MECHANICAL PROPERTIES AND FRACTURE WITH METALLIC INCLUSIONS OF SINTERED HYBRID Fe-Cr-Mo-V-XMn-0.24C STEEL

M. Selecká, A. Šalak

Abstract
The prealloyed Fe-(1,3)Cr-0.3Mo-0.3V powders with admixing of 1-3% manganese in the form of high carbon ferromanganese with uniform 0.24% C compacted at 690 MPa and sintered at 1120°C and 1200°C for 60 min were investigated. Tensile strength of 929 MPa and transverse rupture of 1297 MPa attained the Fe-3Cr-0.3Mo-0.3V steel with 1.5% Mn after sintering at 1200°C. Markedly lower mechanical properties attained the Fe-1Cr-0.3Mo-0.3V steel sintered at 1200°C and both hybrid steel grades after sintering at 1120°C. High microstructure homogeneity exhibited the Fe-3Cr-0.3Mo-0.3V-3Mn steel. Fractures of both hybrid steel grades had ductile mode with dimple morphology. Rounded inclusions in the dimples were formed during sintering. According to the spectra and EDX analyses they were formed by all elements contained in the steels. Such inclusions are therefore 'metallic inclusions' formed as a consequence of the diffusion interaction of manganese vapour and vanadium with assistance of all alloy elements containing the base prealloyed powders.

Keywords: hybrid steels, prealloyed powders, manganese, chromium, vanadium, mechanical properties, fractures, dimples, metallic inclusions

INTRODUCTION
Base alloying elements in production of PM steel components are nickel, copper, molybdenum. The use of these alloy elements is from the beginning of the production of PM components due to their low affinity for oxygen. Above two decades the processing of Ni-free high strength steels is in some range of a great research and development interest.

The development of medium and high strength PM steels exhibiting an optimum combination of the mechanical and toughness properties is the current objective of the investigation. Chromium, manganese and molybdenum with carbon are the elements fulfilling most demands for this purpose. The Cr-Mo-(C) steels can be prepared as premixes and on the basis of prealloyed powder. Chromium and manganese are the cheapest alloying elements, but in term of the thermodynamics belong to the elements with high affinity for oxygen what in some cases represents a problem in sintering with these elements alloyed steels due to the requirements for high purity of the sintering atmosphere.

The problem of Cr-Mo alloyed steels in term of the thermodynamics is solved by the production of prealloyed Fe-(1, 3)Cr-0.3Mo-0.3V powders by water atomisation and vacuum annealing (Kawasaki) [1,2] and of Fe-1.5Cr-.02Mo (CrL) and Fe-3Cr-0.5Mo
(CrM) prealloyed powders, both Höganäs AB [3] what was demonstrated by the interest of the practice [4,5].

Manganese can be introduced as main alloy element into previously mentioned prealloyed powders in the form of electrolytic manganese and of ferromanganese grades forming by this way hybrid steels.

The possibility for sintering manganese alloyed steels without a demand for an atmosphere with very low dew point was explained on the basis of high manganese vapour pressure also at sintering below the equilibrium temperature for Mn-O [6,7]. During sintering a portion of manganese vapour escapes from the sintered components through interconnected pores into the surrounding sintering atmosphere. By this way the atmosphere is cleaned by the manganese itself to the equilibrium conditions and by this also for the material alloyed in combination with chromium [6]. According to Ref. 8, the production of the Fe-Mn-C prealloyed powders by water atomisation was investigated. The compacts from Fe-1.42Mn-0.23C powder compacted at 600 MPa reached the green density of 6.23 g cm$^{-3}$ and that from Fe-2.89Mn-0.29C powder 5.4 g cm$^{-3}$.

In Ref.[9] was explained that the high purity of the sintering atmosphere has an adverse effect on sintering of manganese containing steels. From this reason they are no problem for application of manganese as alloy element in premixed as well in hybrid sintered Cr containing steels. These material systems are proper also for sinter hardening without additional alloy elements.

Within this work, the effect of manganese addition on mechanical properties, microstructure and especially focused on fractures of the hybrid sintered steels, based on prealloyed Fe-(1,3)Cr-0.3Mo-0.3V powders is presented.

**EXPERIMENTAL PROCEDURE**

For the preparation of the test samples the following prealloyed water atomized vacuum annealed powders were used:

- Fe-1Cr-0.3Mo-0.3V (KIP 103V, Kawasaki), coded here K1,
- Fe-3Cr-0.3Mo-0.3V (KIP 30CRV, Kawasaki), coded here K2.

