Cost Effective Material for Heat Treated Gear Applications

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ABSTRACT
Heat treatment of PM components is often used in order to meet requirements on high hardness and other mechanical properties. Traditional processes such as quench and temper, case carburizing and induction hardening are well known routes to meet these requirements. Traditional PM materials for heat treatment often include Copper, Nickel, or Molybdenum in quantities of totally 2-6%. In the light of recent cost increases for these alloying elements these materials are becoming less competitive compared to solid steel process routes. A new diffusion alloyed steel powder having a lean alloy composition has been designed to perform well in different heat treatment operations. This paper describes the performance of this new powder in commonly used heat treatment operations. Static and dynamic properties achieved both with test specimens and components will be presented.

INTRODUCTION
Alloying elements commonly used in materials intended for heat treatment are copper, nickel and molybdenum. The fluctuations in raw material prices for these elements have in recent years been volatile, making material cost predictions difficult. Distaloy AQ is a new lean diffusion alloyed powder intended for manufacturing of heat treated PM components. The composition is Fe-0.5Ni-0.5Mo, where the base powder is pure iron to which Ni and Mo have been diffusion bonded. The low alloying content makes it less sensitive to future price fluctuations and the diffusion alloying concept ensures a consistent robust and economical mass production of components. The diffusion alloying process also allows for maximum compressibility. The possibility to reach high densities is beneficial for both mechanical performance and heat treatment processing as carbon penetration is easier to control. The low alloying content also results in good machinability and sizing properties in as sintered condition but still provides adequate hardenability to achieve high hardness and strength after heat treatment. This is favourable as some machining might be necessary already in the soft sintered state.

Previous work has demonstrated that the new Distaloy AQ material could achieve mechanical properties comparable to more highly diffusion- or pre-alloyed material systems after heat treatment operations [1-3]. While tensile properties are important for design purposes, most applications are subjected to cyclical loading which necessitates an understanding of the fatigue performance of a material. The current work focuses on understanding the complete mechanical performance of the new alloy over a variety of carbon contents. The fatigue performance of the new alloy was investigated on both test bars and prototype gears. The combination of tensile strength and fatigue performance in heat treated condition make this new alloy interesting for gear applications.

EXPERIMENTAL PROCEDURE
Powders and Materials
Three different base powders have been used in the studies presented in this paper. Besides the newly developed diffusion alloy Distaloy AQ also Distaloy AB and Distaloy AE from Höganäs AB have been used. The compositions of the different powders are shown in Table 1.

Base powder	Nickel, %	Molybdenum, %	Copper, %
Distaloy AQ	0.50	0.5	-
Distaloy AB	1.75	0.5	1.5
Distaloy AE	4.00	0.5	1.5

Table 1. Nominal powder compositions (wt%)

To evaluate influence of carbon content, density and heat treatment processing conditions on the mechanical properties, eight different powder mixes with the compositions shown in Table 2 were prepared. The identification codes for the different mixes and materials used throughout this paper are

also defined in Table 2. Natural graphite, UF 4 and Lube E from Höganäs AB were used in the manufacturing of the mixes.

Mix ID	Material ID	Base powder	Graphite, %	Lubricant, %
1	A	Distaloy AQ	0.5	0.6
2	B	Distaloy AQ	0.6	0.6
3	C	Distaloy AQ	0.8	0.6
4	D	Distaloy AB	0.6	0.6
5	E	Distaloy AE	0.6	0.6
6	F	Distaloy AQ	0.2	0.6
7	G	Distaloy AB	0.2	0.6
8	H	Disatloy AE	0.2	0.6

Table 2. Nominal mix compositions (wt%), mix and materials identification codes

Sample Preparation
For Mix1,2 and 3 tensile specimens were compacted to achieve sintered densities of 6.80, 7.00, 7.10 & 7.25 g/cm^3 on a 60 ton hydraulic compaction press. Warm die compaction, tool temperature 60 °C, was used to compact the specimens for the 7.25 g/ cm^3 density level. Plane bending fatigue specimens were compacted from Mix 2 and 4 to green densities of 7.10 g/cm^3.

