Influence of Notches on Fatigue Strength of High Performance PM Materials

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ABSTRACT

The ability of PM to achieve high mechanical properties opens up many possibilities to further extend the use of PM. As fatigue properties are becoming more and more important in the applications of PM parts the demand for high performance materials and data characterising these materials is continuously increasing.

In this paper fatigue life curves of some high performance PM materials are compared at two different notch factors in as-sintered condition. The results are interpreted on the basis of microstructural features, porosity and extend notches. The paper presents statistically based design data about the different materials under different stress concentrations and loading modes.

INTRODUCTION

The development of new steel powders and processes during the last decades has led to a considerably expansion of the applications for PM. In order to further extend the applications for PM there is a demand for alloy systems as well as processes which result in improved mechanical properties in general and dynamic properties in particular with maintained precision of tolerance control at reduced costs. As fatigue properties are becoming more and more important in the applications of PM parts the demand for high performance materials and data characterising these materials is continuously increasing

Due to the fact that most components have local stress concentrations, the fatigue behaviour in the unnotched state is not sufficient for a reliable design. In this paperthe fatigue behaviour of two high performance PM materials are compared at two different densities and notch factors in as-sintered state. The paper presents statistically based design data about the two materials at different stress concentrations.

POWDERS AND PROCESSING CONDITIONS

The powders and processing conditions used are showed in table 1 below. Green and sintered properties were analysed according to standardised test methods.

Table 1. Powders and processing conditions used to prepare test specimens.

Powder	D.HP-1	Astaloy CrM
Carbon content, %	0.7	0,4
Pressing mode	Cold, Warm	Cold, Warm
Compacting pressure, MPa Compacting pressure, tsi	700 50	700 50
Sintering conditions Temperature, ºC / ºF Time, min Atmosphere	 1120 / 2050 30 90/10 N_2/H_2	 1120 / 2050 30 90/10 N_2/H_2

D.HP-1 is based on a 1,5% Mo pre-alloyed powder (Astaloy Mo) and diffusion bonded with 4% Ni, 2 % Cu. Astaloy CrM is a fully pre-alloyed powder containing 3% Cr and 0,5% Mo. The powders that were warm compacted were prepared as Densmix™ powders (1). Densmix™ is the trade name for powder mixes for warm compaction offered by Höganäs AB, Sweden.

In table 2 a comparison of the green densities obtained for the two powders is shown after conventional compaction at room temperature and warm compaction using a compaction pressure of 700 MPa (50tsi). It can be seen that the D.HP-1 based mixes achieved about 0,15 g/cm^3 higher density than the Astaloy CrM based mixes both by conventional compaction and by warm compaction. This is due to the lower compressibility of the Astaloy CrM base powder due to its higher pre-alloyed alloying content.

Table 2. Green and sintered density of different powders after compaction at room temperature and 150ºC.

Powder	D. HP-1		Astaloy CrM	
Carbon content, %	0.7		0,4	
Comp. pressure, MPa Comp. pressure, tsi	700 50		700 50	
Pressing mode	Cold	Warm	Cold	Warm
Green density, g/cm^3	7,15	7,28	6,99	7,15
Sintered density,g/cm^3	7,15	7,29	7,00	7,15

The densities obtained after sintering are consistent with the green density results shown previously. The densities obtained by warm compaction are 0,15 g/cm^3 higher than those obtained by conventional compaction. As the dimensional change during sintering is close to zero for both materials the difference between green and sintered densities is very small.

MECHANICAL PROPERTIES

The mechanical properties obtained for the two materials are shown in table 3. Regarding tensile strength it can be seen that it is about 15 % higher for the warm compacted D.HP-1 material and 8 % for the Astaloy CrM compared to the conventionally pressed materials. The highest tensile strength was obtained with D.HP-1 material at the highest density level of 7,29 g/cm^3. At this density a tensile strength of 980 MPa / 1400 ksi was obtained. By comparing tensile strength of the two materials at the same density, 7,15 g/cm3, it can be seen that the D. HP-1 material and the Astaloy CrM material have about the same tensile strength level, 850 MPa / 120 ksi.

Regarding yield strength it can be seen that the two Astaloy CrM materials achieved higher strength levels than the D.HP-1 based materials despite their lower densities. This is due to the higher content of pre-alloyed alloying elements Cr / Mo of this base powder.

