SINTER HARDENING Cr-Mo PREALLOYED STEELS WITH SUFFICIENT TOUGHNESS
M. Dlapka, H. Danninger, Ch. Gierl, B. Lindqvist

Abstract
Sinter hardening has become a process of high importance in ferrous powder metallurgy in the last few years because of the time- and cost effective manufacturing it permits. In contrast to these advantages a considerable problem with this hardening method is that the toughness after sinter hardening is usually poor. For some applications such as synchronizer hubs this can cause failures e.g. when fixing the hubs on the shaft. For this reason an increase of the toughness is of great interest.
In the present work, factors influencing the toughness were investigated regarding their importance for the prealloyed Cr-Mo steel Astaloy CrM, namely the sintering temperature, the carbon and Ni content and the powder particle size. With the help of this knowledge it is possible to increase the toughness of sinter hardened Astaloy CrM based steels significantly.

Keywords: sinter hardening, toughness, synchronizer hubs, powder particle size, Ni and C content

INTRODUCTION
In recent years sinter hardening has become a process of high importance in ferrous PM parts production. It is an energy and therefore also cost effective heat treatment compared to the conventional through hardening, which makes a reheating to the austenizing temperature necessary. Due to the saving of energy and the absence of quenching oils, sinter hardening is moreover a clean and environmentally friendly process, which factors also have become increasingly important in the last time [1,2].

Another advantage is the lower distortion of the parts due to the milder gas quenching instead of the oil quenching commonly used with through hardening. On the other side, this slower cooling makes higher amounts of alloying elements necessary to form completely martensitic microstructures, which increase the costs of the sinter hardening powders [1]. Another disadvantage of sinter hardening is the need for very precisely shaped green parts, due to the high hardness the pieces have already after sintering [2]. This makes secondary machining operations difficult and expensive, and some operations like sizing are completely impossible for these hard parts.

One of the most pronounced disadvantages of sinter hardened parts is their low toughness [3]. A common application for sinter hardened parts is a synchronizer hub in a synchroset for automotive gears [4]. These hubs have to be fixed on a shaft to be ready for use. During this operation, there is the risk of failures caused by the low toughness of these parts, which makes an increase of this property important.

In the present work, factors influencing the toughness were tested regarding their importance for a widely used sinter hardening material based on Cr alloying in place of the expensive alloying elements Ni and Cu [5], namely based on the prealloyed powder Astaloy CrM. The investigated parameters are the sintering temperature, the carbon and Ni
content and the starting powder particle size. (Another important parameter is the tempering temperature but this was not part of the present work). With the help of this knowledge a significant gain in toughness is possible.

**MATERIAL AND PREPARATION**

The investigated material was prepared from prealloyed water atomized steel powder Astaloy CrM (ASC100.29 + 3% Cr + 0.5% Mo, Höganäs AB) admixed with natural graphite and Kenolube as a pressing lubricant; in part Carbonyl Ni (INCO 123) was also admixed. The samples were pressed to 7.1 g/cm³ density, separately dewaxed (600°C/30 min in N₂) and finally sintered using N₂ as a protective gas atmosphere.

Sintering was done in a SiC rod heated furnace with superalloy retort and a special gas quench unit at one end that enables cooling rates of up to 8 K/s. After the desired isothermal sintering of 60 min at 1120 or 1250°C under flowing N₂ as a protective gas against oxidation the boat containing the specimens was pushed into the quench zone, and cold N₂ gas was blown onto the specimens from above, the cooling rate being adjusted by setting the gas flow. The actual cooling rate could be recorded by a thermocouple placed in a bore within a dummy specimen. For all investigations a cooling rate of 2 K/s was used calculated through Eq(1):

\[
\text{Cooling rate} \ [°C/s] = \frac{600 \ [°C]}{(t_{300} - t_{900}) \ [s]}
\] (1)

For the characterization of the specimens the sintered density, the carbon and oxygen content and the mechanical properties hardness, impact energy (IE) and 3-point transverse rupture strength (TRS) were measured.

The sintered density was measured through water displacement (Archimedes principle) on samples impregnated with a commercial water stop agent.

