WEAR BEHAVIOUR OF CARBON AND LOW ALLOYED SINTERED STEELS

A. Šalak, M. Selecká

Abstract
Material performance in dry wear conditions is important to understand its behaviour in severe tribological conditions. A special case of dry wear is in machining between the material and the tool. Dry tribological testing of sintered Fe-C, Fe-Cu-C, Fe-(1.75, 4)Ni-1.5Cu-0.5Mo-C and Fe-(1-5)Mn-C alloys was carried out. Mechanical properties of alloys were estimated. Tribological testing on impact toughness bars by the Amsler method (disc-prism) at a load of 100 N for a sliding distance of 1000 m was performed. Dry wear as weight loss, the coefficient of friction and temperature of the samples was measured. The dependence of wear on the hardness of the samples was estimated. Manganese steels in dependence on carbon and manganese content exhibited the lowest wear. Microstructure analysis, with the measurement of microhardness of friction surface layers, was performed. For verification of the results, a component - roller from FeMnC- and FeNiCuMoC steel was tested for wear.

Keywords: powder metallurgy, steel, carbon, nickel-copper, manganese, mechanical properties, friction, microstructure

INTRODUCTION
Powder metallurgy (PM) manufacturing process is characterised by high material utilization, and a relatively low capital and production cost. Variability in combination of chemical composition of the alloys and of processing methods enables preparation of the PM parts for a wide severe application in automotive and other industry. All parts being in motion, in contact with a counterpart, are subjected for wear. The build-up of tribological data on PM materials should be a part of the material development, with defined mechanical and structure properties, to help in a correct choice of the materials for new designs [1].

Powder metallurgy materials are characterised by heterogeneous microstructure formed by single phases of different physique-metallurgical properties, including pores of various proportion. The microstructure of materials determines its mechanical and, by this manner, also tribological properties. The microstructure analysis, in relation to the tribology of PM materials, is the aim of the investigation. On the basis of testing the tribological properties of single phases in a Fe-C system, it was stated that lower bainite and spheroidised pearlite exhibited the lowest coefficient of friction, also as compared with martensite [2]. Similarly, the sintered Fe-3.5Mo-C material with bainite attained the lowest wear rate compared with those with martensite microstructure [3]. Sintered Fe-3Mn-1.5Mo-0.5C steel with bainite microstructure exhibited the lowest dry wear in the range of sintered structural and HSS steels, with a hardness of 90 to 550 HV 30 [4]. A positive effect of

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manganese addition on the friction properties of Fe-0.3C material and of nickel on Fe-0.7C was demonstrated in Ref. [5]. The presence of soft phases in material plays a negative role in friction. The localisation of plastic deformation in these phases, in fact, causes an increase in wear by adhesion up to cold welding [6].

Solid lubricants added to PM steel parts, improving the sliding behaviour, seems to be effective only if some wear can be tolerated [7]. The dry wear and coefficient of the friction of HIPed HSS markedly decreased only with addition of 5% MoS$_2$ [8]. The effect of microstructure character on the tribological properties of material is therefore often indicated [6, 9]. Many different heat treatment and surface hardening processes are applied and constantly investigated for the wear resistance increase of various sintered parts loaded under different kinds of friction [5, 6, 9-12].

The knowledge of a material’s performance in dry wear conditions is important to understand their basic behaviour in severe tribological conditions, such as during transients when lubrication is not yet fully effective or at a limited motion. There are also some components working under dry sliding conditions only. A special case of dry friction is machining for PM parts. The tribological properties of the friction pair formed by the sintered material and the tool (chip/tool) under dry cutting conditions, decide the tool life and, in this way, the effectiveness of the machining process. In this case, the adhesive wear is dominant, at which occurs the separation, and a transfer of the material particles from the places where the relative motion of the functional surfaces occurred [13]. This was the main reason for testing the tribological properties of sintered structural materials without additional treatment, within the scope of this work.