Table 3. Mechanical properties of different PM materials after compaction at room temperature and 150ºC followed by sintering at 1120ºC 30 min

Material	D. HP-1		Astaloy CrM	
Carbon content, %	0.7		0,45	
Comp. pressure, MPa Comp. pressure, tsi	700 50		700 50	
Compaction mode	Cold	Warm	Cold	Warm
Sintered density,g/cm^3	7,15	7,29	7,00	7,15
Tensile strength, MPa / ksi	855 / 122	980 / 140	779 / 111	840 / 120
Yield strength, MPa / ksi	504 / 72	558 / 80	583 / 83	610 / 87
Elongation, %	1,0	1,1	0,8	1,0
Hardness, HV10	325	344	257	265

Regarding elongation it can be seen that the materials based on the warm compacted Densmix^{TM} powders achieved slightly higher elongation due to the increased density. At the same density they have the same elongation.

The macro hardness HV10 obtained with the different materials show that very high hardness levels are obtained with D. HP-1 already after sintering due to high level of carbon content in the material.

FATIGUE TESTING

Fatigue test specimens

For the fatigue tests 25 unnotched and notched specimens were pressed and sintered of the two materials at both density levels. The specimen shapes are shown in fig1 and 2 below.

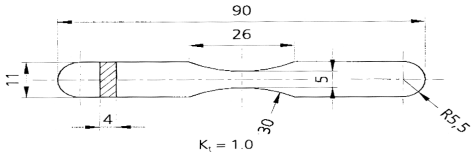


Fig.1 Shape of an notched test specimen
Stress concentration factor Kt= 1,0

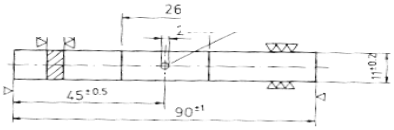


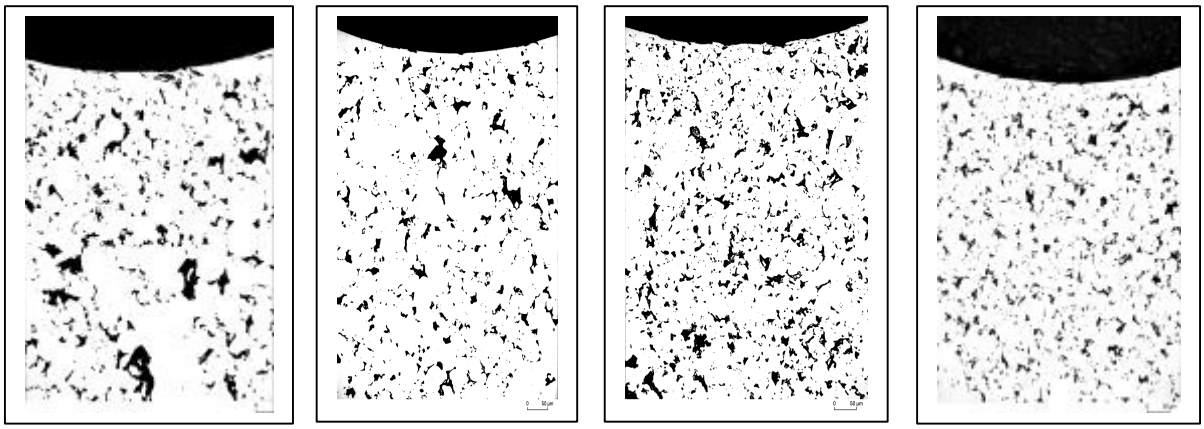
Fig.2 Shape of notched test specimen
Stress concentration factor Kt= 2,8

For the notched specimens the a hole with a diameter of 2 mm was drilled into the sintered specimens using the procedure below to avoid a densification or damage around the :hole.

- solid carbide drill, diameter 2 mm, Type: A1263*2 VHM,
- Manufacturer: Titex Plus,
- Speed: 12.56 m/min,
- Feed: manually by hand,
- lubricated with conventional cutting oil.

With one tool 4 holes could be drilled into the material D. HP-1 and about 10 holes into the material Astaloy CrM. For all specimens the burrs were removed by producing a defined radius of about max. 0.5 mm.

