MECHANICAL PROPERTIES OF HIGH PERFORMANCE CHROMIUM MATERIALS

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ABSTRACT

Two important areas for the growth of PM are increased performance and improved cost effectiveness. Chromium is an alloying element that can help to achieve these goals. Chromium has positive effects on the final properties of steels while being historically less susceptible to fluctuations in cost. This paper will discuss the properties achievable using two chromium steels being standardized, FL-5208 and FL-5305. FL-5208 is a fully pre-alloyed PM steel based on 1.5% Cr and 0.2% Mo. FL-5305 is a fully pre-alloyed PM steel based on 3.0% Cr and 0.5% Mo. Both of these materials exhibit a combination of high material properties and versatility. Static and dynamic material properties achievable by these materials using conventional sintering and high temperature conditions as well as sinter hardening will be discussed.

INTRODUCTION

To continue to expand the PM market into new applications, cost effective materials with increased performance will be required. This can be achieved by different means. The development of new cost effective alloy systems, utilization of increased density by using new compaction techniques, sintering at higher temperatures and adoption of secondary heat treatments are all examples of means that either by themselves or in combination can be used to increase the material performance.

Using pre-alloyed powders is one method to obtain materials with higher performance levels. The most common pre-alloying elements used in PM so far are nickel and molybdenum as these are not sensitive to oxidation during processing. Chromium is interesting as a pre-alloying element due to its performance enhancing ability and relatively low cost. Chromium has not been utilized to a large extent in the past due to its high affinity to oxygen making it difficult to prevent from oxidation during sintering especially at lower sintering temperatures. However, with new pre-alloyed Cr containing powders in combination with the nitrogen-hydrogen atmospheres and furnaces available today, the advantages of chromium can be fully utilized [1-3].

The objective of this paper is to demonstrate the properties achievable with two Cr-Mo pre-alloyed powders now being standardized, FL-5208 and FL-5305. FL-5208 is a fully pre-alloyed PM steel based on 1.5% Cr and 0.2% Mo. FL-5305 is a fully pre-alloyed PM steel based on 3.0% Cr and 0.5% Mo. These two materials exhibit a combination of high material properties and versatility. In this paper static and dynamic material properties obtained with these two materials using different compaction methods and sintering conditions will be discussed.

EXPERIMENTAL PROCEDURE

Powder/Materials

The materials used in the experiments reported in this paper are based on the two pre-alloyed Cr-Mo steel powders, Astaloy CrL[Tm] and Astaloy CrM[Tm] from Höganäs AB, Sweden. These two powders/materials have recently been standardized by MPIF with the designations FL-5208 and FL-5305. The chemical compositions of these powders are shown in Table 1 below.

Table 1. Chemical composition of the base powder used

MPIF designation	Base powder	Cr, %	Mo, %	Fe, %
FL-5200	Astaloy CrL[TM]	1.5	0.2	Bal.
FL-5300	Astaloy CrM[TM]	3.0	0.5	Bal.

Two premixes based on Astaloy CrL[TM] and Astaloy CrM[TM] with the compositions listed in Table 2 were prepared. Asbury 1651 graphite was used in all cases and the lubricant used was Kenolube[TM] from Höganäs AB. In this paper the two materials based on these two powder mixes will be described with the code A and B respectively.

Table 2. Mix compositions

Designation code used in this paper	MPIF designation	Base powder	Graphite, $^w/_0$	Lubricant, %
A	FL-5208	Astaloy CrL[TM]	0.80	0.75
B	FL-5305	Astaloy CrM[TM]	0.50	0.75

Experimental procedure

Tensile strength, transverse rupture strength, impact energy and fatigue strength test specimens were compacted of each mix at North American Höganäs in a 100 ton hydraulic press. Different compaction methods and pressures were used in order to obtain sintered density of 6.70, 6.90, 7.10 and 7.30 g/cm^3. The test specimens were subsequently sintered at both conventional- and high temperature with normal and increased cooling rates with the different conditions described in Table 3 below. It should be noticed that all properties presented in this paper are obtained at a combined carbon content of 0.75% for material A and 0.45% for material B. Specimens subjected to sinter hardening were subsequently stress relieved at 200°C (390°F) for 60 min in air.

