Microstructure enhancement for fatigue improvement

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INTRODUCTION

PM steels with excellent fatigue properties are characterized by high performance microstructures and high density. Much effort has been put on reaching high densities during the last years. High density is important to get high rolling contact fatigue properties. It is well known that a martensitic surface is of outmost importance to get a material that is resistant to high Herzian pressure in combination with sliding. When bending fatigue is considered, however, it must be pointed out that high density alone has a relatively low impact on the fatigue properties.

The two microstructure extremes from mechanical performance point of view are Ferrite and Martensite. A survey of data presented in the literature indicates a fatigue limit of 380 MPa in rotating bending for 100% martensite [2]. The alloying system and processing route to get through hardening seems not to be important [2]. The bending fatigue limit at density 7.1 g/cm3 is about 120 MPa for 100% ferrite and 210 MPa for Copper-Carbon PM steel with 2% Cu and 0.8%C. These values indicate that the fatigue performance of martensite is almost 3 times superior to ferrite and almost 2 times superior to Fe2Cu0.8C.

The influence of density is twofold. Increased density normally implies smaller pores that are favorable, as higher – critical - strains are needed to start crack initiation. Increased density also means a higher Young's Modulus, which in turn demands higher stress to obtain the critical strain [3]. An evaluation from data in the literature [2] reveals that the influence of density in the density interval 7.0 – 7.4 g/cm3 on the fatigue performance is about 5 – 10% per 0.1 g/cm^3 [3]. This indicates that density only has an impact of about plus 15 – 30% when the density is increased from 7.1 to 7.4 g/cm^3. Microstructure is obviously much more important than density from the bending fatigue performance point of view.

This paper presents an overview of the influence of microstructure on the fatigue performance of PM steel. The reference material is AstaloyMo, 1.5%Mo pre-alloyed material with 0.6% sintered carbon and 100% upper bainitic microstructure. The influence on the fatigue performance is evaluated for systematic variations of the microstructure.

EXPERIMENTS

Four base powders with different carbon levels are included in the investigation see Table 1.

Table 1. Three pre-alloyed and one diffusion-alloyed base powders from Höganäs AB included in the study. DistaloyHP is diffusion-alloyed with Ni and Cu and pre-alloyed with Mo.

Nr	Material	Ni [%]	Cu [%]	Mo [%]	Cr [%]
1	Astaloy Mo			1.5	
2	Astaloy CrL			0.2	1.5
3	Astaloy CrM			0.5	3.0
4	AstaloyCrM SH			0.5	3.0
5	DistaloyDC	2.0		1.5	
6	DistaloyHP	4.0	2.0	1.5	

The base powders were mixed to two different graphite levels and 0.8% lubricant (Amide-wax). Table 2 shows sintered carbon. The sintering was performed at 1120 ^{o}C for 30 minutes in a 90/10 mixture of N_2/H_2. The cooling rate was 0.8C/sec for materials 1 – 4 and 2.5 C/sec for sinter hardened AstaloyCrM.

The fatigue tests were performed in instrumented displacement controlled four point bending Schenk machines at a testing frequency of 26-28 Hz. The tests were carried out according to the stair case method with run-outs at 2 million cycles and the evaluation of 50% probability fatigue limits and standard deviations was made according to MPIF standard 56.

Microstructures were evaluated with light optical microscopy. All microstructures shown below (Figure 1 to Figure 6) are to the same scale. The width of the micrographs is in all cases close to 250 μm. The resolutions of the micrographs presented here, however, do not allow a detailed analysis of the microstructures. All microstructures are analyzed directly in the light optical microscope. Characteristics features can only be seen by utilizing different filters and sometimes in combination with focusing and defocusing.

RESULTS

Microstructures

An overview of the results from the microstructure analysis is shown in Table 2.

Table 2. Sintered carbon and microstructures of the 6 materials included in the study. The cooling rate is 0.8C/sec for materials 1, 2, 3, 5, 6 and 2.5 C/sec for material 4. UB: upper bainite, LB: lower bainite, M: martensite, A: austenite. Microstructures within parenthesis indicate small amounts (below three percent).

