EFECT OF MANGANESE ON FRACTURE OF PREMIX AND HYBRID Fe-0.85Mo-XMn-0.3C SINTERED STEEL

V. Simkulet, M. Selecká

Abstract
The properties of Fe-0.85Mo-(1,2,3)Mn-0.3C material prepared as premix based on iron powder and as a hybrid based on Mo-prealloyed powder after industrial sintering at 1180°C were investigated. The tensile and transverse rupture strength, elongation, hardness, impact energy in dependence on manganese content were determined. The strength properties were linearly increased and the elongation decreased with increasing manganese addition. The impact energy values were practically independent of manganese addition and also of material preparation method that means the values were nearly at the level of those for manganese-less alloy. A high hardening effect of manganese in Mo-prealloyed matrix was manifested. Higher mechanical properties were attained by the hybrid steels compared to the premix steels, except for elongation. An increasing fraction of transcrysalline cleavage facets on the fractures of impact test bars with increasing manganese content without an effect on impact energy values was observed.

Keywords: sintered steels, molybdenum, manganese, mechanical properties, fracture

INTRODUCTION
Molybdenum, in terms of powder metallurgy, belongs among the alloying elements with low affinity for oxygen. For this reason, molybdenum in an amount of (0.2-1%) became a common alloying element in many sintered high strength steels. Sintered molybdenum steels can be prepared as premixes of plain iron with molybdenum donor addition or on the basis of Mo-prealloyed powders. The alloying of iron powder matrix by molybdenum at sintering occurs by solid state diffusion which is very slow, and therefore the final microstructure is heterogeneous in dependence on sintering temperature. An increase in microstructure homogeneity can be achieved in sintering premix Fe-Mo-C alloys at a temperature above 1240°C (strong effect of sintering temperature) in the presence of carbon through transient liquid phase [1,2].

The production of Mo-prealloyed powders, e.g. Fe-(0.85, 1.5, 3.5)Mo (Höganäs, QMP), eliminates the problems with microstructure homogenization. On the other hand, molybdenum is an expensive alloying element, and therefore its use is limited to lower contents, e.g. in diffusion alloyed grades, in prealloyed Astaloy A, B, and Astaloy CrL and CrM powders [3].

A flexible possibility for an increase of mechanical and toughness properties of sintered steels is the production of hybrid alloy systems based on Cr-, and/or Mo-prealloyed...
powders with manganese as an additional alloying element in powder form. Manganese, among the alloying elements used in powder metallurgy, is the cheapest one with high hardening effect. The sintering of manganese alloy steels in an atmosphere of common industrial purity without consideration of its high affinity for oxygen (hard reducibility of MnO) was thermodynamically explained and industrially verified by its sublimation from the donor during sintering. The consequence of this is a "self-cleaning" effect for the atmosphere by manganese vapour – reduction agent. Under these conditions the alloying of the matrix occurs in solid phase (base iron or prealloyed powder)-gas phase (Mn vapour) [4-6]. In respect thereof, manganese intensively sublimates still below the $\alpha - \gamma$ transformation temperature, the use of Mo-prealloyed powder for this system is advantageous because molybdenum extends the $\alpha$-region, and by this the diffusion of manganese into Mo-prealloyed matrix could be faster. This presumption was confirmed by the results attained in hybrid Fe-1.5Mo-Mn-C [7] as well in Fe-0.85Mo-xMn-C systems sintered at 1150 and 1200°C under laboratory conditions [8,9].

Within this work, the properties of Fe-0.85Mo-0.3C powder material with an addition of (1,2,3)% Mn, prepared as premixed and as hybrid prepared on the basis of prealloyed Fe-0.85Mo powder after sintering at 1180°C under industrial conditions, are presented.

EXPERIMENTAL PROCEDURE

The test samples were prepared as premixes based on plain iron powder (Fe-0.85Mo-XMn-C) and as hybrid based on Mo-prealloyed powder (Ast85Mo-XMn-C).

The following powders for the preparation of the samples were used:

- prealloyed Astaloy 85Mo powder (Ast85Mo, Höganäs AB),
- elemental molybdenum,
- atomized iron powder ASC100.29 (Höganäs AB),
- manganese in the form of medium carbon ferromanganese (80% Mn, 1.1% C; particle size <45 μm, 0.67% O, milled in air, ERATEM),
- natural graphite CR12 (Grafit, a.s., Netolice).

Powder mixes of Fe-0.85% Mo-(1, 2, 3)% Mn-0.3% graphite with 0.8% HW wax as lubricant were prepared. The samples for tensile strength (ISO 2740), transverse rupture strength (ISO 3325) and impact strength-unnotched (ISO 5754) testing from the powder mixes were compacted at 600 MPa and sintered under industrial conditions at 1180°C for 40 min in a 70N$_2$/30H$_2$ atmosphere (dew point -50°C), cooling rate ~10°C/min.