Mechanical and tribological properties of structural sintered carbon, partially diffusion alloyed and manganese steels characterised by dry wear, and the coefficient of friction and temperature, are presented in this paper.

**EXPERIMENTAL**

The test samples were prepared from the following alloys:

1. carbon and alloyed steels:
   a) Fe-(0.1, 0.3, 0.7)% graphite (C),
   b) Fe-(1.75, 4)% Ni-1.5% Cu-0.5% Mo-(0.3, 0.7)% graphite, without and with 0.5% MnX (solid lubricant, machining aid) addition,
   c) Fe-2% Cu-0.7% C,

2. manganese steels:
   a) Fe-(1-5)% Mn-(0.1-0.40)% C based on three different iron powder grades,
   b) Fe-(2, 3, 4)% Mn-0.4% graphite,
   c) Fe-(2.5, 3)% Mn-(0.2% Mo)-1.0% C based on two iron powder grades.

For the preparation of the samples the following powders were used:
- sponge iron powder SC100.29 and NC100.24 and atomised iron powder ASC100.29,
- partially diffusion alloyed Fe-1.75Ni-1.5Cu-0.5Mo (Distaloy SA), Fe-4Ni-1.5Cu-0.5Mo (Distaloy SE), and prealloyed Fe-0.85Mo (Astaloy85Mo); (SC100.26, ASC100.29, Distaloy SA and SE without and with addition of 0.5 %MnX), all from Höganäs AB, Sweden;
- manganese carrier:
   a) high carbon ferromanganese (76% Mn, 6.5% C; from OFZ Istebné, Slovakia) - coded here FeMnC,
   b) medium carbon ferromanganese (80% Mn, 1.25% C; from ERATEM, Norway) coded here FeMn, both mean size ~20 μm,
- natural graphite (grade CR12, 99.5% C, from GRAFIT Netolice, Czech Republic)
- electrolytic copper.

Standard tensile strength bars (ISO 2740) and impact toughness bars (ISO 5754) were prepared from powder mixtures with 0.6% Kenolube (powders with MnX addition) or 0.8% HW as a lubricant by compaction at 600 MPa (partly 400 MPa). Sintering of the samples at 1120°C for 60 min in dissociated ammonia in a laboratory tube furnace, or in a pusher industrial furnace at 1180°C for 40 min in a 70N₂/30H₂ atmosphere, was performed. For verification of the obtained results, a component - roller (Fig.1) was prepared from the FeMnC and Distaloy SE alloys. The components were compacted and sintered under industrial conditions.

Testing the samples for tribological properties by the disc-block (prism) Amsler method (Glacier Tribometal, Dolný Kubín, Slovakia), at a load of 100 N (component - roller also at 140 N) at speed 0.5 m s⁻¹ for a sliding distance of 1000 m, was carried out as shown in Fig.2. The disc from the tool steel (⌀48 x 10 mm, 54 HRC) and for prism impact toughness bars were used. The samples were tested on both sides perpendicular to the pressing direction. Two samples of each alloy were tested, and as a result, the mean value of 4 results is presented. Tribological properties of the alloys are characterised by dry wear as weight loss, a coefficient of friction and temperature of the tested sample. The temperature was measured at a distance of 5 mm from the friction contact. Combined carbon content, density, tensile strength, hardness and microstructure of the samples were determined and analysed.

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RESULTS AND DISCUSSION

Properties of Fe-C, Fe-Cu-C and Fe-Ni-Cu-Mo-C steels

In the framework of this material group, the samples based on SC100.26 and ASC100.29 iron powder and on Distaloy SA and Distaloy SE powder with an addition of 0.1, 0.3 and 0.7% graphite, both without and with a 0.5% MnX addition, were tested. Sintering of the samples at 1120°C for 60 min in dissociated ammonia was carried out.

Base and mechanical properties

Base characteristics of investigated alloys are shown in Tab.1. The tested samples are characterised with approximately equal density and equal carbon content in relation to the graphite addition.