In addition to the test specimens, gears were compacted from Mix 2 and Mixes 4 to 8 to a green density of 7.10 g/cm^3. The gear parameters are shown in Table 3.

Parameter	Gear Spec.
Outer Diameter (mm)	32
Inner Diameter (mm)	15
Teeth	18
Face width (mm)	10
Module (mm)	1.5875
Pressure angle (°)	20

Table 3. Gear Parameters

Sintering
Sintering was carried out on a mesh belt furnace at 1120 °C for 30 minutes in a 90/10 N2 / H2 atmosphere with a cooling rate of 0.5 °C/s.

Heat Treatment
For heat treatments the specimens were austenitized at 920°C for 20 minutes at different C-potentials to create both through hardening and case hardening. Oil quench was applied with an oil temperature of 60°C. The specimens were tempered at 200°C for 1 hour in air.

Testing
Carbon content of the as heat treated parts was determined using infrared combustion techniques according to ASTM E1019. The apparent hardness was measured on the impact specimens according to MPIF Standard 43. Sintered density was determined using MPIF Standard 42. Tensile strength was evaluated according to ASTM E8-09.

Plane bending fatigue was tested on ISO3928 test bars with R= -1 and a run out limit of 2 x 106 cycles. Evaluation of the fatigue data was performed according to MPIF Standard 56.

Tooth root bending fatigue was performed on gears with stresses evaluated according to ISO 6336 / DIN 3990. A picture of the gear and schematic of the testing is shown in Figure 1.

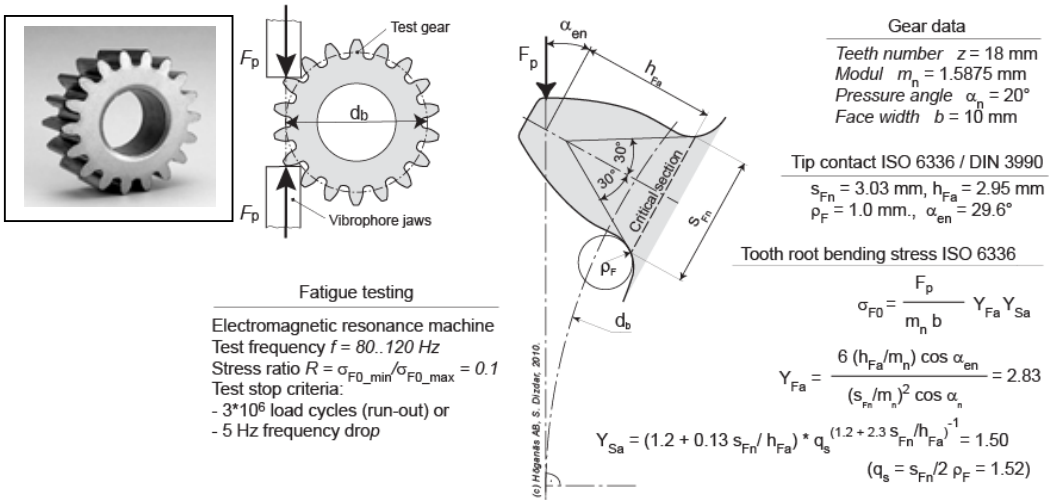


Figure 1. Tooth Root Bending Fatigue Schematic

RESULTS

Microstructure

The microstructures obtained after heat treatment of material A, B and C at a density of 7.00 g/cm^3 are shown in the micro photographs in Figure 2. A completely martensitic microstructure was obtained for all three materials, i.e. for carbon contents of 0,5 to 0,7%. Micro indentation hardness measurements were also performed. The micro hardness HV0.1 obtained, 653, 692 and 749 for material A, B and C respectively are typical for martensitic microstructures. As expected, increased carbon content increases the micro hardness. One item of note is the lack of large nickel rich austenite. Typical diffusion alloyed materials with higher Ni content will still contain large islands of nickel stabilized austenite in the heat treated condition.