Table 3. Sintering conditions

Description	Conventional sintering	High Temperature Sintering
Furnace type	Mesh belt	Pusher
Temperature, ^{0}C (^{0}F)	1120 (2050)	1250 (2280)
Atmosphere, $^v/_0N_2$ / $^v/_0H_2$	90 /10	90 / 10
Time at Temperature. min	30	30
Cooling rate		
Conventional, ^{0}C/s (^{0}F/s)	0.5 (1.0)	0.5 (1.0)
Sinter hardening, ^{0}C/s (^{0}F/s)	2.0 (4.0)	2.0 (4.0)

RESULTS AND DISCUSSION

SINTERING AT 1120°C (2050°F)

Ultimate Tensile Strength

In table 4 below the tensile strength obtained for material A and B after sintering at 1120°C (2050°F) is presented. As expected, the tensile strength increases for both materials by increasing the density. For material A the tensile strength increases about 50% going from 6.70 to 7.30 g/cm³. For material B the corresponding strength increase is 45%. By comparing the tensile strength obtained with the two materials at the same density material B achieves about 15% higher strength compared to material A even though the carbon content is only 0.45% after sintering. It is also interesting to notice that the tensile strength obtained at the density level of 7.30 g/cm³ for material A can be achieved already at a density level of about 7.00 g/cm³ for material B. By further increasing the carbon content up to 0.6% for material B higher tensile strength levels can be achieved.

Table 4. Ultimate tensile strength of materials A and B after sintering at 1120°C (2050°F)

Sintering temperature °C (°F)	Density g/cm^3	Tensile strength, MPa (ksi)	
		Material	
		A	B
1120 (2050)	6.70	620 (90)	760 (110)
	6.90	760 (110)	860 (125)
	7.10	830 (120)	970 (140)
	7.30	930 (135)	1100 (160)

Transverse rupture strength, TRS

The transverse rupture strength obtained for materials A and B is shown in table 5 below. As expected, the transverse rupture strength increases with increased density for both materials. Material B achieved about 15% higher strength compared to material A at the two lower density levels. At the two higher density levels the transverse rupture strength is about 5% higher for material B than for material A.

Table 5. Transverse rupture strength of materials A and B after sintering at 1120°C (2050°F)

Sintering temperature °C (°F)	Density g/cm^3	TRS, MPa, (ksi)	
		Material	
		A	B
1120 (2050)	6.70	1100 (160)	1280 (185)
	6.90	1310 (190)	1450 (210)
	7.10	1520 (220)	1590 (230)
	7.30	1760 (255)	1820 (265)

Yield- and Compressive Yield Strength

The yield strength obtained is presented in table 6 below. As shown, an increase in density from 6.70 to 7.30 g/cm³ increases the yield strength linearly about 40% for material A and 50% for material B. It can also be seen that material B obtains about 25% higher yield strength than material A at the two lower density levels and about 35% higher at the two higher levels. The yield strength obtained at a density of 7.30 g/cm³ for material A can be obtained at only 6.90 g/cm³ with material B.

Similar results were obtained regarding compressive yield strength, also shown in table 6. Material A showed an increase of about 60% and material B an increase of 50% with increasing density. It is also interesting to notice that the compressive yield strength is about the same as the yield strength for material A especially at the higher density levels whereas the yield strength for material B is about 15% higher than the compressive yield strength at all density levels.

Table 6. Yield- and compressive yield strength of materials A and B
after sintering at 1120°C (2050°F)

Sintering temperature °C (°F)	Density g/cm^3	Yield strength, MPa (ksi)		Compressive yield strength, MPa (ksi)	
		Material		Material	
		A	B	A	B
1120 (2050)	6.70	480 (70)	590 (85)	410 (60)	520 (75)
	6.90	550 (80)	690 (100)	520 (75)	600 (87)
	7.10	600 (87)	790 (115)	590 (85)	690 (100)
	7.30	660 (95)	900 (130)	660 (95)	790 (115)

Apparent Hardness

The Rockwell apparent hardness achieved after sintering at 1102C(2050F) is shown in table 7. The apparent hardness values are reported in HRB scale for material A and at the lowest density level for material B. At the three higher densities the HRC scale was used. As shown, the hardness increased as the density increased. For material A the hardness increased from 83 to 98 HRB. Even though the carbon content of material B is 0.3% lower than for material A higher hardness was achieved. At the lowest density level a hardness of 90 HRB was obtained. At the three higher densities the hardness increased from 20 HRC at 6.90 g/cm^3 to 33 HRC at the highest density of 7.30 g/cm^3.

