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THE EFFECT OF THE METHOD AND PARAMETERS OF THE HEAT TREATMENT ON ABRASIVE WEAR RESISTANCE OF 38GSA STEEL

WPŁYW METODY I PARAMETRÓW OBRÓBKI CIEPLNEJ NA ODPORNOŚĆ NA ZUŻYWANIE ŚCIERNE STALI 38GSA

Key words: heat treatment, wear intensity, soil mass, 38GSA steel.

Abstract

This paper presents the structure and the results of abrasive wear resistance testing for 38GSA steel in an as-delivered condition (after heat refining) and after volume hardening. Based on the tests conducted by both light and scanning microscopy methods, it was demonstrated that, due to the performed technological operations, this steel differed significantly in terms of structure compared to the as-delivered condition, which affected its performance characteristics. In an as-delivered condition, 38GSA (38MnSi4) steel is characterised by a fine-grained ferrite-pearlite structure with martensite areas arranged in bands, which significantly differs from the structure typical of the state of equilibrium. After volume hardening, the steel in question is characterised by a homogeneous fine-stripped martensite structure with clearly visible former austenite grain boundaries. The obtained results of structural testing on 38GSA steel were related to the actual abrasive wear resistance indices obtained by the "rotating bowl" method using various abrasive soil mass types. Tests conducted in the following soils, i.e. light (loamy sand), medium (light loam) and heavy (common loam), including hardness measurements, showed a close relationship between the results obtained for abrasive wear resistance and the phase structure resulting from the heat treatment state of the tested material. The obtained results of the tests on 38GSA steel were compared to those for low-alloyed martensitic abrasive wear resistant steels Hardox 500 and Brinar 500.

Słowa kluczowe: obróbka cieplna, intensywność zużycia, masa glebowa, stal 38GSA.

Streszczenie

W pracy przedstawiono budowę strukturalną oraz wyniki badań odporności na zużywanie ścierne stali 38GSA w stanie dostarczenia (po wyżarzaniu normalizującym) oraz po hartowaniu objętościowym. Na podstawie przeprowadzonych badań metodami mikroskopii świetlnej i skaningowej wykazano, że w wyniku wykonanych operacji technologicznych stal ta cechuje się znaczną różnicą w budowie strukturalnej, w stosunku do stanu dostarczenia, rzutującą na jej charakterystyki użytkowe. W stanie dostarczenia stal 38GSA (38MnSi4) charakteryzuje się drobnoziarnistą strukturą ferrytyczno-perlityczną z pasmowo ułożonymi obszarami martenzytu, znacząco odbiegającą od struktury charakterystycznej dla stanu równowagi. Po hartowaniu objętościowym omawiana stal cechuje się jednorodną strukturą drobnolistwowego martenzytu z wyraźnie widocznymi granicami ziaren byłego austenitu. Uzyskane wyniki badań strukturalnych stali 38GSA odniesiono do rzeczywistych wskaźników odporności na zużycie ścierne, uzyskanych metodą „wirującej misy", wykorzystując różne glebowe masy ścierne. Zrealizowane badania w glebie lekkiej (piasek gliniasty), 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 wywołanej stanem obróbki cieplnej badanego materiału. Uzyskane wyniki badań stali 38GSA odniesiono porównawczo do niskostopowych, martenzytycznych stali odpornych na zużywanie ścierne Hardox 500 i Brinar 500.

INTRODUCTION

An analysis of data concerning the criteria for the selection of materials for heavily-loaded structural elements of selected machines used, e.g., in mining, agriculture, or transport, indicates that the main factors limiting their service life are intense abrasive wear processes and dynamic loads. From the materials science perspective, the above-mentioned limitations can be formulated, as cited in the study **[L. 1]**, in accordance

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with the following criteria: abrasive wear resistance, random load resistance, microstructure homogeneity and properties of the entire component's cross-section, and the possibility for joining using welding techniques. Other scientific papers **[L. 2–4]** indicate hardness, chemical composition, microstructure, and the operating environment properties as the main factors determining the course of structural material wear. As regards soil mass, its acidity, grain size, compactness, moisture content, and the size and shape of actively interacting grains are defined. These studies also indicate that abrasive mass grain size is the basic factor that determines the manner in which it interacts with the material, which is additionally intensified when the operating speed and unit load increase and when dynamic loads are present.

