Properties of High Density Cr-Mo Pre-alloyed Materials
High Temperature Sintered

Bo Hu, Alex Klekovkin, Dave Milligan, Ulf Engström
North American Höganäs, USA

Sigurd Berg, Barbara Maroli
Höganäs AB, Sweden

ABSTRACT
Chromium and molybdenum as pre-alloying elements in ferrous powders can offer potentials for achieving excellent sintered properties. The potential properties are further increased when the materials are compacted to high green density, and/or are sintered at high temperature and sinterhardening. This paper evaluated the properties achievable using Cr-Mo prealloyed materials compacted with different compacting techniques such as cold compaction, warm compaction, and high velocity compaction to increase green density. Furthermore, the properties achieved after conventional / high temperature sintering as well as sinterhardening were compared.

INTRODUCTION
Increasing density, alloying element addition, and sinter hardening are ways to increase material performance in demanding applications that require structural integrity. As an alloying element, chromium is widely used in traditional low-alloy structural wrought steels due to its excellent hardenability, good resistance to temper softening, and lower cost than nickel, molybdenum or copper. In powder metallurgy (P/M), nickel, molybdenum, and copper are the most common alloying elements because they are less sensitive to oxidation during sintering. However, recent studies on the oxidation of chromium during sintering show that materials based on Cr-prealloyed powder are less sensitive to sintering atmosphere compared to materials made from powder mixes with high chrome additives. Cr-prealloyed materials can be successfully sintered in conventional sintering atmospheres, such as 90/10 N₂/H₂ atmospheres [1]. In addition, high temperature sintered Cr-prealloyed materials are less sensitive to the atmosphere than low temperature sintered [2].

In 1998, a commercial Cr-Mo pre-alloyed powder (Astaloy CrM) was introduced, which is a water atomized powder prealloyed with 3%Cr and 0.5%Mo [3]. Another prealloyed grade (Astaloy CrL), with a lower Cr-Mo content (1.5%Cr and 0.2%Mo), was introduced in 2001 [4]. Many studies have been performed on the properties of Cr-Mo prealloyed materials using various compaction and sintering conditions [5–9]. These studies have identified that Cr-Mo pre-alloyed materials have advantages in properties achievable, sinter hardening response, and dimensional control compared to conventional materials such as Fe-Cu and Ni-Mo-Cu alloyed steels [10,11].
It is well known that the P/M materials can achieve comparable strength characteristics to traditional low-alloy wrought steels but usually they have lower toughness. Increasing density and high temperature sintering not only increase the strength, but also improves the toughness of P/M materials.

This paper summarizes the properties of Cr-Mo prealloyed materials achieved using various compacting conditions, including compacting techniques such as cold compaction, warm compaction, and high velocity compaction to increase green density. Furthermore, the properties achieved after conventional / high temperature sintering, as well as sinterhardening, are compared.

MATERIALS AND PROCESSING CONDITIONS

Materials

Two grades of commercial Cr-Mo prealloyed powders from North American Höganäs were used as base irons for this study. The base iron powders were mixed with required amount of natural graphite, typically 0.75% for CrL materials and 0.50% for CrM material. Depending on compaction techniques, a different type and amount of lubricant was used to make premix powders, here 0.7% for cold compaction (StarmixTM) and 0.6% for warm compaction (DensmixTM). The chemical composition of each premix is shown in Table 1.

<table>
<thead>
<tr>
<th>Material Definition</th>
<th>Base Iron</th>
<th>Chemical Composition, %wt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cr*</td>
</tr>
<tr>
<td>CrL</td>
<td>Astaloy CrL</td>
<td>1.5</td>
</tr>
<tr>
<td>CrM</td>
<td>Astaloy CrM</td>
<td>3.0</td>
</tr>
</tbody>
</table>

* Prealloyed in iron powder

Compactions

The premixes were compacted into test specimens using different compaction techniques to achieve green densities in the range of 7.0~7.5 g/cm³. Table 2 describes the compaction techniques used in this study.

<table>
<thead>
<tr>
<th>Pressing Technique</th>
<th>Symbol</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Compaction</td>
<td>CC</td>
<td>Conventional press at 400<del>800 MPa (29</del>58 tsi)</td>
</tr>
<tr>
<td>Warm Compaction</td>
<td>WC</td>
<td>Conventional press at 400<del>800 MPa (29</del>58 tsi); powder and die are heated to 120°C (248°F)</td>
</tr>
<tr>
<td>High Velocity Compaction</td>
<td>HVC</td>
<td>Press with intensive shockwaves created by a hydraulic hammer</td>
</tr>
</tbody>
</table>
Sintering

The compacted test specimens were sintered under four different conditions (see Table 3). A nitrogen-based atmosphere with 10% hydrogen was used and the sintering time at each temperature was 30 minutes. The cooling rate was calculated from 800°C (1672°F) to 300°C (932°F). The sinter-hardened specimens were tempered at 200°C (392°F) in air for 60 min.

