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 Sinatoria [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 (Al₂O₃) 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 TiO₂ – 10 wt.% NiAl plasma deposited coatings (approx. 600 HK) presented higher mass losses than the normalized steel grade C45, which has lower hardness then 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 (Al₂O₃) 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. Wirojanapatump 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
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 \( (\text{Al}_2\text{O}_3) \), carborundum \( (\text{silicon carbide, SiC}) \) and garnet composed mainly of silica \( (\text{SiO}_2, 35 \text{ wt.\%}) \) and ferric oxide \( (\text{Fe}_2\text{O}_3, 33 \text{ wt.\%}) \). 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 \( K_w \) (4), the volume material loss of specific material \( Z_{wm} \) was divided by the volume loss of specific material \( Z_{vb} \) – both tested in the same test conditions.

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

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>B</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Max</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>AISI 304</th>
<th>S235JR</th>
<th>S355J2</th>
<th>Hardox 500</th>
<th>C45</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.07</td>
<td>0.17</td>
<td>0.20</td>
<td>0.27</td>
<td>0.45</td>
</tr>
<tr>
<td>Si</td>
<td>1.00</td>
<td>1.4</td>
<td>0.55</td>
<td>0.70</td>
<td>0.17</td>
</tr>
<tr>
<td>Mn</td>
<td>2.0</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>0.37</td>
</tr>
<tr>
<td>Cr</td>
<td>17.0</td>
<td>0.3</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Ni</td>
<td>8.0</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Mo</td>
<td>10.50</td>
<td>0.045</td>
<td>0.30</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>B</td>
<td>0.045</td>
<td>0.035</td>
<td>0.025</td>
<td>0.025</td>
<td>0.040</td>
</tr>
<tr>
<td>P</td>
<td>0.015</td>
<td>0.035</td>
<td>0.025</td>
<td>0.025</td>
<td>0.040</td>
</tr>
<tr>
<td>S</td>
<td>0.015</td>
<td>0.035</td>
<td>0.025</td>
<td>0.025</td>
<td>0.040</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Vickers hardness, HV30</th>
<th>Yield stress, ( R_m (\text{MPa}) )</th>
<th>Ultimate tensile stress, ( R_m (\text{MPa}) )</th>
<th>Elongation, ( \Delta_5 (%) )</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>S235JR</td>
<td>128 ± 2</td>
<td>235</td>
<td>340</td>
<td>21</td>
<td>Ferritic-pearlitic</td>
</tr>
<tr>
<td>S235J2</td>
<td>155 ± 5</td>
<td>355</td>
<td>490</td>
<td>20</td>
<td>Ferritic-pearlitic</td>
</tr>
<tr>
<td>AISI 304</td>
<td>211 ± 7</td>
<td>190</td>
<td>500</td>
<td>45</td>
<td>Austenitic</td>
</tr>
<tr>
<td>C45</td>
<td>229 ± 3</td>
<td>343</td>
<td>570</td>
<td>14</td>
<td>Ferritic-pearlitic</td>
</tr>
<tr>
<td>Hardox 500</td>
<td>521 ± 15</td>
<td>1400</td>
<td>1550</td>
<td>10</td>
<td>Martensitic</td>
</tr>
</tbody>
</table>
where:

\[ K_b = \frac{Z_{ww}}{Z_{wb}} = \frac{Z_{ww} \times \rho_b \times N_b}{Z_{wb} \times \rho_w \times N_w} (-) \quad (4) \]

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 \( \mu m \)), and \( RSm \) acc. to PN-EN ISO 21920–2:2022–06 standard, were analyzed. Moreover, roughness profiles and \( Rk, Rp, Rvk \) 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 (\( \text{SiO}_2 35 \text{ wt.\%} \)) and iron oxide (\( \text{Fe}_2\text{O}_3 33 \text{ wt.\%} \)) while corundum consists of aluminum oxide (\( \text{Al}_2\text{O}_3 \)) while carborundum is pure silicon carbide (\( \text{SiC} \)). 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)
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).

**Table 3. Characterization of abrasive particles used for wear testing**

<table>
<thead>
<tr>
<th>Abrasive type</th>
<th>Density, g/cm³</th>
<th>Bulk density, g/cm³</th>
<th>Parameter of abrasive particle</th>
<th>FEPA*</th>
<th>Mean grain size, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garnet</td>
<td>3.80</td>
<td>2.35</td>
<td>hardness, Vickers 600–1355</td>
<td>1360</td>
<td>7.5 F80</td>
</tr>
<tr>
<td>Corundum</td>
<td>3.95</td>
<td>1.70</td>
<td>hardness, Knoop HK100 1800</td>
<td>2050</td>
<td>9.0 F120</td>
</tr>
<tr>
<td>Carborundum</td>
<td>3.19</td>
<td>1.44</td>
<td>hardness, Mohs 2600</td>
<td>2480</td>
<td>9.5 F230–F240</td>
</tr>
</tbody>
</table>

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

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 summarized 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 Siranora [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 $Ra$, $R_z$, $R_{Sm}$ and $R_{mr}$ 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 $Ra$, $R_z$, $R_{Sm}$) and the lower material component of a profile ($R_{mr}$).

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

$R_k$, $R_{pk}$, $R_{vk}$ 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 ($R_k$) and reduced peak height ($R_{pk}$). When garnet was used in tests – $R_k$, $R_{pk}$ and $R_{vk}$ parameters were usually high. For carborundum used in tests as abrasive material, $R_k$, $R_{pk}$ and $R_{vk}$ 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...
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 Ra and Rz 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 groves well correspond to the high value of Rvk estimated for AISI 304 abraded by carborundum. Carborundum has relatively high
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 Ra and Rz 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 Rk, Rpk and Rvk 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: Ra, Rz, RSm and Rk, Rvk and Rpk 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.
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: $Ra$, $Rz$, $RSm$, $Rk$, $Rvk$ and $Rp$k 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 $Ra$ and $Rz$ roughness parameters.

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

<table>
<thead>
<tr>
<th>Abrasive</th>
<th>Sample code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C45</td>
</tr>
<tr>
<td></td>
<td>S235JR</td>
</tr>
<tr>
<td></td>
<td>S355J2</td>
</tr>
<tr>
<td></td>
<td>AISI 304</td>
</tr>
<tr>
<td>Garnet</td>
<td>Microploughing and microfatigue</td>
</tr>
<tr>
<td>Corundum</td>
<td>Microploughing and microfatigue</td>
</tr>
<tr>
<td>Carborundum</td>
<td>Microcutting</td>
</tr>
</tbody>
</table>

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)
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.

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