężkiej

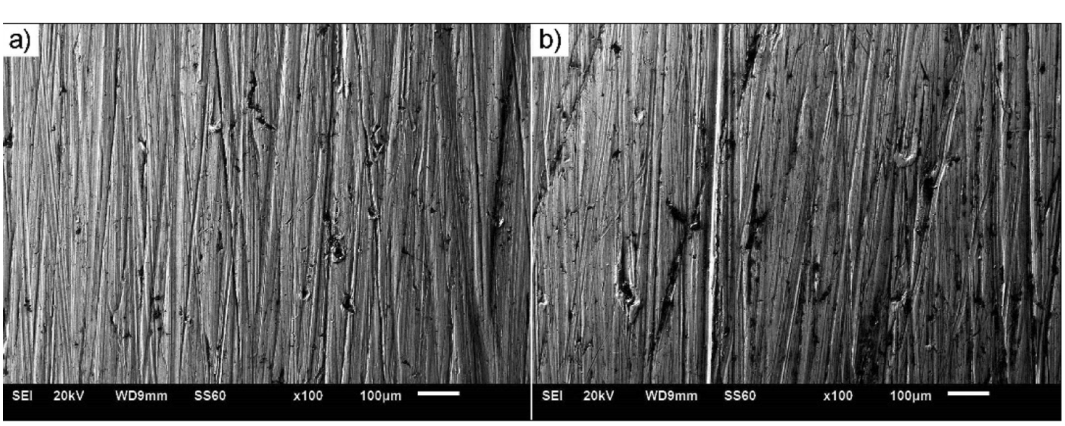

Fig. 6. Surfaces of examined steel specimens after abrasive-wear test in light soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 6. Obrazy powierzchni próbek badanych stali po procesie zużywania ściernego w glebie lekkiej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

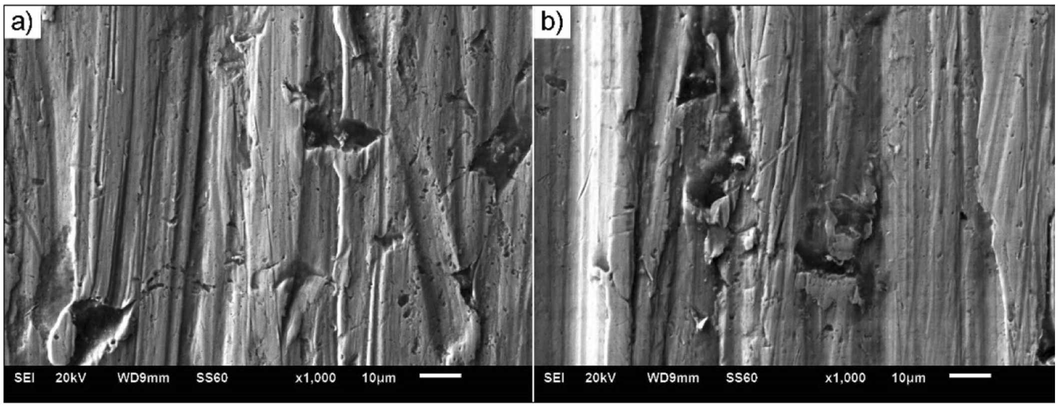

Fig. 7. Magnified images from Fig. 6 after abrasive-wear test in light soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 7. Powiększone obrazy powierzchni próbek pokazanych na rys. 6 po procesie zużywania w glebie lekkiej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