The porosity level as well as the quality of surface of the bore hole is shown on Fig. 3A-D below. As can be seen both the cold compacted D. HP-1 and the warm compacted Astaloy CrM obtained a slight densification of the surface due to the drilling procedure.



A: D.HP-1, Cold B: D.HP-1, Warm C: Astaloy CrM, Cold D: Astaloy CrM, Warm

Fig. 3A-D. Porosity level and quality of surface of the bore hole after machining for cold and warmcompacted D.HP-1 and Astaloy CrM.

Fatigue test procedure

The fatigue tests were performed under constant amplitude axial loading with a load ratio of $R_F = -1$. The testing frequency amounts between 25 and 60 s^{-1}. The maximum number of cycles was fixed to $5*10^6$. After reaching this limit without failure the particular test was stopped and the specimen was retested on a higher stress level.

For each Wöhler-curve minimum 15 specimens were tested on different stress levels in order to determine the slope as well as the endurable nominal stress amplitude at $N = 2 \cdot 10^6$ cycles.

Fatigue testing results

The fatigue testing results obtained are plotted in double logarithmic diagrams. The slope of the Wöhler-curve was determined using the linear regression for a probability of survival of $P_s = 50\%$. For all materials the knee-point was fixed to $2 \cdot 10^6$ cycles and a uniform scatter of the endurable stress amplitde between $P_s = 10$ and 90% with $T_\sigma = 1 : 1.25$ for more than $2 \cdot 10^6$ cycles respectively $T_\sigma = 1 : 1.15$ for 10^5 cycles was assumed.

The S-N curves obtained for the cold and warm compacted D. HP-1 are shown in fig 4 and 5 respectivly and for Astaloy CrM in fig. 6 and 7.

As can be seen from fig 4 the endurance limit obtained for D. HP-1 in unnotched condition at a density of 7,15 g/cm^3 is 255 MPa / 36 ksi. In notched condition the endurance limit dropped

to 148 MPa / 21 ksi which is equivalent to a decrease of about 40 %. This corresponds to a fatigue notch factor of 1.72.