Tab.1. Carbon content, density, tensile strength, hardness of investigated alloys. Iron powder: SC - SC100.26, ASC - ASC100.29, SA - Distaloy SA, SE - Distaloy SE, C - graphite, C<sub>c</sub> - combined carbon.

<table>
<thead>
<tr>
<th>Alloy No.</th>
<th>Alloy</th>
<th>C&lt;sub&gt;c&lt;/sub&gt; [%]</th>
<th>ρ [g cm&lt;sup&gt;-3&lt;/sup&gt;]</th>
<th>Rm [MPa]</th>
<th>*HV 10</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>SC-0.1C</td>
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<td>151</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>SC-0.3C</td>
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<td>189</td>
<td>76</td>
</tr>
<tr>
<td>3</td>
<td>SC-0.3C-MnX</td>
<td>0.29</td>
<td>6.82</td>
<td>214</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>SC-0.7C</td>
<td>0.61</td>
<td>6.94</td>
<td>234</td>
<td>110</td>
</tr>
<tr>
<td>5</td>
<td>SC-0.7C-MnX</td>
<td>0.63</td>
<td>6.84</td>
<td>248</td>
<td>111</td>
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<tr>
<td>6</td>
<td>ASC-0.3C</td>
<td>0.29</td>
<td>7.04</td>
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<td>74</td>
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<tr>
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<td>80</td>
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<tr>
<td>8</td>
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<tr>
<td>16</td>
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<td>623</td>
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</tbody>
</table>

*hardness measured on cross-section of tested bars

Tribological properties

Dry wear values of investigated alloys are shown in Fig.3. The Fe-0.1C steel exhibited the highest wear. In relation to the carbon content, lower wear was on the samples with higher carbon content (0.7% C) compared with those of 0.3% C. An increase in wear resistance of materials with 0.5% MnX addition was recorded only for those with 0.3% C. Small differences in wear between the alloys based on SC and ASC iron powder were recorded. In the investigated range of materials, the lowest wear was obtained for the Distaloy SA-0.7C. On the other hand, Distaloy SA-0.3C steel reached the same wear as ASC-0.3C steel. The Fe-Cu-C material exhibited only some minor wear compared with Fe-
0.7C alloys. The difference in dry wear values between the investigated alloys was greater than between the values of tensile strength and hardness.

The coefficient of friction of these materials was in the range of 0.40 to 0.65, and the temperatures of 48 to 63°C, without direct relation to the wear. Only a very slight tendency could be deduced that a coefficient of friction is lower for materials with higher wear resistance [14].

**Properties of manganese steels**

**Base and mechanical properties**

Within the framework of this material group, the samples based on three iron powder grades with addition of manganese in an amount of 1 to 5% in the form of high and medium carbon ferromanganese with the starting carbon content of 0.1 to 1%, were tested. Base characteristics and mechanical properties of these alloys are shown in Tab.2.

Tab.2a, b. Base characteristics and mechanical properties of alloys No.17-45. Iron powder grade: SC – SC100.26, NC – NC100.24, ASC – ASC100.29. Manganese carrier: alloys No.17-31 – FeMnC incl. Carbon; No.32-37 – FeMn + 0.4% graphite; No.38, 40, 43 – FeMnC + graphite to 1% C; No.39, 41, 42, 44, 45 – FeMn + 1% graphite. Combined carbon content: 0.30-0.35% for alloys No.32-37 and 0.83-0.91% for alloys No.38-45.