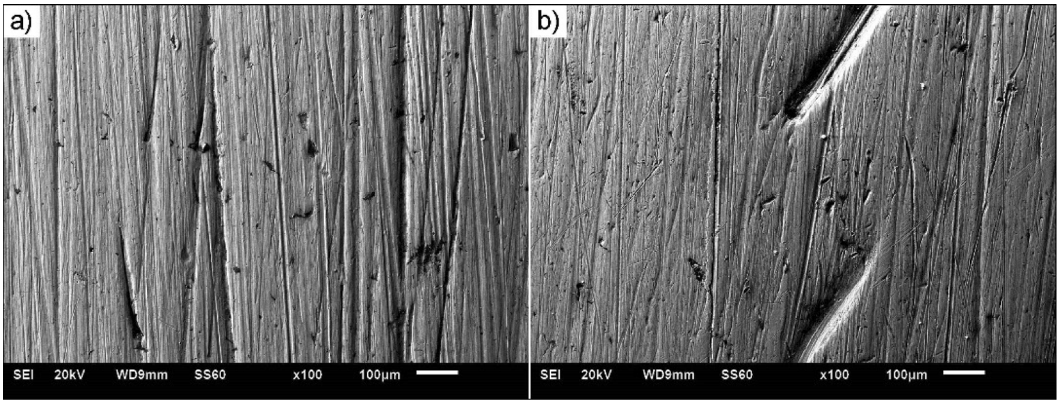

Fig. 8. Surfaces of examined steel specimens after abrasive-wear test in medium soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 8. Obrazy powierzchni próbek badanych stali po procesie zużywania ściernego w glebie średniej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

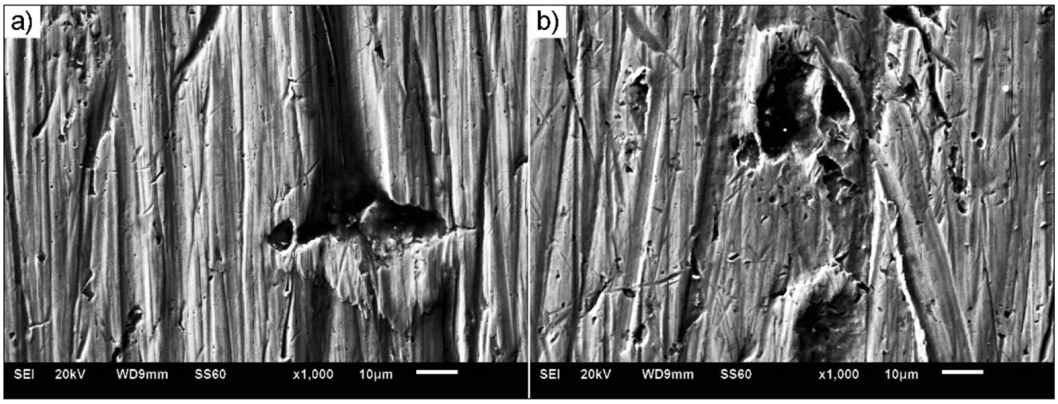

Fig. 9. Magnified images from Fig. 8 after abrasive-wear test in medium soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 9. Powiększone obrazy powierzchni próbek pokazanych na rys. 8 po procesie zużywania w glebie średniej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

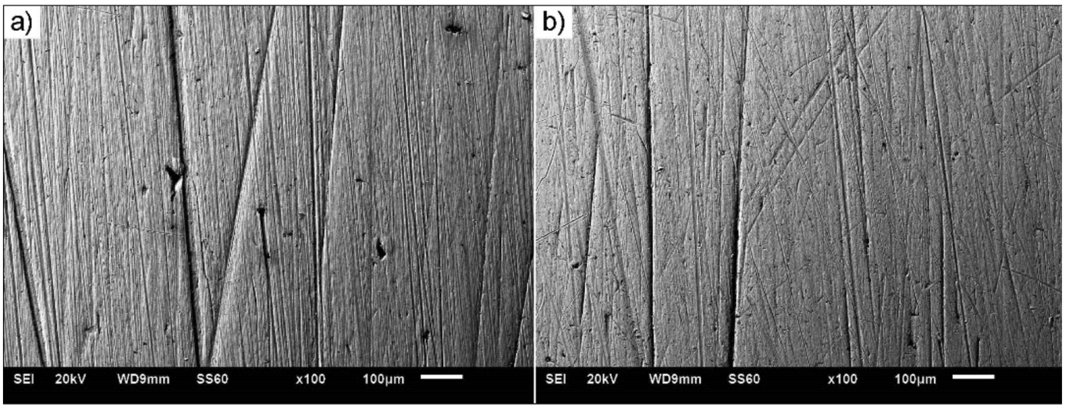

Fig. 10. Surfaces of examined steel specimens after abrasive-wear test in heavy soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 10. Obrazy powierzchni próbek badanych stali po procesie zużywania ściernego w glebie ciężkiej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

