

Abrasive Wear Mechanisms of S235JR, S355J2, C45, AISI 304, and Hardox 500 Steels Tested Using Garnet, Corundum and Carborundum Abrasives

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ABSTRACT

Wear resistance is one of the main indicators of the reliability of machine parts. The selection of wear-resistant material should consider the operational environment and specific types of abrasive material. The steel abrasive wear resistance depends not only on its hardness and microstructure but also on the abrasive material's properties, such as hardness and particle morphology. This work aimed to determine abrasion wear mechanisms of a set of steels, i.e., S235JR, S355J2, C45, AISI 304 and Hardox 500, abraded by different types of grit i.e. garnet, corundum and carborundum. The abrasion tests were conducted using T-07 tribometer (rubber wheel method). Wear traces were examined with a scanning electron microscope (SEM), and a contact profilometer. SEM analysis revealed that apart from Hardox 500, ploughing and microfatigue were the dominant wear mechanisms. Microcutting was the main wear mechanism for Hardox 500 tested with carborundum (SiC). The highest mass loss was usually obtained for carborundum. The lowest wear resistance in garnet and carborundum was obtained for the S235JR and S235J2 steels and Hardox 500 tested with corundum. The effect of steel microstructure on the wear mechanism has been confirmed. AISI 304 austenitic steel abraded by carborundum grit, presented outstanding roughness parameters: *Ra*, *Rz*, *RSm*, *Rk*, *Rvk* and *Rpk* than other steels tested with carborundum. Steel hardness affects the morphology of the wear trace reducing the *Ra* and *Rz* roughness parameters. The effect of abrasive hardness and grain morphology on abraded surfaces has been stated. Contrary to fine grains of the hardest carborundum, coarse garnet grains caused high roughness parameters (*Rk*, *Rpk* and *Rvk*) determined in wear trace.

Keywords: abrasion; wear resistance; dry sand-rubber wheel; tribology; steel; wear mechanism; roughness analysis; failure analysis.

INTRODUCTION

Recently, many studies have been related to wear [1–4], primarily focusing on anti-wear surface treatment or new materials/coatings selection for anti-wear applications [5, 6]. The effect of variable factors such as size, shape and type of abrasive, sliding distance, sliding velocity, the magnitude of applied load, ambient temperature, impact angle, abrasive feed rate etc., were studied on wear resistance of materials. Even though it is generally believed that the abrasion resistance of

steels depends on their hardness, microstructure (e.g. martensite and retained austenite fraction), morphology, grain size, etc. [7, 8], the change of abrasive material can seriously affect the wear mechanism and overall steel abrasion resistance. Albertin and Sinatora [9] conducted their studies with three different types of abrasive (phosphate rock, hematite, quartz) and with different ferrous material microstructures (martensite, austenite, pearlite) of high chromium white cast irons. The authors showed that the abrasion wear resistance of martensite was higher than austenite and

pearlite among all used abrasives. Furthermore, the effectiveness of carbides' content on the wear resistance for the high chromium cast irons was proven. On the other hand, Turenne et al. [10] conducted two-body abrasion wear tests using three different kinds of abrasive paper: garnet, alumina (Al_2O_3) and silicon carbide (SiC). They concluded that the austenitic matrix shows better wear resistance than the martensitic matrix even though the initial hardness of the austenitic matrix is lower than the hardness of the latter.

Movassagh-Alanagh and Mahdavi [11] presented tests of a multi-layer Ti/TiN/TiSiN coating deposited on AISI 304 stainless steel (SS) substrate. The wear rate of the samples was 18.7 times less than that of the bare SS [11], which was attributed to the superior hardness of PVD coating. On the other hand, hard TiO_2 – 10 wt.% NiAl plasma deposited coatings (approx. 600 HK) presented higher mass losses than the normalized steel grade C45, which has lower hardness than the coatings [12]. The serious microstructural differences between steel and mentioned ceramic coatings have a stronger effect on wear resistance than the hardness itself. Besides, a similar finding that material microstructure is more critical factor than hardness was reported by Beköz Üllen [13] who studied abrasion wear resistance of low-alloy boron (martensitic) Hardox 400, 450 and 500 steels. Nonetheless, the wear resistance of Hardox 500 was higher than other, softer tested steels. Additionally, Ligier et al. [14] proved that Hardox 600 had better abrasion resistance than Hardox Extreme and Hardox 500. Despite of higher hardness of Hardox Extreme than Hardox 500 and 600, Hardox Extreme had lower plasticity, no tendency to strain hardening, and greater size of austenite grains, which finally contributes to higher mass loss of this steel.

Pawlak et al. [15] tested Hardox 450 steel after austenitizing at different temperatures. The researchers determined that the heat treatment conditions influence austenite grain size, which impacts the abrasion wear resistance. They found that microcutting wear was the dominant mechanism of material removal when corundum was used as an abrasive. The wear mechanism was the same for tested steel in the delivery state and after austenitizing at different temperatures. Jafarian et al. [16] investigated e.g. the influence of austenitization temperature on the wear mechanism of a Hadfield, high manganese steel. Again, the abrasive mechanism was revealed and higher

austenitization temperature increased mechanical properties (yield/tensile strengths, hardness), thus increasing Hadfield steel's wear resistance. Furthermore, Białobrzeska [17] observed ploughing with plastic deformation, microcutting and fatigue wear of quenched low-alloy steels. She proved that low-abrasion resistance steels had many areas of plastic deformation with random orientation concerning the abrasive particles' motion. Steels with a microaddition of boron, apart from plastic deformations zones, also had smooth areas, created as a result of microcutting.

Wieczorek [18] examined abrasion wear using three different types of abrasives i.e., corundum, quartz and coal, applying three different loads. The author concluded that the abrasion wear mechanism is affected by the type of abrasive material and steel hardness (also microstructure). Like in Pawlak's et al. [15] conclusions, Wieczorek [18] found microcutting as the predominant form of damage caused by corundum abrasive when the martensitic wear resistant steels were tested. Also, the reference S355J2 steel abrasion wear resistance was reported as the poorest. In addition, Zhou et al. [19] clearly showed that the abrasive particle size impacted on surface roughness parameters. They investigated AISI 304 stainless steel while corundum was chosen as abrasive material. Three different abrasive grits were employed, namely 60# (165–405 μm), 180# (25–114 μm), and 400# (11–45 μm). Furthermore, Thakare et al. [20] presented that abrasive particle size influences wear rates. The authors conducted an experiment using the modified ASTM G65 test system with fluid: NaOH solution of pH 11 or distilled water. The abrasion type was carborundum in three different mesh: 180 μm (fed via hopper), 17.5 μm (fed via hopper) and 4.5 μm (pre-mixed slurry). The influence of the type of abrasive on wear test results was investigated by Wang et al. [21] as well. The opposite trends of wear rate, with dependence on abrasion type was obtained in the abrasion wear testing of three WC-20Cr₃C₂-7Ni coatings consisting of different WC size. Moreover, Kamdi et al. [22] determined an influence of abrasive type and size on wear behavior of tungsten carbide-based cermet coatings and claimed that the abrasive hardness controls wear behavior, among others. Hard alumina (Al_2O_3) abrasive caused wear of tungsten carbides. Silica abrasive was softer than these carbides and unable to abrade. Wear rate of coatings was always much less using silica

than using alumina. Moreover, Yu et al. [23] studied cutting performance for waterjet technology with garnet, corundum and carborundum. Size of abrasives and abrasive flow rate were variable factors. The abrasives: garnet and alumina (both in 120 mesh) were also mixed in various proportions. Morphology of abrasive particles, such as roundness impacted on worn surface roughness.