### a) alloy 17-21

<table>
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<tr>
<th>Alloy No.</th>
<th>Iron Powder</th>
<th>Mn-C [%]</th>
<th>ρ [g cm⁻³]</th>
<th>Rm [Mpa]</th>
<th>HV 10</th>
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<td>18</td>
<td>SC</td>
<td>2-0.16</td>
<td>6.94</td>
<td>454</td>
<td>137</td>
</tr>
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<td>SC</td>
<td>3-0.24</td>
<td>6.90</td>
<td>545</td>
<td>158</td>
</tr>
<tr>
<td>20</td>
<td>SC</td>
<td>4-0.32</td>
<td>6.85</td>
<td>582</td>
<td>192</td>
</tr>
<tr>
<td>21</td>
<td>SC</td>
<td>5-0.40</td>
<td>6.80</td>
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b) alloy 22-45

<table>
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<th>Mn-C [%]</th>
<th>ρ [g cm(^{-3})]</th>
<th>Rm [Mpa]</th>
<th>HV 10</th>
</tr>
</thead>
<tbody>
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<td>22</td>
<td>NC</td>
<td>1-0.08</td>
<td>6.88</td>
<td>334</td>
<td>108</td>
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<tr>
<td>23</td>
<td></td>
<td>2-0.16</td>
<td>6.84</td>
<td>394</td>
<td>147</td>
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<td>3-0.24</td>
<td>5.93</td>
<td>458</td>
<td>162</td>
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<tr>
<td>25</td>
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<td>6.78</td>
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<td>5-0.40</td>
<td>6.72</td>
<td>495</td>
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<tr>
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<td>681</td>
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<tr>
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<td></td>
<td>6.87</td>
<td>613</td>
<td>202</td>
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</tbody>
</table>

*compacting pressure 400 MPa, "Mo added as Astaloy85Mo

**Tribological properties**

The values for dry wear of the tested alloys are shown in Fig.4.

![Fig.4. Dry wear of alloys No.17 - 45 (characteristics of the alloys - see Tab.2).](image-url)
It follows from the results, that the wear of these materials was affected by iron powder grade, manganese and carbon content, and processing conditions. Within the Fe-(1-5)Mn-(0.1-0.4)C alloys, the highest wear exhibited the alloys based on NC100.24 iron powder, especially for 2 and 3% of Mn. It is possible to assume differences in alloying of an iron matrix based on different iron powder grades by manganese in the form of vapour, due to their specific structure and substructure characteristics [15]. It is necessary to note the differences in wear for alloys based on various iron powder grades as is also shown in Fig.3.

The lowest wear in the range of 5.6 to 12.6 mg was exhibited by the Fe-(2.5 and 3)Mn-1C steel group (No.38-45). It means the lowest wear in relation to previous results with lower manganese content and higher carbon content. It is especially necessary to note the wear of the Fe-3Mn-0.4 alloy (No.33, 36). The addition of 0.2% Mo did not contribute to a wear resistance increase of the materials. The wear of investigated manganese steels is basically in coincidence with the knowledge for manganese wrought steels, that the wear resistance increases with increasing carbon content [16]. It is also possible to deduce that the steel with higher manganese content and lower carbon content, with a favourable microstructure, may exhibit high wear resistance, as for instance the alloys No.21, 33, 36 and 37.

The coefficient of friction for alloys No.17-37 was in the range of 0.49 to 0.66, for alloys No.32-37 of 0.47 to 0.64, and for alloys No.38-45 of 0.26 to 0.48. The temperature for the alloys No.17-37 was in the range of 52 to 61°C, and for the alloys No.38-45 in the range of 42 to 51°C. It is possible to note that a coefficient of friction below 0.5 and the temperature below 50°C was recorded only for alloys with the highest carbon content, as well as the highest hardness and wear resistance in the investigated range [14].

**Wear vs. hardness**

The wear values obtained under the given test conditions of all alloys presented in this work, in dependence on hardness, are shown in Fig.5.

![Fig.5. The dependence of wear on the hardness of investigated alloys (No.1–45).](image)
In this diagram it is possible to identify three different areas. The first one represents mainly the Fe-C materials with wear values of ~20 to 53 mg, with a sensible decrease in wear with hardness. The second area represents the FeCuC, Distaloy SA and the FeMnC alloys characterised by the mean wear value of about 15 mg, and by hardness in a large range of ~100 to 185 HV 10. The third area represents the materials characterised by the lowest wear values of 10 to 5 mg, with a sudden decrease in wear in a small range in hardness of 185 to 200 HV 10 obtained with manganese and Distaloy SA, SE steels.

