PROPERTIES OF HIGH-STRENGTH PM MATERIALS OBTAINED BY DIFFERENT COMPACTION METHODS IN COMBINATION WITH HIGH TEMPERATURE SINTERING

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ABSTRACT

New applications for PM steels are continuously introduced on the market. Many of these new applications utilize the unique possibilities of PM to achieve high strength in combination with close dimensional tolerances and a minimum of manufacturing operations.
Materials like Astaloy CrM and Astaloy Mo+2%Ni are all aimed at applications combining high strength with close dimensional tolerances. These materials reach tensile strength levels in the range of 650 MPa to 1000 MPa after conventional compaction at room temperature and sintering in belt furnaces at 1120°C (2050°F). By applying high temperature sintering i.e. sintering at temperatures > 1200°C (2200°F), these strength levels can be further increased. By combining high temperature sintering with warm compaction or high velocity compaction (HVC) PM materials with even higher strength levels can be obtained.
This paper describes the influence of sintering temperature on static and dynamic properties for conventionally pressed, warm compacted and high velocity compacted powder mixes based on Astaloy CrM and Astaloy Mo+2%Ni.

I. INTRODUCTION

The development of pressing techniques, such as warm compaction [1-4] and HVC [2-8] enables higher densities than conventional compaction. High Velocity Compaction (HVC) is a recently developed ultra-fast forming method. A hydraulic impact machine compacts parts by intensive single or multiple strokes to very high density. In the investigation presented in this paper the HVC technique has been used in the second step of double pressing in order to achieve densities in the range of 7.57 – 7.67 g/cm³.
This paper explores the benefits of increased density, in combination with high temperature sintering 1250°C/ 2282°F. Static and dynamic properties are evaluated for conventionally pressed, warm compacted and high velocity compacted specimens of two materials.
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II. EXPERIMENTAL

Premix and Densmix powders based on Astaloy CrM [9-12] and Astaloy Mo were made according to the compositions in table 1. Astaloy CrM and Astaloy Mo + 2% Ni are pre-alloyed powders with a nominal alloying content of 3% Cr + 0.5% Mo and 1.5% Mo respectively. The nickel was added as INCO 123. Amide wax was used in all Premix powders as lubricant and a special high temperature lubricant in the case of Densmix powders.

Table 1.

Mix	Base powder	Mix type	C-UF (%)	Lubricant (%)	Ni addition (%)
1	Astaloy CrM	Premix	0.46	0.8	
2	Astaloy CrM	Densmix	0.46	0.6	
3	Astaloy CrM	Premix	0.40	0.8	
4	Astaloy Mo	Premix	0.60	0.8	2
5	Astaloy Mo	Densmix	0.60	0.6	2

Different pressing techniques were used to make specimens to density levels in a range of 7.0 – 7.7 g/cm³, namely conventional compaction (1P), warm compaction (WC), double compaction (DP) and double compaction with high velocity compaction in the second pressing step (HVC-DP). Densmix powders were used for warm compaction, whereas premixes were used for the other pressing techniques. Warm compaction was performed with a powder temperature of 130ºC (266°F) and a tool die temperature of 150ºC (302°F). The double compacted specimens were pre-sintered at a temperature of 800ºC (1472°F) for 20 minutes in synthetic DA atmosphere. In the case of HVC double compaction, the first compaction step was done in a conventional press.
Three types of specimens were used in the investigation; TS-bars (ISO 2740), IE-bars (ISO 5754) and FS-bars (ISO 3928).

Sintering was performed under two conditions:

- Sintering A: in a laboratory belt furnace at 1120ºC (2050°F) for 30 minutes in 90/10 N_2/H_2, cooling rate 0.8 – 1°C/s
- Sintering B: in a lifting hearth furnace at 1250ºC (2282°F), for 30 minutes in 90/10 N_2/H_2, cooling rate is lower than in sintering A, estimated to <0.5°C/s. After sintering B, specimens were tempered at 200°C (392°F).

Specimens made for high temperature sintering were compacted from mix 1 and 2 with higher graphite content. The reason for the higher addition is an expected decarburization for sintering B.

Tensile testing was made according to ISO 6892 and hardness was evaluated according to ISO 7498.

Fatigue tests were performed according to the four point bending method. The mechanical equipment was assisted by computer control of all test parameters. Plane bending fatigue testing with load ratio R=-1, i.e. fully reversed loading at 25-30 Hz was performed. The fatigue endurance limit was determined by the staircase method with 10 samples and 2 million cycles considered as run outs.

