PM STEEL FOR HIGH LOADED APPLICATIONS

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ABSTRACT

Diesel engine components conventionally made of wrought steel are identified as candidates to be replaced by high performance PM steel. An investigation is made on notch sensitivity and bending fatigue performance of as sintered Chromium/Molybdenum pre-alloyed Astaloy CrL and sintered-hardened Astaloy CrM. Best bending fatigue performance, 437 MPa at load ratio R=-1, is found for 1120 °C (2050F) sintered-hardened Astaloy CrM+0.4% graphite with addition of methane to the sintering atmosphere. Astaloy CrL+0.85% graphite sintered at 1250°C (2280F) with regular cooling 0.8%C/sec have a fatigue limit of 296 MPa. Lowest notch sensitivity index in this investigation is found for Astaloy CrM+0.4% graphite followed by Astaloy CrL+0.85% graphite sintered at 1120 °C (2050F) and 1250°C(2280F) respectively.

INTRODUCTION

Increased mechanical performance of PM steels accelerates the process to replace components made of wrought steel with PM steel components. However, there is an ongoing competition from the wrought steel industry to recapture what earlier has been replaced by PM. For example the yoke for injector in a Volvo Diesel engine has been exchanged from wrought steel to PM, then back to wrought steel and now to PM again. Higher fatigue performance of PM steel is an important characteristic in the process to defend and conquer components. Higher mechanical performance opens the possibility to reduce component weight. This is a critical and very important characteristic for many automotive components. High mechanical performance in combination with the obvious advantages minimum of material waste and near net-shape directly after pressing and sintering underline that PM shall be considered for new components conventionally manufactured in wrought steel in the future design process in the automotive industry.

Candidates for future PM components are for example rocker arms for diesel engines. Rocker arms are used for exhaust valves, injectors and inlet valves. Rocker arm for the inlet valve has the lowest demand of

these components and therefore has the highest potential to be converted see figure 1. Conversion to PM includes a design challenge to utilize the near net shape quality of PM steel. Rocker arms in wrought steel are subjected to extensive machining.



Figure 1. Inlet valve rocker arm for diesel engine presently made in wrought steel. The weight of the component is approximately 0.5 kg.

The present investigation is focused on two Chromium-Molybdenum pre-alloyed PM steels, Astaloy CrL and Astaloy CrM. The Cr/Mo pre-alloyed materials have been developed to find low cost alternatives to high fatigue performance nickel-containing PM steels. Bending performance of these materials has shown to meet demand for high loaded parts [1].

PM material include in it microstructure pores. These pores at the surface of the component will act as notches. Modern design tools include FEM calculation of stresses and the material database must therefore in addition to the performance of un-notched material also include detailed information about the notch sensitivity for materials that are considered. To take the influence of surface pores into account in the FEM calculation it is important to have access to systematic information of notch sensitivity of PM steel. Today there is information about notch sensitivity for a given radius of 3 mm [3]. This article is a continuation of the study on warm compacted Astaloy CrL with 0.85% graphite [1,2]. Notch sensitivity at a radius of 0.9 and 0.24 mm is evaluated in this investigation.

EXPERIMENTS

Material

Two Cr – Mo pre-alloyed base powders are included in this investigation. Materials A and B are based on pre-alloyed powder with 1.5% Cr and 0.2% Mo, Astaloy CrL. Material C is based on pre-alloyed powder with 3% Cr and 0.5% Mo, Astaloy CrM. Addition of graphite (C-UF4 from Kropfmühl) is shown in Table 1. Material A and B are warm compacted at a temperature of 120 ^{o}C with a compaction pressure of 800MPa to a green density of 7.19 g/cm3. Material C is cold-compacted to a green density of 7.1 g/cm3. Sintered carbon and densities are shown in Table 1.

Sintering is made in 90/10 N_2/H_2. Conventional cooling rate about 0.8C/sec was used for Material A. Material C was sinter-hardened with cooling rate about 2°C/sec and 0.2% methane was added to the sintering atmosphere.

Table 1. Base powders, graphite addition and sintered densities of FS and notched bars.