It follows from this, especially from the data shown in area 2, that hardness is not sufficient characteristic for dry wear of a metal alloy. This was confirmed also by the low wear values of specimens with hardness of 128 and 142 HV 10, and by the high wear values of specimens with hardness of 147 and 162 HV 10. The explanation of these differences in the dry wear of alloyed sintered steels must be sought in microstructure character, with its singularities in dependence on the alloying and processing of the materials.

Microstructure

The microstructure of the sections carried out through the centre of the friction traces of the samples, demonstrated plastic deformation and, by this, work hardening of the surface layer. Micrographs with the indentation impressions for both surface layer and subsurface area are shown in Fig.6, and in these areas, measured microhardness values are listed in Tab.3.

![Micrographs](image1.png)

a) Alloy No.2, wear = 41.9 mg  
b) Alloy No.5, wear = 23.4 mg  
c) Alloy No.10, wear = 18.4 mg  
d) Alloy No.14, wear = 10.3 mg
Fig. 6. Micrographs of section through the friction trace for alloy: 2, 5, 10, 14, 16, 21, 24, 40 (see Tab. 2). Nital etched.

Tab. 3. Microhardness HV 0.01 (HV 0.025 for alloy No. 40) of surface layer (S-L) and subsurface area (S-A) of samples tested for dry friction at load 100 N (see Tab. 2).

<table>
<thead>
<tr>
<th>Alloy No.</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>14</th>
<th>16</th>
<th>21</th>
<th>24</th>
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<td>Composition</td>
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<td>SC-0.7C</td>
<td>SC-Cu-0.7C</td>
<td>SA-0.7C</td>
<td>SE-0.7C</td>
<td>SC-5Mn</td>
<td>NC-3Mn</td>
<td>ASC-2.5Mn</td>
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<td>342</td>
<td>477</td>
<td>n. d.</td>
<td>531</td>
<td>707</td>
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</tbody>
</table>

The microstructure of the alloys No. 2, 5 and 9 (Figs. 6a, b, c) is ferritic-pearlitic. The deformation of the surface layer of these samples in the thickness of 3-5 μm is clearly seen. Both the mean and the range of microhardness values in the surface layer increased. Pearlite lamellae in the layer volume failed, initially by a deformation perpendicular to the load action as shown in Fig. 6b (circle). The plastic deformation of soft ferrite, with an increasing of its portion in the microstructure, was the main reason for the increase in wear. The microstructure of Distaloy SA-0.7C alloy was formed by pearlite, bainite and martensite, single grains were ferritic. In the microstructure of Distaloy SE-0.7C, a higher portion of martensite was observed as shown also in the surface layer (Fig. 6e). The work hardening of softer phases in the surface layer by higher microhardness was also detected.
The presence of ferrite, as also shown in Fig.6g, caused an increase in wear. Figures 6f and 6h show the microstructure of Mn-steels with the relatively lowest wear in spite of the fact that the microstructure in the Fe-5Mn-0.4C alloy (faster cooling rate at laboratory sintering) was formed by martensite, and in the Fe-2.5Mn-1C alloy, by pearlite and bainite (slower cooling rate at industrial sintering). Homogeneity of the microstructure, and the base alloying of phases with their specific sliding properties, played an important role in the wear resistance of investigated materials.

**Friction properties of component - roller**

At the friction test method (Fig.2), the component (Fig.1) formed the disc and the counterpart (15 mm in width) formed the prism: a) mild steel (EN S 2355R, STN 11373; 128 HV 10), b) hardened tool steel (55 HRC). The components were tested also for seizure, e.g. the load was increased by 100 N each 3 min up to the seizure. The highest applied load at seizure was the measure for the seizure resistance. The results of the friction test for optimum manganese alloy (further combination in manganese and carbon content were investigated) and for Distaloy SE are given in Tab.4. Under given test conditions, the best FeMnC rollers exhibited substantially lower wear compared with FeNiCuMoC rollers, especially when testing against a hardened counterpart, which showed on the interaction of the friction pair.