Vargova et al. [24] looked for methods of abrasion resistance improvement of a ploughshare's blade. An old solution was that S355J2G3 steel was used as a substrate and 37MnSi5 was used as a raking blade material. An abrasive material used in tribological tests was Ottawa silica sand. The authors gave the following solution: application Hardox 450 steel as basic material and UTP 690 hardfacing material as a coating on exposed parts for increased ploughshare lifetime. In addition to that, Napiórkowski et al. [25] tested selected steels in field, operating conditions, i.e. the samples were placed in specially prepared holders which were fixed in the cultivator teeth. One of the tested steel was Hardox 500. Tests were conducted in three different types of soils: loamy sand (light soil), light loam (medium soil) and common loam (heavy soil). Interestingly, as the soil's heaviness increased (increased clay content), wear processes through microcutting began to dominate. The authors described that microcutting dominated in soils with a significant content of debris, e.g. sand, with a hardness of 1200 HV. Microploughing had a large share in the wear in concise soils, and occurred with much higher intensity than in light soils. In the light soil, the highest wear values were noted for Hardox 500 in comparison with B27, XAR 600 and TBL Plus tested steels. Similar to Napiórkowski et al. [25] findings, Singh Mann and Kaur Brar [26] studied abrasion wear on agriculture tools. The researchers described that the content of stones and gravel cause the wear of tillage implements in most soils. Therefore, they proposed hardfacing as the best method to prevent agricultural components from abrasion wear.

Sigolo et al. [27] investigated microstructure and wear resistance of boron-modified stainless steel coatings'. The coatings were deposited by Plasma Transferred Arc (PTA) method, with powders of supermartensitic and superduplex stainless steel with 1 and 3 wt.% B addition, respectively. The substrate material was AISI 4140 steel. The authors conducted dry sand-rubber wheel and reciprocating pin-on-plate tests. Quenched and

tempered AISI 4140 steel with a fully martensitic microstructure (hardness 35 HRC) was used as a reference material for both tests. The pin-on-plate was carried out with model TE67 tribometer and two different loads were applied: 31.4 N, 70.6 N. The authors proved e.g., that the boride fraction is a determinant for the wear resistance of the boron-modified stainless steel coating. Wirojanupatump and Shipway [28] examined the abrasive wear behaviour of low-carbon mild steel (BS 080A15) using a special rotary wheel-type apparatus. Abrasive wear tests were performed with both rubber and steel wheels. The abrasive particles used in this work were angular alumina and rounded silica. Three different size fractions were of each abrasive used (125–150 μm , 355–425 μm and 500–600 μm). They concluded that the abrasive wear rate of mild steel is a function of abrasive type, size, shape and test environment. Angular particles were more abrasive than rounded one. Different materials of wheel's outside ring influenced the wear rate. Using lubrication (water) reduced the wear rate.

Summing up, the above-mentioned different research shows a disperse in results regarding the wear resistance of steels, mainly depending on the different test conditions, microstructure, hardness and abrasive material type as well as its properties. However, none of the research includes the wear mechanism analysis of S235JR, S355J2, C45, AISI 304, and Hardox 500 steels tested in corundum, carborundum and garnet. Therefore, this investigation aims to reveal and understand the quantitative results of the research initiated in the previous paper [29]. The work aimed to investigate the abrasive wear mechanisms of S235JR, S355J2, C45, AISI 304 and Hardox 500 steels tested using garnet, corundum and carborundum abrasives. The profilometric evaluation follows SEM investigations of wear traces roughness.

MATERIALS AND METHODS

Steel coupons characterization

Table 1 shows the chemical composition properties of tested steels, namely C45 (1.0503; AISI 1045); X5CrNi18–10 (1.4301; AISI 304); S235JR (1.0038); S355J2 (1.0577) and Hardox 500 in order of increasing carbon content. Table 2 presents the mechanical properties and microstructure of investigated steels in order

Table 1. Nominal chemical composition of tested steels [29]

Steel grade	Chemical composition, wt. %												
	C	Si		Mn		Cr		Ni		Mo	B	P	S
	Average	Min	Max	Min	Max	Min	Max	Min	Max	Max	Max	Max	Max
AISI 304	0.07		1.00		2.0	17.0	19.5	8.0	10.50			0.045	0.015
S235JR	0.17				1.4							0.035	0.035
S355J2	0.20		0.55		1.6		0.3		0.30			0.025	0.025
Hardox 500	0.27		0.70		1.6		1.0		0.25	0.25	0.004	0.025	0.010
C45	0.45	0.17	0.37	0.5	0.8		0.3		0.30	0.10		0.040	0.040

of increasing hardness. It should be pointed out that investigated set of steels differs not only in chemical composition and properties but also shows different microstructures i.e. different ratios of ferrite, pearlite or martensite, which was discussed in [29].

Abrasion wear testing

The tribological studies employed the three-body, dry sand-rubber wheel testing according to GOST 23.208–79 standard. There were done using T-07 test rig, shown in Figure 1. The tribotester was equipped with a rubber wheel (a dimension of Ø44 mm x 15 mm, $n = 62$ revolutions of roll per minute, rubber hardness: 78–85 ShA) loaded to the surface of test sample, through a lever mechanism, with force $P = 44$ N. Total test time for each sample equaled 10 minutes. The abrasive was fed gravitationally to the friction node. Three different abrasives were used: corundum (Al_2O_3), carborundum (silicon carbide, SiC) and garnet composed mainly of silica (SiO_2 , 35 wt.%) and ferric oxide (Fe_2O_3 , 33 wt.%). The morphology of the abrasives was studied with the usage of a scanning electron microscope (SEM, Phenom World ProX). The abrasive wear test for each sample material was repeated three times. Then, the mass loss (with 0.1 mg accuracy) was

calculated according to the procedure stated in formulas 1–4:

$$Z_w = m_1 - m_2 \text{ (g)} \tag{1}$$

where: Z_w – specimen mass loss during testing (g),
 m_1 – specimen mass before wear testing (g),
 m_2 – specimen mass after wear testing (g).

The C45 steel was used as a reference material; therefore, the average mass loss for the reference and other examined samples were calculated as variables Z_{ww} (2) and Z_{wb} (3), respectively.

$$Z_{ww} = \frac{\sum_{i=1}^m Z_{wi}}{m} \text{ (g)} \tag{2}$$

$$Z_{wb} = \frac{\sum_{i=1}^m Z_{wi}}{m} \text{ (g)} \tag{3}$$

where: m – the total quantity of samples,
 Z_{wi} – mass loss of each sample (g).

To calculate the unitless relative abrasive wear resistance K_b (4), the volume material loss of specific material Z_{vw} was divided by the volume loss of specific material Z_{vb} – both tested in the same test conditions.

Table 2. Characterization of steels used in abrasive testing [29]

Steel grade	Mechanical properties						Microstructure
	Vickers hardness, HV30	Yield stress, R_e (MPa)	Ultimate tensile stress, R_m (MPa)		Elongation, A_5 (%)		
			Min	Max	Min	Max	
S235JR	128 ± 2	235	340		21	26	Ferritic-pearlitic
S235J2	155 ± 5	355	490		20	22	Ferritic-pearlitic
AISI 304	211 ± 7	190	500	700	45		Austenitic
C45	229 ± 3	343	570		14	17	Ferritic-pearlitic
Hardox 500	521 ± 15	1400	1550		10		Martensitic

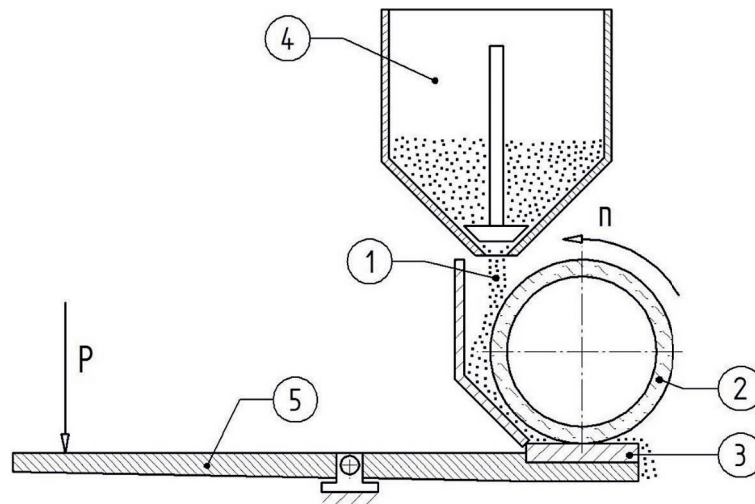


Fig. 1. Scheme of dry sand-rubber wheel T-07 tribotester: 1 – abrasive, 2 – rubber wheel, 3 – steel sample, 4 – feeder, 5 – lever arm, n – rubber wheel revolutions, P – load force

$$K_b = \frac{Z_{vw}}{Z_{vb}} = \frac{Z_{ww} \times \rho_b \times N_b}{Z_{wb} \times \rho_w \times N_w} \quad (-) \quad (4)$$

where: Z_{ww} – mass loss of the reference specimen (g),
 Z_{wb} – mass loss of the examined specimen (g),
 ρ_w, ρ_b – material density of the reference (C45) and examined specimen (g/cm^3),
 N_w – number of roll revolutions for the reference specimen,
 N_b – number of roll revolutions for the examined specimen.