The above-mentioned requirements are fulfilled by low-alloyed martensitic steels due to their favourable performance properties. They are manufactured based on precisely selected chemical composition (determined by the sheet thickness), low harmful additive content, and the homogeneous microstructure over the entire steel semi-finished product's cross-section, which is obtained due to specialised thermoplastic treatment. The leading manufacturers of these materials include the following steel plants **[L. 5, 6]**: SSAB-Oxelösund (Hardox), ThyssenKrupp Steel Europe AG (TBL and XAR®), Grobblech GmbH (Durostat and Brinar), Industeel (Fora and Creusabro), Tata Steel Group (Abrazo), Titus Steel (Endura), Sumimoto Metal (Sumihard) and many others. In Poland, the Hut-Trans Katowice steel plant offers steels under the trade name of HTK. It is also worth including 38GSA steel (38MnSi4 according to standards BN-85/0642-48 and EN 10083-2) in the above list, which was developed in 1985 for the purposes of domestic agricultural industry. This steel, despite the fact that it is no longer manufactured, is still commercially available and used primarily for ploughshares and other parts operating in an abrasive steel mass. 38GSA steel has already been the subject of many studies, e.g., **[L. 3, 4, 7, 8]**; however, in each of the cases under consideration, the results of tests on this steel referred only to the normalised state which, in many instances, prevents a reliable assessment of this material in terms of resistance to abrasive wear processes, particularly in relation to other modern martensitic steels. In view of the above issue, this paper is a follow-up to research on 38GSA (38MnSi4) steel which takes into account the delivery condition for this steel.

RESEARCH MATERIAL AND METHODOLOGY

The study used sheets of 38GSA steel manufactured using the hot rolling technology and subjected to heat refining under metallurgical conditions. Specimens for the structural tests and abrasive wear resistance tests were taken in the form of rectangles with dimensions of 30x25x10 mm using methods ensuring their structure stability. Some of the specimens were then subjected, under laboratory conditions, to heat treatment procedures by means of water volume hardening and low-temperature tempering. The heat treatment procedures were performed in a gas-tight chamber furnace FCF 12SHM/R by Czylok under inert gas (99.95% argon). The heat treatment parameters were selected based on the requirements of industry standard BN-85/0642-48 and the actual chemical composition of the analysed steel, which at the same time enables obtaining a homogeneous martensitic structure over the entire cross-section of the specimens. The applied parameters were as follows: austenitising temperature – T_A = 880°C, austenitising time – t_A = 20 minutes, tempering temperature – T_O = 200°C, tempering time – t_O = 180 minutes, cooling medium (H_2O) temperature – T_W = 30°C. After the tempering, cooling was carried out in the open air.

Five specimens were prepared for each of the test variants. Hardox 500 and Brinar 500 steels (which are similar to 38GSA steel in terms of the chemical composition and properties) were selected as the reference material for the analysed steel. To cut out laboratory specimens, the high-energy abrasive water jet method and wire EDM cutting were applied. Tests for resistance to abrasive wear were conducted by the "rotating bowl" method using a MZWM−1 device. Considering that the general design and the schematic diagram of the device have already been discussed extensively, e.g., in studies **[L. 3, 4, 7–10]**, this paper avoided their re-presentation. **Table 1** presents only the basic soil parameters in which the research experiments were conducted.

Table 1. Characteristics of the abrasive soil mass (Polish Soil Science Society (PTG) classification, 2008)
Tabela 1. Charakterystyka glebowej masy ściernej (klasyfikacja PTG 2008)

Soil mass type	Granulometric group	Fraction content [%]			Moisture content by weight [%]
		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	Light loam	58.3	22.5	19.2	11–13
HEAVY	Common loam	38.0	35.7	26.3	12–15

Tests on abrasive wear resistance were carried out applying the following friction parameters: a velocity of 1.66 m/s, a friction distance of 20 000 m, and a unit pressure of 67 kPa. The mass wear was measured every 2000 m. During the testing, a slightly acidic pH of the soil (pH = 6.4–6.8), measured by the electrometric method using an EpH-117/118 meter by Alsmeer-Holland, was ensured. The moisture content of the soil was determined using the oven-drying method by measuring the weight of the solid phase dried at a temperature of 105°C, according to Formula (1):

$$W = \frac{m_1 - m_2}{m_2 - m_n} \times 100\% \quad (1)$$

where
W – moisture content [%],
m_1 – soil sample weight prior to drying [g],
m_2 – sample weight after drying [g],
m_n – sample container weight [g].

Prior to testing, specimens were subjected to finishing grinding to ensure roughness Ra = 0.22––0.28 μm along the friction plane, and Ra = 0.32––0.42 μm along the perpendicular plane. Specimen weight loss was measured using Sartorius ED224S-OCE laboratory scales with the minimum graduation of 0.0001 g. Each measurement of the weight was preceded by cleaning a specimen in an ultrasonic cleaner. The mass wear was determined using Formula (2):

$$Z_{pw} = m_w - m_i \quad (2)$$

where
Z_{pw} – specimen weight loss after the pre-determined friction distance s [g],
m_w – initial specimen weight prior to friction test [g],
m_i – specimen weight after covering the friction distance s [g].