The chemical composition of K1 powder was: 0.01C, 0.08Mn, 1.07Cr, 0.32Mo, 0.29V, 0.15O and of K2 powder: 0.01C, 0.09Mn, 3.02Cr, 0.29Mo, 0.23V, 0.24O, balance Fe in mass %. The apparent density of the powders was of 2.8 g cm$^{-3}$.

The specimens based on prealloyed CrM (3Cr, 0.5Mo) powder (Höganäs AB) with 3% manganese addition for comparison of the fractures of the specimens to the fractures of the specimens based on K1 and K2 powders were prepared.

The manganese in amount of 0 - 3.0% in the form of high carbon ferromanganese (FeMnC) (6.7% C, 0.2% Si, 0.2% P, 76% Mn, balance Fe, milled in air, mean particle size 20 μm) and natural graphite in amount of 0 – 0.24% to reach the same carbon content in K1 and K2 mixtures with 3% of Mn introduced as FeMnC. By this way all powder mixtures contained starting 0.24% C.

The investigated material systems are coded here: K1, K2 – 0% Mn, K11, K21 – 1% Mn, K12, K22 – 1.5% Mn, K13, K23 – 2% Mn, K14, K24 – 3% Mn. The standard tensile, transverse rupture and impact energy test specimens were compacted at 690 MPa and sintered: a) at 1120°C for 60 min under cracked ammonia (dew point -33°C, flow rate of 7 l/ min) in a retort laboratory furnace under getter (alumina + 5% graphite) in double steel box and a part: b) at 1200°C for 60 min in hydrogen (d.p. -55°C) in a laboratory pusher furnace (Degussa Baby, TU Vienna), both under getter (alumina + 5% graphite) in double steel box. Evaluation of the sintered specimens and of their fractures consisted of mechanical testing, metallography, chemical analysis and of analysis of the inclusions.
One of the fractures with inclusions presented in this paper was presented in Ref. 11 without the explanation of the formation of such inclusions as will be shown in K1 and K2 sintered steels.

RESULTS

Basic characteristics

The as sintered carbon and manganese contents in K1 and K2 steels in dependence on manganese addition and sintering conditions are listed in Tab.1.

Tab.1. Carbon ($C_c$) and manganese content of K1 and K2 steels in dependence on manganese addition and sintering temperature at uniform starting carbon content of 0.24% C.

<table>
<thead>
<tr>
<th>Steel</th>
<th>K1, 1120°C/60 min</th>
<th>K2, 1120°C/60 min</th>
<th>K2, 1200°C/60 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Mn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (K)</td>
<td>1.5 (K12)</td>
<td>2 (K13)</td>
<td>3 (K14)</td>
</tr>
<tr>
<td>C$_c$</td>
<td>0.22</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td>Mn</td>
<td>0.15</td>
<td>1.47</td>
<td>2.64</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K2, 1120°C/60 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Mn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (K)</td>
<td>1.5 (K22)</td>
<td>2 (K23)</td>
<td>3 (K24)</td>
</tr>
<tr>
<td>C$_c$</td>
<td>0.23</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>Mn</td>
<td>0.21</td>
<td>1.46</td>
<td>2.55</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K2, 1200°C/60 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Mn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (K)</td>
<td>1.5 (K22)</td>
<td>2 (K23)</td>
<td>3 (K24)</td>
</tr>
<tr>
<td>C$_c$</td>
<td>0.21</td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>Mn</td>
<td>0.17</td>
<td>1.24</td>
<td>2.35</td>
</tr>
</tbody>
</table>

The carbon content in K1 and K2 steel samples sintered at 1120°C in cracked ammonia and at 1200°C in hydrogen was in the range of 0.21 to 0.23%. It means that only small decarburization of the samples compared to the starting carbon content of 0.24% occurred.

Manganisation of the samples to 0.15% - 0.21% Mn without manganese addition (K1, 1120°C) and K2 after sintering at both temperatures occurred. The loss of manganese in the samples with starting manganese addition was determined. The loss of manganese after sintering at 1120°C (Mn vapour pressure of 19.88 Pa) was in the range of 0.03% - 0.45% Mn and after sintering at 1200°C (Mn vapour pressure of 94.69 Pa) in the range of 0.13% - 0.65% Mn, it means moderately higher with increasing manganese addition and after sintering at 1200°C. The given manganese loss during sintering was caused by the reverse Mn vapour escape from the surfaces of the samples alloyed with manganese due to high manganese vapour gradient between the samples alloyed with manganese and the sintering atmosphere.