In this study, total number of wheel revolutions for both reference and examined samples was the same: $N_w = N_b = 620$ revolutions.

Profilometric and microscopy analysis of wear traces

The wear traces of steel samples were examined using SEM microscope. Worn areas were investigated with magnifications: 1000x, 2000x, 3000x or 5000x and SEM-EDS method was employed to identify the chemical composition of the particles stacked in the wear trace. Moreover, the roughness of wear traces was measured using Taylor Hobson Surtronic S-100 contact profilometer. The following roughness parameters: *Ra*, *Rz*, *Rmr* (estimated for 1 μm), and *RSm* acc. to PN-EN ISO 21920–2:2022–06 standard, were analyzed. Moreover, roughness profiles and *Rk*, *Rpk*, *Rvk* parameters (acc. to ISO 1356–2 standard)

were investigated. The measurements were preceded by ultrasonic cleaning of the samples. The wear traces’ roughness parameters were studied comparatively concerning the properties of abrasive material, steel samples and abrasive testing results.

RESULTS AND DISCUSSION

Comparative analysis of abrasives and samples properties

Based on the literature data, in Table 3 the abrasive properties are characterized in order of descending mean grain size. It is known from the literature [9, 10, 18–21, 28–30], that the properties of the abrasive material influence the wear results. The hardness, shape and size of particles strongly affect the abrasion wear results. Therefore, the properties of abrasive materials applied in the current study differ. Garnet is mainly composed of silica (SiO_2 , 35 wt.%) and iron oxide (Fe_2O_3 , 33 wt.%) while corundum consists of aluminum oxide (Al_2O_3) while carborundum is pure silicon carbide (SiC). Table 3 shows data in order of increasing hardness, and garnet is almost two times harder than the hardness of tested steel, namely Hardox 500 (521HV30). The hardness of corundum and carborundum is about two and approximately three times, respectively, higher than garnet.

Figure 2 shows SEM micrographs of abrasives which hardness, size and morphology differ. For example, in comparison to garnet (Fig. 2a)

Table 3. Characterization of abrasive particles used for wear testing

Abrasive type	Parameter of abrasive particle							Meangrain size, μm
	Density	Bulk density	Hardness [29]			FEPA*		
			Vickers	Knoop, HK100	Mohs	Size	Grits type	
Garnet	3.80	2.35	600–1355	1360	7.5	F80	macro	180
Corundum	3.95	1.70	1800	2050	9.0	F120	macro	100
Carborundum	3.19	1.44	2600	2480	9.5	F230–F240	macro + micro	50

Note: * characterization according to FEPA-Standard 42–1:2006.

abrasive particles of corundum (Fig. 2b) and carborundum (Fig. 2c) are characterized by irregular shape with sharp edges, while garnet particles have rounded edges (Fig. 2a). Garnet abrasive material presents fine and average grain size, the corundum is composed of a fine and very fine grains and carborundum presents very fine grains with sharp edges (Table 3).

Abrasive wear resistance and wear traces roughness investigations

Following our previous study [29] and rubber wheel standard recommendations, the normalized abrasive wear resistance K_b , eq. (4) has been estimated in reference to C45 steel. Results of three different abrasives and five tested materials are

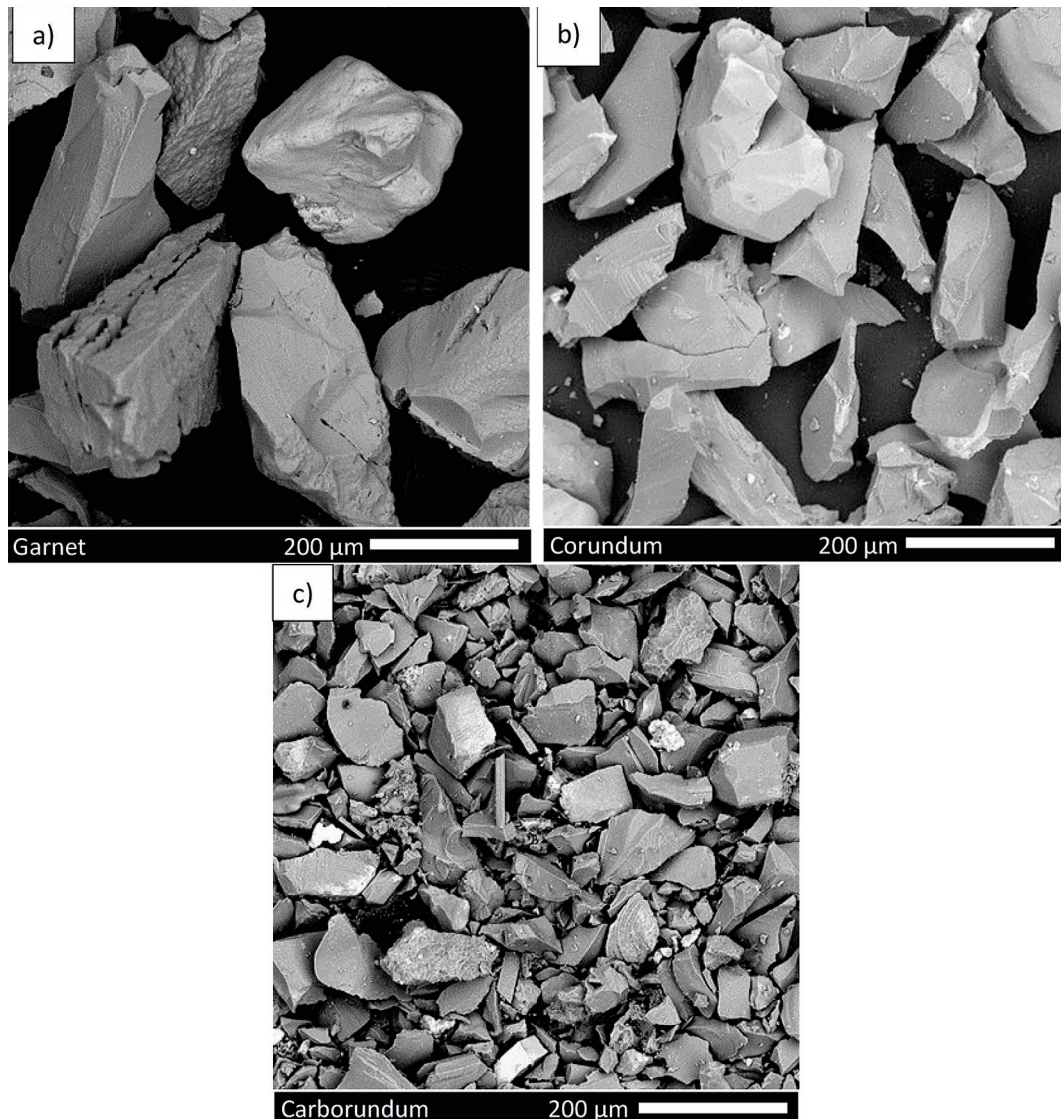


Fig. 2. Morphology of abrasives: (a) garnet; (b) corundum; (c) carborundum, SEM

shown in Figure 3. Analysis of the results indicates that there is no simple correlation between the calculated K_b parameter and the abrasive particle type. Although the overall wear resistance can be summarised based on the steel microstructure. Thus, ferritic-pearlitic steels (S235JR and S355J2) were less resistant than austenitic (AISI 304) and martensitic (Hardox 500) steels abraded by garnet and carborundum, which follows results given by Albertin and Sinatora [9]. Nevertheless, the austenitic AISI 304 steel presented superior wear resistance while testing with corundum (Fig. 3). This steel was more resistant than reference carbon steel C45 in the cases of interactions with all of the three examined abrasives. Even though the Hardox 500 has superior hardness and martensitic microstructure and the highest abrasive resistance in garnet and carborundum. Hardox 500 showed the lowest wear resistance under corundum, what is visible in Figure 3.