Nr	Material	Sintered carbon [%]	Microstructure
1	Astaloy Mo	0.60	UB
		0.82	UB/LB
2	Astaloy CrL	0.60	UB/(LB)
		0.80	LB/(UB)
3	AstaloyCrM	0.35	Dense UB
		0.56	60%M/40%LB
4	Astaloy CrM SH	0.45	M
5	Distaloy DC	0.60	UB/islands of Ni-rich A surrounded by M
		0.80	D:o
6	Distaloy HP	0.65	UB/Ni-rich A/M/LB
		0.85	UB/Ni-rich A/M/(LB)

Molybdenum pre-alloyed PM steel

Astaloy Mo +0.6%C exhibit a microstructure of 100 % upper bainite. Increased carbon to 0.8% shifts the microstructure to a mixture of upper bainite and lower bainite. The fatigue limits are 212 and 211 MPa respectively for 0.65%C and 0.82%C. The standard deviations are in both cases less than 5 MPa. The S-N diagrams are shown in Figure 1.

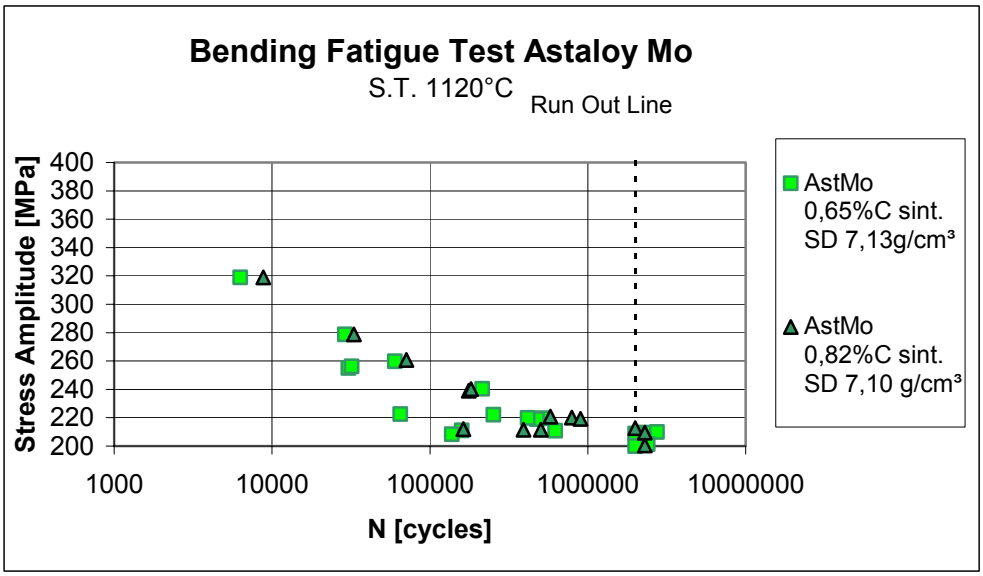


Figure 1. S-N diagrams for Astaloy Mo with 0.6 and 0.8%C. The fatigue limits are 212 and 211 MPa respectively.

Chromium/Molybdenum pre-alloyed PM steel

The microstructure of Astaloy CrL change from a mixture of upper and lower bainite at 0.6%C to almost 100% lower bainite with small amounts of martensite and upper bainite at 0.8%C. The difference in microstructure has a pronounced influence on the fatigue performance of Astaloy CrL. The 0.6%C material has a fatigue limit of 240 MPa. The fatigue limit for the 0.8%C material is 267 MPa. The S-N diagrams for Astaloy CrL +0.6% and +0.8%C are shown in Figure 2.