Analyses of the chemical composition were conducted by the spectral method using a GDS500A Glow Discharge Atomic Emission Spectrometer manufactured by Leco. During analyses, the following parameters were applied: U = 1250 V, I = 45 mA, and argon 99.999%. The obtained weight percentages of particular chemical elements were an arithmetic mean of at least five measurements.

Observations of the microstructure were conducted using a Nikon Eclipse MA200 optical microscope coupled with a Nikon DS-Fi2 digital camera. The obtained microphotographs were recorded and edited using NIS Elements software by Nikon. Observations of the microstructure were conducted at magnifications ranging from 100 to 1000 times. Observations of the microstructure at higher magnifications were conducted using a Joel JSM-6610A scanning electron microscope (SEM). During the tests, an accelerating voltage of 20 kV was applied. Observations of the microstructure were conducted in a material contrast using SE detectors.

Measurements of hardness using the Brinell hardness test method were performed in accordance with standard PN-EN ISO 6506-1:2014-12, using a Zwick/Roel ZHU 187.5 hardness tester with a 2.5 mm sintered carbide ball at a load of 187.5 kgf (1838.746875 N) operating for 15 s. All measurements were performed on specimens previously subjected to an assessment of the microstructure on their cross-sections.

Strength tests were conducted at ambient temperature according to standard PN-EN ISO 6892--1:2016-09 using a universal testing machine Instron 5982 on proportional rectangular specimens with an assumed measurement line length L_0 = 50 mm. During the tests, force value control was applied to ensure that the elongation of specimens was constant until they broke and the tensile strength (R_m), proof stress ($R_{p0.2}$), and the percentage value of elongation after break (A) were then determined.

TEST RESULTS

Based on the analyses of chemical composition (**Table 2**), it can be generally concluded that the analysed steel meets the standard BN-85/0642-48 requirements. Compared to Hardox 500 and Brinar 500 steels, 38GSA steel is characterised by a slightly increased carbon content (by 0.17 and 0.08%, respectively) and an increased content of copper, whose presence in Hardox and Brinar steels is not specified by the manufacturers. In addition, both a similar percentage of manganese and a low content of harmful additives of phosphorus and sulphur can be indicated in all the analysed steels. On the other hand, the characteristic distinguishing 38GSA steel from other materials is the absence of the chemical element boron in the chemical composition as well as only a minor percentage of chromium.

It can generally be concluded that the hardenability of the analysed 38GSA steel was obtained through an increased carbon content which also determines the increased hardness in the heat processed state. However, in Hardox 500 and Brinar 500 steels, the hardenability is obtained through increased chromium content and the micro-addition of boron (both steels) as well as of molybdenum (Brinar). The content of nickel, which is most frequently added to steel to decrease both the austenitising temperature and the plastic-brittle transition temperature, was noted in none of the analysed steels. It is also worth noting that potent carbide-forming chemical elements, e.g., Cr and Mo, increase the hardenability of steels by delaying diffusional transformations. In order to enhance this effect and prevent tempering brittleness, the above chemical elements are very frequently used together.

Table 2. Chemical compositions and selected mechanical properties of the analysed steels [L. 2, 6, 7, 9, 10, 12]
Tabela 2. Składy chemiczne i wybrane właściwości mechaniczne badanych stali **[L. 2, 6, 7, 9, 10, 12]**

Chemical element [% w/w]	38GSA		Hardox 500		Brinar 500	
	OR – based on own research; PD – producer's data					
	OR[1]	PD[1]	OR[2]	PD[2]	OR[2]	PD[2]
C	0.38	0.34–0.42	0.21	≤ 0.27	0.30	≤ 0.28
Mn	0.97	0.70–1.10	0.73	≤ 1.60	0.97	≤ 1.50
Si	0.90	0.80–1.10	0.31	≤ 0.70	0.60	≤ 0.80
P	0.011	≤ 0.035	0.007	≤ 0.025	0.015	≤ 0.020
S	0.007	≤ 0.040	0.002	≤ 0.010	0.001	≤ 0.005
Cr	0.05	≤ 0.30	0.56	≤ 1.00	0.87	≤ 1.50
Ni	0.08	≤ 0.30	0.05	≤ 0.25	0.04	–
Mo	0.02	–	0.01	≤ 0.25	0.20	≤ 0.40
V	–	–	0.005	≤ 0.004	0.005	–
Cu	0.25	≤ 0.30	0.004	–	0.020	–
Al	0.02	0.02–0.06*	0.057	–	0.038	≤ 0.10
Ti	0.002	0.03–0.06*	0.003	–	0.007	–
Nb		–	0.005	–	0.000	–
Co	0.010	–	0.009	–	0.013	–
B	–	–	0.0008	–	0.0008	–
HBW	548 ±5	440	506 ±6	470–530	472 ±4	480
$R_{p0.2}$ [MPa]	1523^{L} ±14	1200	1348^{L} ±6	1300	1278^{L} ±10	1350
R_m [MPa]	1816^{L} ±18	1500	1653^{L} ±3	1550	1494^{L} ±8	1500
A_5 [%]	11.7^{L} ±0.4	8	9.6^{L} ±0.4	10	11.0^{L} ±0.2	8
KCV_{+20} [J/cm^2]	27.5^{L} ±1.3	30**	60.2^{L} ±3.0	10	72.0^{L} ±3.5	8