Garnet is characterized by the largest particles and the lowest hardness; carborundum displays the smallest particles and the highest hardness. Steel hardness impacts the roughness of wear traces. When garnet and carborundum were used as abrasives (Fig. 4), increasing steel hardness caused decreasing Ra roughness parameter of steels, apart from AISI 304 tested in carborundum. AISI 304 steel surface worn by carborundum grit, exhibits the highest Ra , Rz , RSm and Rmr parameters (Fig. 5 and Fig. 6). This austenitic steel has high wear resistance (Fig. 3), at a comparable level to Hardox 500. Generally, apart from the stainless steel sample, the increasing size of abrasive particles, the less smooth surface of the wear track (higher Ra , Rz , RSm) and the lower material component of a profile (Rmr).

However, the roughness of C45 worn by carborundum shows the highest value of $Rmr = 23.4\%$ while other steels shows Rmr values at least two times lower, what is shown in Figure 6a.

Rk , Rpk , Rvk parameters have no simple correlation to the K_b wear results (Fig. 3) and roughness parameters (Fig. 7a–c). On the other hand, AISI 304 steel surface abraded by carborundum particles presents outstanding core roughness (Rk) and reduced peak height (Rpk). When garnet was used in tests – Rk , Rpk and Rvk (reduced valley depth) parameters were usually high. For carborundum used in tests as abrasive material, Rk , Rpk and Rvk parameters were usually low (except of AISI 304 steel worn surface). It seems that abrasive grains size and morphology affect the wear trace roughness, which is visualized by SEM.

Microscopic analysis of wear traces

On the basis of SEM investigations of abraded surfaces (Fig. 8), the wear mechanisms were determined and summarized in Table 4. Ploughing and low-cycle fatigue were the predominant wear mechanisms observed for most steels-abrasives interactions (Fig. 8a–m). Abrasive particles made ridges at the front and at the sides of grooves. Many repetitions of ploughing provided plastic deformation and cracking due to low-cycle fatigue. Microcutting was a dominant wear mechanism only when Hardox 500 steel was abraded by carborundum (SiC) particles (Fig. 8n). Model microcutting makes that a volume loss is equal to groove volume firstly described in [30]. In the Fig. 8n, ploughing was secondary wear mechanism, dominated by microcutting. These results contradict Pawlak et al. [15] who tested Hardox

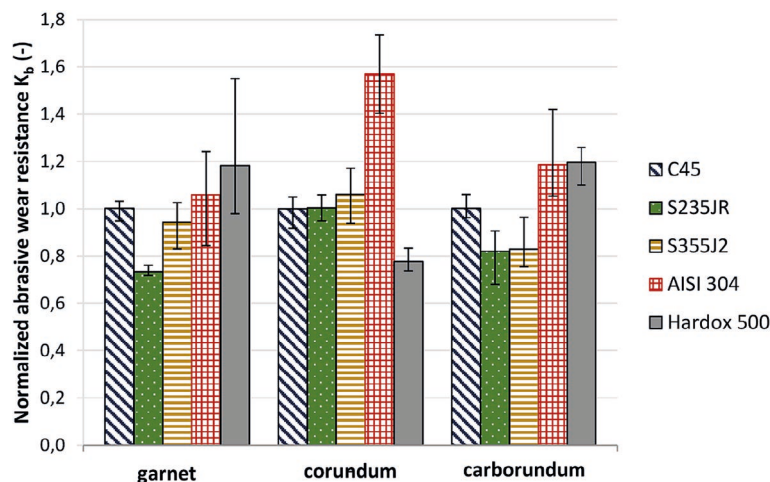


Fig. 3. Normalized abrasive wear resistance, estimated for different abrasives (calculated relating to C45)

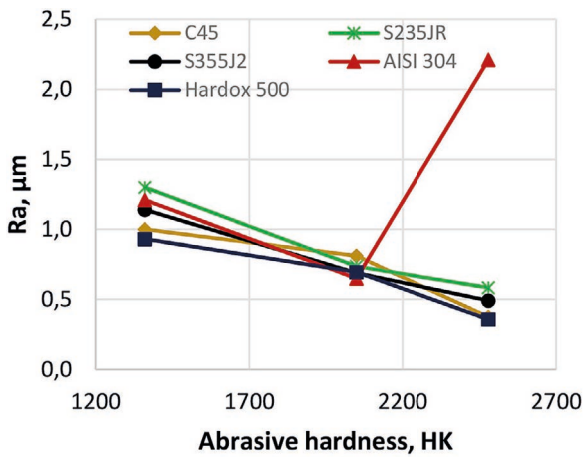


Fig. 4. Effect of abrasive grit hardness on wear traces R_a roughness of investigated steels

450 steel in corundum, revealed the microcutting wear mechanism, and agree with the findings given by Białobrzeska [17] for corundum. Analysis of Fig. 8c, d, g, i, l-n, confirm that abrasive

particles almost totally shaped some wear tracks orientated parallel to abrasive motion. Other wear tracks show random scratches orientation (Fig. 8a, b, e, f, h, j, k). Figure 8k presents embedded SiC particles into S235JR steel sample after ploughing. The SEM images of C45, S235JR and S355J2 confirm similar wear trace morphology and domination of ploughing and microfatigue wear mechanisms (Fig. 8a–m). The softest structural steels S235JR and S355J2, usually show the highest R_a and R_z of abraded surface (see Fig 5). Though cleaning the samples before making SEM images, there is a lot of stuck debris on the surfaces due to ploughing character of wear (e.g. Fig. 8f, m). In Figure 8m there is a deep, wide groove (near the yellow arrow), produced by ploughing and microcutting wear mechanisms and deep grooves well correspond to the high value of R_{vk} estimated for AISI 304 abraded by carborundum. Carborundum has relatively high

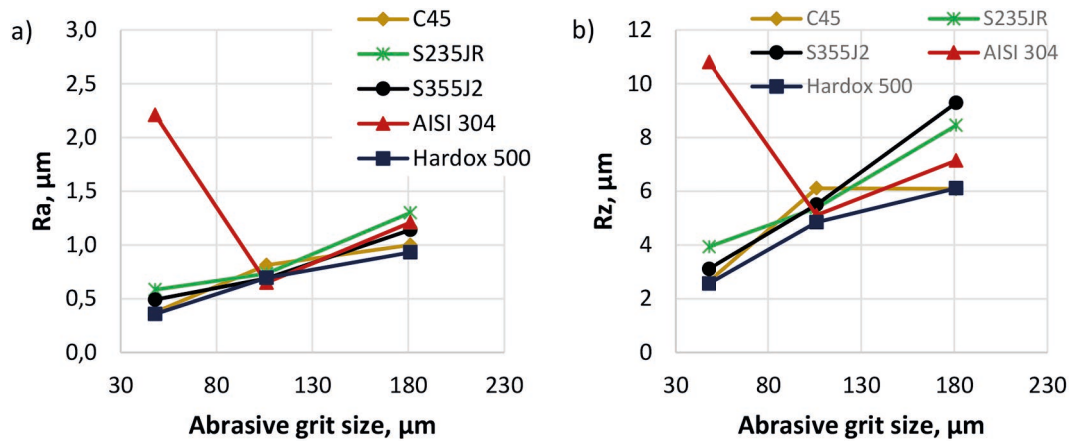


Fig. 5. Influence of abrasive grit size on (a) R_a and (b) R_z roughness parameters of wear traces