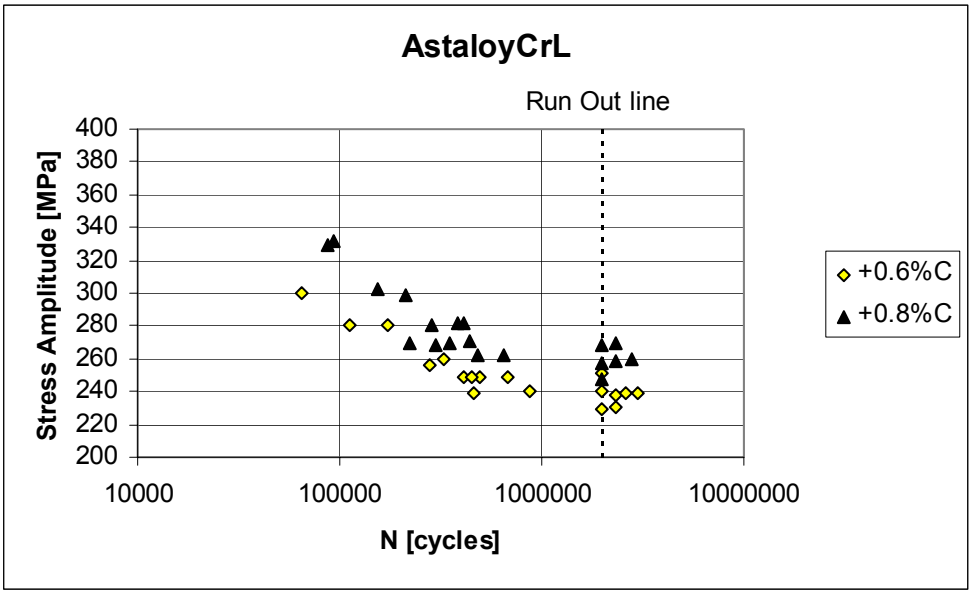


Figure 2. . S-N diagrams for Astaloy CrL with 0.6 and 0.8%C. The fatigue limits are 240 and 267 MPa respectively.

Astaloy CrM with 3%Cr and 0.5%Mo also shows a shift of the microstructure when the carbon level is raised, in this case from 0.35%C to 0.56%C. The 0.35%C variant shows upper bainite. However, in this case the upper bainite is pronounced dense compared to the upper bainite that characterizes Astaloy Mo and Astaloy CrL. This is also revealed in the fatigue performance. Astaloy CrM+0.35%C has a fatigue limit of 278 MPa with a standard deviation of 10 MPa. Increased carbon to 0.56%C completely changes the microstructure to a mixture of martensite and lower bainite with a fatigue limit of 316 MPa and a standard deviation of less than 6 MPa. Sinterhardened Astaloy CrM with fully martensitic microstructure has a fatigue limit of 380 MPa. S-N diagrams for 0.35%C and 0.56%C materials are shown in Figure 3.

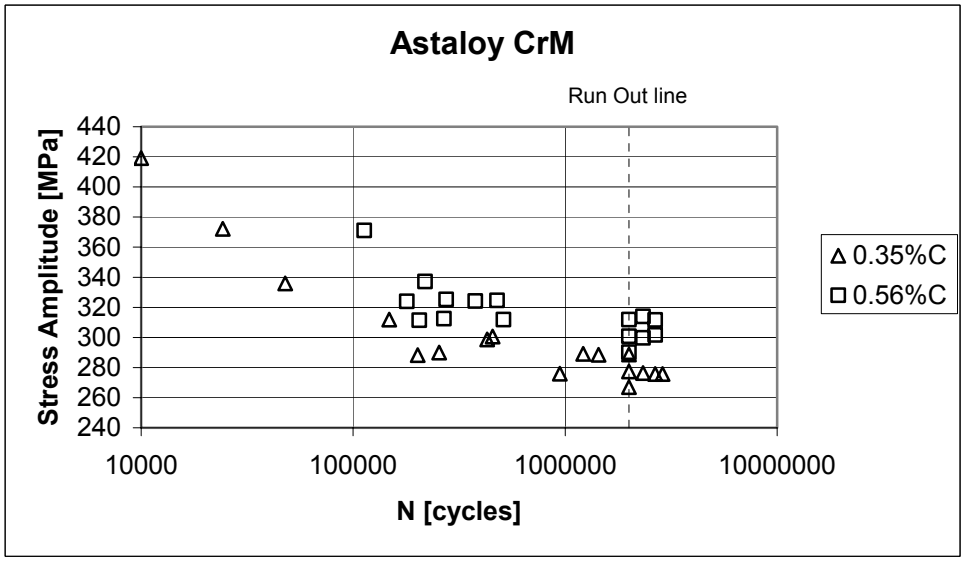


Figure 3. S-N diagrams for Astaloy CrM with 0.35%C and 0.56%C. The fatigue limits are 278 and 316 MPa respectively

Nickel diffusion alloyed Molybdenum pre-alloyed PM steel

Nickel diffusion alloyed materials that are sintered at 1120C exhibit a pronounced heterogeneous microstructure. Almost no diffusion of Nickel into the Fe-matrix takes places. The microstructure is characterized by Ni-rich austenite islands that are surrounded by a shell of martensite. The remaining material displays an upper bainitic microstructure. The fatigue limits of Distaloy DC with 0.6% and 0.8%C are 238 and 240 MPa respectively. The S-N diagrams are shown in Figure 4.