The sintered density of the tensile test specimens based on the powder K1 was in the range from 7.06 to 7.04 g cm$^{-3}$ and the density of the specimens based on the powder K2 was in the range from 7.01 to 6.95 g cm$^{-3}$. The manganese addition caused a decrease of sintered density of steels based on the powder K1 by 0.3 to 1.7% and of steels based on the powder K2 by 0.6 to 1.3% compared to the density of the steels without manganese addition.
|Mechanical properties|

The dependence of tensile strength on manganese addition and sintering temperature of the investigated steels is shown in Fig.1. The effect of higher sintering temperature was demonstrated on all tested mechanical properties. The manganese addition to the powder K1 after sintering at 1120°C caused a linear increase of tensile strength from 291 MPa (0% Mn) to 594 MPa (3% Mn). The K2 steel after sintering at 1200°C reached the highest tensile strength of 929 MPa with addition of 1.5% Mn (K22) without change with increasing Mn addition to 3% (~310 MPa/1% Mn).

Fig.1. Tensile strength of the steels based on the K1 and K2 powders sintered at 1120°C and 1200°C for 60 min on manganese addition [10,11].

The transverse rupture strength (bending strength) of the investigated steels in dependence on manganese addition and sintering temperature is shown in Fig.2. The course of the bending strength curves is similar to the curves for the tensile strength. The bending strength of K1 steel after sintering at both temperatures was increasing with manganese addition up to 2% (1095 MPa and 1125 MPa) with moderate changes with 3% Mn (maximum 1200 MPa).

The K2 steel after sintering at 1200°C steel with addition of 1.5% Mn attained the bending strength of 1297 MPa (329 MPa/1% Mn).

The sintered density of the bending strength specimens based on the powder K1 was in the range from 7.00 to 6.88 g cm\(^{-3}\) and the density of those based on the powder K2 was in the range from 6.92 to 6.85 g cm\(^{-3}\).

In the case of the tensile and bending strength it can be stressed high strengthening effect of manganese on K1 and K2 steels compared to those without Mn addition.

The dependence of hardness on manganese addition of all investigated steel specimens is shown in Fig.3. Usually a positive effect of increasing manganese addition is demonstrated in relatively small increase of the hardness values. The proof of this are the hardness values of K2 steel sintered at 1200°C. It is possible to suppose that their feature was caused by previously mentioned loss of manganese in the surface areas of the samples. The highest hardness values were attained in the steels with 2% Mn addition.
Dependence of the impact energy values of the investigated steels on manganese addition and on sintering temperature was recorded in the range of 16.6 to 11.8 J for K1 steel group and in the range of 12.4 to 8.5 J for K2 steel group as shown in Fig.4. Sintering at 1200°C caused a marked increase in impact energy values for K2 steel group to 18.0 - 11.2 J. Impact energy of K1 steel group sintered at 1200°C reached average values of 18.9 J (maximum of 20.8 J at 2% Mn) without dependence on manganese addition.

The relatively highest strength values after sintering at both temperatures were obtained with the total starting Cr+Mn content 4.5% + 0.6% Mo and V at the sintered carbon content in the range of 0.21 to 0.24% and at manganese content in the range of 0.87 to 2.64%. This is the proof that the investigated material systems reached at above mentioned total concentration of alloy elements relatively the highest strength and adequate toughness properties.

**Microstructure**

In Figs.5(a), (b) are shown the microstructures of the specimens based on K1 and in Figs.6(a), (b) of the specimens based on K2 powder.

Any Mn-oxides networks on cross-sections were observed. The microstructure of the samples sintered at 1120°C based on the powder K1 without manganese addition was ferritic-pearlitic with the microhardness of 134 to 194 HV 0.02 and of 272 HV 0.02 of pearlite. A substantial alloying of the matrix by manganese proceeded yet by addition of 1% Mn. There was formed a bainitic homogeneous microstructure with the microhardness of 405 HV 0.02. The microstructure shown in Fig.5(a) of the sample K1 with 3% Mn was homogeneous with the microhardness of 410 HV 0.02.