III. RESULTS AND DISCUSSION

Static properties

The mechanical properties for the two materials are presented in tables 2 and 3.

Table 2. Mechanical properties for Astaloy Mo + 2% Ni

Pressing technique	Sintering temperature	SD (g/cm³)	HV10	HRC	TS (MPa) (ksi)	YS (MPa) (ksi)	E (GPa) (10^6 Psi)	A (%)	IE (J) (Ft lb)	C (%)	O (%)
1P	1120ºC (2050ºF)	7.03	228	10	692 (100)	489 (71)	141 (20)	1.4	18 (13)	0.57	0.009
WC	1120ºC (2050ºF)	7.34	258	18	844 (122)	547 (79)	169 (25)	2.4	29 (21)	0.52	0.009
DP	1120ºC (2050ºF)	7.38	260	20	855 (124)	570 (83)	165 (24)	2.3	44 (32)	0.56	0.009
HVC-DP	1120ºC (2050ºF)	7.67	302	27	982 (142)	622 (90)	177 (26)	4.7	82 (60)	0.56	0.022
HVC-DP	1250ºC (2282ºF)	7.66	296	24	921 (134)	628 (91)	180 (26)	5.0	78 (57)	0.54	0.018

Some of the data for Astaloy Mo + 2% Ni are also presented in figures 1, 2, 3,4 and 5. The figures show the influence of the density and the sintering temperature on the tensile strength, hardness, impact energy and elongation.

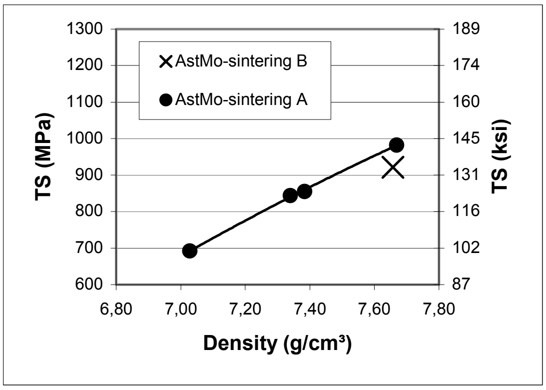


Figure 1. Influence of density on tensile strength

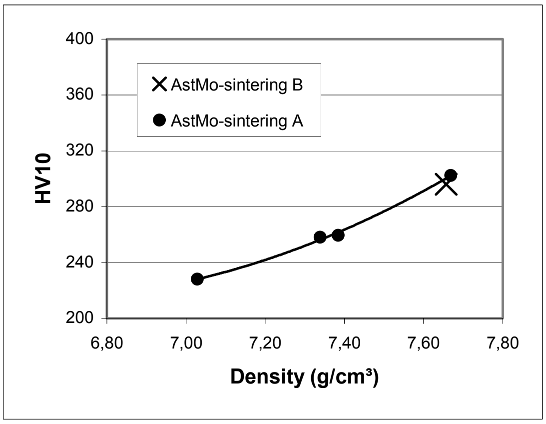


Figure 2. Influence of density on hardness (HV10)

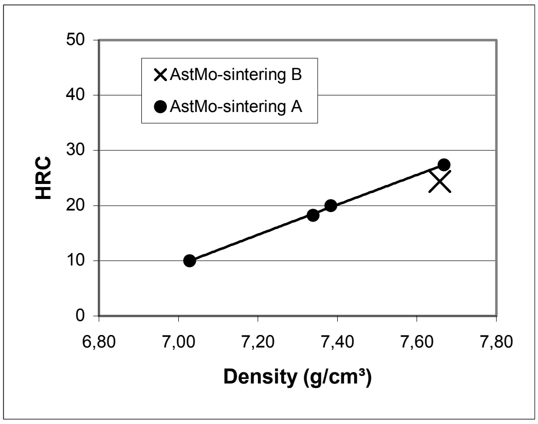


Figure 3. Influence of density on hardness (HRC)