Table 3. Sintering Conditions

<table>
<thead>
<tr>
<th>Process</th>
<th>Symbol</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Sintering</td>
<td>CS</td>
<td>1120 (2050) 0.5<del>1 (0.9</del>1.8)</td>
</tr>
<tr>
<td>Sinter-Hardening</td>
<td>SH</td>
<td>1120 (2050) 2<del>3 (3.6</del>5.4)</td>
</tr>
<tr>
<td>High Temperature Sintering</td>
<td>HTS</td>
<td>1250 (2350) 0.5<del>1 (0.9</del>1.8)</td>
</tr>
<tr>
<td>High Temperature Sintering plus Sinter-Hardening</td>
<td>HTS + SH</td>
<td>1250 (2350) 2<del>3 (3.6</del>5.4)</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

General Properties of Cr-Mo Prealloyed Materials

*Powder characteristics:* Alloying elements such as chrome have limitations to be directly added to P/M premixes due to their high affinity to oxygen. However, the oxidation of chrome can be minimized or overcome by using powders with low contents of chrome, i.e. prealloyed powder. In prealloyed powders, the chrome is homogeneously diffused into the iron so that the Cr-prealloyed powder is much less sensitive to oxidation compared to mixes with Cr-master alloy additives. Therefore, it can be sintered in conventional atmospheres except the high oxygen potential atmosphere such as Endogas. Figure 1 shows the powder morphology of Cr-Mo prealloyed powders.

![Figure 1. SEM of Cr-Mo prealloyed iron powders](image-url)
Compressibility: The compressibility of Cr-Mo prealloyed iron powders is shown in Figure 2. As expected, the prealloyed powders have approximately 0.1 g/cm³ lower compressibility than a plain iron powder such as AHC100.29. However, the difference in compressibility can be minimized by using warm compaction that can provide an increase in density of about 0.1–0.2 g/cm³ compared to cold compaction. Figure 3 compares the pressures required to compact CrL, Fe-Cu (FC-0205 and FC-0208), and Fe-Ni-Cu-Mo (FLC-4608) mixes for making a 7.0 g/cm³, 2-inch diameter planetary gear. The mixes with CrL prealloyed iron needed 20–25% more pressure than the Fe-Cu mixes, which use a plain base iron, but they require similar compacting pressures to the 4600 mix with Ni-Mo prealloyed base iron such as Astaloy A (1.9%Ni and 0.55%Mo prealloyed).

Figure 2. Compressibility of Cr-Mo prealloyed iron powders (note: WC denotes Warm Compaction)

Figure 3. Pressures needed to compact CrL, Fe-Cu, and Fe-Ni-Mo-Cu mixes for making 7.0 g/cm³, 2-inch diameter planetary gears
Optimum combined carbon amount: Carbon is a major element added in P/M materials to achieve desired mechanical properties. Depending on the amount dissolved in iron, combined carbon not only strengthens the iron matrix but also determines eutectoid compositions of the iron and affects phase transformation as well. In general, a material achieves its highest strength only at certain combined carbon levels in the material, i.e. at the optimum carbon content. For prealloyed steels, the optimum carbon content will shift to lower carbon levels as the alloying amount increases. As shown in Figure 4, the optimum amount of combined carbon for CrL material is 0.7–0.75%. For CrM material, the optimum carbon level is approximately 0.4–0.45%. Higher alloyed Cr-Mo steel needed less carbon to achieve maximum strength properties. The excess combined carbon amount causes a decrease in strength due to a formation of brittle, coarser martensitic phase in CrM and grain boundary cementite in the case of CrL.

![Figure 4. Effect of combined carbon content on the strength of Cr-Mo prealloyed materials](image-url)

Figure 4. Effect of combined carbon content on the strength of Cr-Mo prealloyed materials
**Sintered density and dimensional change:** The dimensional changes of Cr-Mo prealloyed materials with different densities after sintering at 1120°C (2050°F) and 1250°C (2350°F) are shown in Figure 5. When sintered at 1120°C (2050°F), both of CrL and CrM materials presented a stable shrinkage (0.1%) regardless of the density. When the sintering temperature increased to 1250°C (2350°F), there was 0.4–0.6% shrinkage for CrL material and 0.6–0.8% shrinkage for CrM material depending on the sintered density. Studies on dimensional stability and reproducibility showed the Cr-Mo prealloyed materials are better than conventional Fe-Cu and Fe-Ni-Mo prealloyed materials [10, 11].

