Processing conditions for high strength PM steels alloyed with chromium.

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ABSTRACT

Increased mechanical properties of sintered steels are the major factor for the introduction of PM components as substitute for wrought steels. Materials based on grades pre-alloyed with chromium have proved to be an attractive choice for the production of high performance PM parts. Already in the as-sintered condition materials alloyed with 1.5% res. 3% chromium achieve high strength compared to PM steels alloyed with up to 4% Ni. Further improved mechanical performance is achieved utilizing increased cooling rate i.e. sinter-hardening has been the break-through.

In this paper the influence of process conditions on the static and dynamic properties of materials prealloyed with chromium is presented and explained through their microstructure. Alternative process routes such as for example high temperature sintering followed by rapid cooling are shown to give outstanding performance such as yield strength of 1250Mpa and bending fatigue strength of 445MPa.

INTRODUCTION

Powder metallurgy is a strong growing market. Since most of the parts made by PM are produced for the automotive industry, cost is a major driving force. In recent years new processing techniques and alloying systems have been developed in order to increase the performance/cost ratio [1]. Pre-alloyed materials have become more and more used in the PM industry. One reason for this is that the core of the iron particle is strengthened and as a consequence the mechanical properties are enhanced. Molybdenum is the main pre-alloying element used in the PM industry because of its relatively small impact on the compressibility compared to other alloying elements and the good response in hardenability. Chromium as a pre-alloying element has an even higher performance/cost ratio compared to molybdenum and is therefore of great interest for the future. Chromium is of interest due to low cost, even distribution if pre-alloyed and greater possibility to recycle than copper containing materials. A consequence of pre-alloying compared to mixing is the reduction of scatter in dimensional change.

Chromium as an alloying element is attractive not only because of the cost but also due to the high hardenability. This opens up the possibility to use even normal cooling rates in the sintering furnaces to obtain a hardened microstructure[2]. By using this type of PM process, cost for the part can be reduced.

In this paper pre-alloyed chromium material is compared to other PM grades in order to position the material in general. In the second part the performance of pre-alloyed material in respect of different processes is shown. Finally the influence of shot peening on high temperature sintered Astaloy CrM in respect of dynamic properties is presented.

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CHROMIUM MATERIAL IN COMPARISON TOWARDS OTHER PM GRADES

Chemical composition of the investigated materials is shown in table 1.

Table 1. Composition for the material used.

Material	Chromium (%)	Molybdenum (%)	Copper (%)	Nickel (%)	Manganese (%)
Astaloy CrM	3.0**	0.5**			
Astaloy CrL	1.5**	0.2**			
Astaloy A		0.55**		1.9**	0.2**
Distaloy HP-1		1.5**	2*	4*	
Distaloy AE		0.5*	1.5*	4*	
Distaloy AB		0.5*	1.5*	1.75*	
Fe - Cu			2		

* Diffusion bonded alloying element. ** Pre-alloyed alloying element.

Chromium pre-alloyed material is compared to other PM grades regarding ultimate tensile strength at different combined carbon contents, figure 1. Property is evaluated at a compaction pressure of 600 MPa and sintered at 1120°C/s for 30 minutes in 90/10 N_2/H_2. The cooling rate in the investigation is 0.8°C/s, measured between 850°C and 300°C.

Astaloy CrM
The performance of Astaloy CrM in respect of tensile strength is between Distaloy AE and Distaloy HP-1. The tensile strength at 0.3% C is 700 MPa. Increased carbon content raises the tensile strength to 800 MPa at 0.5% C. The microstructure consists of bainite at 0.3% C. Martensite starts to form at 0.4% C.

Astaloy CrL
At a combined carbon content of 0.2% the performance for Astaloy CrL is close to Astaloy A and the Iron 2% Copper material. The properties are determined by the microstructure, which consists of ferrite and perlite. Increased carbon to 0.4% changes the microstructure to bainite. At a carbon content of 0.4% an increase in tensile strength of 180Mpa compared to Astaloy A and Fe 2% Copper material is achieved. The obtained tensile strength at 0.6% carbon exceeds the one from Distaloy AE.