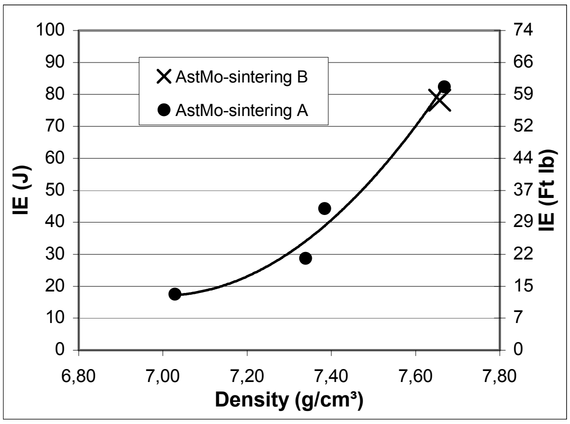


Figure 4. Influence of density on impact energy

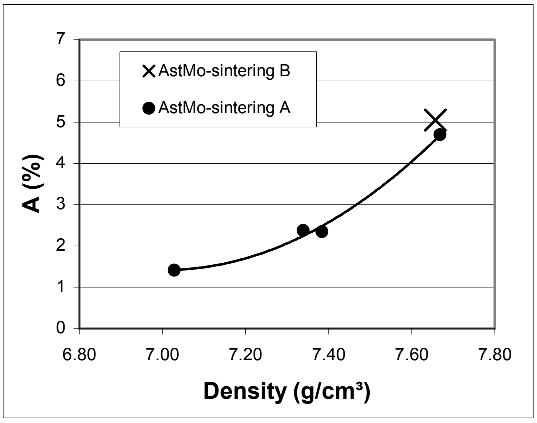


Figure 5. Influence of density on elongation

By increasing the density from 7.03 to 7.67 g/cm³, the mechanical properties of Astaloy Mo increase significantly. Tensile strength and hardness increase linearly with the density, independent of the pressing technique used for the compaction of the specimens. For impact energy and elongation the increase is even more pronounced. By increasing the density from 7.38 to 7.67 g/cm³, impact energy and elongation doubles.

Mechanical properties are not improved by an increase in sintering temperature from sintering A (1120°C/ 2050°F) to sintering B (1250°C/ 2282°F), for a density level of 7.67 g/cm³. Other density levels were not evaluated. This is due to lower cooling rate for the high temperature sintering compared to the sintering at 1120°C/2050°F. Elongation and impact energy do not increase with increased temperature.

Table 3. Mechanical properties for Astaloy CrM

Pressing technique	Sintering temperature	SD (g/cm³)	HV10	HRC	TS (MPa) (ksi)	YS (MPa) (ksi)	E (GPa) (10^6 Psi)	A (%)	IE (J) (Ft lb)	C (%)	O (%)
1P	1250ºC (2282ºF)	7.11	270	17	924 (134)	612 (89)	165 (24)	3.2	48 (35)	0.32	0.015
WC	1250ºC (2282ºF)	7.38	314	25	1022 (148)	702 (102)	182 (26)	3.9	55 (41)	0.34	0.072
DP	1120ºC (2050ºF)	7.39	297	28	1033 (150)	700 (102)	175 (25)	2.5	37. (27)	0.39	0.113
HVC-DP	1120ºC (2050ºF)	7.58	342	32	1151 (167)	793 (115)	187 (27)	2.0	45 (33)	0.38	0.164
HVC-DP	1250ºC (2282ºF)	7.58	375	33	1157 (168)	826 (120)	183 (26)	3.2	67 (49)	0.43	0.184

The influence of the density and sintering temperature on tensile strength, hardness, impact energy and elongation for Astaloy CrM is presented in figures 6, 7, 8, 9 and 10.