Table 7. Hardness, HRB and HRC, of material A and B after
sintering at 1120°C (2050°F)

Sintering temperature, °C(°F)	Density, g/cm^3	Hardness, HRB, HRC*	
		Material	
		A	B
1120 (2050)	6.70	83	90
	6.90	88	20*
	7.10	93	26*
	7.30	98	33*

Elongation and Impact energy

The elongation and un-notched Charpy impact energy values obtained for the two materials are shown in table 7. As can be seen the elongation for material A increased from 1% at the lowest density to 3.0% at the highest density. Material B obtained a slightly lower elongation at the lowest density level compared to material A. At the higher density levels the elongation increased but was about 50 % lower compared to material A. This is due to the higher hardness of material B.

Regarding the un-notched Charpy impact energy it increases for both materials with increases in density. Similar to the elongation, material A obtained higher impact energy than material B at all density levels. The difference is larger at the higher densities.

Table 7. Elongation and un-notched Charpy Impact Energy of material A and B
after sintering at 1120°C (2050°F)

Sintering temperature °C (°F)	Density g/cm^3	Elongation, %		Un-notched Charpy Impact Energy, J (ft.lbf)	
		Material		Material	
		A	B	A	B
1120 (2050)	6.70	1.0	<1.0	12 (9)	11 (8)
	6.90	1.5	1.0	16 (12)	14 (10)
	7.10	2.0	1.2	20 (15)	15 (11)
	7.30	3.0	1.5	24 (18)	18 (13)

Fatigue strength

In table 8 below the rotating bending fatigue , 90%survival, results obtained for both materials after sintering are shown. By comparing the results obtained at different density levels it can be observed that the fatigue strength increased significantly for both materials, about 50% for material A and 40 % for material B, when density is increased from 6.70 to 7.30 g/cm^3.

Table 8. Fatigue strength of materials A and B after sintering at 1120°C (2050°F)

Sintering temperature, °C(°F)	Density, g/cm^3	Rotating bending fatigue strength, 90% survival MPa (ksi)	
		Material	
		A	B
1120 (2050)	6.70	190 (28)	240 (34)
	6.90	220 (32)	260 (37)
	7.10	250 (36)	290 (41)
	7.30	280 (40)	330 (47)

SINTERING AT 1250°C (2282°F)

Most production sintering of parts is still carried out at 1120°C (2050°F), with a cooling rate of approximately 0.5-1°C/s (1-2°F/s). With proper atmosphere control sintering at this temperature is sufficient for pre-alloyed chromium materials [3]. However, sintering at higher temperatures can be beneficial. At increased sintering temperature, diffusion and sintering activity are enhanced, resulting in stronger sintering necks, more rounded pores, and more effective oxide reduction. These factors all contribute to an increase of the mechanical properties of the sintered material. Not only the strength is increased, but also, as a result of the more favorable pore structure, the ductility is increased. Figures 1 and 2 below show the pore structures obtained for material A at a density of 7.00 g/cm^3 after sintering at 1120°C (2050°F) and 1250°C (2282°F) respectively.
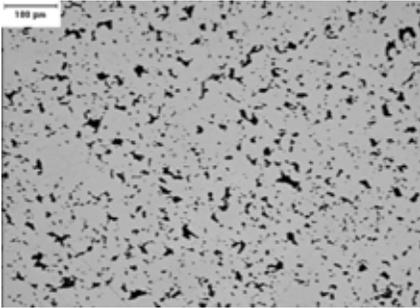
Fig. 1. Microstructure of material A sintered at 1120°C (2050°F).
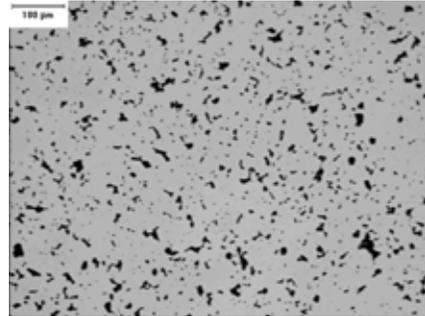
Fig. 2. Microstructure of material A sintered at 1250°C (2282°F).