The oxygen and nitrogen content was measured through carrier-gas hot extraction using a LECO TC 400 analyzer. For this, the samples were cut into small pieces of 0.2 to 1 g, done manually with a HSS saw blade in dry cut, to make sure that the preparation of the samples did not have any influence on the result (e.g. by oxidation, corrosion, carbon contamination etc.).

The hardness HV30 was tested with an EMCO M4U-025 in metallographic sections, i.e. on embedded, polished and etched pieces of impact energy (IE) samples.

The cross section area of the IE bars was measured using a precision slide rule (resolution 0.01 mm), and then a Charpy impact test at room temperature was accomplished. For the bending strength the cross section area was measured and then the test was accomplished on 5 samples of each composition with a universal tester Zwick 1474. The distance between supports was 25.4 mm and the crosshead speed 5 mm/min. The supports were hard metal rolls with a diameter of 3 mm.

The microstructure was characterized by metallographic methods and the fracture surface with SEM.

For metallography, small pieces of the IE bars were cut with a water cooled SiC disc at low cutting speed, to avoid thermal effects, and then the samples were cold embedded, to prevent tempering of the sinterhardened samples. Grinding was done with a Struers Piano grinding disk (120 µm), the polishing with an Allegro polishing disk with 9 µm and a Dac polishing disk with 3 µm diamond suspension, respectively. The samples were etched with a Picral (4g Picric acid in 100 ml methanol, 2 ml HNO₃ added) etching agent.
The fracture surface was investigated on tested IE bars that had been broken at room temperature. The SEM used for this was a SEM JEOL 7000F at the Institute of Materials Research in Kosice.

**INFLUENCING FACTORS**

**Carbon content**

Increasing the carbon content is one of the cheapest and easiest ways to increase the hardenability of a material. Therefore carbon is an alloying element of extremely high importance for materials designed for sinter hardening like the Astaloy CrM, which should provide excellent hardenability also for moderate cooling rates as attained by gas quenching, which is usually done for sinter hardening.

To test the influence of the carbon content, Astaloy CrM was admixed with different amounts of carbon, namely 0.5% and 0.7%. After sintering at 1120 and 1250°C the mechanical properties such as apparent hardness, impact energy and 3-point transverse rupture strength were tested to quantify the influence of the carbon. The results are given in Table 1, and the IE/HV data are plotted in Fig.2.

Tab.1. Mechanical properties of sinter hardened Astaloy CrM + 0.5–0.7% C, compacted to 7.1 g/cm³, differently sintered, cooled at 2 K/s.

<table>
<thead>
<tr>
<th>Sintering temperature [°C]</th>
<th>Sintered density [g/cm³]</th>
<th>Carbon combined [%]</th>
<th>Oxygen combined [%]</th>
<th>Apparent hardness HV30</th>
<th>Impact energy [kJ/m²]</th>
<th>Transverse rupture strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 % Cnominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1120</td>
<td>7.16±0.01</td>
<td>0.44±0.004</td>
<td>0.069±0.002</td>
<td>461 ± 11</td>
<td>1.9±0.1</td>
<td>1407±142</td>
</tr>
<tr>
<td>1250</td>
<td>7.24±0.01</td>
<td>0.39±0.01</td>
<td>0.021±0.002</td>
<td>469 ± 21</td>
<td>3.9±0.2</td>
<td>2317±36</td>
</tr>
<tr>
<td>0.7 % Cnominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1120</td>
<td>7.18±0.01</td>
<td>0.74±0.01</td>
<td>0.072±0.004</td>
<td>543 ± 9</td>
<td>0.9±0.1</td>
<td>801±38</td>
</tr>
<tr>
<td>1250</td>
<td>7.26±0.01</td>
<td>0.60±0.01</td>
<td>0.016±0.001</td>
<td>593 ± 17</td>
<td>1.3±0.2</td>
<td>1179±39</td>
</tr>
</tbody>
</table>

Lowering of the admixed carbon content results in a significant increase of the impact energy which was measured as a value representing the toughness of the samples. This increase is particularly pronounced when higher sintering temperatures (1250°C) are used.