[1] a condition after hardening (870-900 °C/water) and tempering (200–250 C/air or oil); [2] in an as-delivered condition;
* if combined, then Al+Ti ≥ 0.03% w/w.; **KCU_{+20}; [L] specimens longitudinal to the plastic working direction

Figures 1–8 show the microstructures of the analysed steels. In an as-delivered condition (after heat refining), 38GSA steel is characterised by a structure of unbalanced ferrite grains with perlite of a lamellar structure and tempered martensite areas arranged in bands in line with the sheet plastic working direction (**Fig. 1**). The perlite structure can also be described as very morphologically diversified (**Fig. 2**). This indicates very diversified rates of the course of phase transitions in this steel, which results from both the cooling conditions and the dendritic segregation of chemical composition. The conducted heat treatment procedures (**Figs. 3–4**) caused very significant structural changes in 38GSA steel. In the hardened and tempered condition, it is characterised by a fine-stripped hardening martensite structure with a low variability of the particular packet orientation within the former austenite grains. This type of structure allowed a high level of hardness and static tensile strength to be obtained (**Table 2**). However, the low variability of the crystallographic orientation of the martensite packet structure, in accordance with the literature data **[L. 11]**, does not allow a high level of impact strength to be obtained despite a satisfactory unit elongation. Therefore, according to the authors, this type of steel structure may affect the obtained abrasive wear resistance indices, particularly under various conditions of the abrasive soil mass.

Hardox 500 steel in an as-delivered condition is characterised by a homogeneous martensitic structure with precipitates of finely dispersed carbide phases (**Figs. 5–6**). The very small size of martensite strips distributed in the form of blocks and sub-blocks allows a high level of hardness, yield point, and static tensile strength to be obtained in this steel (**Table 2**). This type of the structure and the relatively low carbon content predispose Hardox 500 steel to applications requiring a high resistance to not only abrasive wear but also to dynamic loads. The results of tests on this steel, reported in this paper, indicate that an impact strength level exceeding 60 J/cm^2 allows a safe value of the plastic fracture percentage (exceeding 50% of the fracture area), which also determines the most frequently adopted nil ductility transition temperature value to be maintained in this steel.

Having referred to the results of structural tests on Brinar 500 steel, it can be concluded that, in an as-delivered condition, it is characterised by martensitic structure with a rather varied morphology (**Figs. 8–9**). In the microstructure of this steel, areas of block martensite with a very small thickness of strips (similar to Hardox 500 steel) and of strip martensite, similar in terms of the structure to 38GSA steel in the heat-treated condition, can be distinguished. The presented type of the structure of Brinar 500 steel allowed strength indices slightly lower than those for Hardox 500 to be obtained, and it enabled obtaining a rather high and safe (in terms of brittle cracking) impact strength level of 72 J/cm^2 (**Table 2**).

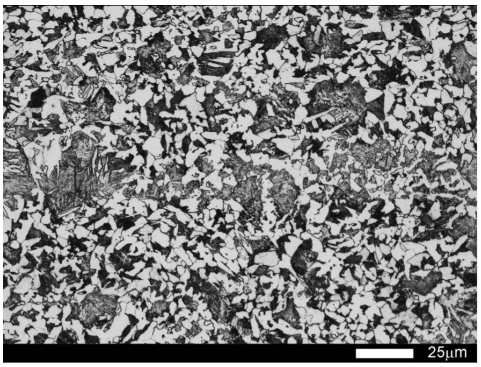

Fig. 1. An image of 38GSA steel microstructure in the normalised condition. Ferrite-pearlite structure with martensite areas arranged in bands. Etched with 2% HNO3; Light microscopy

Rys. 1. Obraz mikrostruktury stali 38GSA w stanie normalizowanym. Struktura ferrytyczno-perlityczna z obszarami pasmowo ułożonego martenzytu. Trawiono 2% HNO3; Mikroskopia świetlna