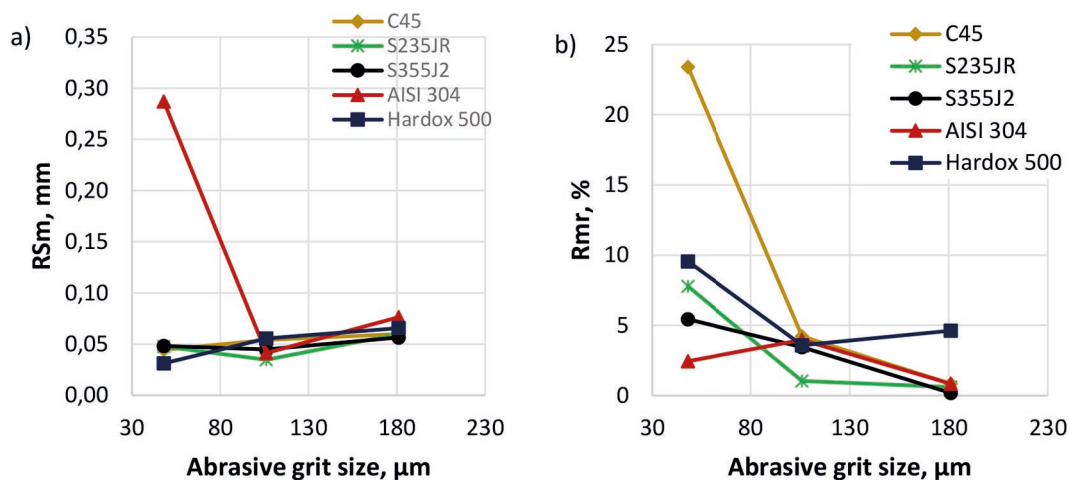


Fig. 6. Influence of abrasive grit size on (a) R_{Sm} and (b) R_{mr} (estimated for $c = 1 \mu\text{m}$) roughness parameters wear traces

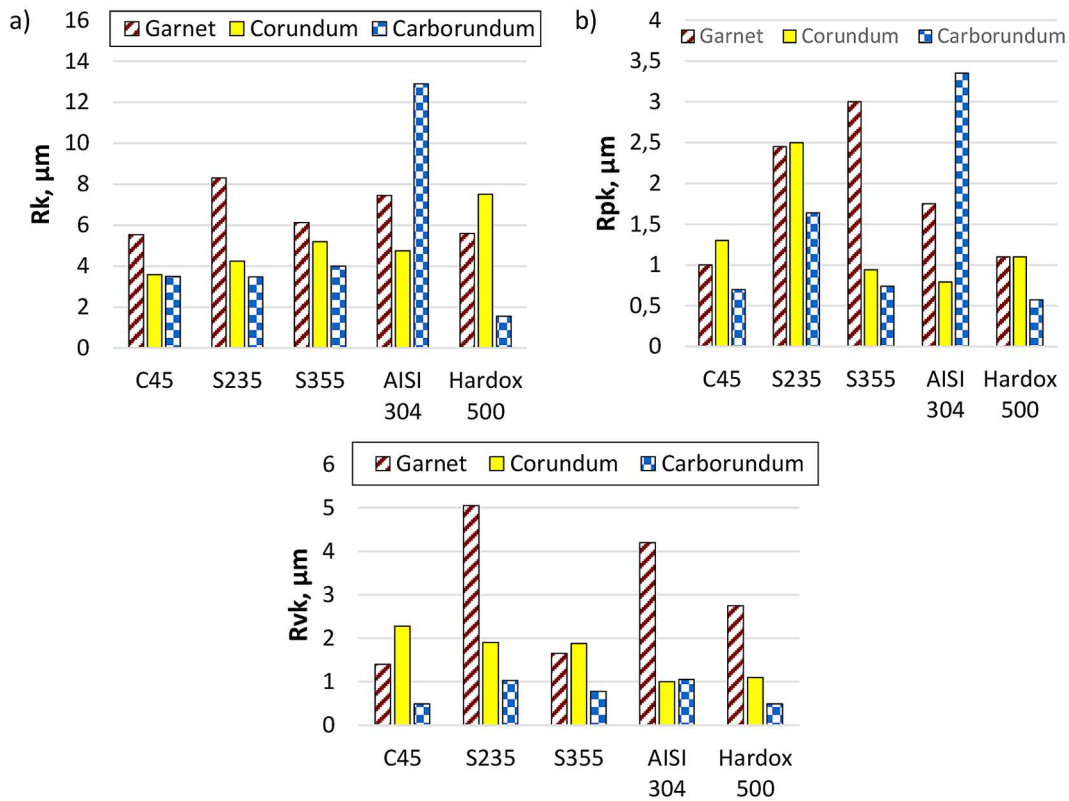


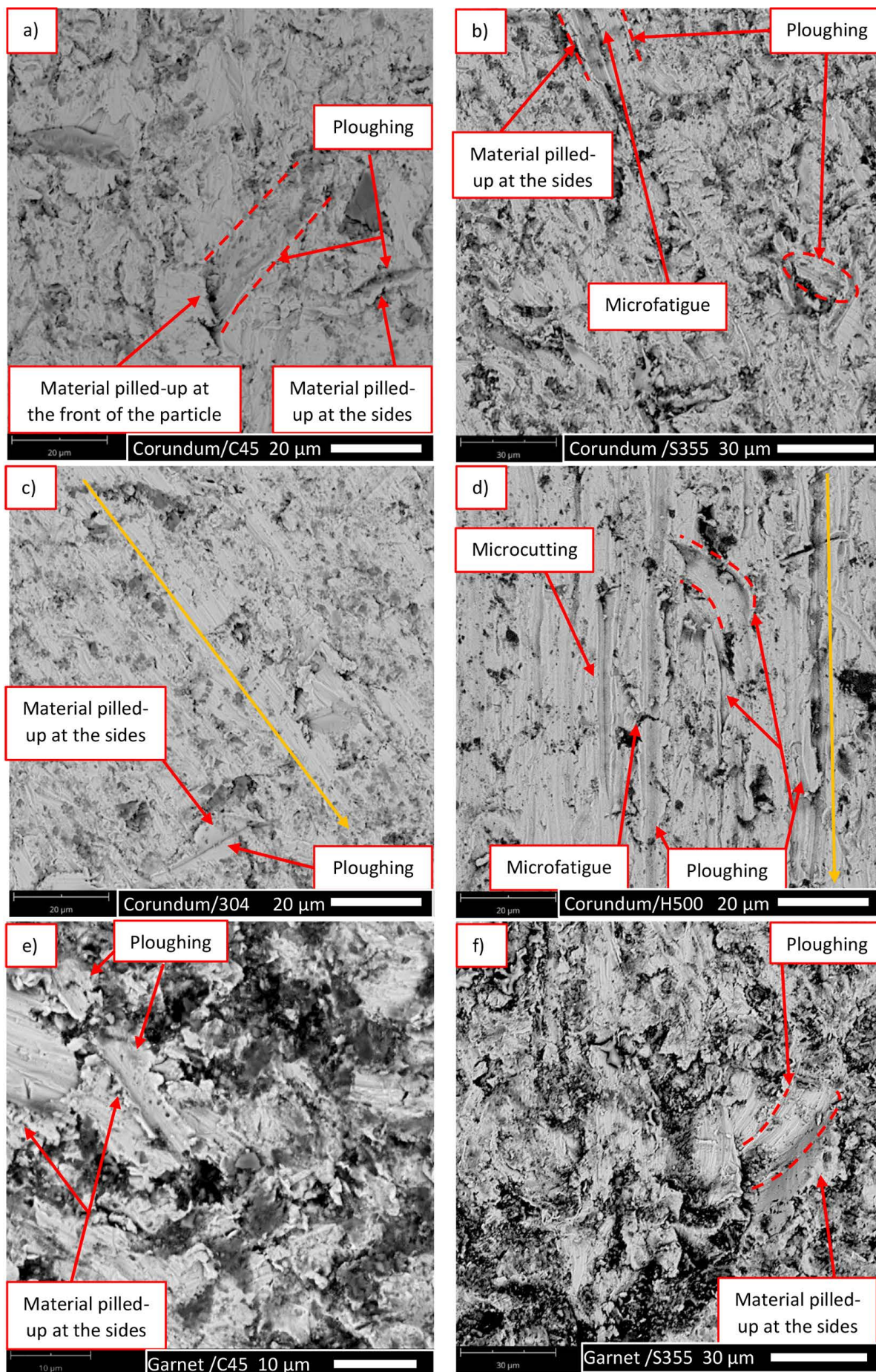
Fig. 7. Wear track roughness parameters: (a) core roughness R_k , (b) reduced peak height R_{pk} , and (c) reduced valley depth R_{vk} of worn surfaces