One reason for this is the higher sintered density reached when sintering at 1250°C (Tab.1). Another fact is the lower amount of combined carbon after sintering at 1250°C. The reason for this is the carbothermal reduction of chromium oxides at higher temperatures which uses the combined carbon as reducing agent. The carbon forms CO (and some CO₂), being transferred into the gaseous phase [6]. This lowering of the carbon content influences the IE in a positive way.

Another reason for this might be a shift of the eutectoid point to the left when chromium is used as an alloying element (Fig.1) [7]. This means that adding higher amounts of carbon results more likely in the formation of proeutectoid cementite which embrittles the material drastically, even if present as very thin films. (If this was actually the case, it should be possible to find intergranular failure on the fracture surface). As a consequence, the carbon content added to Astaloy CrM should be kept as low as possible to just manage full martensite formation, which is required for sinter hardened materials.
Fig. 1. Calculated phase diagram for Astaloy CrM-x% C. [7]

Fig. 2. Influence of the carbon content on the hardness and impact energy (IE).

Fig. 3. Microstructures of sinter hardened Astaloy CrM admixed with different amounts of carbon, sintered 60 min at 1250°C in N₂, cooled at 2 K/s.
The microstructure of the material was investigated by optical microscopy and microhardness measurements (Fig.3). Both showed that the microstructure is fully martensitic, which means that adding higher amounts than 0.5% C is neither beneficial nor necessary, at least not at the cooling rates applied here.

Another reason for the better ductility of the materials containing less carbon contents can be found in the fracture surface (Fig.4). For these investigations the fracture morphology of broken IE bars was considered.

Lower carbon content results in the formation of dimples in the fracture surface (Fig.4a). The dimples are mainly shallow but also some deep dimples could be observed, caused by pores or ductile areas. Anyway some cleavage is also present.

When adding higher amounts of carbon the fracture changes to a cleavage-dominated one with some dimples (Fig.4b). This failure mechanism is of course less ductile. Anyway the observed fracture surfaces do not indicate the formation of cementite at the grain boundaries. If this were actually the case, intergranular failure would be expected.

Nickel content (admixed)

Nickel is known as an alloying element that increases the toughness due to the fact that it forms Ni rich martensite [3] and retained austenite [8]. This was tested by admixing two different amounts of Carbonyl Ni powder (1 and 2 mass %) to the mix Astaloy CrM + 0.5% C + 0.6% Kenolube followed by compacting and sinter hardening from two different temperatures (1120 and 1250°C) after 60 min isothermal hold in N₂.

It is clearly evident that the highest toughness can be obtained by admixing 1% of Ni. This is due to the extreme heterogeneities observed when admixing 2% Ni. There are Ni rich regions which indicate that the distribution of Ni was not sufficient. Due to this the admixed Ni does not strengthen the sintered contacts as Ni is not present in this areas of the material but is ‘wasted’ in areas of high Ni concentration. Furthermore, adding more than 1% Ni causes the formation of retained austenite clusters in the matrix. This can be seen in Figs.5a to 5d.
Tab.2. Mechanical properties of sinter hardened Astaloy CrM + 0-2% Ni + 0.5% C. 60 min isothermal, cooling rate 2 K/s.

<table>
<thead>
<tr>
<th>Sintering temperature [°C]</th>
<th>Sintered density [g/cm³]</th>
<th>Combined Carbon [%]</th>
<th>Apparent hardness HV30</th>
<th>Micro hardness HV0.025</th>
<th>Impact energy [kJ/m²]</th>
<th>TRS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0% Ni</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1120</td>
<td>7.16±0.01</td>
<td>0.44±0.004</td>
<td>398</td>
<td>731</td>
<td>2.5±0.2</td>
<td>1396±14</td>
</tr>
<tr>
<td>1250</td>
<td>7.24±0.01</td>
<td>0.39±0.01</td>
<td>411</td>
<td>768</td>
<td>3.2±0.1</td>
<td>2395±79</td>
</tr>
<tr>
<td>1% Ni</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1120</td>
<td>7.13±0.01</td>
<td>0.40±0.004</td>
<td>399</td>
<td>726</td>
<td>2.7±0.2</td>
<td>1618±33</td>
</tr>
<tr>
<td>1250</td>
<td>7.24±0.01</td>
<td>0.39±0.002</td>
<td>411</td>
<td>740</td>
<td>4.6±0.1</td>
<td>2497±26</td>
</tr>
<tr>
<td>2% Ni</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1120</td>
<td>7.14±0.01</td>
<td>0.48±0.01</td>
<td>461</td>
<td>786</td>
<td>1.9±0.1</td>
<td>1407±142</td>
</tr>
<tr>
<td>1250</td>
<td>7.23±0.01</td>
<td>0.41±0.01</td>
<td>469</td>
<td>825</td>
<td>3.9±0.2</td>
<td>2317±36</td>
</tr>
</tbody>
</table>