No.	Base powder	C-UF4 [%]	Lubricant	Sint.temp. [C] (F)	Cooling Rate (°C/s	Sintered carbon [%]	Sint.density [g/cm3]
A	Astaloy CrL	0.85	Densmix 0.6%	1120 (2050)	0.8		7.18
B				1250 (2280)	0.8		7.25
C	Astaloy CrM	0.4	Licowax 0.8%	1120 (2050)	2	0.40	7.12

Fatigue tests

Fatigue tests are made in plane four bending, displacement control with load ratio R=-1 and test frequency 25-30Hz. Tests are terminated when the compliance has raised 2.5 %. The staircase method with 8 - 12 samples in each series and run-out limit 2 million cycles is used to find 50% fatigue endurance limits. The tests are evaluated according to MPIF standard 56.

Specimens

Un-notched fatigue test bars and notched bars with 0.9 and 0.25 mm notch radii are included in the investigation see Figure 2.

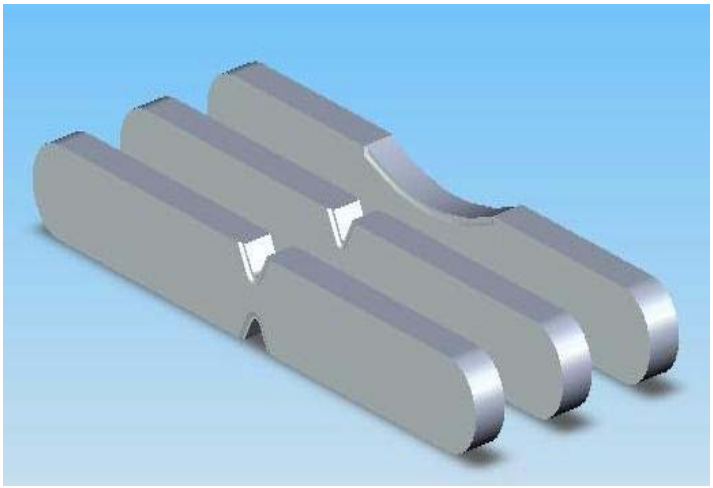


Figure 2. Un-notched to the right and two notched test bars with notch radii 0.9 and 0.25 mm respectively used in the investigation. All three types have chamfered edges in the minimum cross-section.

The first two test bars are included in the ISO standard 3928. The 0.25mm radius geometry is smaller than what is given in the same ISO standard. The smaller radius is chosen to cover the design of many components today produced in PM steel. All three tests bars have chamfered edges [3]. The specimens are tested with maximum bending stress in the die surfaces. The stress concentration factors are 1.79 and 2.81 for 0.9 and 0.25 mm notch radii respectively [5].

Notch sensitivity index

Results from fatigue tests on un-notched and notched test bars are evaluated and characterized by the notch sensitivity index, q. It is defined from the theoretical stress concentration factor (K_t) and the fatigue ratio (K_f). The stress concentration factor is obtained from theoretical calculations of the stress concentration assuming a linear elastic material. The fatigue ratio is obtained directly from the fatigue performance tests according to $K_f=\sigma_0 /\sigma_N$, where σ_0 is the fatigue limit for un-notched and σ_N of notched test bars. Notch sensitivity index is calculated according to $q=(K_f-1)/(K_t-1)$.

RESULTS

Fatigue performance

The nominal fatigue limits together with standard deviations within brackets are listed in Table 2. At 1120°C sintering temperature a bending fatigue performance of 254 MPa with a standard deviation of 13,4 is reach for material A. When sintering at 1120°C with rapid cooling a fatigue performance of 437MPa with a standard deviation of 14.2MPa is reached for material C. Increased sintering temperature to 2280°C increases the fatigue performance to 296 MPa with a standard deviation of 20.8 MPa for material B

Notch radius 0.9mm,
At a sintering temperature of 1120°C material C has a notch sensitivity of 0.53 compared to 0.62 for material A. Increased sintering temperature increases the notch sensitivity to 0.71, material B

Notch radius 0.25mm,
At a sintering temperature of 1120°C material C has a notch sensitivity of 0.48 compared to 0.60 for material A. Increased sintering temperature increases the notch sensitivity to 0.85, material B

Highest notch sensitivity is found for Material B followed by Material A. Lowest notch sensitivity is found for Material C.