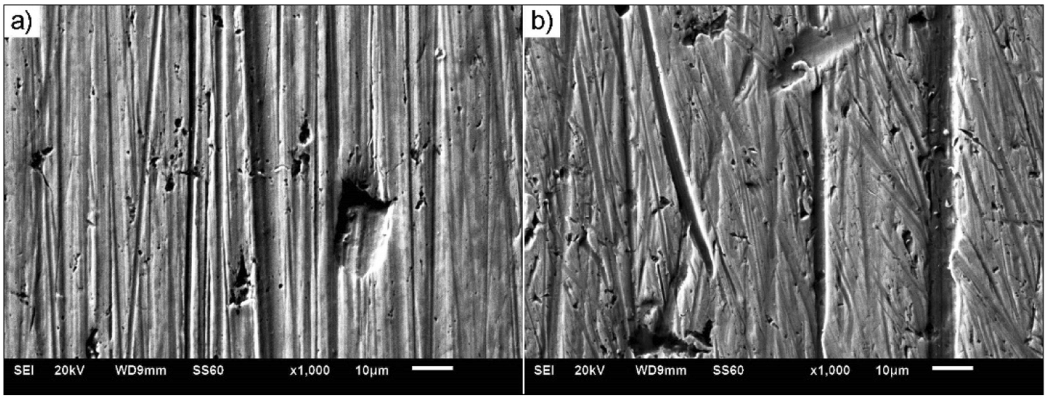

Fig. 11. Magnified images from Fig. 10 after abrasive-wear test in heavy soil: a) Brinar 400, b) Brinar 500. SEM, unetched

Rys. 11. Powiększone obrazy powierzchni próbek pokazanych na rys. 10 po procesie zużywania w glebie ciężkiej: a) Brinar 400, b) Brinar 500. SEM, stan nietrawiony

In general, beside hardness, a very important parameter that should be considered in the abrasive-wear process is also tensile strength of the material. Most often, a proper combination of the above material parameters results in the highest abrasive-wear resistance. In the conditions of abrasive soil mass, Brinar 500 was characterised by the most favourable set of mechanical parameters, which also resulted in a much higher abrasive-wear resistance index in comparison to the other materials. In addition, it can be said that light abrasive soil acts on surfaces of the examined materials mainly by micro-cutting and micro-ridging. On the other hand, wear in heavy soil occurs mostly by action of abrasive grains towards the exposed surfaces. This is connected with high content of silty fractions that play a role of a binder between larger soil grains.

CONCLUSIONS

Spectral chemical analyses of the steels Brinar 400 and Brinar 500 showed slightly lower concentrations of selected alloying elements in comparison to those declared by the manufacturer. In addition, the presence of elements not specified in manufacturers' information materials was found in the examined steels. Moreover, the Brinar steels were characterised by reduced concentration of harmful admixtures of phosphorus and sulphur.

Microscopic examinations showed that the steels Brinar are characterised by similar microstructures composed of low-alloy lath martensite without clearly visible carbide phases. Such a microstructure indicates that the manufacturer delivers these materials in quenched condition only, with no tempering processes. On the grounds of electron-microscopy observations, very subtle differences in microstructures of the examined steels can be indicated. In Brinar 500, these differences are visible mostly in form of the larger variability of crystallographic orientation of blocks created by martensite laths, which, on the grounds of the data in **[L. 21]**, can indicate the higher impact strength of the steel. This parameter was not verified in the presented research. However, in the case of the steel 38GSA, this issue was already considered in **[L. 18–19]**. Therefore, examination results of this steel are not widely presented in this paper. It is only worth mentioning that the steel 38GSA in normalized condition has a microstructure of non-equilibrium ferrite grains with colonies of quasi-eutectoid and fine-dispersive pearlite. With such microstructure, it reaches a hardness of 272 HBW.

With regard to abrasive-wear resistance, it can be said that Brinar 500 is characterised by the smallest mass loss in all the soil types. In light and medium soils, this steel showed nearly four times higher abrasive-wear resistance than that of the steel 38GSA, and this advantage increased to 11.5 times in heavy soil. Abrasive-wear resistance of Brinar 500 in light and heavy soils was found to be 26% and 13% higher than that of Brinar 400, resp. However, in medium soil, abrasive-wear resistance of Brinar 400 was slightly better than that of Brinar 500.