![Figure 5](image-url)  
*Figure 5. Dimensional change of Cr-Mo prealloyed materials after conventional and high temperature sintering*
Microstructures: Figure 6 showed the microstructures of Cr-Mo prealloyed materials obtained under conventional sintering conditions with slow and fast cooling rates. Both of the CrL and CrM materials mainly had a bainitic structure (upper bainite) at the slow cooling rate (0.5~1°C/s or 0.9~1.8°F/s). They achieved a fully martensitic structure with a higher cooling rate (2~3°C/s or 3.6~5.4°F/s), indicating they have a good response to sinterhardening. The upper bainitic structure (a non-lamellar aggregate of ferrite and carbides) can provide increased strength properties compared to pearlite structure (a lamellar aggregate of ferrite and cementite). In other words, it can present comparable strength and hardness to traditional Fe-Cu materials while using lower carbon content in conventional sintering [10].

Figure 6. Microstructures of Cr-Mo prealloyed materials after sintered in conventional sintering with different cooling rates
Properties Enhanced by Density Increases

PM technology can be simply described as a type of rapid shaping technology. It is capable of producing large volumes of parts with very close dimensional tolerances and minimized machining operations. Compared to traditional wrought materials, however, P/M materials generally have lower mechanical properties, especially fatigue performance, due to their internal porosity. Although the matrix /structure of P/M materials can be strengthened and optimized by well-designed alloying system, the pores (size, shape and amount) greatly influence the material properties. Therefore, increasing density of P/M materials is still a big challenge to P/M industry in order to expand P/M technology into further applications.

High densities can be achieved by using higher compaction pressure, modified lubricants, and new compaction technologies. Much progress has been made in last 10 years in improving/developing compaction techniques. Warm compaction is a cost-effective technique with many benefits [12]. It can provide up to 0.2 g/cm³ higher density than conventional compaction and provides the possibility to replace double pressing/sintering as well as allows for green machining. High velocity compaction (HVC) is a newly developed technique that is able to increase by 0.4g/cm³ or more density compared to conventional compaction [13].

Current Cr-Mo prealloyed powders can provide greater mechanical properties than admixed and diffusion-bonded powders. The advanced compaction techniques enable the Cr-Mo prealloyed materials to achieve further improvement in properties and performance. Figure 7 presents the green densities achieved with different compaction techniques for Cr-Mo prealloyed materials. The increasing density provides promise for the Cr-Mo prealloyed materials to achieve higher mechanical properties.

Figure 7. Green densities of Cr-Mo prealloyed materials obtained with different compaction techniques
Figure 8 demonstrates how density increases improve mechanical properties of Cr-Mo prealloyed materials. By increasing the density from 6.9 to 7.4 g/cm³, the tensile strength increases 30% and the elongation increases approximately 65%. The density increase improves the hardness by 25%.

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**8a. Tensile Strength**

**8b. Elongation**

**8c. Hardness**

Figure 8. Effect of density on the properties of Cr-Mo prealloyed materials after conventional sintering for 30 min at 1120°C (2050°F) with a cooling rate of 0.5–1 °C/s (0.8–1.9°F/s)
Properties Enhanced by High Temperature Sintering and Sinterhardening

For P/M components, sintering is generally performed at temperatures around 1120°C (2050°F). Since sintering is the result of metal atomic movement via diffusion at elevated temperatures, higher temperatures increase the diffusion dramatically and induce more, and faster, atomic movement. Therefore, higher temperatures provide better sintering, or the possibility to reduce the sintering time and still achieve comparable properties to conventional sintering. Also, higher temperatures provide more favorable oxidation-reduction equilibrium for alloying elements such as chrome. No oxidation takes place at 1120°C (2050°F) if the oxygen partial pressure of sintering atmosphere is below 5x10^{-18} atm. When sintering is performed at 1210°C (2210°F), the limit of oxygen partial pressure can be raised to 1x10^{-16} atm [1,2].