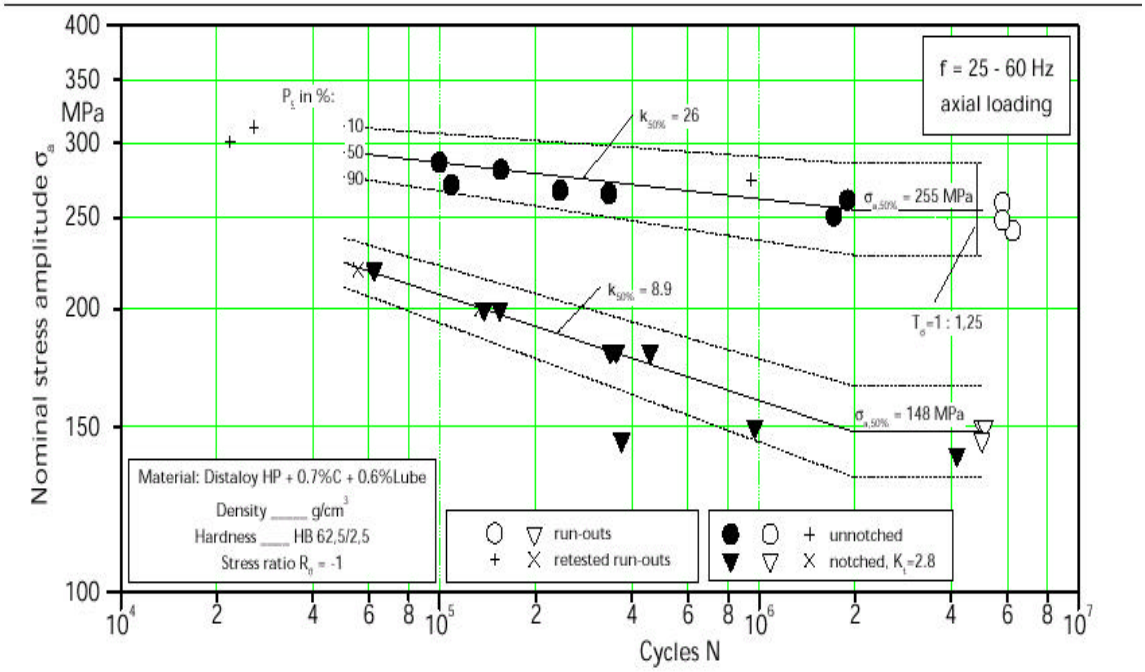


Fig 4. S-N curves for D.HP-1 at density 7,15 g/cm^3

By increasing the density level to 7,29 g/cm^3 of this material by utilizing warm compaction the endurance limit increased to 270 MPa / 39 ksi for the unnotched condition , see fig 5, whereas in notched condition the endurance limit is155 MPa / 22 ksi or 42 % lower. The fatigue notch factor of 1.74 is nearly identical to the cold compacted material.

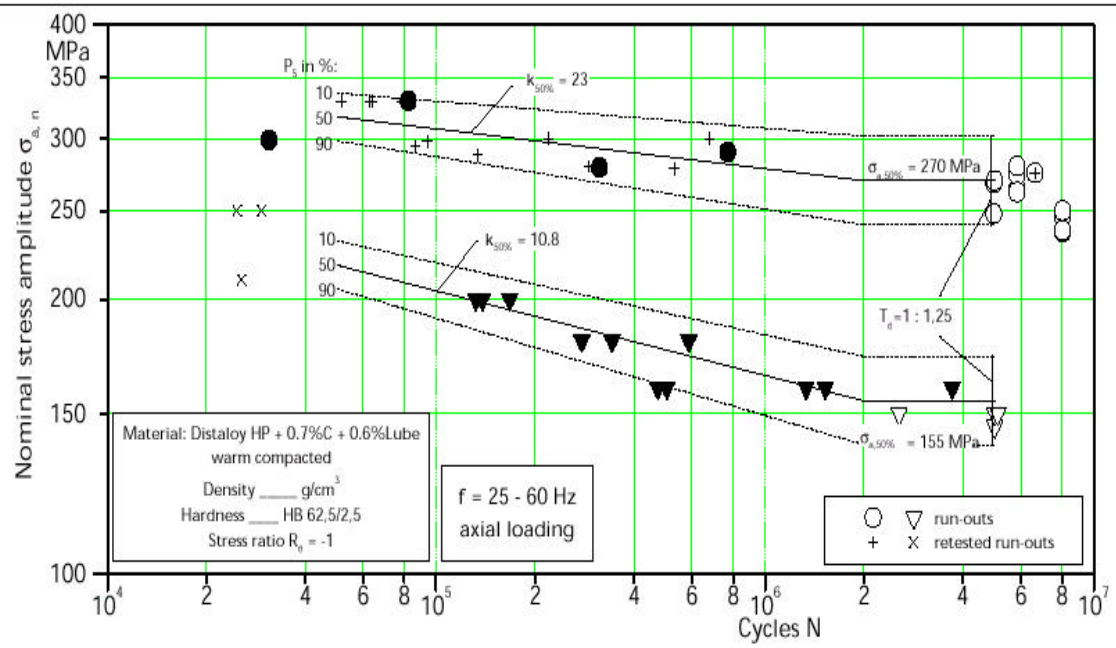


Fig 5. S-N curves for D. HP-1 at density 7,29 g/cm^3

From the S-N curves in fig 6 it can be seen that the endurance limit obtained for the Astaloy CrM material in unnotched condition at a density of 7,00 g/cm^3 is 207 MPa / 30 ksi. In

notched condition the endurance limit dropped to 123 MPa / 18 ksi. With a fatigue notch factor of 1.68.