The white grains (solid solutions) with the microhardness of 247 HV0.02 only sporadically were observed. The microstructure of the samples sintered at 1200°C based on the powder K2 without manganese addition was also ferritic-pearlitic with the microhardness up to 281 HV 0.02 (0.21C, 0.17Mn). As shown in Fig.6, the microstructure was formed by bainite with the microhardness of 405 HV 0.02.
Fig. 5. Microstructure of Fe-1Cr-0.3Mo-0.3V-1.0Mn-0.23C steel sintered 1120°C. (a) – K12 (1.5Mn); Rm = 473 MPa, TRS = TRS = 965 MPa, KC = 12.8 J, 136 HV10, (b) – K13 (2Mn), Rm = 611 MPa, TRS = 1137 MPa, KC = 20.8 J, 175 HV10. Nital etched.

Fig. 6. Microstructure of Fe-3Cr-0.3Mo-0.3V-1.0Mn-0.24C steel sintered at 1200°C. (a) - specimen K21 (1.5Mn); Rm = 670 MPa, TRS = 1053 MPa, KC = 17.7 J and 206 HV10, (b) - specimen K22 (1.5Mn); Rm = 929 MPa, TRS = 1297 MPa, KC = 15.3 J and 212 HV10. Nital etched.

The microstructure analysis of the steel K21 (1Mn) showed that the matrix of the starting powders used is more advantageous for alloying with manganese than matrices of plain iron powder (different iron powder grades) what demonstrated in higher homogeneity of the microstructures.

Fracture

Fractures of the steels without manganese addition

The fractures of the steels based on K1 and K2 prealloyed powders without Mn addition exhibited by ductile dimple morphology as shown in Fig. 7 and Fig. 8. The load bearing cross-section of the sample K2 exhibited by much finer uniform dimples with larger rupture surface compared to K1 steel fracture what has been demonstrated by the difference in the strength properties, Fig.1, Fig.2.
Fractures of the steels based on K1 (1Cr) powder with manganese addition

Another character of the fractures exhibited both steels with manganese addition. The fractures had also characteristic ductile rupture dimple morphology. Deciding feature of these fractures are relatively larger dimples in which occurred rounded inclusions running through a large pore. The smaller inclusions were formed and adjoined with the pore surface shown in Fig.9. In Fig.10 is shown the spectrum of one such inclusion. According to the peaks, the inclusion was formed by Fe, Mn, Cr, V, Mo, Si and O. Silicon could be introduced in the material systems only by high carbon ferromanganese as manganese carrier containing 0.2% Si. This is the proof that this inclusion was 'metallic inclusion' (further inclusion) contrary to the known non-metallic inclusions in the wrought steels.
In Fig.11 is shown the fracture of K14 steel specimen with dimples containing inclusions in fine pores. In Fig.12 is shown the spectrum of one inclusion. This inclusion was also formed by all alloy elements of K1 steel, i.e. the inclusion had also metallic character but without peaks of Si and O.

Fractures of the steels based on K2 (3Cr) powder with manganese addition

In Fig.13 is shown the fracture of the specimen K24 (3Mn) sintered at 1200° C for 60 min in H₂ and in Fig.14 the spectrum of the inclusion.

The fracture in this case is possible to characterize by more uniform dimples with approximately sphere inclusions compared to the fractures of K1 steel. The spectrum of the inclusion 1 exhibited by highest peak of Mn, followed by Cr and Fe peaks. The peaks of Si
and V exhibited by halves of the intensity compared to the previous one. High O peak in this inclusion was recorded. Figures 13 and 14 were presented in Ref.11 as curiosity without some analysis and explanation of the formation of such inclusions.

As shown in Fig.15, such inclusions were formed also on the free fracture surfaces running through a large pore of the sintered K2 specimen as in Fig.9.

The spectrum of the inclusion 2, shown in Fig.16, confirmed its basic equal composition as in Fig.12, it means alloying with Fe, Mn, Cr, V and O without of Si. The distribution of these inclusions corresponded to the possible distribution of ferromanganese particles in the green compact.

Fig.15. Fracture through a pore – free, non failed surface of a large pore of the steel K2 with 3Mn addition (original 1:10000). SEM.

Fig.16. Spectrum of the inclusion 3 shown in Fig.15.

Fig.17. Fracture of K2 (3Mn) steel sintered at 1200°C, 60 min, H\textsubscript{2} (original 1:10000). SEM.