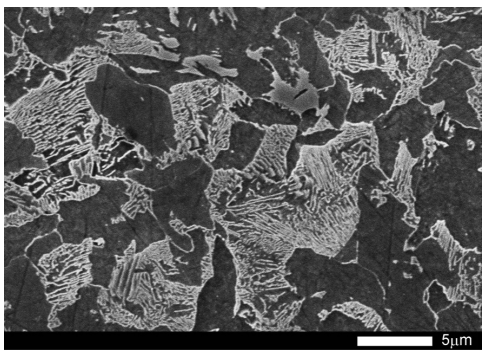

Fig. 2. A magnified image of 38GSA steel microstructure shown in Fig. 1. Structure of unbalanced ferrite grains with perlite diversified in terms of lamella size. Etched with 2% HNO3; SEM

Rys. 2. Powiększony obraz mikrostruktury stali 38GSA pokazanej na **rys. 1**. Struktura nierównowagowych ziaren ferrytu ze zróżnicowanym pod względem wielkości płytek perlitem. Trawiono 2% HNO3; SEM

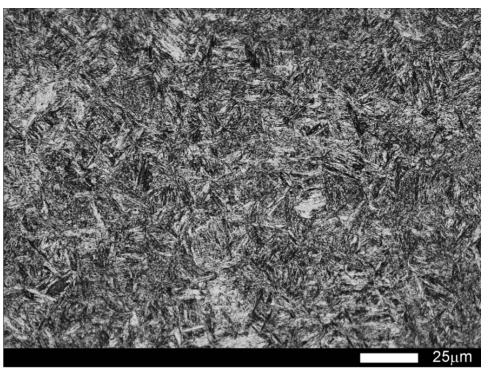

Fig. 3. 38GSA steel microstructure in the heat treated condition. Homogeneous tempered martensite structure. Etched with 2% HNO3; Light microscopy

Rys. 3. Mikrostruktura stali 38GSA w stanie obrobionym cieplnie. Jednorodna struktura martenzytu odpuszczania. Trawiono 2% HNO3; Mikroskopia świetlna

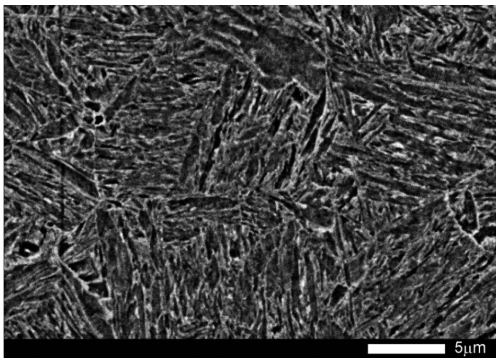

Fig. 4. A magnified image of 38GSA steel microstructure shown in Fig. 3. Packet structure of fine-stripped tempered martensite. Etched with 2% HNO3; SEM

Rys. 4. Powiększony obraz mikrostruktury stali 38GSA pokazanej na **rys. 3**. Struktura drobnolistwowego martenzytu odpuszczania o budowie pakietowej. Trawiono 2% HNO3; SEM

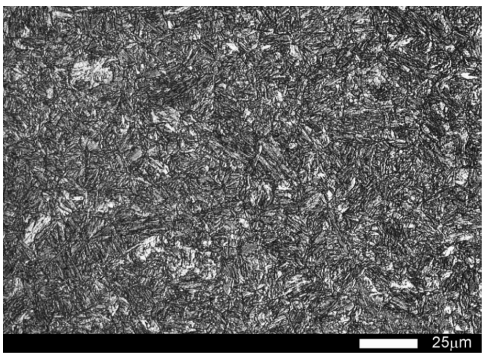

Fig. 5. Hardox 500 steel microstructure in an as-delivered condition [L. 6]. Tempered martensite structure. Etched with 2% HNO3; Light microscopy

Rys. 5. Mikrostruktura stali Hardox 500 w stanie dostarczenia **[L. 6]**. Struktura martenzytu odpuszczania. Trawiono 2% HNO3; Mikroskopia świetlna

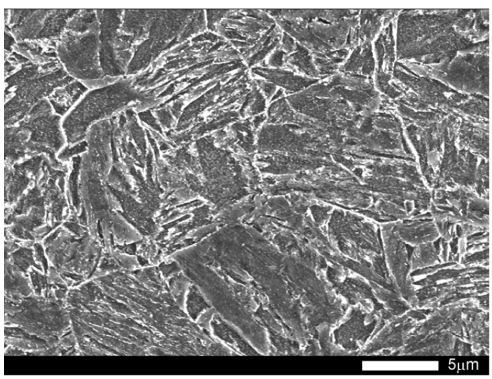

Fig. 6. A magnified image of Hardox 500 steel microstructure shown in Fig. 5 [L. 6]. Fine-stripped tempered martensite structure with clearly visible former austenite grain boundaries. Etched with 2% HNO3; SEM

Rys. 6. Powiększony obraz mikrostruktury stali Hardox 500 pokazanej na **rys. 5 [L. 6]**. Struktura drobnolistwowego martenzytu odpuszczania z wyraźnie widocznymi granicami ziaren byłego austenitu. Trawiono 2% HNO3; SEM