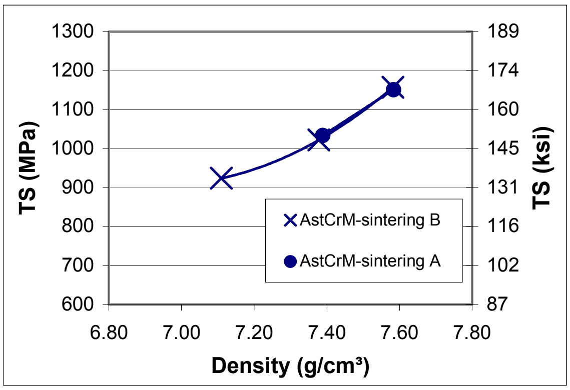


Figure 6. Influence of density on tensile strength

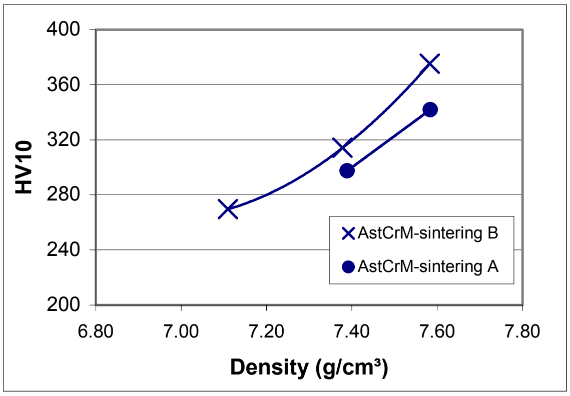


Figure 7. Influence of density on hardness (HV10)

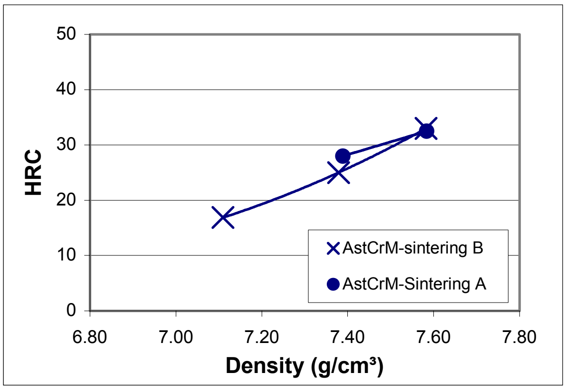


Figure 8. Influence of density on hardness (HRC)

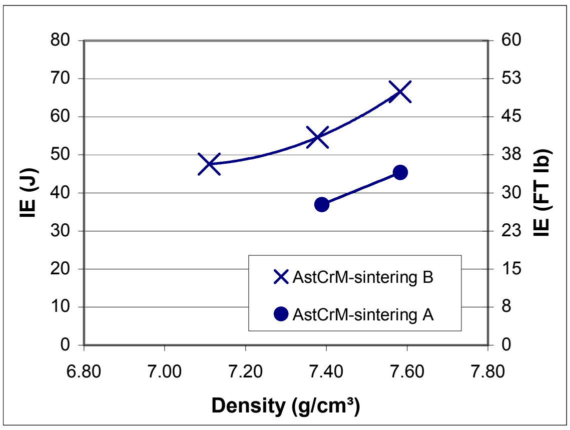


Figure 9. Influence of density on impact energy

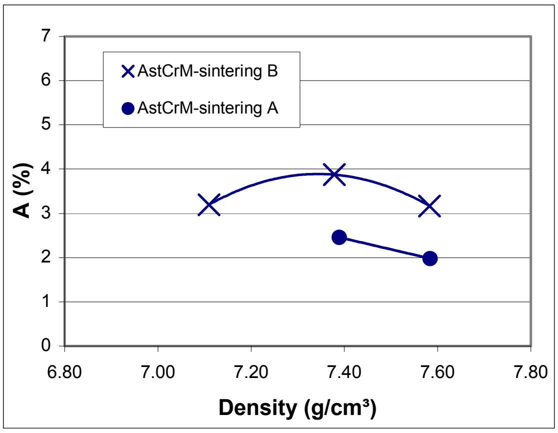
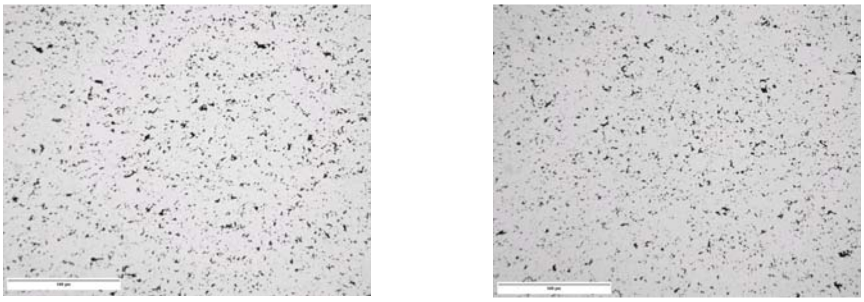


Figure 10. Influence of density on elongation

Tensile strength and hardness increase with density as for to Astaloy Mo + 2% Ni. The increase in impact energy and elongation is less significant compared to Astaloy Mo + 2% Ni. Elongation even drops somewhat at the highest density level. A possible explanation for this is the high oxygen content at the highest density level. The oxygen content increases with increased density. At high density levels an open pore system is not present for gas transport. This makes the reduction of oxides more difficult; it will also decrease the carbon loss during sintering. A similar effect is also seen for Astaloy Mo + 2%Ni, even though the absolute oxygen content is much lower. The sintering process was not optimized to reduce the oxygen content in the sintered material.