Sinter hardening is a cost effective process where the martensite transformation takes place during cooling and high strength and hardness can be achieved immediately after sintering. Alloying elements are utilized to promote the formation of martensite and/or bainite during cooling from sintering temperature. Prealloyed steel powders have proven to be more useful for sinter hardening than admixed alloying elements because the alloying elements are fully dissolved in the iron matrix and a homogenous microstructure can be achieved after sintering.

The effect of high temperature sintering and sinterhardening on the tensile strength and ductility of Cr-Mo prealloyed materials is shown in Figure 9. Compared to conventional sintering at 1120°C (2050°F), high temperature sintering at 1250°C (2350°F) significantly enhances tensile strength, 18% for CrL and 20% for CrM respectively. At the same time, the material ductility was also dramatically improved. The elongation increased 40% for CrL and 75% for CrM respectively. This demonstrates that high temperature sintering provides better diffusion of metal atoms in material structure than conventional sintering. With sinterhardening in conventional sintering (1120°C or 2050°F), the tensile strength increases but the material elongation reduced. When sinterhardening from high temperature sintering (1250°C or 2350°F), however, both tensile strength and ductility were improved.

Figure 9  Effect of high temperature sintering and sinterhardening on tensile strength and ductility of Cr-Mo prealloyed materials.
Properties Achieved with Combinations of High Density, High Temperature Sintering and Sinterhardening

As demonstrated previously, the Cr-Mo prealloyed materials offer the potential for achieving excellent sintered properties. The potential properties are further improved when the materials are compacted to high green densities, and/or are sintered at high temperature and sinter hardened. Combinations of high density, high temperature sintering and sinterhardening enable the Cr-Mo prealloyed materials to maximize their material properties and performance. Figure 10 shows the results obtained with different sintering processes for Cr-Mo prealloyed materials with a sintered density of 7.3 g/cm³. When the materials were sintered at a high temperature (1250°C or 2350°F) and sinterhardened with a cooling rate of 2–3°C/s (3.6–5.4°F/s), CrL can achieve a tensile strength of 1200 MPa (174 ksi) and CrM can achieve a tensile strength of 1400 MPa (203 ksi).

Figure 10. Tensile strength of high density Cr-Mo prealloyed materials enhanced by different sintering processes

Comparisons between Cr-Mo Prealloyed Steels and Traditional P/M Steels

As with conventional P/M materials, the properties of Cr-Mo prealloyed materials depend on their density and sintering processes. The results presented in this paper show that Cr-Mo prealloyed materials can provide favorable mechanical properties by selecting a suitable combination of manufacturing processes. Since the properties of P/M materials also depend on their compositions, the Cr-Mo prealloyed materials present an excellent alloying system to achieve desired properties. In other words, Cr-Mo prealloyed materials can provide flexibility for material selection to produce medium to high strength structural parts. Figure 11 shows comparisons between the Cr-Mo prealloyed materials and traditional P/M materials. Compared to traditional Fe-Cu, Fe-Cu-Ni, and Fe-Ni-Cu-Mo steels, Cr-Mo prealloyed steels can achieve comparable or superior tensile strength but use less alloying content. The small alloying content presents benefits not only in cost saving, but also in dimensional control. As can be seen in Figure 12, the Cr-Mo prealloyed materials have better dimensional control than Fe-Cu and Fe-Ni-Cu-Mo steels, whether in conventional sintering or in sinterhardening.
Figure 11. Comparison of tensile strength between Cr-Mo prealloyed steels and traditional P/M steels

Figure 12. Comparison of dimensional variation between Cr-Mo prealloyed steels and traditional P/M steels

* Based on an evaluation on 42-inch planetary gear (7.0 g/cm³, 176g, 100 parts per material)
CONCLUSIONS

- Cr-Mo prealloyed materials can be successfully sintered in conventional N₂ based atmosphere. High temperature sintering improves sintering.
- Cr-Mo prealloyed materials exhibit good sinterhardening response. A fully martensitic structure can be achieved at a cooling rate of 2~3°C/s (3.6~5.4°F/s) during conventional and high temperature sintering.
- Cr-Mo prealloyed materials provide flexibility for material selection for producing medium to high strength structural parts. They can achieve desired material properties with less alloying content and better dimensional control compared to traditional Fe-Cu and Fe-Ni-Mo-Cu steels.
- The combinations of high density, high temperature sintering and sinterhardening enable the Cr-Mo prealloyed materials to maximize their material properties and performance. With proper processing conditions, a tensile strength of 1200 MPa (174 ksi) for 1.5%Cr+0.2%Mo prealloyed material and 1400 MPa (203 ksi) for 3%Cr+0.5%Mo prealloyed material can be achieved.

REFERENCES