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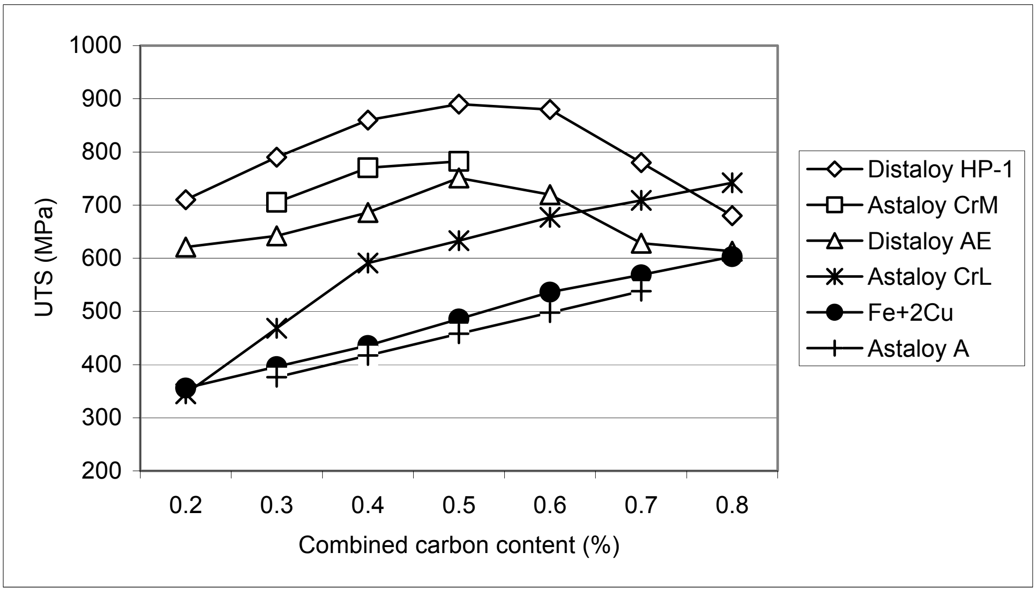

Figure 1. Ultimate tensile strength obtained at different combined carbon contents.

Compressibility

Compressibility is used in the PM industry to indicate the mechanical properties. Pre-alloyed material has a lower compressibility due to the solution hardening effect from the alloying elements compared to plain Iron, figure 2. Material based on plain iron like Distaloy AE and Distaloy AB achieves therefore a green density near the plain iron. Distaloy HP-1 which is based on Astaloy Mo, pre-alloyed 1.5% Mo, has slightly higher compressibility compared to Astaloy CrL even though the pre-alloyed amount is similar.

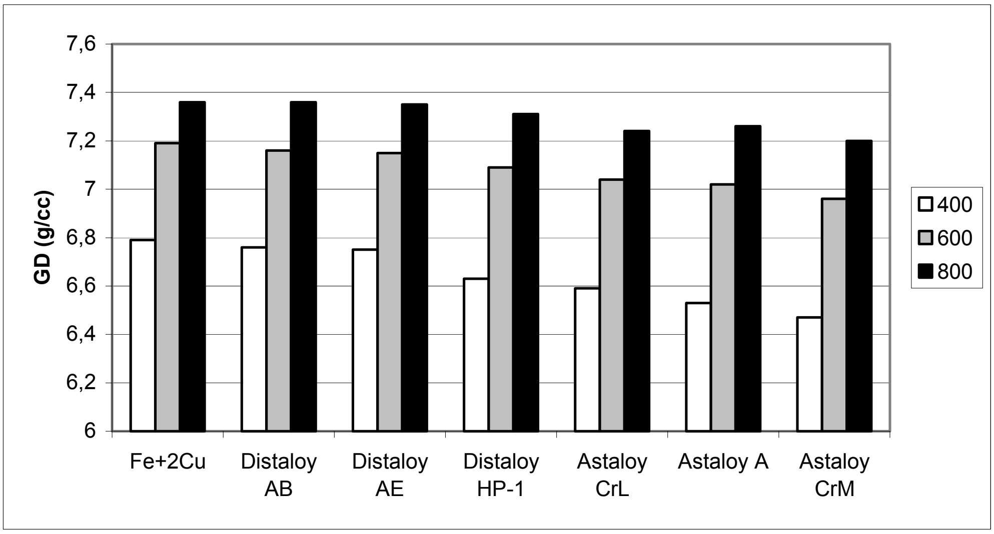

Figure 2. Compressibility for PM grades with 0.6% Kenolube.