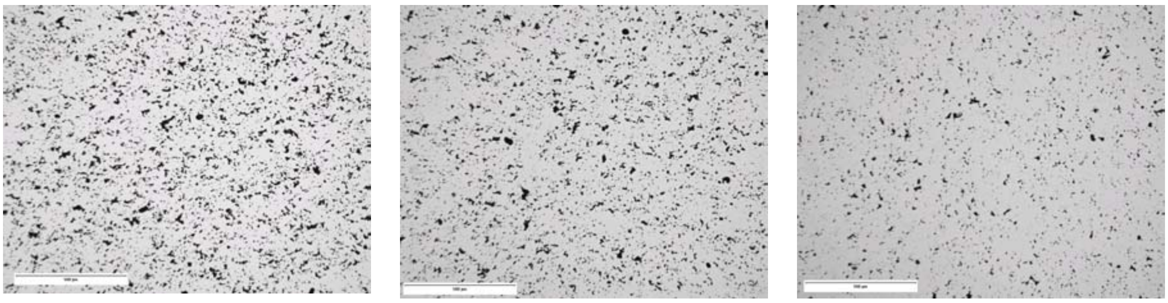
For Astaloy CrM, ductility (elongation and impact energy) is significantly improved by increasing sintering temperature. Tensile strength and HRC hardness are not improved by the increase in sintering temperature, due to the lower cooling rate for high temperature sintering. HV10 does increase somewhat with increased sintering temperature. The discrepancy between HRC values and HV10 values from the two sintering conditions can be explained by a slight surface decarburization of the specimens from sintering A and a slight surface carburization of the specimens from sintering B. A carburization/decarburization of the surface has a stronger influence on HV10 compared to HRC due to the lower load at HV10 measurement.

Figures 4 and 5 show pore structures for Astaloy CrM at different density levels and sintering temperatures.



(DP - 7.40 g/cm³)   (HVC-DP - 7.58 g/cm³)

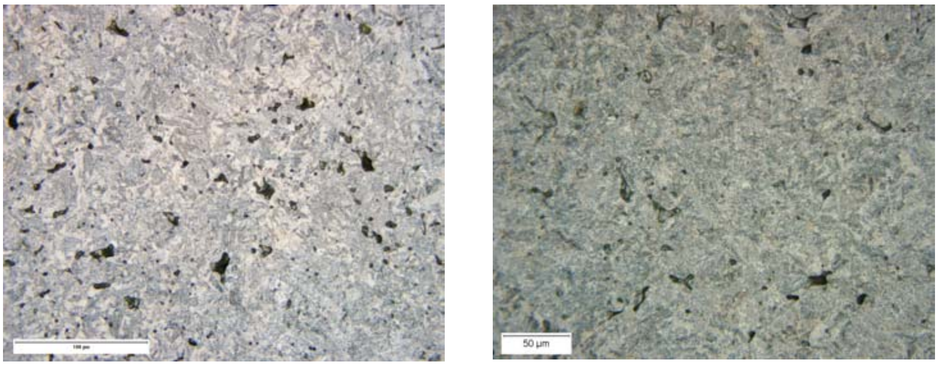
Figure 4. Pore structure for Astaloy CrM sintered at 1120ºC (sintering A), different densities



(1P - 7.10 g/cm³)   (WC - 7.38 g/cm³)   (HVC-DP - 7.58 g/cm³)