Table 2. As sintered materials A and B and sinter-hardened material M. Results from the fatigue tests and calculated notch sensitivity index q. SD: standard deviations are given in brackets.

Material	σ_0 (SD) [MPa]	$\sigma_{N0.9}$ (SD) [MPa]	$Kf_{N0.9}$ [$\sigma_0/\sigma_{N0.9}$]	$q_{N0.9}$	$\sigma_{N0.25}$ (SD) [MPa]	$Kf_{N0.25}$ [$\sigma_0/\sigma_{N0.25}$]	$q_{N0.25}$
A	254 (13,4)	171 (<4)	1.49	0.62	121 (<3)	2,09	0.60
B	296 (20,8)	190 (<5)	1.56	0.71	117 (<4)	2.53	0.85
C	437 (14,2)	307 (20,3)	1.42	0.53	234 (6,9)	1,88	0.48

Microstructures

Astaloy CrL with 0.85% graphite has a mixed microstructure of upper bainite and pearlite. The pearlite includes areas with very fine pearlite and areas with coarse pearlite.

The microstructure of the sinter-hardened Astaloy CrM reveals a gradient with almost 100% martensite in the surface and a mixture of 5 – 15% lower bainite and martensite in the core.

SUMMARY
The fatigue performance and notch sensitivity have been determined for Astaloy CrL+0.85%graphite sintered at 1120°C (2050F) and 1250°C (2280F) and for Astaloy CrM+0.4%graphite sintered at 1120°C (2050F) in 90/10 N2/H2 with addition of 0.2% methane to the sintering atmosphere and rapid cooling. Un-notched and notched test bars with notch radii 0.9 and 0.25mm are included in the investigation. The fatigue performance with scatter bands ± one standard deviation are shown in figure 3 below.

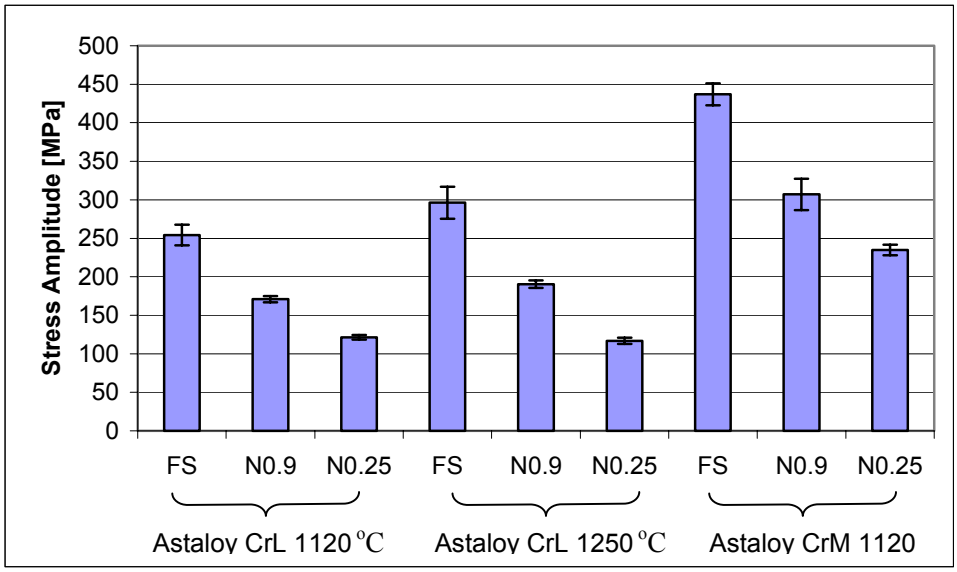


Figure 3. Fatigue performance of Astaloy CrL and Astaloy CrM including scatter bars showing ± one standard deviation.