REFERENCES

1. Napiórkowski J., Wear action of soil on working parts of agricultural machines. Agricultural Engineering 9(12) (2005), 3–171 (in Polish).
2. Napiórkowski J., Abrasive soil pulp properties analysis in wear impact aspect. Tribologia 41(5) (2010), 53-62.
3. Cegiel L., Konat Ł., Pawłowski T., Pękalski G., Hardox steels – new generation of constructional materials for surface mining machines. Węgiel Brunatny 56(3) (2006) 24–29 (in Polish).
4. Kostencki P., Łętkowska B., Nowowiejski R., Field tests of abrasive-wear resistance of ploughshares made of steels with an addition of boron. Tribologia 3 (2013) 49–79 (in Polish).
5. Napiórkowski J., Ligier K., Pękalski G., Tribological properties of sintered carbides in abrasive soil mass. Tribologia 2 (2014) 123–133 (in Polish).
6. Examination and modelling of abrasive-wear and fatigue processes. Ed. by J. Napiórkowski. Publishing House of UWM. Olsztyn 2014 (in Polish).
7. BN-85/0642-48.
8. Dudziński W., Konat Ł., Białobrzeska B., Fractographic analysis of selected boron steels subjected to impact testing. Archives of Metallurgy and Materials 60(3) (2015) 2373–2378.
9. Dudziński W., Białobrzeska B., Konat Ł., Comparative analysis of structural and mechanical properties of selected low-alloy boron-containing steels resistant to abrasive wear. Polish metallurgy in the years 2011–2014, Kraków (2014), pp. 871–888 (in Polish).
10. Dudziński W., Konat Ł., Pękalski G., Modern constructional steels. Maintenance strategy of surface mining machines and facilities with high technical degradation levels. Ed. by Dionizy Dudek. Wrocław, Publishing House of Wrocław University of Technology (2013), pp. 346–366 (in Polish).
11. Frydman S., Konat Ł., Białobrzeska B., Pękalski G., Impact resistance and fractography of low-alloy martensitic steels. Archives of Foundry Engineering 8(1) (2008) 89–94.
12. Dudziński W., Konat Ł., Pękalski G., Structural and strength characteristics of wear-resistant martensitic steels. Archives of Foundry Engineering 8(2) (2008) 21–26.
13. Dudziński W., Konat Ł., Pękalska L., Pękalski G., Structures and properties of steels Hardox 400 and Hardox 500. Materials Engineering 7(3) (2016) 139–142 (in Polish).
14. Napiórkowski J., Kołakowski K., Pergoł A., Wear evaluation of modern constructional materials used for soil processing. Agricultural Engineering 15(5) (2011) 191–197 (in Polish).
15. Napiórkowski J. , Drożyner P. , Kołakowski K. , Mikołajczak P. , Analysis of tribological processes of construction materials in the soil mass abrasive wear process. International Virtual Journal for Science, Technics and Innovations for the Industry 6 (2012) 27–29.
16. http://www.ilsenburger-grobblech.de/fileadmin/mediadb/ilg/infocenter/downloads/werkstoffblaetter/eng/abrasion_resistant_brinar400.pdf.
17. http://www.ilsenburger-grobblech.de/fileadmin/mediadb/ilg/infocenter/downloads/werkstoffblaetter/eng/abrasion_resistant_brinar500.pdf.
18. Konat Ł., Napiórkowski J., Kołakowski K., Resistance to wear as a function of the microstructure and selected mechanical properties of microalloyed steel with boron. Tribologia 4 (2016) 101–114.
19. Napiórkowski J., Konat Ł., Ligier K., The structural properties and resistance to abrasive wear in soil of Creusabro steel. Tribologia 5 (2016) 105–119.
20. BN-85/0642-48.
21. Wang C., Wang M., Shi J., Hui W., Dong H., Effect of microstructure refinement on the strength and toughness of low alloy martensitic steel, Journal of Material Science and Technology 23(5) (2007) 659–664.