An observed fact is that adding more Ni results in slightly higher hardness levels (Table 2). This holds for the apparent hardness as well as for the micro hardness, which is a parameter for the matrix hardness without any porosity effects. This is caused by the fact that Ni is an element increasing the hardenability. Anyway this effect is not as pronounced for Ni as it is for other elements like Cr or Mn. This high matrix hardness results in lower impact energy when adding more than 1% Ni.

Fig.5a. 1% Ni, 100x.  
Fig.5b. 1% Ni, 1000x  
Fig.5c. 2% Ni, 100x  
Fig.5d. 2% Ni, 1000x  
Fig.5. Retained austenite in CrM+x% Ni+0.5% C SH at 1250°C.
Furthermore, looking at the toughness values in Tab.2 it is quite obvious that admixing Ni is only beneficial when sintering at the higher temperature. The reason for this is the very low diffusion rate of this relatively heavy element. It takes quite some time to distribute it homogeneously in the matrix. Anyway, even after sintering for 1 hour at 1250°C there are still Ni rich areas left which are likely to form retained austenite.

There are some publications dealing with the problem of the reluctance of Ni to homogenize in the matrix, due to the very low diffusivity of Ni in austenite [9,10]. These describe using an ultrafine Ni powder which is claimed to provide better diffusion rates compared to the INCO 123. Anyway, when using this finer Ni powder surely a special mixing treatment has to be carried out, and the addition of an admixed lubricant should be avoided due to the high tendency to agglomerate.

**Sintering temperature**

The steel Astaloy CrM + 0.5% C + 1% Ni was sintered 60 min isothermally at 1120 and 1250°C followed by a gas quenching with N₂ with a cooling rate of 2 K/s. It was found that the sintering at higher temperatures resulted in much better mechanical properties, especially in the toughness values (Table 3). Furthermore, also the sintered density is significantly higher after sintering at 1250°C which is always beneficial in terms of strengthening the material because an increase of the sintered density also raises the load bearing cross section.

Tab.3. Influence of the sinter hardening temperature on the sintered density and the mechanical properties of Astaloy CrM – 1% Ni – 0.5% C isothermal sintered at 1120 or 1250°C for 60 min, cooling rate 2 K/s.

<table>
<thead>
<tr>
<th>Sintering temperature [°C]</th>
<th>Sintered density [g/cm³]</th>
<th>Oxygen content [%]</th>
<th>Apparent hardness HV30</th>
<th>Impact energy [kJ/m²]</th>
<th>TRS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1120</td>
<td>7.13±0.01</td>
<td>0.11±0.004</td>
<td>399±3</td>
<td>2.7±0.2</td>
<td>1618±33</td>
</tr>
<tr>
<td>1250</td>
<td>7.24±0.01</td>
<td>0.018±0.0002</td>
<td>411±6</td>
<td>4.6±0.1</td>
<td>2497±26</td>
</tr>
</tbody>
</table>

This can be attributed to the oxides in the Cr containing materials which are not completely removed by the carbothermal reduction at 1120°C [11]. There is a quite large amount of oxides in the material (total oxygen content of 0.1%) which are located also at sintering necks, which weakens the material [6]. The results are listed in Fig.6. The relatively low amount of Cr and O, although the measured particle is a chromium oxide, is caused by the large emitting volume when measuring small particles with EDX due to the excitation bulb.