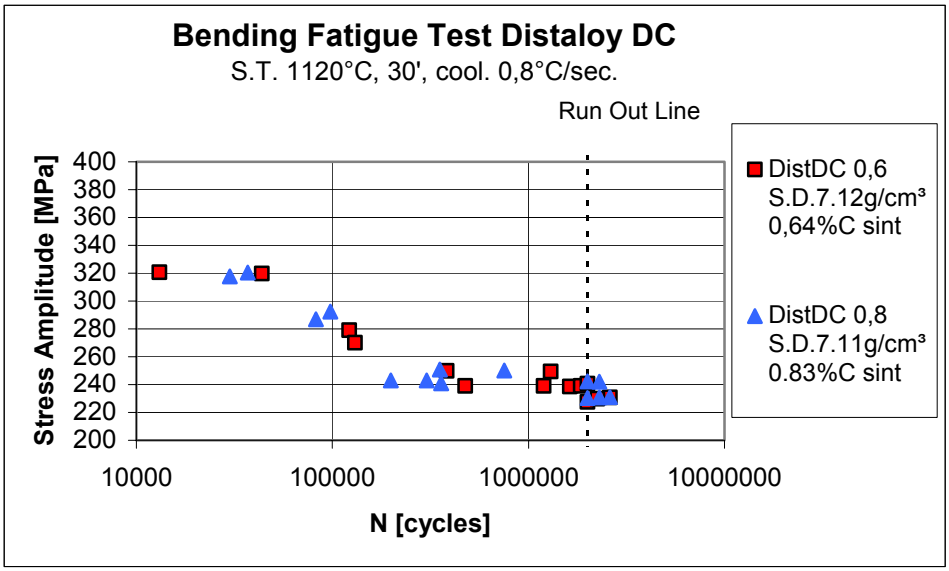


Figure 4. S-N diagrams for Distaloy DC with 0.6% and 0.8%C. The fatigue limits are 238 and 240 MPa respectively.

Nickel/Copper diffusion-alloyed Molybdenum pre-alloyed PM steel

Nickel and Copper diffusion alloyed PM steel exhibits a heterogeneous microstructure with a network of copper rich martensite that surrounds the upper bainitic cores of the base powder particles. Ni-rich austenite islands are embedded in the martensitic network. The S-N diagrams of Distaloy HP with 0.65% and 0.85%C are shown in Figure 5. The fatigue performance is closely related to the formation of the martensitic network around the upper bainitic areas.

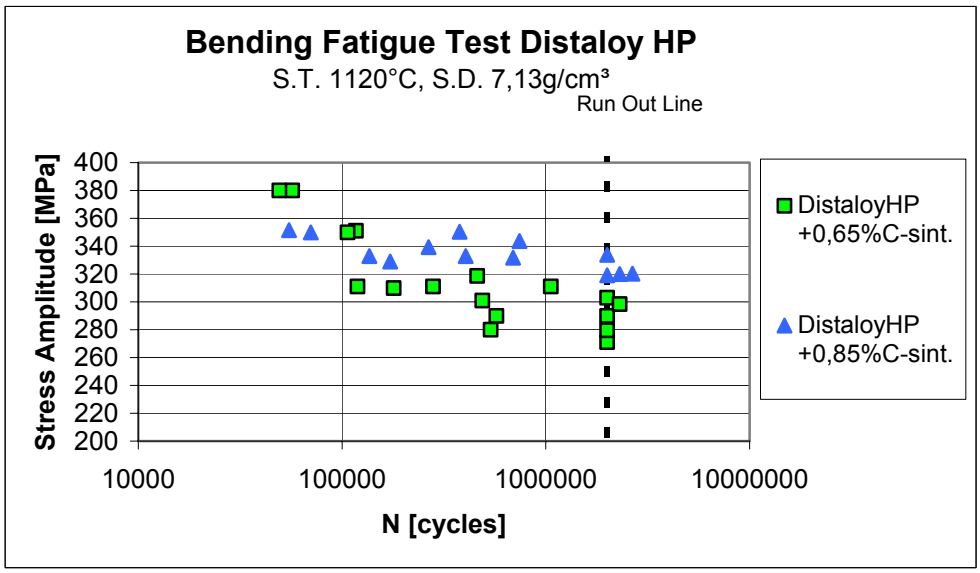


Figure 5. S-N diagrams for Distaloy HP with 0.6% and 0.8%C. The fatigue limits are 280 and 330 MPa respectively.

DISCUSSION AND SUMMARY

The influence of density on the fatigue performance of PM steel is about 5 – 10% per 0.1 g/cm3 in the interval 7.0 to 7.4 g/cm^3 [3]. The results from the present investigation clearly show that the influence of microstructure is larger. 1.5% Molybdenum pre-alloyed PM steel with density 7.1 g/cm^3 exhibits upper bainitic microstructure and plane bending fatigue limit close to 210 MPa. Sinterhardened 3%Cr+0.5%Mo with fully martensitic microstructure has a fatigue limit of 380 MPa or about +80% compared to the 1.5% Mo pre-alloyed material.