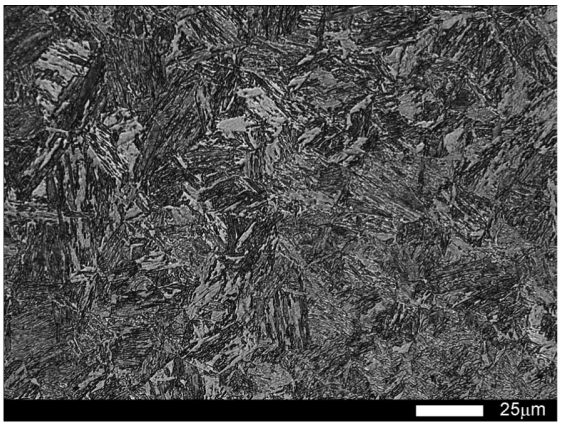

Fig. 7. Brinar 500 steel microstructure in an as-delivered condition [L. 8]. Striped martensite structure. Etched with 2% HNO3; Light microscopy

Rys. 7. Mikrostruktura stali Brinar 500 w stanie dostarczenia **[L. 8]**. Struktura martenzytu o budowie listwowej. Trawiono 2% HNO3; Mikroskopia świetlna

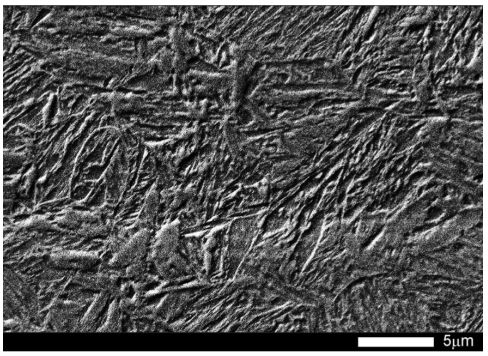

Fig. 8. A magnified image of Brinar 500 steel microstructure shown in Fig. 7 [L. 8]. Martensitic structure with varied sizes of strips arranged in the form of blocks in particular packets. Etched with 2% HNO3; SEM

Rys. 8. Powiększony obraz mikrostruktury stali Brinar 500 pokazanej na **rys. 7** [**L. 8**]. Struktura martenzytu o zróżnicowanej wielkości listew ułożonych w formie bloków w poszczególnych pakietach. Trawiono 2% HNO3; SEM

Table 3 and Figs. 9–11 show the results of tests for abrasive wear resistance of the analysed steels. The obtained experimental results indicated that Brinar 500 steel in an as-delivered condition was most resistant to the abrasive soil mass impact. The very clear advantage of this steel over other materials was noted for all soil types.

Table 3. A comparison of mass wear of 38GSA, Hardox 500 and Brinar 500 steel specimens over a friction distance of 20 000 m in various abrasive soil mass types [L. 3, 8]. N – normalised condition, HT – hardened and tempered condition

Tabela 3. Zestawienie zużycia masowego próbek stali 38GSA, Hardox 500 i Brinar 500 na drodze tarcia 20000 m w różnych rodzajach glebowych mas ściernych **[L. 3, 8]**. N – stan normalizowany, HT – stan zahartowany i odpuszczony

Soil mass type	38GSA (N)		38GSA (HT)		HARDOX 500		BRINAR 500	
	Weight loss: AV – average value [g]; UN – unit value [g/km/cm^2]							
	AV	UN	AV	UN	AV	UN	AV	UN
LIGHT	2.4049 ±0.3260	0.0160	4.2398 ±0.7647	0.0283	0.8931 ±0.2018	0.0060	0.6374 ±0.1971	0.0042
MEDIUM	2.2084 ±0.2112	0.0147	2.9067 ±0.3187	0.0194	1.6531 ±0.1493	0.0110	0.5896 ±0.2460	0.0039
HEAVY	3.7087 ±0.4008	0.0247	2.3255 ±0.2178	0.0155	2.2279 ±0.1729	0.0149	0.3231 ±0.1359	0.0022

An analysis of particular indices for the specimen weight loss over a friction distance of 20 000 m indicates that, in the light soil, for Brinar 500 steel, it was lower compared to the normalised and heat treated 38GSA steel and Hardox 500 steel by ≈1.77 g, ≈3.60 g, and ≈0.26 g, relatively, which translates to percentage wear indices of 377%, 665%, and 140%, respectively, in relation to Brinar 500 steel. In the medium soil, the advantage of Brinar 500 steel over the other materials can be presented analogously as above, i.e. ≈1.62 g (375%), ≈2.32 g (493%), and ≈1.06 g (280%). On the other hand, for the heavy soil, the above relationships were as follows: ≈3.39 g (1148%), ≈2.00 g (720%), and ≈1.90 g (690%), respectively. Therefore, in terms of the heat treatment procedures applied, it should be concluded that volume hardening and low-temperature tempering of 38GSA steel did not increase the abrasive wear resistance of this material in light soils. A significant increase in the wear resistance index for this steel was noted only in the heavy soil. This confirms the authors' previous observations **[L. 3, 4]** about the different course of steel wear in various soil types. This may result from different elementary types of wear and the differences in the chemical composition of the analysed steels. These