Fig.18. Spectrum of the inclusion 11 shown in Fig.17.
The fracture of K24 (3Mn) steel shown in Fig.17 doesn't exhibit the characteristic dimple morphology as in previous cases. The inclusions in ball form different in size were formed in clusters. This was caused by insufficient mixing of ferromanganese particles with base powder in the compact. In Fig.18 is shown the spectrum of one inclusion with prevailing peaks of Mn, Si and O and with minimal peak of V compared to the previous spectra. It is possible to assume that the starting FeMnC particles were not completely in contact during preheating with the base K2 powder matrix.

Beside previous characterization of the composition of the individual inclusions by the spectra, the concentrations of the metallic elements forming the presented inclusions in more fractures of K1 and K2 steel were determined. The results are listed in Tab.2.

Tab.2. Concentrations of the metallic elements in three inclusions in dimples of K21 and K13 steels and of four inclusions in dimples of K14 steel sintered at 1200° for 60 min in H₂ (EDX, LINK analyzer).

<table>
<thead>
<tr>
<th>Fe-xCr-xMn-0.3Mo-0.3V-0.24C steel</th>
<th>FeK</th>
<th>MnK</th>
<th>CrK</th>
<th>VK</th>
<th>MoL</th>
<th>SiK</th>
</tr>
</thead>
<tbody>
<tr>
<td>K21: 3Cr-1Mn</td>
<td>35.1</td>
<td>23.6</td>
<td>5.1</td>
<td>8.7</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>29.2</td>
<td>31.2</td>
<td>24.8</td>
<td>6.3</td>
<td>1.7</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>39.1</td>
<td>25.1</td>
<td>28.9</td>
<td>5.7</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>K13: 1Cr-2Mn</td>
<td>32.4</td>
<td>65.3</td>
<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>51.7</td>
<td>41.2</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>54.1</td>
<td>38.4</td>
<td>1.0</td>
<td>0.2</td>
<td>1.7</td>
<td>4.7</td>
</tr>
<tr>
<td>K14: 1Cr-3Mn</td>
<td>56.0</td>
<td>18.5</td>
<td>9.3</td>
<td>12.9</td>
<td>0.4</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>62.3</td>
<td>15.4</td>
<td>9.3</td>
<td>12.0</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>25.3</td>
<td>29.5</td>
<td>14.5</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>10.7</td>
<td>40.3</td>
<td>19.2</td>
<td>19.6</td>
<td>4.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Mean value</td>
<td>44.6</td>
<td>29.8</td>
<td>14.4</td>
<td>7.4</td>
<td>1.1</td>
<td>2.7</td>
</tr>
</tbody>
</table>

As follows from Tab.2, the highest concentration (except iron) of manganese followed by chromium, vanadium and silicon was demonstrated. The concentrations of other analysed elements were affected by manganese addition. The highest concentration of vanadium in the inclusions up to 19.6% is, really for the K1 steel with 3% Mn, followed by K2 steel (1Mn) with 8.7% of vanadium (3% Cr) in spite of it that the concentration of V in the base powders was 0.3%.

The formation of the metallic inclusions in the dimples of K1 and K2 steel fractures was the result of the diffusion interaction of manganese introduced as FeMnC particles yet during preheating of the samples to the sintering temperature, especially of manganese vapour with base alloying elements. The mean concentration 29.8% of manganese proves that the sublimation of manganese from the ferromanganese particles in the time of the beginning of the formation was not finished.

It follows from it that the formation of the shown metallic inclusions was initiated by the diffusion interaction of manganese vapour and vanadium from the surrounding matrices of the base powders containing the vanadium.

To the formation of the presented fractures it is necessary to say that the ductile rupture void is a space non integrity formed by the expansion of a nucleus (in this case of formed metallic inclusion). The rupture surfaces as was shown are essentially perpendicular at right angles to the loading direction - mostly equiaxed dimples.
Such ductile fractures were not presented in the systematic characterization of the wrought steel fractures [12,13], nor in fractography review of sintered iron and steel presented in Ref.14.

In Ref.15 was analyzed the residue of medium carbon ferromanganese particle in fracture of the mixed Fe-0.5Mn-0.6C steel sintered at 1120°C for 30 min in a 97N₂/3H₂ atmosphere with the dew point of -60°C. It was stated that such residue contained up to 30% Mn what was the cause for high microstructure inhomogeneity near ferromanganese residue.