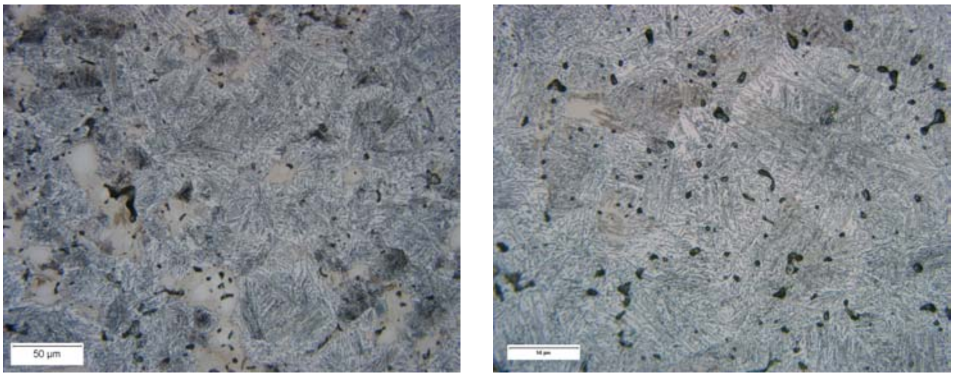
Figure 5. Pore structure for Astaloy CrM sintered at 1250ºC (sintering B), different densities

The benefit of higher temperature can be seen from rounder pores and better sintering necks. This is expected to improve ductility as can be seen from Astaloy CrM. For both materials, the lack of improvement in hardness and tensile strength with increased temperature is found in the microstructure (see Figure 6 and 7). Investigation of the microstructure reveals different amounts of martensite for samples sintered at 1120ºC /2050°F and 1250ºC/2282ºF. Microstructures are presented in figures 6 and 7.



(a) (b)

Figure 6. Microstructure for Astaloy CrM sintered at 1120ºC (a) and 1250ºC (b)



(c) (d)

Figure 7. Microstructure for Astaloy Mo sintered at 1120ºC (c) and 1250ºC (d)

All micrographs are from the center of the specimens. Structure close to the surface cannot be seen on these micrographs. The structure of Astaloy CrM consists of bainite and martensite, see table 4. Astaloy Mo + 2% Ni consists of bainite and martensite and when sintered at 1120°C /2050°F, some nickel-rich austenite areas.

Table 4

	Material	Pressing technique	Sintering Temp.	SD (g/cm³)	C (%)	Phase constituents
a	Astaloy CrM	HVC-DP	1120ºC	7.58	0.38	25-30% Martensite + 70-75% Bainite
b	Astaloy CrM	HVC-DP	1250ºC	7.58	0.43	1-2% Martensite + 98-99% Bainite
c	Astaloy Mo + 2% Ni	HVC-DP	1120ºC	7.67	0.56	20% Martensite + 75% Bainite + 5% Austenite
d	Astaloy Mo + 2% Ni	HVC-DP	1250ºC	7.66	0.54	5% Martensite + 95% Bainite

Microstructures show that the percentage martensite is lower for samples sintered at 1250ºC /2282°F than for those sintered at 1120ºC /2050°F. The difference in martensite content is due to different cooling rates in the two furnaces. Cooling rate in the belt furnace used for sintering A (1120°C /2050°F) was 0.8 – 1°C/s. The cooling rate in the lifting hearth furnace used for high temperature sintering was lower, from the microstructures estimated to be significantly lower. Differences in martensite amounts, due to cooling rate, explain the fact that properties such as tensile strength are not higher for the specimens sintered at 1250°C /2282°F than for those sintered at 1120°C /2050°F. For Astaloy Mo + 2% Ni, one effect of the increase in sintering temperature is elimination of the nickel-rich austenite areas. This is due to the better diffusion of nickel at the higher temperature.

Dynamic properties

Fatigue strength was tested for Astaloy Mo + 2% Ni at three density levels and Astaloy CrM at a density of 7.58 g/cm³. Results are presented in Figure 8 and in table 5.

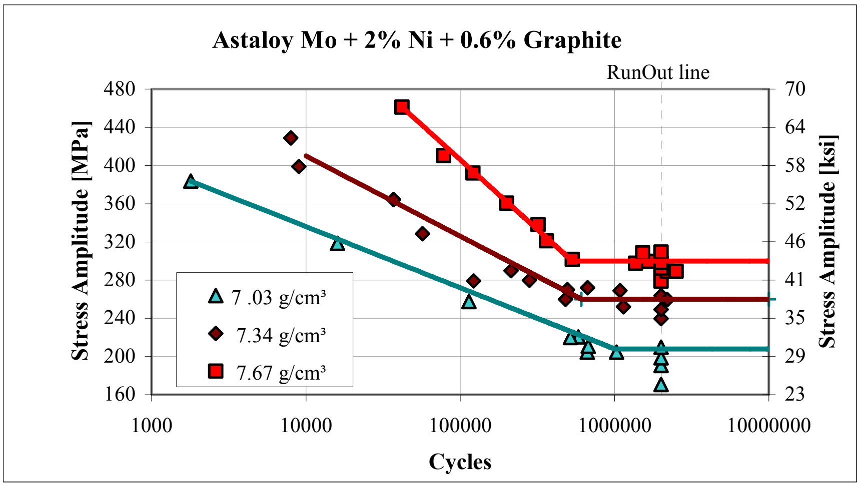


Figure 8. Bending fatigue test for Astaloy Mo + 2% Ni, Sintering A (1120ºC /2050°F)