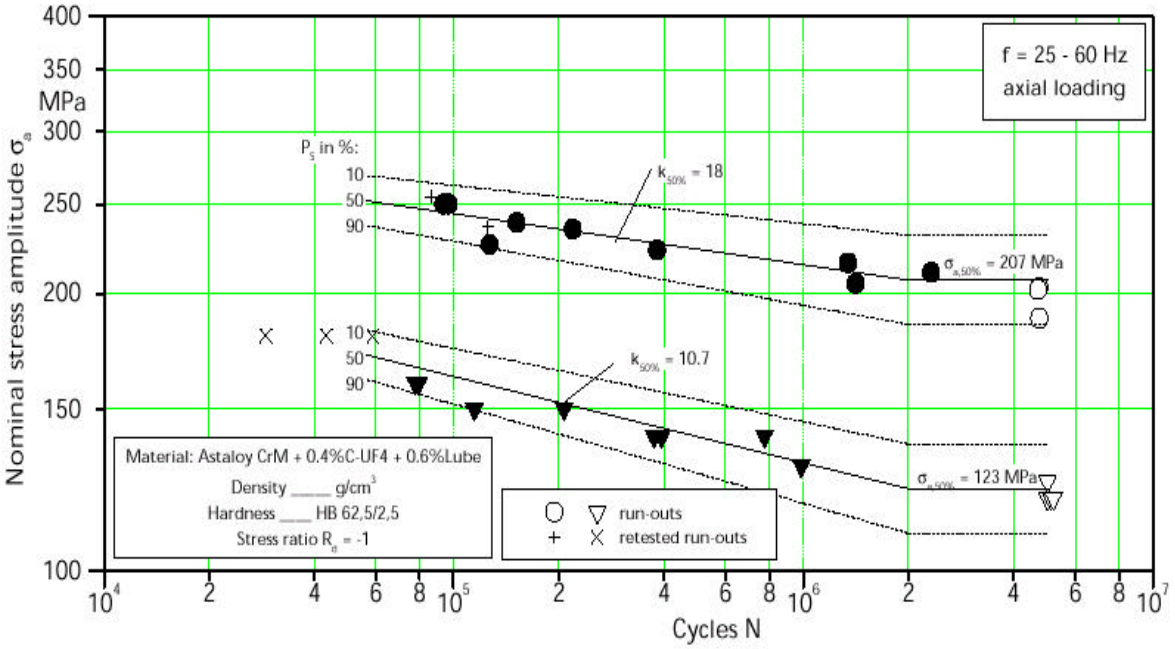


Fig. 6. S-N curves for Astaloy CrM at density 7,00 g/cm^3

By increasing the density level to 7,15 g/cm^3 of the Astaloy CrM material by utilizing warm compaction the endurance limit increased to 230 MPa / 33 ksi for the specimens tested in unnotched condition , see fig 7. In notched condition the endurance limit decreased to 135 MPa / 19 ksi which corresponds to a fatigue notch factor of 1.70.