Another benefit when increasing the sinter hardening temperature in relation to the addition of Ni was already mentioned, namely the better, i.e. more homogeneous, distribution of the Ni in the matrix (Fig.7). Therefore less Ni rich austenite is found. Connected to this also retained austenite is distributed more homogeneously in the matrix, which will lead to better properties.
Tab.4. EDAX analyse of a chromium oxide particle.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>1.93</td>
<td>7.56</td>
</tr>
<tr>
<td>O K</td>
<td>4.43</td>
<td>13.04</td>
</tr>
<tr>
<td>Cr L</td>
<td>7.87</td>
<td>7.13</td>
</tr>
<tr>
<td>Fe L</td>
<td>82.39</td>
<td>69.48</td>
</tr>
<tr>
<td>Ni L</td>
<td>2.95</td>
<td>2.37</td>
</tr>
</tbody>
</table>

Fig.6. Fracture surface of Astaloy CrM – 0.5 %C sintered isothermal at 1120°C for 60 min, cooling rate 2 K/s and chemical analysis of non metallic inclusion.

Fig.7. Ni distribution after 1 h sintering at 1120°C (left) and 1250°C (right).

**Particle size of the starting powder**

For wrought steels the grain size is known as a very important influencing factor for the toughness [12,13]. In powder metallurgical steels there are not many studies dealing with this question since the grains are not expected to grow as pronouncedly at high temperatures as in wrought steels because of the pinning effect of the pores, at least in materials with a significant amount of pores like the investigated Astaloy CrM with a density of 7.1 g/cm³. Usually the austenite grain size in powder metallurgy steels is expected to have maximum the same size as the starting powder particles. For investigating the influence of the grain size, a commercial Astaloy CrM powder was sieved to obtain different starting particle fractions and therefore different austenite grain sizes. The fractions used here were < 45 µm, 45 – 90 µm, 90 – 125 µm and >125 µm. The sieved powders were admixed with 0.5% C, compacted and once more sinter hardened at 1120 and 1250°C.

The revealing of the austenite grain boundaries was done by a thermal etching which allowed an investigation of the material exactly at the desired heat treatment conditions [14]. This was accomplished by sinter hardening in N₂ of a polished presintered specimen. A grooving at the grain boundaries revealed them perfectly after the sinter hardening without the need for any chemical etching.
Figure 8 clearly shows that there is an influence of the starting particle size on the austenite grain size. Increasing the sinter hardening temperature from 1120 to 1250°C resulted in grains which were approximately double the size. This is also obvious when looking at the average intercept length of the specimen of different sieving fractions of the powder (Fig.9). The shown values are comparable to the average particle size after sinter hardening.

![Fig.8. Microstructure of Astaloy CrM+0.5%C from the finest and coarsest sieving fraction sinter hardened at 1120 and 1250°C.](image)

![Fig.9. Average intercepts distance of the different sieving fractions.](image)
Tab.5. Mechanical properties of AstaloyCrM-0.5%C from different powder fractions.

<table>
<thead>
<tr>
<th>Powder fraction [µm]</th>
<th>Green density [g/cm³]</th>
<th>Sintered density [g/cm³]</th>
<th>Hardness HV5</th>
<th>Impact energy [kJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>6.83±0.01</td>
<td>6.92</td>
<td>448±15</td>
<td>1.4±0.1</td>
</tr>
<tr>
<td>45-90</td>
<td>6.91±0.03</td>
<td>6.98</td>
<td>421±12</td>
<td>2.2±0.1</td>
</tr>
<tr>
<td>90-125</td>
<td>6.96±0.01</td>
<td>6.96</td>
<td>464±22</td>
<td>1.6±0.1</td>
</tr>
<tr>
<td>125</td>
<td>6.97±0.02</td>
<td>6.96</td>
<td>454±25</td>
<td>1.3±0.1</td>
</tr>
<tr>
<td>1120°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>6.83±0.01</td>
<td>7.04</td>
<td>502±1</td>
<td>3.1±0.2</td>
</tr>
<tr>
<td>45-90</td>
<td>6.91±0.03</td>
<td>7.03</td>
<td>441±12</td>
<td>3.0±0.3</td>
</tr>
<tr>
<td>90-125</td>
<td>6.96±0.01</td>
<td>7.05</td>
<td>458±4</td>
<td>2.7±0.3</td>
</tr>
<tr>
<td>125</td>
<td>6.97±0.02</td>
<td>7.04</td>
<td>372±26</td>
<td>2.2±0.2</td>
</tr>
<tr>
<td>1250°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mechanical properties of the resulting material are shown in Table 5. The IE decreases with increasing austenite grain size. The hardness is not affected as much by the austenite grain size as is the IE for the lower sintering temperature.