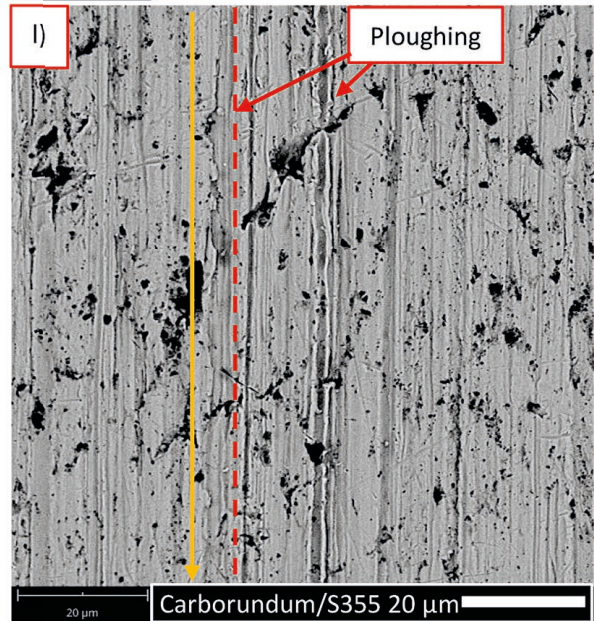
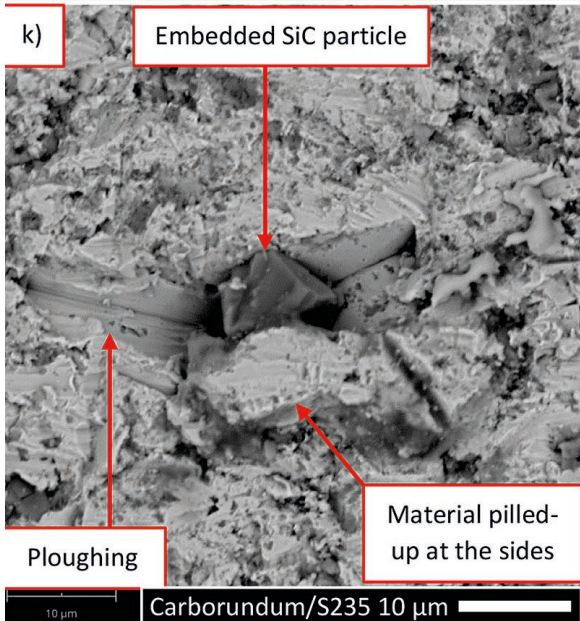
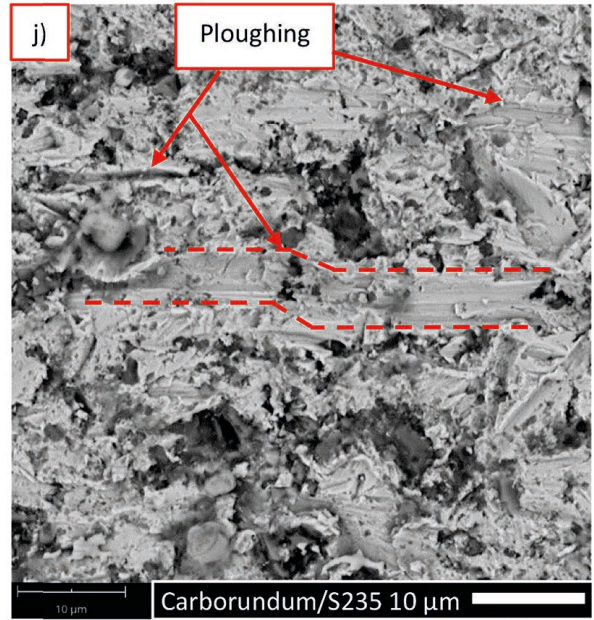
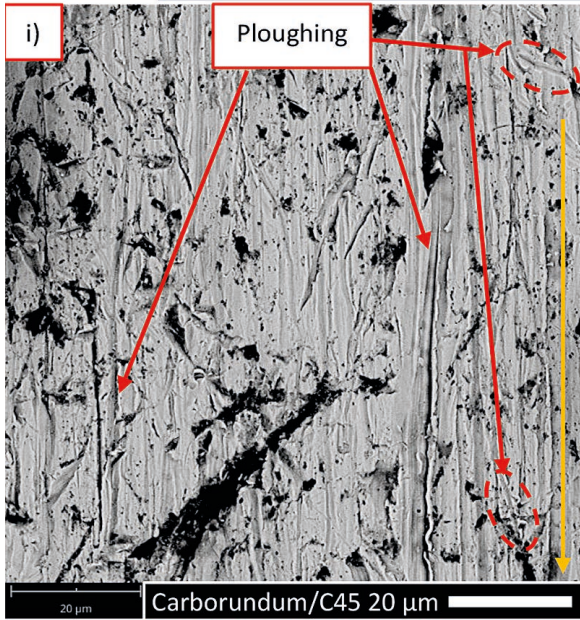
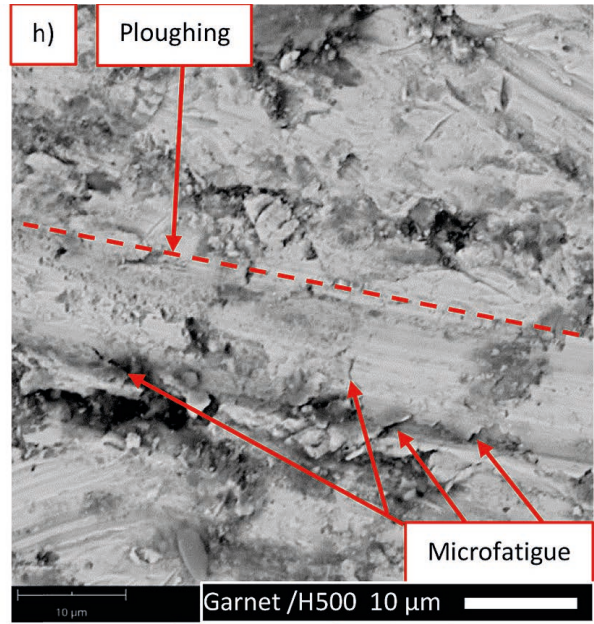
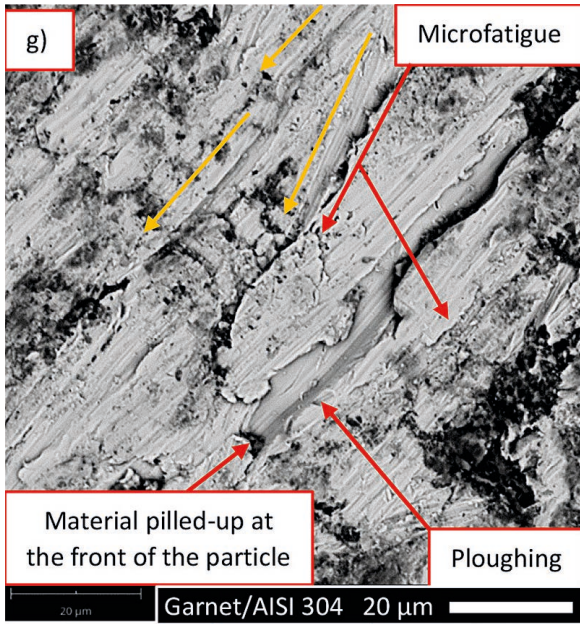
hardness (exceeding hardness of corundum and garnet, see Table 3). Thus, the interaction of carborundum abrasive with relatively hard Hardox 500 steel caused mainly the microcutting wear. The abraded Hardox 500 shows the lowest roughness estimated by R_a and R_z parameters (Fig. 5). When relatively soft abrasives: garnet and corundum, were used, and relatively soft steels: S235JR, S355J2, C45 and AISI 304 were tested, then ploughing and joined with ploughing – microfatigue were the dominant wear mechanisms, which is clarified in details in works [18,30]. In the case of garnet, the R_k , R_{pk} and R_{vk} parameters (Fig. 7) were usually high, but using the carborundum lowers these parameters (except for the worn surface of AISI 304 steel), which suggests the effect of hardness and abrasive grain size and morphology. The hard and small size of corundum grains soothes the abraded surface, contrary to coarse garnet particles. AISI 304 abraded by carborundum grit, presented outstanding roughness parameters: R_a , R_z , R_{Sm} and R_k , R_{vk} and R_{pk} than other steels tested with carborundum. Probably the reason for these extraordinary values was the small grain size, relatively high carborundum hardness and the ability of AISI 304 austenitic microstructure for plastic deformation.