Calculation of the theoretical density for these materials and a comparison at 11% porosity gives the following densities. Distaloy HP-1; 7.04, Distaloy AE; 7.01, Astaloy CrM; 6.96 and Astaloy CrL; 6.96. This means that compressibility does not completely describe the performance of PM materials. Pre-alloyed material with Chromium due to the specific weight of the alloying elements achieves a higher density at a given porosity level, in this case 11%. The lower theoretical density for pre-alloyed materials compensates the lower compressibility to some extent.

EFFECT OF INCREASED DENSITY, SINTERING TEMPERATURE AND COOLING RATE FOR PRE-ALLOYED CHROMIUM MATERIAL.

Astaloy CrM

Astaloy CrM 0.4% C at 6.9 g/cc and 1120°C sintering achieves a tensile strength of 800 MPa and an elongation of 1%, figure 3. Increased cooling rate from 0.8°C/s to 2.5°C/s increases the tensile strength to 1020MPa and the elongation decreases to 0.3%. The decreased elongation is due to transformation from bainitie to martensite microstructure when increasing the cooling rate. The influence from temperature, 1120°C to 1250°C, enhances the sintering activity which here can be seen as an increase in elongation to 2.4% and a tensile strength increase to 950. The density after 1250°C sintering is increased from 6.93 g/cc to 7.0 g/cc. This also contributes to the increased properties. By utilising warm compaction the gain in density is 0.15 g/cc that after 1250°C sintering gives a sintered density of 7.15 g/cc. Achieved tensile strength is 1085MPa with an elongation of 3.8%. The microstructure is bainitic. By utilising increased cooling rate after 1250 sintering the tensile strength increases to 1315MPa with an elongation of 0.8%. A tempering operation increases the tensile strength to 1420MPa and the elongation to 1.4%.

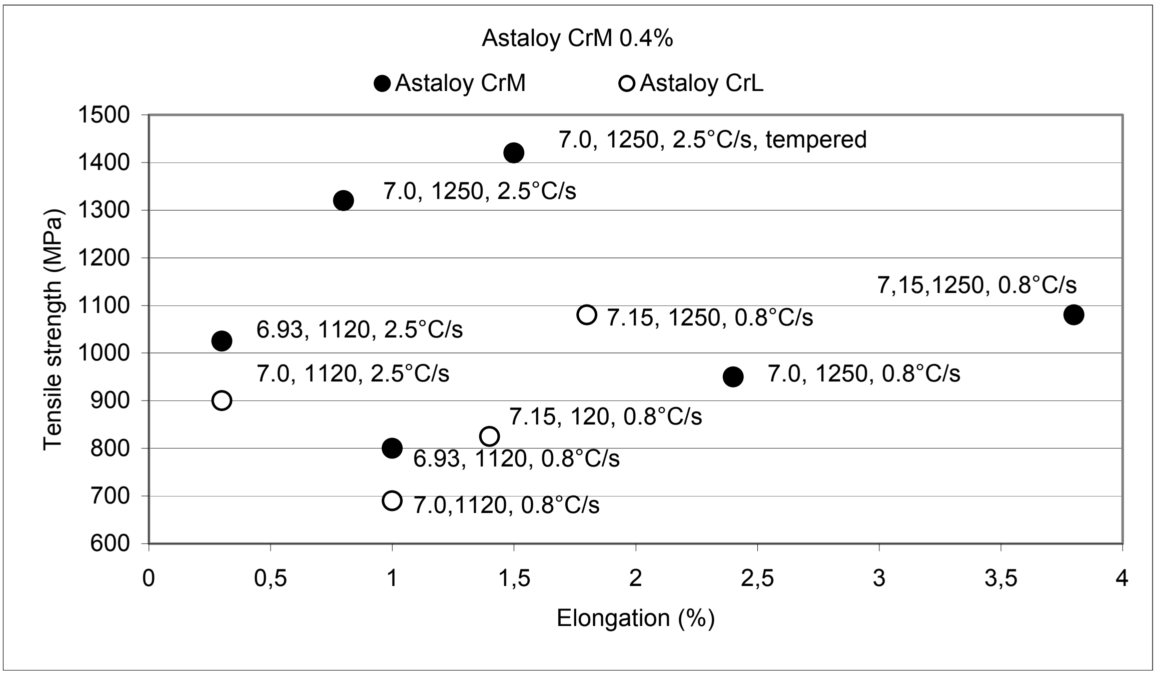

Figure 3. Influence of processing on Astaloy CrM 0.4% C and Astaloy CrL 0.6% C.
Denoted in the figure are density, sintering temperature and cooling rate, 7.0 g/cm^3, 1120°C, 0.8°C/s.