The effect of increased sintering temperature on tensile strength is visualized in Figure 3 below. As can be seen, the tensile strength is significantly increased for both materials. The strength is increased about 15% for both materials A and B at a density of 7.00 g/cm^3. This is primarily due to more developed sintering necks, rounder pores and a slightly lower oxygen content compared to what was achieved at the lower sintering temperature.
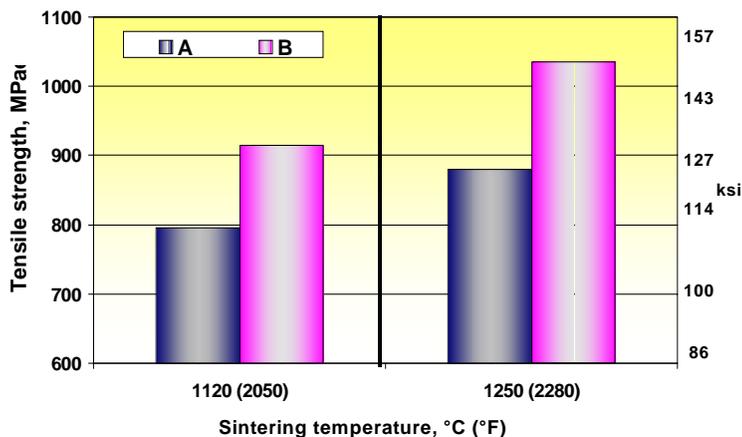

Figure 3. Effect of sintering temperature on tensile strength for materials A and B at a density of 7.0 g/cm^3.

The positive effect of increased sintering temperature on both tensile strength and elongation is visualized in Figure 4 below. As can be seen the elongation is significantly increased for both materials at the same time as the tensile strength is increased. The elongation is increased almost 100 % for both materials.
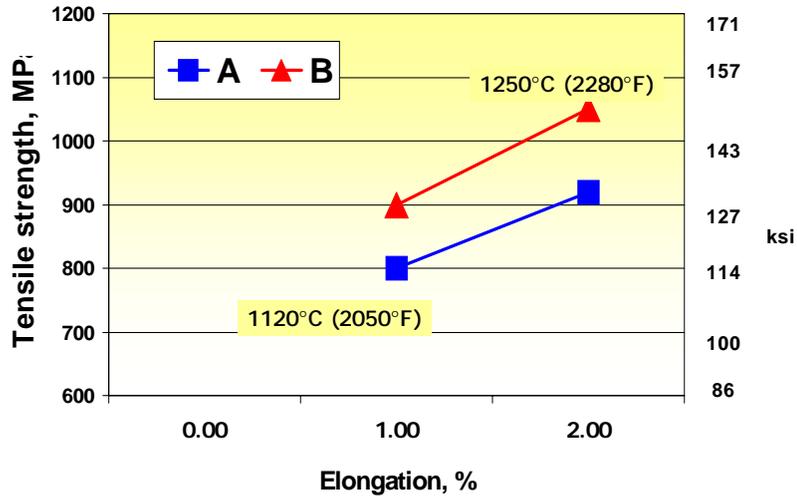
Figure 4. Effect of sintering temperature on tensile strength and elongation
for material A and B at a density of 7.0 g/cm^3.