Austenite has the highest elongation than other ferritic-pearlitic and martensitic steels shown in Table 2. This enables the material to be smashed and plastically deformed, finally contributing to deeper grooves than those produced by garnet and corundum abrasives. Therefore, the effect of steel microstructure on the wear mechanism has been confirmed, too.

CONCLUSIONS

Wear resistance is one of the main indicators of the reliability of machine parts. The selection of wear resistant material should include information about the operational environment, likewise a specific type of abrasive material. Overall abrasive wear resistance of steel depends not only on its hardness and microstructure but also on the abrasive material’s hardness and morphology. These factors determine the abrasive behavior of steel. This investigation continues the research done in the previous paper [29], which revealed the quantitative results of wear resistance obtained for the tested set of steels. Therefore, current work aimed to investigate the wear mechanisms of S235JR, S355J2, AISI 304 and Hardox





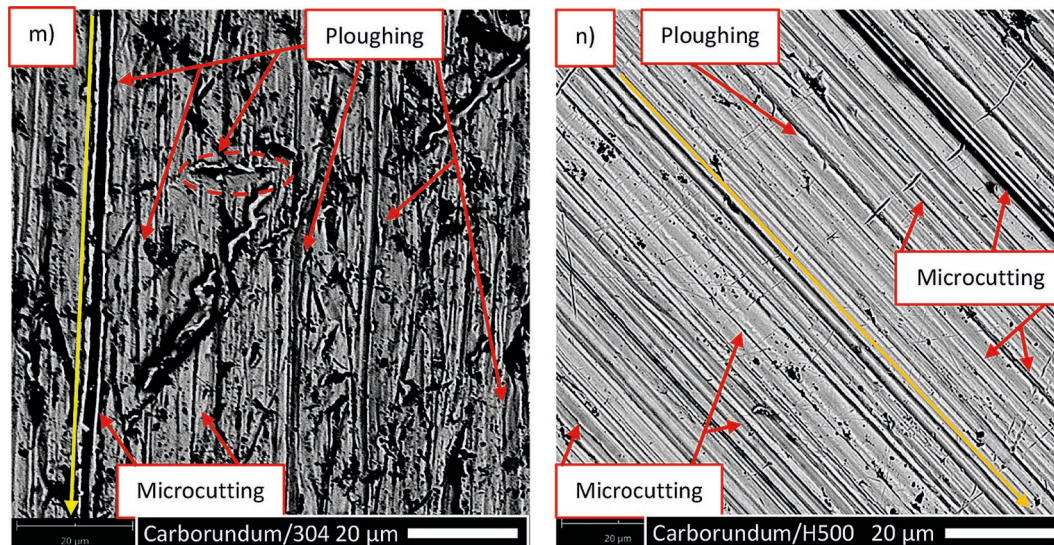


Fig. 8. Wear traces disclosed by SEM: (a) C45-corundum; (b) S355J2-corundum; (c) AISI 304-corundum; (d) Hardox 500-corundum; (e) C45-garnet; (f) S355J2-garnet; (g) AISI 304-garnet; (h) Hardox 500-garnet; (i) C45-carborundum; (j) and (k) S235JR-carborundum; (l) S355J2-carborundum; (m) AISI 304-carborundum; (n) Hardox 500-carborundum; (yellow/orange arrows indicate track of most the abrasive particles)

500 steels tested using garnet, corundum and carborundum abrasives. As a result of the presented investigations, the following findings are stated.

1. Steel grades S235JR and S355J2 (ferritic-pearlitic microstructure) were less abrasive wear resistant than AISI 304 (austenitic structure) and Hardox 500 (martensitic) when tested in garnet and carborundum environments. The AISI 304 steel presented a superior wear resistance while testing with corundum and has higher resistance than C45 investigated using each of the three abrasives. Hardox 500 showed the lowest wear resistance tested in corundum and the highest abrasive resistance in garnet and carborundum.
2. Ploughing and low-cycle fatigue were the dominant wear mechanisms observed for most of the steels-abrasives interactions. Only in the case of Hardox 500, when carborundum was used as abrasive, microcutting was a dominant wear mechanism.
3. Carborundum had relatively high hardness (much more than corundum and garnet) and

interaction of this abrasive with relatively hard Hardox 500 steel caused almost only the microcutting wear. However, when relatively soft abrasives such as garnet and corundum were used and relatively soft steels such as S235JR, S355J2, C45 and AISI 304 were tested, then ploughing and microfatigue were the main wear mechanisms.

4. The effect of steel microstructure on the wear mechanism has been confirmed. AISI 304 abraded by carborundum grit, presented outstanding roughness parameters: R_a , R_z , R_{Sm} , R_k , R_{vk} and R_{pk} than other steels tested with carborundum. It seems that fine grain size, relatively high hardness of carborundum and the ability of AISI 304 austenitic microstructure for plastic deformation contributes to deeper grooving than those reported for garnet and corundum abrasives.
5. Steel hardness affects the morphology of the wear trace. For example, Hardox 500 is the hardness of investigated steels and usually shows the wear trace's lowest R_a and R_z roughness parameters.

Table 4. Summary of the dominant wear mechanisms of investigated steels

Abrasive	Sample code				
	C45	S235JR	S355J2	AISI 304	Hardox 500
Garnet	Microploughing and microfatigue				Microploughing and microfatigue
Corundum					
Carborundum					Microcutting

6. The effect of abrasive hardness and grain size and morphology has been stated. Contrary to fine grains of carborundum, roughness parameters (R_k , R_{pk} and R_{vk}) were usually high when abraded by garnet, which had coarse grains.

Acknowledgment

The paper has been submitted under the duties of the international scientific scholarship of Mirosław Szala, Lublin University of Technology (Poland), taking place in the term of July 11 – August 8, 2022, at Vilnius Gediminas Technical University (Lithuania), conducted and financed in the framework of the project “Lublin University of Technology-Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19)”.