Astaloy CrL

Astaloy CrL 0.6% C at 6.93 g/cm^3 and 1120°C sintering has a tensile strength of 700MPa and an elongation of 1.1%, figure 3. Increased density to 7.08 g/cc by using warm compaction increases the tensile strength to 830MPa and the elongation to 1.5%. Increased temperature from 1120°C increases the tensile strength to 1085MPa and the elongation to 1.8%. Increased cooling rate from 0.8°C/s to 2.5°C/s gives a tensile strength of 900MPa and an elongation of 0.35%.

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As-sintered properties, processing conditions

Mixes based on Astaloy CrM at 4 different graphite levels, 0.55, 0.65, 0.75 and 0.85% were cold compacted to a density of 7.0 g/cm^3. Tensile testing bars (ISO 2740) and modified ISO 3928 fatigue bars with chamfered edges [3] were pressed. Pressing was carried out in a semiautomatic laboratory press. Sintering was carried out at 1250°C for 60 minutes in 90/10 N_2/H_2 atmosphere in a lifting earth furnace with no methane addition. Two cooling rates were investigated; 0.8°C/s and 2.5°C/s. The cooling rate refers to the temperature range 800-300°C. All materials were tempered at 200°C for 60 minutes in air except for material A cooled at 0.8 °C/s. The materials cooled at 0.8°C/s were shot peened with steel sand for 5 minutes.

Hardness HRC was measured on the as-sintered samples. Vickers hardness, HV10, was measured on the shot peened samples since HRC (150 kg load) would have covered a too deep area. Static properties were investigated both for the materials cooled at 0.8°C/s and 2.5°C/s. Dynamic properties were investigated for the materials cooled at 0.8°C/s.

When raising the cooling rate from 0.8 °C/s to 2.5°C/s, figure 4, the yield strength is increased. At 0.4%C the yield strength is raised from 770 MPa to 1157 MPa. This is due to a transformation in the microstructure from mainly upper bainite (85%) to an entirely martensitic structure. Maximum yield strength is found at ~0.45%C. Increased cooling rate moves this optimum to lower carbon content [3]. Further increase in sintered carbon decreases the yield strength. At carbon content above 0.5% same hardness level (45 HRC) is achieved at both cooling rates tested, figure 5.

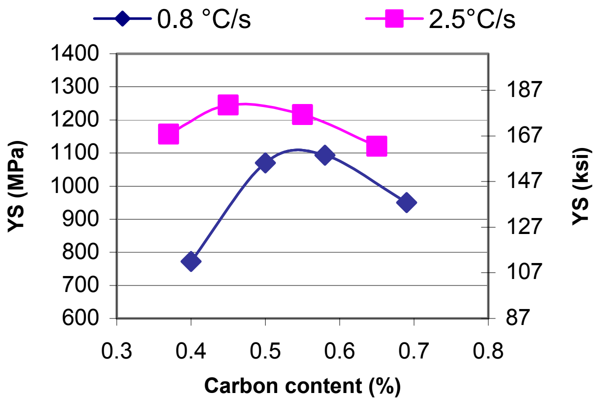


Figure 4. Yield strength vs. carb content, at cooling rate of 0.8 °C/s and 2.5 °C/s.

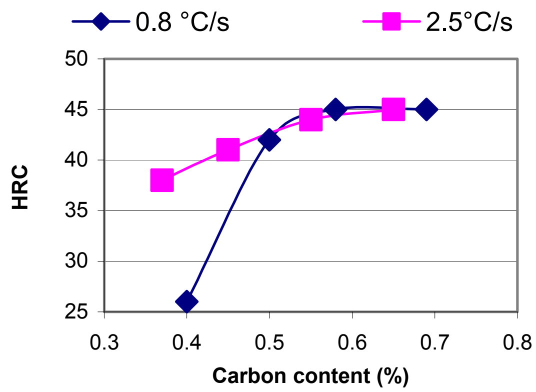
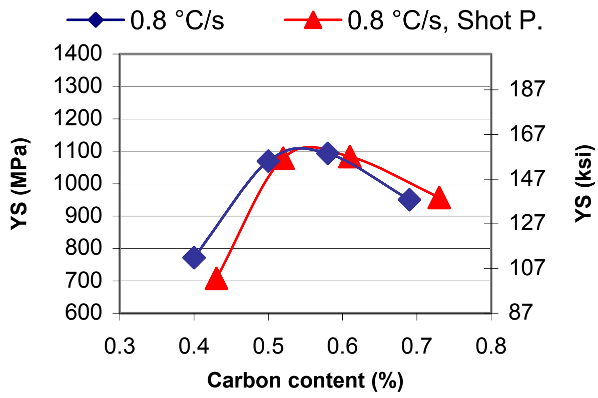


Figure 5. HRC vs. carb content, at cooling rate of 0.8 °C/s and 2.5 °C/s.