Anyway for higher sintering temperature some influence is observed. A reason for this seems to be a combination of smaller austenite grains and the higher sintering activity a finer powder offers. This leads to better sintering contacts. Furthermore the bigger particles seem to result in the formation of big pores (Fig.8) which might weaken the load bearing cross section and therefore also the IE. But it has to be considered that finer particle size can cause problems during powder filling and pressing, which latter was already seen for the specimen produced from the finer particle fractions. For the <45 µm fraction the green density was 6.83 g/cm³ while it was 6.97 g/cm³ for the >125 µm fraction. However, for the higher sintering temperature this difference was compensated most likely because of the mentioned higher sintering activity (7.04 g/cm³ sintered density both for <45 and >125 µm).

CONCLUSIONS

Low toughness of sinter hardened materials can be a problem for example for synchronizer hubs when they fail during fixing on a shaft. Therefore parameters influencing the toughness of sinter hardened Astaloy CrM based steel were investigated in this work.

The tested factors were the carbon content, the Ni content, the sintering temperature and the particle size of the starting powder.

The sintering was done isothermal at 1120 or 1250°C for 60 min followed by a gas quenching with 2 K/s cooling rate (eq.1). The sintering was done under flowing nitrogen as a protective agent against oxidation.

The carbon content was tested on samples containing 0.5 and 0.7% carbon admixed, respectively. It turned out that lowering the carbon content increased the IE and the bending strength extremely while the microstructure was still martensitic even for 0.5% C. The fracture analyses showed that the lower carbon content results in dimple dominated failure while the higher one is dominated by cleavage. Another theory is a shift of the eutectoid point to the left caused by the admixing of Cr [6]. Therefore the formation of embrittling proeutectoid cementite is very likely when admixing 0.7% C while it is not for 0.5% C. Anyway if cementite were formed some intergranular cleavage should be observed on the fracture surface which was not the case. However, in summary this means...
that the carbon content should be just high enough to form fully martensitic structures at the
given cooling rate, but every further increase of this alloying element in the matrix results
in a lowering of the toughness.

Admixing Ni was beneficial up to 1% Ni. Higher amounts caused the formation of
clusters of retained austenite and therefore a very heterogeneous microstructure. The Ni
rich areas are not sufficient in terms of increasing the toughness because the Ni is not
present at the sintering contacts where it would strengthen the material. This is also a
problem when using higher carbon contents. What was obvious is that the admixing of Ni is
only beneficial on the toughness when using higher sintering temperatures due to the low
diffusivity of Ni in austenite, which necessitates higher temperatures to homogenize Ni in
the matrix.

Another outstanding effect is caused by the sintering temperature. An increase
from 1120 to 1250°C resulted in almost double IE values. The reason is the presence of
chromium oxides which cannot be completely reduced by a carbothermal reaction during
sintering at 1120°C (Tab.3). These oxides embrittle the material and are a barrier for the
formation of sintering contacts. These necks can only be formed on metal-metal joints and
not within a metal-oxide contact. Another reason for the lower IE at lower sintering
temperatures is the lower sintered density and the higher combined carbon which is not
used for reduction. Furthermore, a better distribution of Ni is caused by higher sintering
temperatures.

Finally the influence of the starting particle size was studied using standard CrM
powder which was sieved to different fractions. It was observed that finer particles resulted
in better toughness and strength. The reason is the higher sintering activity of finer powders
which form better sintering contacts; also the finer austenite grain size may be helpful. A
disadvantage of finer powder is the lower flowability and compressibility. Therefore
pressing of powder mixes from finer fractions can be a difficult task.

Summing up it can be stated that for Astaloy CrM based steels the best toughness
values can be reached by using carbon contents which are just causing formation of fully
martensitic microstructures, by adding 1% Ni and by sintering at high temperature, e.g. at
1250°C, and finally fine particle fractions also are positive at least for sinter hardened
properties.

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