Mechanical properties, microstructure and the fracture of impact test bars were analyzed. Mechanical properties of the samples sintered under laboratory conditions at 1150 and 1200°C were presented [8,9].

RESULTS AND DISCUSSION

Density and dimensional change

In Table 1 is listed the green and as-sintered density and dimensional changes of tested materials. Due to the lower density of manganese, the green as well as the as-sintered density of the samples was decreasing with increasing addition of manganese. Minimal differences were observed in density values between the hybrid prealloy and premix compacts as well in small dimensional change ($\Delta l/l$) in dependence on Mn addition with a maximum +0.26%.
Tab.1. Green, as-sintered and relative density, dimensional changes and manganese and carbon content of Fe-0.85Mo-(1,2,3)Mn-0.3C tensile strength bars prepared as premixes (premix) and as hybrid (prealloy). Industrial sintering at 1180°C for 40 min in a 70N\(_2\)/30H\(_2\) atmosphere.

<table>
<thead>
<tr>
<th></th>
<th>Ast85Mo (prealloy)</th>
<th>Fe-0.85Mo (premix)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 Mn</td>
<td>1 Mn</td>
</tr>
<tr>
<td>Green density [g/cm(^3)]</td>
<td>6.92</td>
<td>6.91</td>
</tr>
<tr>
<td>As-sintered density [g/cm(^3)]</td>
<td>7.00</td>
<td>6.96</td>
</tr>
<tr>
<td>Rel. as-sintered density [%]</td>
<td>89.0</td>
<td>88.6</td>
</tr>
<tr>
<td>Δl/l [%]</td>
<td>-0.28</td>
<td>-0.16</td>
</tr>
<tr>
<td>Mn content [mass %]</td>
<td>0.11</td>
<td>0.97</td>
</tr>
<tr>
<td>C content [mass %]</td>
<td>0.29</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Mechanical Properties**

In Figure 1 are shown the mechanical and toughness properties of tested alloys in dependence on manganese addition. The effect of the preparation method of the base powder mix was determined. Mechanical properties such as tensile strength, transverse rupture strength, and hardness of hybrid – prealloy materials were higher than those of premixes. The differences in properties, caused by higher hardenability of Mo-prealloyed powder compared to plain iron powder [8,9], were increasing with increasing manganese content. Higher activity of the base prealloy Ast85Mo powder for alloying by Mn-vapour compared to the premix based on ASC100.29 powder without manganese addition (0 Mn) manifested itself in higher tensile and transverse rupture strength. The strengthening effect of manganese was manifested in a different effect of the hybrid and premix alloy properties. The tensile strength of hybrid alloy was increased by 107 MPa/1% Mn, and of premix alloy by 80 MPa/1% Mn. Some differences in values of mechanical properties of these materials compared to the published data can be caused by the sintering conditions. The prealloy Fe-0.85Mo-3Mn-0.6C material sintered at 1120°C in a H\(_2\)/N\(_2\) atmosphere attained the tensile strength of 460 MPa, transverse rupture strength of 750 MPa and elongation <1% [10]. When sintering the prealloy Fe-0.85Mo-2Mn-0.5C alloy by getter also, under industrial conditions as in this work, tensile strength of 542 MPa, transverse rupture strength of 1216 MPa, hardness of 209 HV 10, and impact energy of 10 J was attained [11].

Contrary to the strength properties, the premix system attained higher elongation decreasing with increasing manganese addition to an equal value at 3% Mn. The main difference in elongation between both systems manifested already in manganese-less state. The tested mechanical properties (Rm, TRS, HV 10, A5) of tested Fe-Mo-Mn-C alloys are higher compared to Fe-Mn-C alloys [6].
Fig. 1. Tensile strength (Rm), tranverse rupture strength (TRS), hardness (HV 10), elongation (A5), and impact energy of samples sintered at 1180°C for 40 min in 70N2/30H2 atmosphere in dependence on manganese addition.

The impact energy values are possible to be considered approximately independent of manganese addition and the preparation method of the powder mixes. It means, the impact energy of the tested materials was not decreasing with manganese addition. This was higher than that of plain Fe-Mn-C alloys [6]. An increase in impact energy of premix alloy with a 1% Mn addition has to be noted. These alloys sintered under laboratory conditions at 1200°C attained with 1% Mn the impact energy of 31 and 42 J respectively [9].