The positive effect of increased sintering temperature on bending fatigue strength is shown in Figure 5 below. As can be seen fatigue strength is significantly increased for both materials. The fatigue strength was increased about 20 % for both materials by increasing the sintering temperature to 1250°C (2280°F). Higher bending fatigue strength levels can be obtained by further increasing the carbon content in material B from the present level of 0.45%.
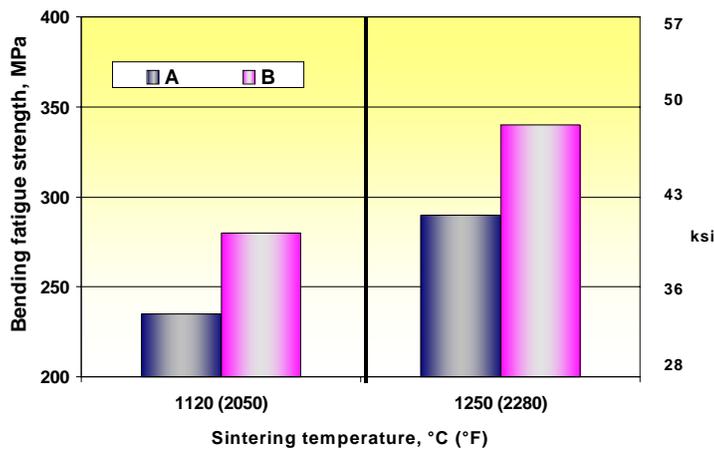
Figure 5. Effect of sintering temperature on plane bending fatigue strength
for material A and B at a density of 7.0 g/cm^3.

The improvements in elongation and bending fatigue strength are primarily due to more developed sintering necks, rounder pores, a change in microstructure and a slightly lower oxygen content compared to what is achieved at the lower sintering temperature.

SINTER HARDENING

Alloy composition, carbon content and cooling rate have a strong influence on the final microstructure of the material. Chromium and molybdenum are elements that increase hardenability and thereby suppress the pearlite formation. At lower cooling rates the microstructure will transform to mainly ferrite, pearlite and/or upper bainite. At higher cooling rates the resulting microstructure will mainly consists of martensite. To obtain homogenous microstructures after sinter hardening, it is favorable to have a homogenous distribution of the alloying elements already in the compacted part. By utilizing powders pre-alloyed with chromium and molybdenum, martensitic structures can be formed after sintering at 1120ºC (2050ºF) already at moderate cooling rates, 1.5~2.5ºC/s (3~5ºF/s) and proper amounts of carbon.

Influence of carbon content

The higher alloying content of material B suppresses the pearlite formation at conventional cooling rates, and makes the material suitable when bainitic or martensitic structures are desired. Material A, on the other hand, with its lower alloying content offers a wider range of microstructures. By optimising carbon content and cooling rate, desired microstructures with corresponding mechanical properties can be achieved which will be described below.

The diagram in Figure 6 below shows the resulting phase composition of the microstructure obtained with material B at two different carbon levels, 0.4 and 0.5%, and different cooling rates. As can be seen the microstructure obtained at 0.4% carbon and a cooling rate of 0.8ºC/s (1.6°F/s) consists mainly of bainite, 75%, and about 25% martensite. By increasing the carbon content to 0.5%, the microstructure changes towards a mainly martensitic structure with some bainite. It can also be seen that an almost completely martensitic microstructure can be obtained using a cooling rate of 1.0ºC/s (2.0°F/s) with material B with 0.5% carbon.
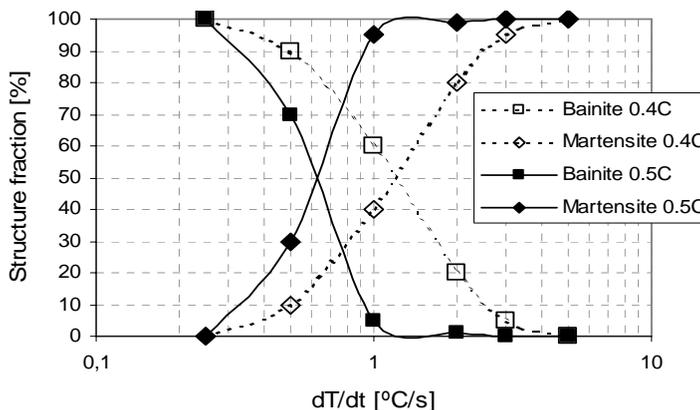

Figure 6. Phase amount vs. cooling rate for material B with 0.4 and 0.5% C.