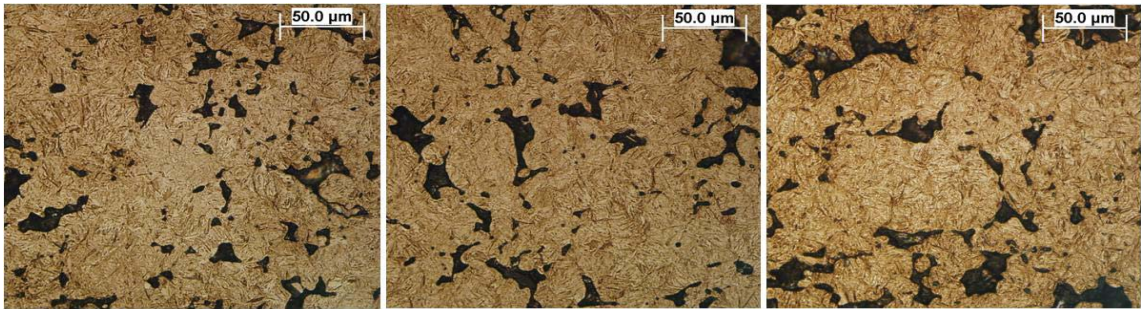


Figure 2. Microstructure Photographs of material A, B and C (Left to Right)

Mechanical Properties

Hardness

The apparent hardness measurements of material A, B and C are shown in Figure 3. As expected, increasing carbon content and density resulted in an increased hardness. Hardness levels greater

than 40 HRC were achieved for material C with the highest carbon content at densities larger than 7.00 g/cm3.

Tensile strength

The tensile strength obtained after quench and tempering of material A, B and C at different density levels is shown in Figure 4. As can be seen the tensile strength increases with increasing density for all three materials. Depending on density level tensile strengths in the range 800 MPa to1300 MPa could be achieved at carbon content between 0.5% and 0.6%. For material C with the highest carbon content level of 0,70%, the tensile strength drops off especially for the two higher density levels.This is due to an increased brittleness of the material at this carbon level.

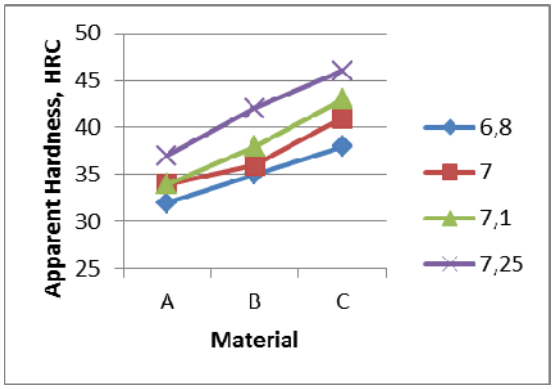


Figure 3. Apparent Hardness for material A, B and C

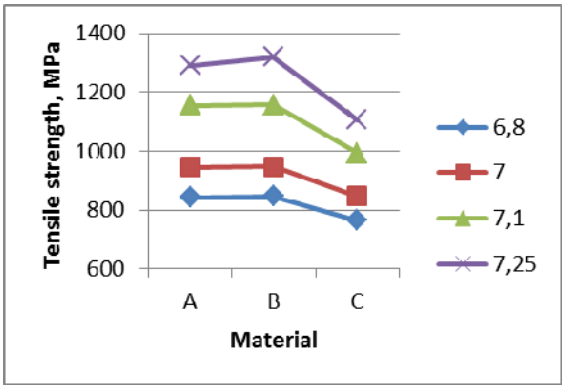


Figure 4. Tensile strength for material A, B and C

Plane bending fatigue strength

The fatigue strength of material B in quench and tempered condition is presented in Table 4. For reference test bars of material D were processed and tested under the same condition as material B. The density of the fatigue specimens was around 7.15 g/cm^3.

Material	Density, g/cm3	Bending fatigue strength, MPa σ50%	Bending fatigue strength, MPa σ90%
B	7.16	381	358
D	7.13	341	319

Table 4. Plane bending fatigue strength

Material B obtained about 10% higher fatigue performance compared material D. This difference is partly due to the slightly higher density of the material B.

Gear tooth root bending results

Quench and temper

Tooth root bending fatigue tests were performed on the quenched and tempered prototype gears described in Table 3. The endurance limit was evaluated in 10 to 12 points using stair-case method by Dixon and Mood (4). The SN curve slope in the limited fatigue life region was evaluated by testing at two load levels where 10%, 50%, and 90% survival probability was estimated according lognormal statistic distribution. The obtained data is listed in Table 5.