**Microstructure**

Presented differences in the values of tested properties in dependence on manganese addition as well on the preparation method of the powder mixes are a consequence of microstructure character. The alloying of plain iron and of prealloy matrix, in both cases in solid phase-gas (Mn) phase [4,5], occurs differently as shown, e.g. in Fig.2. The cores of starting iron powder particles in Fig.2b are ferritic with small pearlite grains. The total surface of singular particles was alloyed by the manganese in a layer of geometrically measurable thickness. This is a characteristic phenomenon for the diffusion induced grain boundary migration (DIGM) of manganese [12]. Contrary to this, the prealloy matrix was without white ferrite grains, and some particles were fully alloyed by
manganese (dark areas). It means the prealloy matrix was more homogeneously alloyed by manganese compared to plain iron matrix, which was at this state not fully alloyed by molybdenum.

![Fig.2. Microstructure of Fe-0.85Mo-3Mn-0.5C alloys sintered at 1120°C for 3 min, dissociated ammonia, dew point of -30°C. a – Ast85Mo-3Mn, b – Fe-0.85Mo-3Mn. Nital etched.](image)

The mentioned differences in alloying of premix (Fe) and prealloy (Ast85Mo) matrix by manganese are shown in the microstructures in Fig.3, which are reflected in tested properties. Softer ferrite in the microstructure was manifested in lower strength properties and hardness and in higher elongation. Knowledge regarding the fractions of singular microstructure constituents in the microstructures (ferrite, pearlite, bainite) in dependence upon manganese addition is lacking.

![Fig.3. Microstructure of Fe-0.85Mo-3Mn-0.3C steel samples sintered at 1180°C for 40 min in 70N₂/30H₂ atmosphere. Nital etched.](image)

**Fracture**

In Figures 4 – 7 are shown the fractures of impact energy test bars. The fractures of both alloys without manganese addition have a ductile character with fine dimple morphology, Fig.4.
Fig. 4. Fracture surface of Fe-0.85Mo-0.3C impact test bars. SEM.

Fig. 5. Fracture surface of Fe-0.85Mo-1Mn-0.3C impact test bars. SEM.

Fig. 6. Fracture surface of Fe-0.85Mo-2Mn-0.3C impact test bars. SEM.

Fig. 7. Fracture surface of Fe-0.85Mo-3Mn-0.3C impact test bars. SEM.
The fractures of alloys with 1% Mn addition had basically the same ductile character as compared to the previous case. Only some singular transcryrstalline cleavage facets were observed on the fracture of the premix alloy, Fig.5a, which exhibited the highest impact energy value. The fraction of the transcryrstalline cleavage facets was increasing with increasing manganese addition, Fig.6. It is possible to deduce from Fig.7 that the transcryrstalline cleavage facets were prevailing beside the ductile dimple facets on the fractures of alloys with a 3% Mn addition. The intercrystalline cleavage facets on the fractures were not observed.

The character of the shown fractures, i.e. increasing fraction of the transcryrstalline cleavage facets with increasing manganese addition, is not possible to give in to relation with the impact energy values, Fig.1. They were not affected by the increasing fraction of transcryrstalline cleavage facets. The reason for this can be the microstructure character affected by manganese in which the fraction of bainite was increasing with increasing manganese addition, because manganese is a bainite forming element. Bainite is characterized by high toughness/strength properties which were manifested in the equal impact energy values of both alloy systems with 3Mn as well as those without Mn-addition.

CONCLUSIONS

The following main results were obtained:

- Manganese addition in an amount of 1 to 3% to the hybrid and premix Fe-0.85Mo-0.3C steel caused a linear increase in tensile strength, transverse rupture strength and in hardness. The highest values with 3% Mn were achieved. The elongation of the alloys was decreasing with increasing manganese addition. The impact energy of the alloys was not affected by manganese addition.

- The hybrid materials attained higher tensile and transverse rupture strength and hardness and lower elongation compared to the premixed ones. The preparation method of the powder mixes did not manifest itself in impact energy values, except for the premix alloy with 1% Mn.

- The differences in properties of investigated steels are a consequence of the microstructure. The microstructure of hybrid material was more homogeneous than that of pre premix alloys in which the grain cores were formed by soft ferrite.

- The impact energy values were not affected by the increasing fraction of transcryrstalline facets on the fracture of the alloys with increasing manganese content. It can be deduced that under sintering conditions applied, the microstructure of both systems at some manganese content was formed by an equal fraction of bainite. The transcryrstalline cleavage fracture occurred in that case equally, more through bainite grains, which are characterized by high toughness/strength properties.

- The results are the contribution to the production of nickel-free sintered structural steels, and of those for sinter hardening.

Acknowledgements

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