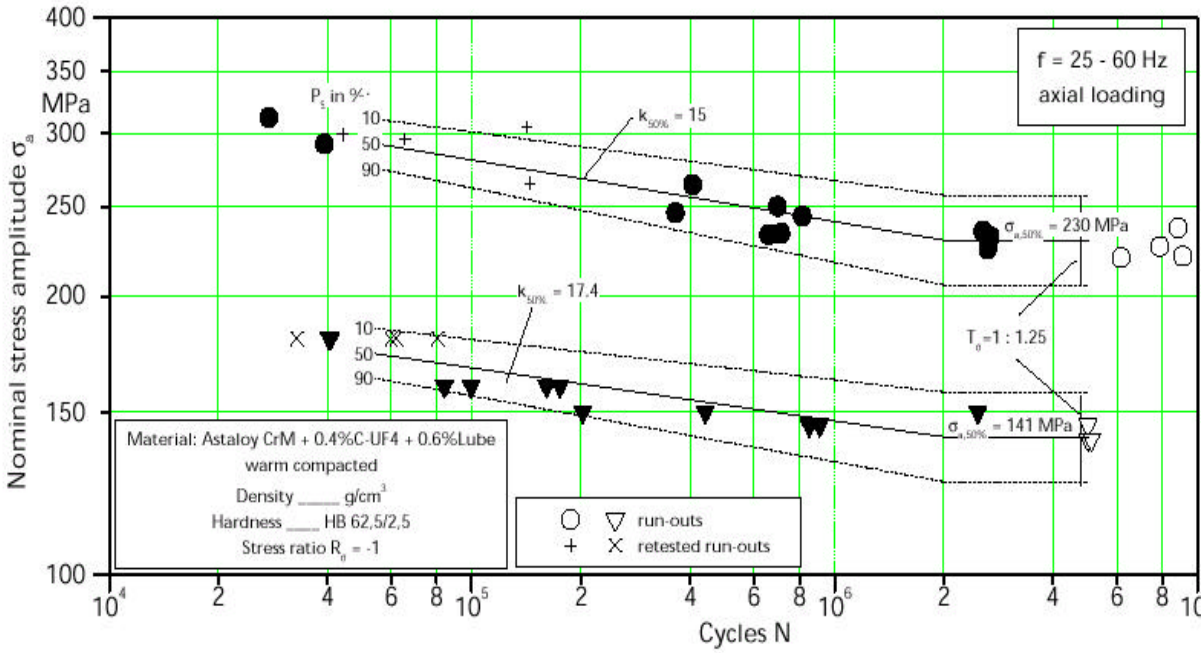


Fig 7. S-N curves for Astaloy CrM at density 7,15 g/cm^3

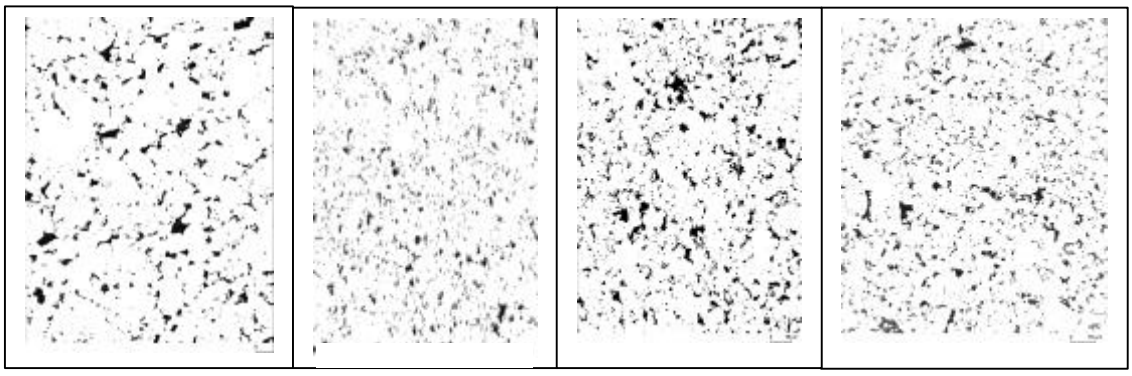
All relevant fatigue data obtained within this investigation is summarized in table 4.

Table 4. Fatigue testing results obtained with D. HP-1 and Astaloy CrM after compaction at room temperature and 130ºC followed by sintering at 1120ºC 30 min.

Material	Density g/cm^3	Stress concentration factor K_t	Endurance limit $\sigma_{a,\ 50\%}$, MPa / ksi	Fatigue notch factor K_f
D. HP-1 0,7%C	7,15	1.0	255 / 36	1.72
		2.8	148 / 21	
	7,29	1.0	270 / 39	1.74
		2.8	155 / 22	
Astaloy CrM 0.4%C	7,00	1.0	207 / 30	1.68
		2.8	123 / 18	
	7,15	1.0	230 / 33	1.70
		2.8	135 / 19	

The endurance limit for the warm compacted Distaloy HP is about 5% higher than for the cold compaction whereas for the Astaloy CrM the increase of the endurable stress amplitude for the warm compacted specimens results in about 10% in comparison to the cold compacted specimens. All these improvements in fatigue strength are related to the increase in density obtained by warm compaction. The notch sensitivity of the Astaloy CrM material is slightly lower than the D. HP-1 material. This might be due to the higher yield strength.