Materials processed in order to get homogenous microstructures with either upper bainite, lower bainite or martensite are included in this study. The results obtained for three different materials processed to get upper bainitic microstructures show different fatigue limits. Obviously, the classification "upper bainite" is not a unique index for mechanical performance. The features of upper bainite are irregular lamellas of cementite in a matrix of free ferrite. Dense upper bainite as found in Astaloy CrM + 0.35%C is characterized by much smaller distances between cementite compared to upper bainite in Astaloy Mo + 0.6%C. The crack walk in upper bainitic materials has been reported [4] to follow ferrite areas. The fatigue limit of Astaloy CrM with dense upper bainite is about 32% higher than the bainitic structure in Astaloy Mo

One material in the investigation exhibits a microstructure of lower bainite (Astaloy CrL+0.8%C). A shift from upper bainite to lower bainite in Astaloy CrL improves the fatigue limit about 11% from 240 to 267 MPa. However, Astaloy CrM with dense upper bainite microstructure has a slightly higher fatigue limit of 278 MPa.

PM steel with martensite obtained by the sinterhardening process has a bending fatigue limit of 380 MPa at density 7.1 g/cm3. The same level has been reported for several different martensitic materials at densities close to 7.1 g/cm3 [2]. The result obtained here confirm the note that the fatigue performance of fully martensitic materials is independent of the alloying system.

PM steel based on diffusion-alloyed base powder exhibit a pronounced heterogeneous microstructure. Two diffusion alloyed materials based on 1.5% Mo pre-alloyed Astaloy Mo are included in this study. The microstructure of the 2%Ni diffusion alloyed material Distaloy DC is characterized by Ni-rich austenitic islands surrounded by a thin layer of martensite. The fatigue limit is raised about 14% as compared to Astaloy Mo + 0.6% and 0.8%C. A considerably higher improvement of the fatigue limit is found for Distaloy HP, i.e. Astaloy Mo base powder diffusion alloyed with 2%Cu and 4%Ni. The main difference between the two diffusion-alloyed materials is that a continuous martensitic network is formed in Distaloy HP. No such network can be seen in Distaloy DC where the Ni-rich austenite islands are isolated from each other. Systematic studies of the relation between fatigue performance at different carbon levels show that the formation of the martensitic network is the main strengthening mechanism in the Cu-Ni diffusion alloyed materials.

CONCLUSIONS

- The Astaloy Mo (1,5% Mo) based materials exhibit 100% upper bainitic microstructure with a bending fatigue limit of about 210 MPa for carbon contents of 0.6 and 0.8% at density 7.1 g/cm^3.
- The microstructure of Astaloy CrL (1.5%Cr/0.2%Mo) material with 0.6%C is characterized by upper bainite with small amounts of lower bainite. The fatigue performance is 240 MPa.
- Astaloy CrL with increased carbon to 0.8% changes the microstructure to almost 100% lower bainite with small amounts of upper bainite. The fatigue limit is raised to 278 MPa.

- Astaloy CrM (3%Cr/0.5%Mo) with addition of 0.35%C exhibit mainly dense upper bainite with a fatigue limit of 278 MPa.
- This different fatigue limits for materials with upper bainitic microstructures indicate that there is a close relation between the sizes of the free ferrite areas in upper bainite and fatigue performance.
- Astaloy CrM with 0.56%C show a microstructure of 60%/40% martensite/lower bainite with a fatigue limit of 316 MPa.
- Fully martensitic Astaloy CrM + 0.45%C obtained by sinterhardening has a fatigue limit of 380 MPa.
- Distaloy DC i.e. 2%Ni diffusion-bonded to Astaloy Mo with 0.6% and 0.8% carbon show a microstructure Ni-rich austenitic island in a upper bainitic matrix. The fatigue performance is raised about 14% compared to upper bainitic Astaloy Mo materials.
- Distaloy HP-1 i.e. 2%Cu and 4%Ni diffusion-bonded to Astaloy Mo with 0.65% and 0.85% C show a microstructure with a continuous network of martensite with islands of Ni-rich austenite and upper bainite in the particle cores.
- The fatigue performance for Distaloy HP +0.8%C is improved by about 51% compared to Astaloy Mo + 0.8%C and +37% compared to Distaloy DC + 0.8%C.
- The main strengthening mechanism in Cu-Ni diffusion alloyed PM steel is the formation of the martensitic network.

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