REFERENCES

- Drozd K., Walczak M., Szala M., Gancarczyk K. Tribological Behavior of AlCrSiN-Coated Tool Steel K340 Versus Popular Tool Steel Grades. *Materials* 2020; 13(21). <https://doi.org/10.3390/ma13214895>
- Karumuri S., Das C., Krishna Mallarapu G. Tribological Properties of Al 7075 Composite Reinforced with ZrB₂ Using Grey Relational Analysis. *Advances in Science and Technology Research Journal* 2022; 16(4): 22–28. <https://doi.org/10.12913/22998624/152020>
- Walczak M., Szala M., Pieniak D. Effect of Water Absorption on Tribological Properties of Thermoplastics Matrix Composites Reinforced with Glass Fibres. *Advances in Science and Technology Research Journal* 2022; 16(2): 232–239. <https://doi.org/10.12913/22998624/147515>
- Morozow D., Siemiątkowski Z., Gevorkyan E., Rucki M., Matijošius J., Kilikevičius A., Caban J., Krzysiak Z. Effect of Yttrium and Rhenium Ion Implantation on the Performance of Nitride Ceramic Cutting Tools. *Materials* 2020; 13(20). <https://doi.org/10.3390/ma13204687>
- Nana Sekyi Appiah A., Bialas O., Czupryński A., Adamiak M. Powder Plasma Transferred Arc Welding of Ni-Si-B+60 wt%WC and Ni-Cr-Si-B+45 wt%WC for Surface Cladding of Structural Steel. *Materials* 2022; 15(14). <https://doi.org/10.3390/ma15144956>
- Nana Sekyi Appiah A., Bialas O., Żuk M., Czupryński A., Konadu Sasu D., Adamiak M. Hardfacing of mild steel with wear-resistant Ni-based powders containing tungsten carbide particles using powder plasma transferred arc welding technology. *Materials Science-Poland* 2022; 40(3): 42–63. <https://doi.org/10.2478/msp-2022-0033>
- Hejwowski T., Szala M. Wear-Fatigue Study of Carbon Steels. *Advances in Science and Technology Research Journal* 2021; 15(3): 179–190. <https://doi.org/10.12913/22998624/140200>
- Xu X., Xu W., Hipgrave Ederveen F., van der Zwaag S. Design of low hardness abrasion resistant steels. *Wear* 2013; 301: 89–93. <http://dx.doi.org/10.1016/j.wear.2013.01.002>
- Albertin E., Sinatora A. Effect of carbide fraction and matrix microstructure on the wear of cast iron balls tested in a laboratory mill. *Wear* 2001; 250: 492–501. [https://doi.org/10.1016/S0043-1648\(01\)00664-0](https://doi.org/10.1016/S0043-1648(01)00664-0)
- Turenne S., Lavallée F., Masounave J. Matrix microstructure effect on the abrasive wear resistance of high-chromium white cast iron. *Journal of Materials Science* 1989; 24: 3021–3028. <https://doi.org/10.1007/BF02385662>
- Movassagh-Alanagh F., Mahdavi M. Improving wear and corrosion resistance of AISI 304 stainless steel by a multilayered nanocomposite Ti/TiN/TiSiN coating. *Surfaces and Interfaces* 2020; 18. <https://doi.org/10.1016/j.surf.2019.100428>
- Szala M., Dudek A., Maruszczyk A., Walczak M., Chmiel J., Kowal M. Effect of Atmospheric Plasma Sprayed TiO₂-10% NiAl Cermet Coating Thickness on Cavitation Erosion, Sliding and Abrasive Wear Resistance. *Acta Physica Polonica Series A* 2019; 136(2): 335–341. <https://doi.org/10.12693/APhysPolA.136.335>
- Beköz Üllen N. Investigation of the wear resistance of Hardox steel plates, Second International Conference On Tribology “TURKEYTRIB’18”, Istanbul, Turkey, 18–20 April 2018.
- Ligier K., Zemlik M., Lemecha M., Konat Ł., Napiórkowski J. Analysis of Wear Properties of Hardox Steels in Different Soil Conditions. *Materials* 2022; 15(21). <https://doi.org/10.3390/ma15217622>
- Pawlak K., Białobrzaska B., Konat Ł. The influence of austenitizing temperature on prior austenite grain size and resistance to abrasion wear of selected low-alloy boron steel. *Archives of Civil and Mechanical Engineering* 2016; 16: 913–926. <https://doi.org/10.1016/j.acme.2016.07.003>
- Jafarian H.R., Sabzi M., Mousavi Anijdan S.H., Eivani A.R., Park N. The influence of austenitization temperature on microstructural developments, mechanical properties, fracture mode and wear mechanism of Hadfield high manganese steel. *Journal of Materials Research and Technology* 2021; 10: 819–831. <https://doi.org/10.1016/j.jmrt.2020.12.003>
- Białobrzaska B. The influence of boron on the re-

- sistance to abrasion of quenched low-alloy steels. *Wear* 2022; 500–501. <https://doi.org/10.1016/j.wear.2022.204345>
18. Wiczczyński A. Experimental studies on the influence of abrasive materials on the wear of hard-wearing steels. *Tribologia* 2018; 5: 133–141.
19. Zhou N., Lin Peng R., Pettersson R. Surface characterization of austenitic stainless steel 304L after different grinding operations. *International Journal of Mechanical and Materials Engineering* 2017; 12(6). <https://doi.org/10.1186/s40712-017-0074-6>
20. Thakare M.R., Wharton J.A., Wood R.J.K., Menger C. Effect of abrasive particle size and the influence of microstructure on the wear mechanisms in wear-resistant materials. *Wear* 2012; 276–277: 16–28. <https://doi.org/10.1016/j.wear.2011.11.008>
21. Wang Q., Zhang Y., Ding X., Wang S., Seshadri Ramachandran C. Effect of WC Grain Size and Abrasive Type on the Wear Performance of HVOF-Sprayed WC-20Cr3C2-7Ni, *Coatings*. *Coatings* 2020; 10. <https://doi.org/10.3390/coatings10070660>.
22. Kamdi Z., Shipway P.H., Voisey K.T., Sturgeon A.J. Abrasive wear behaviour of conventional and large-particle tungsten carbide-based cermet coatings as a function of abrasive size and type. *Wear* 2011; 271(9–10): 1264–1272. <https://doi.org/10.1016/j.wear.2010.12.060>
23. Yu Y., Sun T., Yuan Y., Gao H., Wang X. Experimental investigation into effect of abrasive process parameters on the cutting performance for abrasive waterjet technology: a case study. *The International Journal of Advanced Manufacturing Technology* 2020; 107: 2757–2765. <https://doi.org/10.1007/s00170-020-05183-3>
24. Vargova M., Tavodova M., Monkova K., Dzupon M. Research of Resistance of Selected Materials to Abrasive Wear to Increase the Ploughshare Lifetime. *Metals* 2022; 12(6). <https://doi.org/10.3390/met12060940>
25. Napiórkowski J., Lemecha M., Konat Ł. Forecasting the Wear of Operating Parts in an Abrasive Soil Mass Using the Holm-Archard Model. *Materials* 2019; 12(13). <http://dx.doi.org/10.3390/ma12132180>.
26. Singh Mann P., Kaur Brar N. Tribological aspects of agricultural equipments: a review. *International Research Journal of Engineering and Technology (IRJET)* 2015; 2(3): 1704–1708. <https://www.irjet.net/archives/V2/i3/Irjet-v2i3267.pdf> (accessed January 22, 2023).
27. Sigolo E., Soyama J., Zepon G., Shyinti Kliminami C., Botta W.J., Bolfarini C. Wear resistant coatings of boron-modified stainless steels deposited by Plasma Transferred Arc. *Surface and Coatings Technology* 2016; 302: 255–264. <https://doi.org/10.1016/j.surfcoat.2016.06.023>
28. Wirojanupatump S., Shipway P.H. Abrasion of mild steel in wet and dry conditions with the rubber and steel wheel abrasion apparatus. *Wear* 2000; 239(1): 91–101. [https://doi.org/10.1016/S0043-1648\(00\)00310-0](https://doi.org/10.1016/S0043-1648(00)00310-0)
29. Szala M., Szafran M., Macek W., Marchenko S., Hejwowski T. Abrasion Resistance of S235, S355, C45, AISI 304 and Hardox 500 Steels with Usage of Garnet, Corundum and Carborundum Abrasives. *Advances in Science and Technology Research Journal* 2019; 13(4): 151–161. <https://doi.org/10.12913/22998624/113244>
30. Zum Gahr K.-H. *Microstructure and wear of materials*. Elsevier Science Ltd 1987; 80–351.