DISCUSSION
PM steel as an alternative for high loaded components is a question of high fatigue performance and, depending on the component, also high surface hardness. High performance already in the as sintered condition without need of secondary operation to improve the performance is a strong economic argument. The strongest material in this investigation, material C, is sintered at 1120 °C (2050F) in 90/10 N_2/H_2 with addition of methane in the sintering atmosphere followed by rapid cooling. The amount of graphite added (0.2%) to the base powder is relatively low. The microstructure gradient with almost 100% martensite in the surface and about 15 – 25% lower bainite and the rest martensite in the core is obtained from a combination of a small carburizing effect and rapid cooling that is most effective in the surface. The bending fatigue limit 437MPa of the un-notched fatigue test bars is very high for a regularly processed material with martensitic microstructure at the density 7.1 g/cm^3 without any secondary operation.

A low notch sensitivity index (q) will allow the designer more freedom in the design of the components whereas high notch sensitivity will severely impede the possibility of a successful design. Lowest notch sensitivity in this investigation is found for Astaloy CrM. It must, however, be considered that the low notch sensitivity index at least partly is explained by the microstructure gradient with possible compressive residual stresses in the surface. The given values for notch sensitivity of Astaloy CrM can therefore not be taken directly as a material characteristic. The results clearly show that the combination of sinter hardening and a slight carburizing in the sintering furnace followed by rapid cooling has a large impact on the fatigue properties.

The fatigue limit obtained for Astaloy CrL is 297 MPa after high temperature sintering and 254 MPa after 1120 °C (2050F) sintering. I.e. about 17% higher fatigue performance is obtained by high temperature sintering. The microstructure is characterized by mixed upper bainite and pearlite. Two types of pearlite are found: very fine pearlite and regular pearlite. **T**he slightly lower fatigue performance compared to earlier investigations on Astaloy CrL and the relatively high scatter found for the un-notched Astaloy CrL bars (5 and 7% at 1120°C (2050F) and 1250°C (2280F) sintering temperatures respectively) is probably related to the presence of regular pearlite in the microstructure of relatively low performance. This indicates that measures, which promote fine pearlite or small amounts of martensite in the surface should be applied, for example slightly more graphite added to the premix and/or rapid cooling.
The difference between high and low temperature sintered Astaloy CrL, however, decreases when the performance of notched samples is considered. Performance in the same range is obtained for the smallest notch radius 0.25 mm independent of the sintering temperature.

Hans Ericsson [4] investigated 3mm pressed notch radius samples of Astaloy CrL with 0.6% graphite addition. Found in the investigation was a relatively large scatter. The scatter could be related to scatter in microstructure characteristics between different samples. Reported was a notch sensitivity index q=0.7 for 1120 °C (2050F) sintered and at 1250°C sintering a full notch sensitivity, i.e. q=1, for Astaloy CrL.
The rocker arm for the exhaust valve presented in the introduction does not have sharp notches in high loaded areas. The notch sensitivity index is therefore not a critical factor as long as the performance of the un-notched material is high. Furthermore, the necessity of machining indicates that a martensitic or partly martensitic material shall be avoided. This points out Material B as a strong candidate for this application. The raised performance from shot peening of fine fine pearlitic Astaloy CrL [1] in high loaded areas qualifies the material also for the injector and inlet valve rocker arms.
Sinter-hardened Astaloy CrM shall be considered as a strong candidate for components that have demands on both high bending fatigue performance and are opposed to surface loads. It is noticeable that 1120 °C (2050F) sintering in combination with a slightly carburizing sintering atmosphere in combination with rapid cooling, i.e. a uncomplicated process route, is enough to reach very high mechanical performance.

CONCLUSIONS

Astaloy CrL sintered at 1120° C or 1250° C has the potential from the mechanical performance point of view to replace wrought steel in the exhaust valve rocker arm in a Volvo diesel engine.

Fatigue performance of 254 MPa (std dev 13.4 MPA) at 1120°C and 296 MPa (std dev 20.8MPa) at 1250° sintering temperature is reached.

Fatigue performance of 437 MPa (std dev 14.2 MPa) is achieved after cold compaction to a density of 7.1 g/cm^3, 1120°C sinterhardening with slight carburization for Astaloy CrM.

Astaloy CrM material display a marked microstructure gradient with almost 100% martensite in the surface and about 15% lower bainite in the core. The low notch sensitivity index is most probably related to the microstructure gradient.

Sinter-hardened Astaloy CrM has a performance that makes it a strong candidate for components that have demands on both high bending fatigue performance and are opposed to surface loads.

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