The influence of cooling rate on the resulting microstructure is more complex for material A. Figure 7 shows the different phase amounts obtained with varying cooling rates at 0.75% C. Due to the overall lower alloying content, mainly pearlite is formed at lower cooling rates. As cooling rate increases towards 1ºC/s (2°F/s), the structure changes towards bainite. At cooling rates above 2ºC/s (4ºF/s) martensite starts

to form, but bainite dominates the structure even at high cooling rates. To obtain a completely martensitic microstructure a cooling rate of 4-5ºC/s (8-10°F/s) is required. This cooling rate is in many cases not possible to achieve in an industrial production environment. Therefore, to be able to use material A in sinter hardening applications it is recommended to add 1 to 2% Cu to the material to increase the hardenability. As can be seen from Figure 7 an addition of 1% Cu to material A makes it possible to obtain an almost completely martensitic microstructure at a cooling rate of 1.0ºC/s (2.0°F/s).
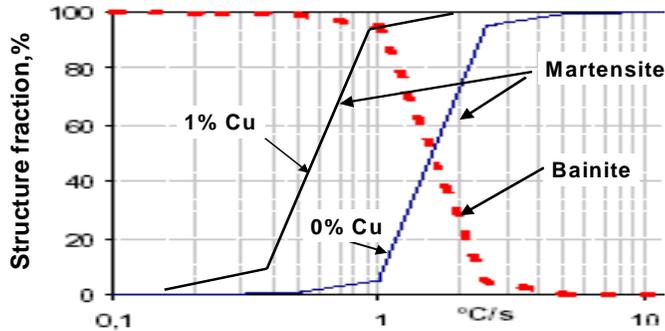

Figure 7. Influence of cooling rate and 1.0% Cu addition on phase amount for material A

Mechanical properties obtained with sinter hardening

Figure 8 below shows the tensile strength obtained for materials A and B subjected to sinter hardening using both conventional sintering temperature 1120ºC (2050ºF) and high sintering temperature 1250ºC (2280ºF). The data shown is obtained at a sintered density of 7.0 g/cm^3. As can be seen, the processing conditions have a strong influence on the strength of the material. The lowest strength is obtained with the material sintered at the conventional temperature 1120ºC (2048ºF) and cooling rate 0.5ºC/s (1.0°F/s).
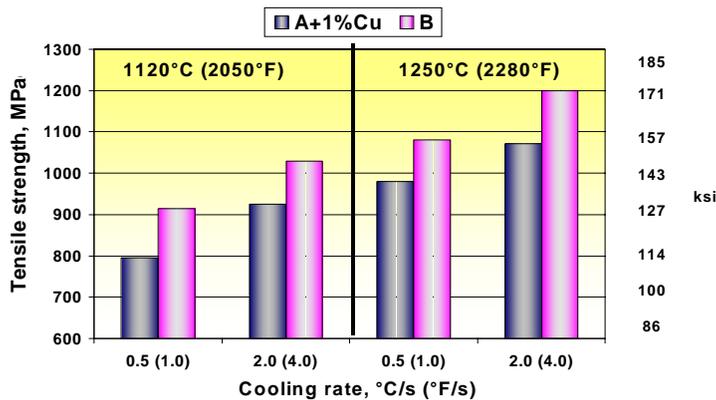

Figure 8. Tensile strength obtained for material A+1%Cu and B after
different processing at a density of 7.0 g/cm^3.

By utilizing sinter hardening the tensile strength level is increased to about the same level as obtained by high temperature sintering. As shown, the tensile strength increases more than 20%, to over 900 MPa

(130 ksi) for material A, and to over 1000 MPa (144 ksi) for material B. If high temperature sintering is combined with sinter hardening, even higher strength is obtained. Material A can reach a strength of 1080 MPa (155 ksi), and material B a strength of 1200 MPa (170 ksi).

The influence of different processing on hardness is shown in Figure 9. It can be seen that increased cooling rate when using a sintering temperature of 1120°C (2050°F) increases the hardness from a level slightly lower than 20 HRC to about 35 HRC for material A. For material B the hardness increases from 25 to 33 HRC when the cooling rate is increased from 0.5°C/s (1.0°F/s) to 1.0°C/s (2.0°F/s). By combining high temperature sintering, 1250°C (2280°F) with sinter hardening, the hardness can be increased further. Hardness levels between 35 and 40 HRC can be achieved with both materials.
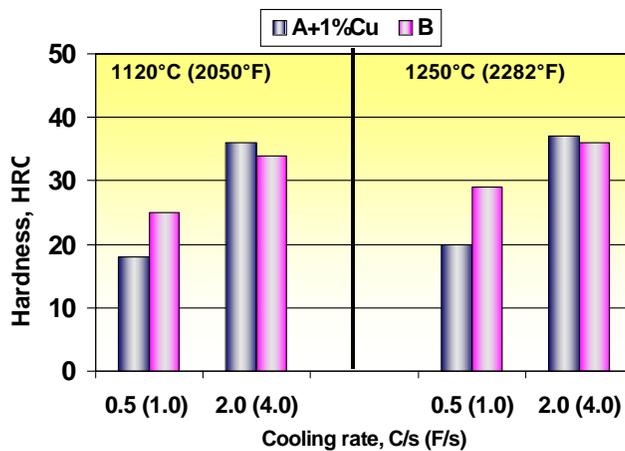