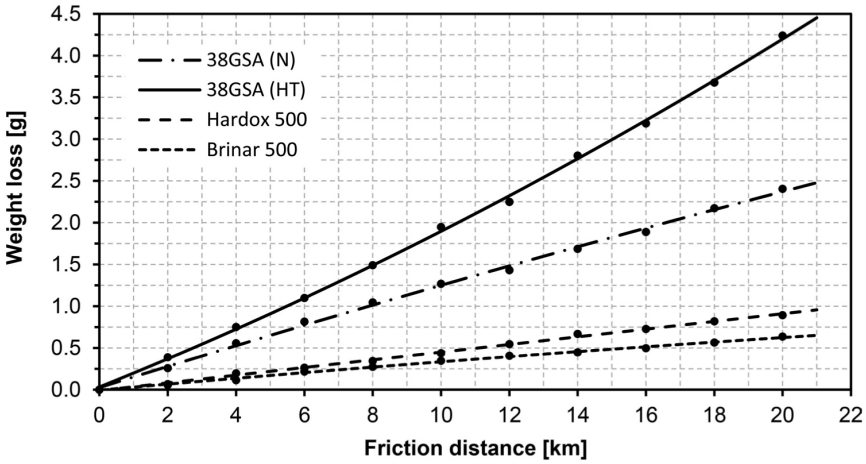

Fig. 9. The course of weight loss for the tested steel specimens as a function of the friction distance. Tests conducted in a light soil mass [L. 3, 8]. N – normalised condition, HT – hardened and tempered condition

Rys. 9. Przebieg ubytku masy próbek badanych stali w funkcji drogi tarcia. Próby zrealizowane w masie glebowej lekkiej **[L. 3, 8]**. N – stan normalizowany, HT – stan zahartowany i odpuszczony

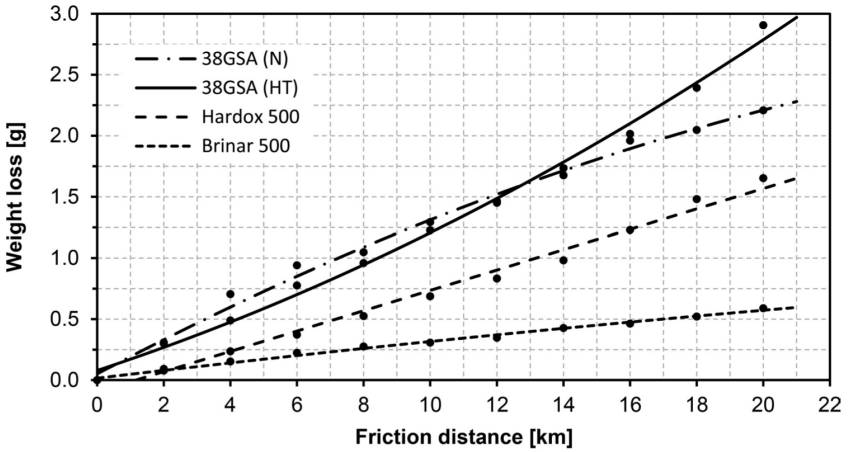

Fig. 10. The course of weight loss for the analysed steel specimens as a function of the friction distance. Tests conducted in a medium soil mass [L. 3, 8]. N – normalised condition, HT – hardened and tempered condition

Rys. 10. Przebieg ubytku masy próbek badanych stali w funkcji drogi tarcia. Próby zrealizowane w masie glebowej średniej **[L. 3, 8]**. N – stan normalizowany, HT – stan zahartowany i odpuszczony