In the case of Astaloy Mo, the fatigue limit increases from 208 MPa to 300 MPa when density increases from 7.03 to 7.67 g/cm³. These three series have the same microstructure; only a slight increase in austenite was found, from 2-3% at the lowest density to 5% at the highest density. With similar microstructure the increase in fatigue strength is mainly due to the increase in density.

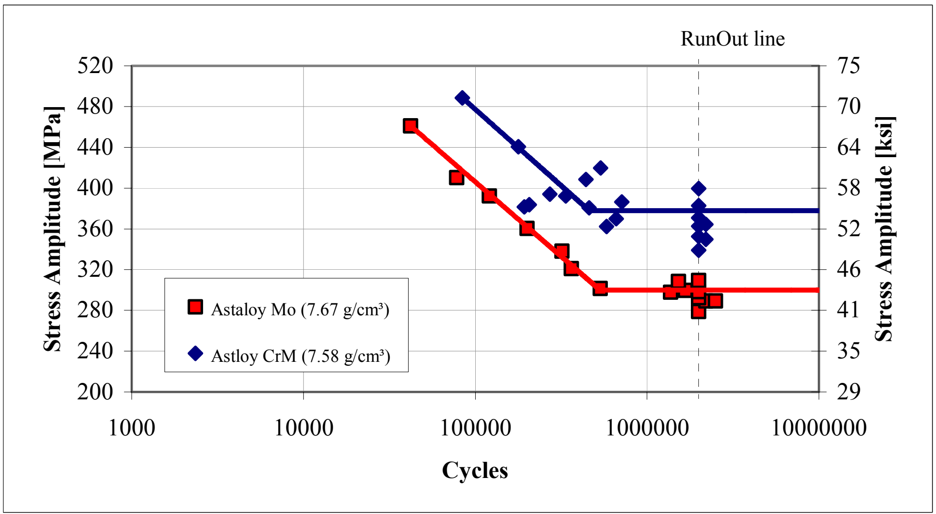


Figure 9. Bending fatigue test for Astaloy Mo + 2% Ni sintering A (1120°C/2050°F) and Astaloy CrM , Sintering B (1250ºC /2282°F)

Astaloy CrM has a fatigue limit of 378 MPa. This is achieved at a density of 7.58 g/cm³ and with an almost fully bainitic microstructure. Fatigue strength is much higher for Astaloy CrM compared to Astaloy Mo + 2% Ni even though the density is 0.09 g/cm³ lower. One difference is that Astaloy CrM is high temperature sintered, resulting in better sintering necks and pore rounding. High oxygen content is expected to reduce fatigue strength. With further optimization of the sintering process to have lower oxygen content, Astaloy CrM would have the potential to further improve fatigue strength.

Table 5. Fatigue Limit

Material	Pressing technique	Sintering temperature	Density (g/cm^3)	Fatigue Limit (MPa)
Astaloy Mo + 2% Ni	1P	1120ºC (2050ºF)	7.03	208
Astaloy Mo + 2% Ni	WC	1120ºC (2050ºF)	7.34	260
Astaloy Mo + 2% Ni	HVC - DP	1120ºC (2050ºF)	7.67	300
Astaloy CrM	HVC - DP	1250ºC (2282ºF)	7.58	378

IV. CONCLUSIONS

Very high mechanical properties are achieved by increasing the density to levels up to 7.6 g/cm^3. Tensile strength and hardness increase linearly with density whereas ductility increases exponentially.

The type of pressing technique used does not influence the properties.

By increasing density from 7.03 g/cm^3 to 7.67 g/cm^3, fatigue strength is improved by 50% for Astaloy Mo + 2% Ni.

Astaloy CrM compacted with HVC to a density of 7.58 g/cm^3 reaches after sintering at 1250ºC /2282°F a very high fatigue strength of 378 MPa.

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