Figure 9. Hardness obtained for material A+1%Cu and B after
different processing at a density of 7.0 g/cm^3.

The positive effect of increased cooling rate after sintering at 1120°C (2050°F) on bending fatigue strength is shown in Figure 10 below. As can be seen, fatigue strength is significantly increased for both materials. For material A the fatigue strength is increased about 25 % and for material B the increase is almost 35%. It should be pointed out that higher bending fatigue strength levels could be further increased by combining increased cooling rate with sintering at higher temperature.
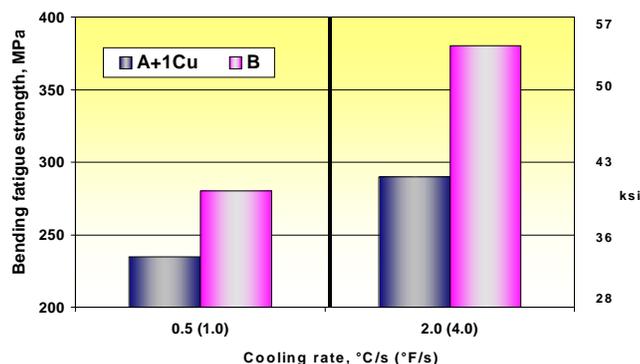
Figure 10. Bending fatigue strength obtained for material A+1% Cu and B
after sinter hardening at 1120°C (2050°F). Density 7.0 g/cm^3

CONCLUSIONS

Astaloy CrL^{Tm} and Astaloy CrM^{Tm} now being standardized under the MPIF designations FL-5208 and FL-5305 respectively, are suitable for manufacturing of high performance PM components after sintering at 1120°C (2050°F). Depending on density, tensile strength levels from 620 MPa (90 ksi) to 930 MPa (135 ksi) ca be obtained with materials based on FL-5208. For materials based on FL-5305, tensile strength levels of 760 MPa (110 ksi) to 1100 MPa (160 ksi) can be obtained.

Bending fatigue strength levels from 190 MPa (28 ksi) to 280 MPa (40 ksi) can be achieved with materials based on FL-5208 in the density range 6.70 to 7.30 g/cm^3. For materials based on FL-5305 corresponding fatigue strength levels are 240 MPa (34 ksi) to 330 MPa (47 ksi).

By utilizing high temperature sintering 1250°C (2280°F) both tensile strength and bending fatigue strength are increased by 20-25% for both materials. At the same time elongation is improved almost 100%.

Materials based on FL-5208 and FL-5305 possess good hardenability, and give excellent response to sinter hardening operations. Fully martensitic structures can be achieved already at a cooling rate of 1.0°C/s (2.0°F/s) with FL-5305 and FL-5208 with 1% Cu addition.

At a density of 7.0 g/cm^3 tensile strength of 900 MPa (128 ksi) is obtained with FL-5208 with 1% Cu addition and 1050 MPa (150 ksi) with FL-5305 after sintering at 1120°C (2050°F) combined with sinter hardening. The hardness obtained at these processing conditions is about 35HRC for both materials. Bending fatigue strength increases 25 to 35 % for the two materials with increasing cooling rate. With FL-5305 a bending fatigue strength of 380 MPa (54 ksi) is reached.

By combining sinter hardening with high temperature sintering at 1250°C (2280°F) tensile strength levels up to 110 MPa (157 ksi) can be achieved with FL-5208 based materials and 1200 MPa (171 ksi) with FL-5305. At these processing conditions hardness levels of 35-40 HRC are obtained with both materials.

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