Influence of shot peening

Shot peening operation densifies the surface to a depth range of 5 to 30µm depending on the surface hardness, which is related to the material microstructure and density. No gain in yield strength was found, figure 6. The effect from the surface densification on hardness is shown in figure 7.



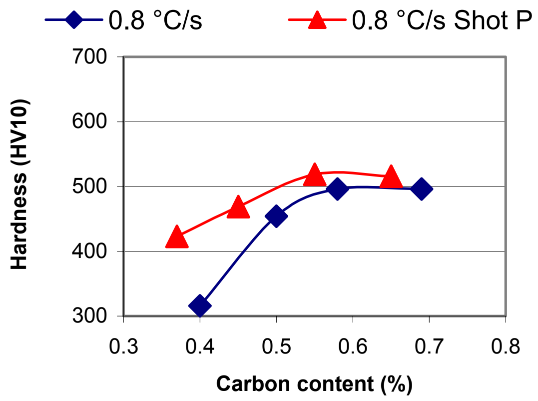
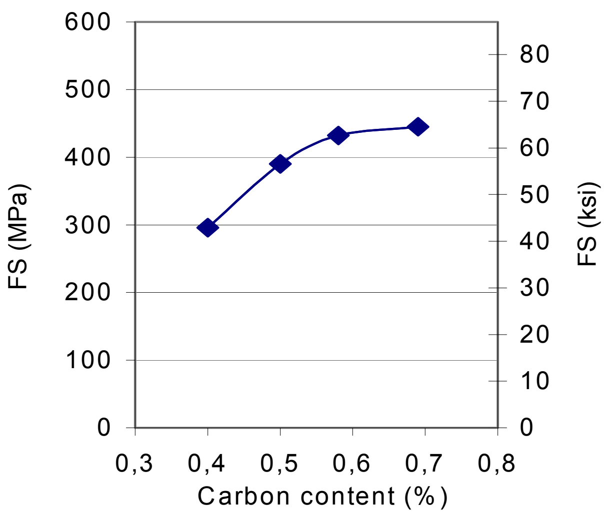


Figure 6. Yield strength vs. carbon content, cooling rate 0.8°C/s.

Figure 7. Hardness, HV10, vs carbon content, 0.8°C/s.

Dynamic properties

Four point plane bending fatigue, R= -1 frequency 25 Hz, run out at 2 million cycles was evaluated at a cooling rate of 0.8°C/s. Fatigue strength limit [$\sigma_{A\ 50}$] was determined with staircase method according to MPIF standard No. 56, 2001. Fatigue performance as sintered at 1250°C.
Results obtained are summarised in figure 8. A fatigue strength of 300 MPa is found at carbon content of 0.4%[4]. By raising the carbon content to 0.5% C, an optimum is found regarding static properties, while the fatigue strength goes up to 390 MPa. At higher carbon content the static properties decrease but the fatigue strength continues to increase. A fatigue strength of 445 MPa is found at 0.7% C. At this carbon content the microstructure consists of martensite with some retained austenite between the martensite needles.



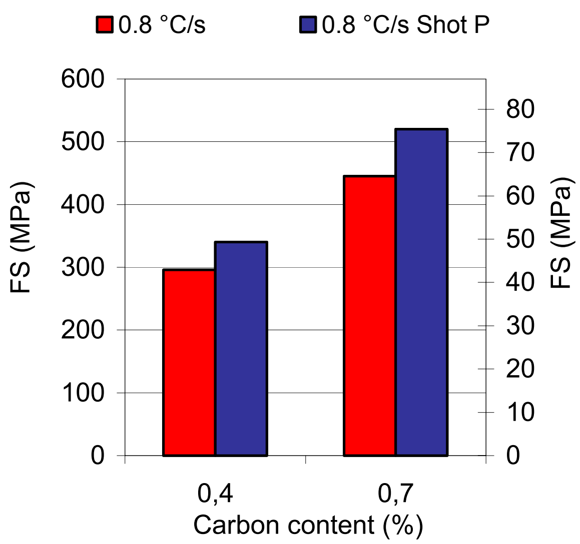


Figure 8. Fatigue strength as a function of carbon content at a cooling of 0.8°C/s.