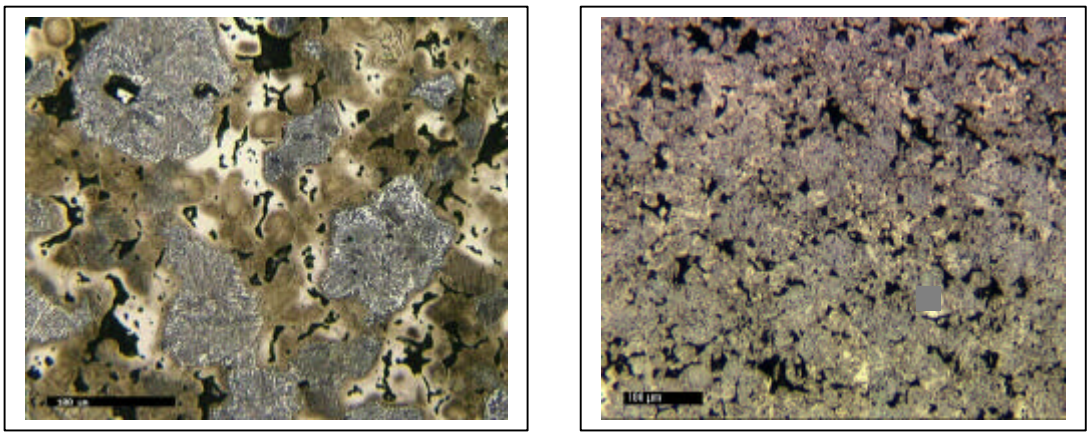
One advantage that has been found with warm compaction is the finer pore size which results in slightly improved fatigue properties in combination with a decreased scatter compared to conventionally compacted materials (2). In fig 8 A-D below a comparison of the porosity obtained in the two different materials at the different density levels obtained is shown. As can be seen both the overall porosity is decreased at the higher density level but also the size of the pores have become smaller in the warm compacted materials.



A: D.HP-1 Cold | B: D.HP-1 Warm | C: Astaloy CrM Cold | D: Astaloy CrM Warm

Fig. 8A-D. Porosity in cold and warm compacted D.HP-1 and Astaloy CrM.

By comparing the fatigue testing results obtained for the two materials in unnotched condition at the same density, 7,15 g/cm^3 it can be seen that there is a difference of about 10%. The D. HP-1 material obtained an endurance limit of 255 MPa / 36 ksi compared to 230 MPa / 33 ksi for the Astaloy CrM material. As the density of the two materials is equivavlent and the porosity within the materials are comparable this difference is explained by the difference in microstructure. The microstructures obtained for the two materials are shown in fig 9A and B below. As can be seen the D.HP-1 material has achieved a heteogeneous microstructure consisting of pearlite, bainite, nickelrich austenite and martensite whereas te Astaloy CrM material obtained a more homogeneous microstructure consisting of mainly bainite with some martensite. Earlier investigations, (3-5), have shown that at density levels in the range of 7,00-7,30 g/cm^3 it is favorable for fatigue properties to have heterogenous microstructure of the kind obtained with D.HP-1.



A: D.HP-1 B: Astaloy CrM

Fig. 9A-B. Microstructures obtained for D.HP-1/ 0,7%C and Astaloy CrM / 0,4%C

Notch sensitivity index

The notch sensitivity index, q, was calculated for the four different material combinations tested. The results are shown in table 5. As can be seen the notch sensitivity index is similar for both materials and between 0,35 and 0,41 which is comparable to wrought steels.

Table 5. Calculated notch sensitivity index for D. HP-1 and Astaloy CrM

Material	D. HP-1		Astaloy CrM	
Density, g/cm^3	7,15	7,29	7,00	7,15
Notch sensitivity index, q $q = \frac{Kf-1}{K-1}$	0,40	0,41	0,37	0,39

CONCLUSIONS

Axial fatigue tests of 2 high performance PM materials, D. HP-1 and Astaloy CrM, at 2 different density levels in unnotched and notched conditions show that:

- the endurance limit for these materials is depending on both density and microstructure

- the highest endurance limit, 270 MPa/39 ksi, is obtained with D. HP-1 / 0,7%C at density 7,29 g/cm^3

- at density 7,15 g/cm^3 the heterogeneous microstructure achieved in D. HP-1 resulted in 10% higher endurnce limit, 255 MPa /36 ksi vs 230MPa/ 33ksi for the homogeneous microstructure obtained in Astaloy CrM.

- the endurance limits for the D.HP-1 and Astaloy CrM in notched condition at density 7,15 g/cm^3 are comparable

- the notch sensitivity index is similar for both materials 0,39 and 0,41. It is slighly higher for the Astaloy CrM material probably due to its higher yield strength

- tensile strength of D. HP-1/ 0,7%C and Astaloy CrM/0,4%C is comparable at density 7,15 g/cm^3

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