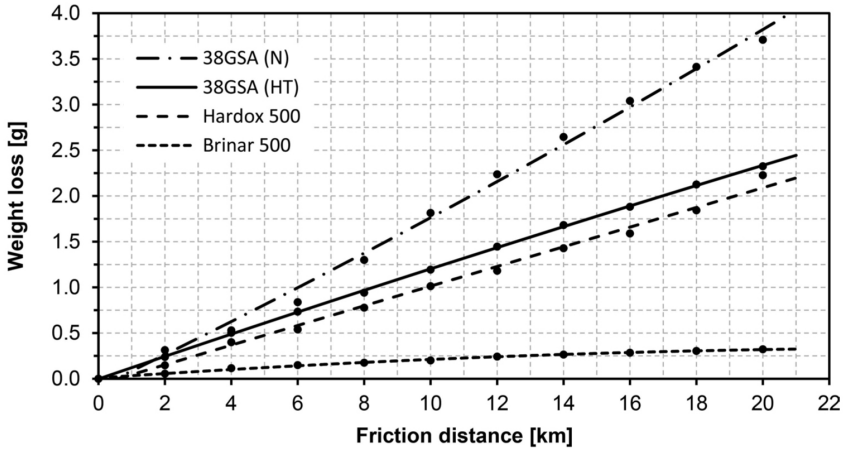

Fig. 11. The course of weight loss for the analysed steel specimens as a function of the friction distance. Tests conducted in a heavy soil mass [L. 3, 8]. N – normalised condition, HT – hardened and tempered condition

Rys. 11. Przebieg ubytku masy próbek badanych stali w funkcji drogi tarcia. Próby zrealizowane w masie glebowej ciężkiej **[L. 3, 8]**. N – stan normalizowany, HT – stan zahartowany i odpuszczony.

discrepancies primarily relate to potent carbide-firming chemical elements, e.g., chromium and molybdenum. The presence of hard carbide phases in steel, which are coherently related to the post-martensitic matrix, enables the formulation of a statement about their positive effect on the indices of resistance to intense abrasive wear processes. This statement, in particular, appears to be appropriate for the increased carbon content of steel. In addition, it is worth indicating that the increased silicon content of 38GSA (38MnSi4) steel, which delays transitions during the tempering of previously hardened steel, may be not a positive effect in the case of abrasive wear processes. The insolubility of silicon in cementite, and thus its inhibiting effect in terms of iron carbide release as a result of tempering, leads to the lack of a clear effect of an increase in resistance to abrasive wear processes, despite the fact that the material obtained high hardness and very high strength indices. Therefore, it can be concluded that the basic strength indices of steel (mainly hardness) are not a reliable model of forecasting the resistance to the processes of abrasive wear in abrasive soil masses.

SUMMARY

The performed chemical analyses of compositions of 38GSA (38MnSi4), Hardox 500 and Brinar 500 steels demonstrated slightly lower contents of selected alloying elements in relation to the values provided by their manufacturers. The above conclusion primarily applies to Hardox and Brinar steels for which only limit values determined by the sheet thickness are provided. In terms of the latter steels, the presence of chemical elements that have not been included in their material issue lists have been noted in them. For Hardox 500 and Brinar 500 steels, however, the chemical composition is not a criterion for their classification, and it is provided only for information purposes.

The conducted structural tests revealed that 38GSA (38MnSi4) steel is delivered in a heat-refined condition. In such a state, it is characterised by a ferrite-pearlite-martensitic structure with an average hardness of approx. 270 HBW. The applied heat treatment procedures resulted in a significant reconstruction of the microstructure and the selected properties of this steel. After volume hardening and low-temperature tempering, 38GSA (38MnSi4) steel was characterised by fine-stripped martensitic structure with no clearly visible carbide phase precipitations. This type of structure allowed an average hardness of 548 HBW as well as the proof stress and static tensile strength which exceeded 1500 MPa and 1800 MPa, respectively, to be obtained. It should be stressed that, despite obtaining very high strength indices, it was possible to maintain satisfactory plastic characteristics determined by the unit elongation and impact strength measure in the analysed steel. As regards Hardox 500 and Brinar 500 steels, in an as-delivered from steel works condition, they are characterised by a similar type of structure typical of hardening processes. Unlike 38GSA steel, the presence of carbide phases can be additionally identified in their structure. Given the actual chemical composition of these steel, it can be concluded with high probability that these precipitations are hard carbide phases of the $M_{23}C_6$ type (both steels) and of the MC type for Brinar 500 steel. The precise determination of the types of phases found in these materials requires the application of additional tests by transmission electron microscopy methods, which are currently being carried out.

In terms of resistance to abrasive wear, the highest resistance was exhibited by Brinar 500 steel (the smallest weight loss). The advantage of this steel over other materials was noted for all abrasive soil mass types under consideration. As regards 38GSA (38MnSi4) steel, it should also be concluded that the performance of additional heat treatment operation, despite obtaining the highest strength indices for all presented metallic materials, did not clearly improve the characteristics responsible for the resistance to wear processes in this material. Therefore, the thesis can be formulated that forecasting, based on mechanical indices, of the behaviour of a selected grade of steel (with a post-martensitic structure) under the conditions of wear in abrasive soil masses raises serious objections. According to the authors of this study, modelling the phenomena of material wear under the presented tribological conditions should primarily take into account the chemical composition and the conditions of material delivery (heat treatment state) and, thus, the resulting microstructure type and morphology as well as the phase composition.

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