Figure 9. Influence of shot peening on fatigue strength

Fatigue performance after 1250°C sintering and shot peening.

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Fatigue strength can be increased by shot peening the samples (figure 9). At carbon content 0.4% the gain in fatigue strength is 15%. By raising the carbon content to 0.7% a fatigue strength of 520 MPa is achieved corresponding to an increase by 17%. Investigation of the microstructure close to the surface for Astaloy CrM 0.69% C shows thatthe amount of retained austenite after a shot peening operation is decreased.

DISCUSSION

At a sintering temperature of 1120°C and a compaction pressure of 600MPa chromium materials achieve properties that with regard to cost/performance are attractive alternatives for part manufacturing. Raising the sintering temperature from 1120 °C to over 1200 °C is beneficial both for the strength and toughness of Astaloy CrM and Astaloy CrL. As the alloying elements chromium and molybdenum are prealloyed to the iron, the reason for the higher mechanical properties obtained after high temperature sintering, if as-sintered carbon content, sintered density and cooling rate are kept constant, is the formation of more developed sintering necks between the powder particles.

Due to the presence of chromium and molybdenum Astaloy CrM and Astaloy CrL have a good hardenability. For Astaloy CrM an almost entirely martensitic structure (> 85% martensite) is obtained at 0.55% carbon when cooling at the rate of 0.8 °C/s. At this carbon level and density of 7.15 g/cm^3, a hardness of 45 HRC is obtained after high temperature sintering (1250°C) in combination with a yield strength of 1092 MPa, elongation of 1.3% and bending fatigue of 410 MPa.

At 0.55% C maximum in yield properties is reached. Further increase in carbon content results in decreased static properties due to increased fragility of the martensite and formation of retained austenite [5]. Dynamic properties instead increase when raising the carbon content from 0.4 to 0.7% and a fatigue strength of 445 MPa is obtained at 0.7% C. This is in compliance with the behavior of Distaloy AE and Distaloy HP-1.

Optimum carbon content when cooling at 2.5 °C/s is 0.45%, which is lower compared to 0.8°C/s in cooling rate [5]. Increased cooling rate, 2.5°C/s, gives an increase in yield strength by ~150 MPa reaching 1245 MPa at a combined carbon content of 0.45%. This at the expense of the elongation which decreases by 0.5%.

For carbon content ≥ 0.55% Astaloy CrM has a hardness HRC of 45 units independently of the cooling rate. At 0.55% the material has an almost entirely martensitic structure both when cooling at 0.8 °C/s and 2.5 °C/s. When further increasing the carbon content no further increase in hardness HRC is observed due to the formation of retained austenite.

Shot peening introduces compressive stresses in the material, if the microstructure can take plastic deformation, contributing in this way to an improvement in fatigue properties. Modification of crack initiation sites at the surface, i.e closure of surface pores is another mechanism that will enhance the fatigue performance. By carrying out a shot peening operation after high temperature sintering followed by cooling at 0.8 °C/s an increase in fatigue strength by 15% was obtained. At 0.7% C a fatigue strength of 520 MPa was reached.

CONCLUSIONS

- Astaloy CrM and Astaloy CrL are suitable for manufacturing of high performance PM parts after 1120°C sintering.
- High temperature sintered Astaloy CrM is suitable for manufacturing of higly loaded PM parts

- Plane bending fatigue strength increases from 300 MPa (43 ksi) to 445 MPa (65 ksi) when raising the carbon content from 0.4-0.7%C.
- Fatigue strength can be further increased by carrying out a shot peenening operation. A plane bending fatigue strength of 520 MPa can be achieved at 0.7%C and density 7.2 g/cm^3.
- Optimum yield strength, 1093 MPa, is obtained at 0.58% C when cooling at the rate of 0.8°C/s.
- By combining high temperature sintering with rapid cooling optimum yield strength, 1245 MPa is obtained at 0.45% C.
- Hardness of 45 HRC is obtained at 7.2 g/cm^3 in density for carbon content above 0.5% C, independently of cooling rate.

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