The EDX analysis of the fracture of mixed Fe-0.8Mn-0.5C steel sample sintered at 1120°C for 30 min in 90N₂/10H₂ atmosphere with the dew point -40°C was also perfected [16]. According to the spectrum of one such ferromanganese residue it was determined that the residue contained 11.58C, 22.96O, 4.91Si, 11.10S, 27.72Mn and 15.73 Fe. In fractures of Fe-(0.8, 1.2)% Mn steels dilatometer samples were analyzed and characterized by the EDX analyses in ductile fractures the inclusions with high peaks of Mn [17].

In Fig.19 is shown a typical ductile fracture with dimple morphology of sintered iron with added Al₂O₃ particles as inclusions without describing some details of the preparation of that sample. This picture was shown as only one in the frame of the characteristic fractures of wrought steels [13].

Fractures of the steels based on prealloyed Fe-3Cr-0.5Mo powder with manganese addition

As described previously, for comparison of the fractures in K1 and K2 sintered steel specimens with manganese addition, the hybrid steel on the basis of prealloyed Fe-3Cr-0.5Mo powder (CrM) with addition of manganese also in form of high carbon ferromanganese in amount of 3% was prepared (starting carbon content 0.24%). The samples were compacted at 600 MPa and sintered in a laboratory tube furnace at 1250°C for 30 min (d.p. -40°C) and at 1180°C for 40 min in an industrial pusher furnace in 75N₂/25H₂ atmosphere (d.p. -50°C) [18].

In Figs.20 and 21 are shown the fractures of the tensile strength samples of the steels sintered under both mentioned sintering conditions.
Fig. 20. Fracture surface of sintered Fe-3Cr-0.5Mo-3Mn-0.24C steel based on prealloyed (CrM) powder. Sintering at 1250°C/30 min, c. a., d. p. -30°C (Rm = 856 MPa) (original 1:1500).

Fig. 21. As in Fig. 20. Sintering 1180°C/40 min under industrial conditions in 75N2/25H2 atmosphere, d. p. -50°C (Rm = 806 MPa) (original 1:1000).

As shown in the fractures of hybrid Fe-3Cr-0.5Mo-3Mn-0.24C steels sintered under laboratory as well as under industrial conditions no dimples with some inclusions were observed compared to the fractures of the hybrid steels based on K1 and K2 powders containing 0.3% V. This is also the proof that the formation of metallic inclusions in the dimples of K1 and K2 steels was possible only by reaction of manganese vapour with vanadium with the assistance of other elements listed in Tab. 2.

CONCLUSIONS
The mechanical properties and microstructure of hybrid Fe-(1, 3)Cr-0.3Mo-0.3V-0.24C steels sintered at 1120°C and 1200°C with addition of manganese in amount of 1 to 3% were presented and the fractures analyzed.

The following main results are:
• After sintering at 1200°C the Fe-3Cr-0.3Mo-0.3V steel attained the highest tensile strength of 929 MPa and transverse rupture strength of 1297 MPa both with 1.5% Mn and hardness of 220 HV 10 with 2% Mn. At this sintering temperature the Fe-1Cr-0.3-0.3V steel attained the highest impact energy value of 19 J independently on manganese addition.
• The hybrid Fe-3Cr-0.3Mo-0.3V-xMn steel should be sintered at 1200°C for attainment the highest mechanical properties. The hybrid Fe-1Cr-0.3Mo-0.3V-xMn steel attained significantly lower mechanical properties at sintering also at 1200°C.
• High microstructure homogeneity exhibited the 3Cr (K2) steel after sintering at 1200°C.
• Minimum demanganisation of he tested steel grade samples after sintering at both sintering temperatures occurred.
• The fractures of both investigated steel grades exhibited by ductile rupture mode with dimple morphology.
• The rounded and in ball form inclusions were formed in the dimples. According to the peaks in spectra of individual inclusions showed that they were formed by all metallic elements (Fe, Mn, Cr, V, Mo, Si) containing the investigated sintered steels. The formation of mentioned inclusions in the fractures of 3Cr-0.5Mo steel was not detected.
• Such inclusions were 'metallic inclusions' formed by diffusion interaction of manganese vapour and vanadium accompanied by Cr, Mo and Si from the surrounding matrices.
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REFERENCES