The results of the seizure tests are shown in Tab.5. A small difference in load for the seizure of roller from both materials, with a slight advantage for Mn- steel, was recorded.

Tab.4. Results of dry friction test (wear W, coefficient of friction μ, temperature T) of the component - roller made from Fe-MnC (ρ = 6.69 g cm\(^{-3}\), C\(_c\) = 0.51%, 170 HV 10) and FeNiCuMoC (ρ = 6.99 g cm\(^{-3}\), C\(_c\) = 0.60%, 206 HV 10) alloy. Test load: 140 and 100 N, sliding rate 0.5 m s\(^{-1}\), sliding distance of 1000 m.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>*Load 140 N</th>
<th>*Load 100 N</th>
<th>**Load 140 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-NiCuMoC</td>
<td>344</td>
<td>0.40</td>
<td>63</td>
</tr>
<tr>
<td>MnC</td>
<td>96</td>
<td>0.39</td>
<td>56</td>
</tr>
</tbody>
</table>

*counterpart – mild steel, ** hardened counterpart

Tab.5. Results of seizure test of the components - rollers (see Tab.4).

<table>
<thead>
<tr>
<th>Alloy Fe-</th>
<th>Max. load [N]</th>
<th>Coefficient of friction μ</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCuMoC</td>
<td>1600</td>
<td>0.47</td>
<td>240</td>
</tr>
<tr>
<td>MnC</td>
<td>1700</td>
<td>0.44</td>
<td>238</td>
</tr>
</tbody>
</table>

**Metallographic analysis of Mn-roller**

Figures 7a,b show the micrographs of two FeMnC rollers after friction test at the load of 140 N against a mild steel counterpart. On the surface of the component with high wear, a white etching layer with the microhardness of 716 HV 0.025 was formed (Fig.7a). The microhardness of the material under this layer was 345 HV 0.025. On the surface of the component with low wear shown in Fig.7b (Tab.4), no change in the microstructure character was observed. The microhardness of the microstructure constituents in the subsurface area was of 155 to 460 HV 0.025. It follows from this that the presence of a
greater portion of soft constituents – ferrite and pearlite - was probably the cause for large wear and for the transformation of the microstructure in the surface contact area.

![Micrographs of the Fe-Mn-C roller. Nital etched.](image)

**Fig.7 a,b.** Micrographs of the Fe-Mn-C roller. Nital etched.

### CONCLUSIONS

From the discussed results, the following conclusions can be attained:

- Wear resistance of Fe-C steel increased with increasing carbon content.
- The Fe-2Cu-0.7C alloy exhibited equal wear as that for Fe-0.7C steel.
- Wear of Distaloy SA-0.7C steel was lower than for Distaloy SE-(0.3, 0.7)C and by ~50% lower than for Fe-0.7C steels.
- A marked effect of manganese and carbon content on the wear of manganese steel was recorded. The lowest wear in the investigated range reached the Fe-5Mn-0.4C and Fe-2.5Mn-1C alloys.
- The presence of soft microstructure constituents and microstructure heterogeneity, affected by alloying and processing, was regarded as the main cause for the higher wear of investigated materials.
- The addition of MnX lubricant contributed to the decrease in wear only for alloys with 0.3% carbon.
- Relation between the coefficient of friction and wear of materials was not recorded. The lowest coefficient of friction at the testing of manganese steel with the lowest wear was measured.
- Direct dependence of wear on the hardness of investigated alloys was not recorded. The sudden decrease in wear at the hardness of 185 to 210 HV 10 was recorded.
- The presented results show alternative alloying for structural steels with optimum tribological properties being considered for possible use.

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