Material	Gear Tooth Root Fatigue, MPa		
	σ10%	σ50%	σ 90%
B	625	590	554
D	775	681	587
E	646	575	503

Table 5. Tooth root bending fatigue results of quenched and tempered gears

The gear tooth root bending fatigue results show that the lean diffusion alloy material B is comparable to the more highly alloyed material E and very close to the material D. For material B a gear tooth root bending fatigue limit higher than 550 MPa (σ 90) was obtained. The SN curve for material B is shown in Figure 5.

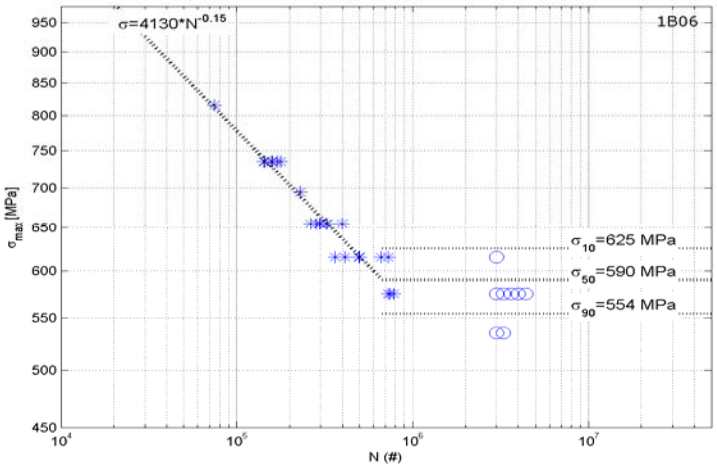


Figure 5. Bending Fatigue SN curve for material B

Case hardening

Tooth root bending fatigue tests were also performed on the case hardened prototype gears of material F,G and H. The purpose of case hardening is to take advantage of the alloying to achieve a high surface hardness and ductile core. The endurance limit was evaluated in the same way as described in previous paragraph above. The obtained data is listed in Table 6.

Material	Gear Tooth Root Fatigue, MPa		
	σ10%	σ50%	σ 90%
F	744	695	647
G	746	710	675
H	688	658	627

Table 6. Tooth root bending fatigue results of case hardened gears

The results show that the lean diffusion alloy material B obtained a higher fatigue strength compared to the much more highly alloyed material H, 695 MPa vs. 658 MPa (σ50%). Gear tooth root bending fatigue limits of close to 700 MPa (σ50%) were achieved for both material F and G. The SN curve for material F is shown in Figure 6.

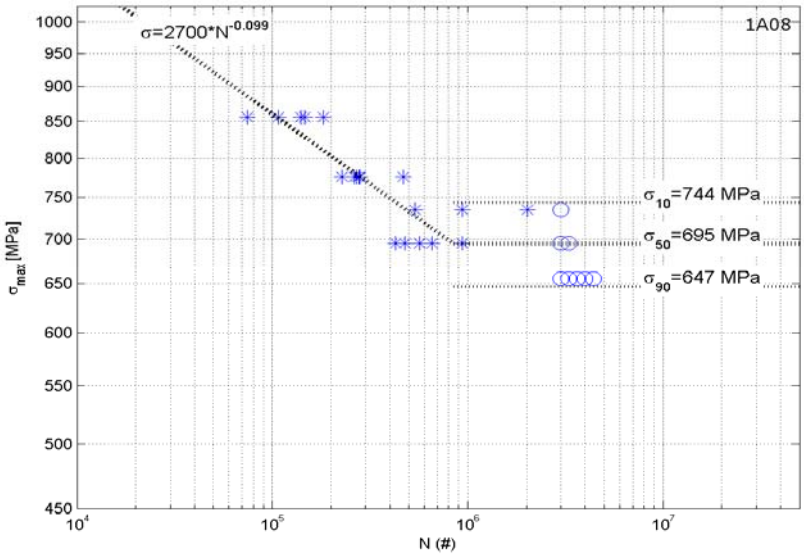


Figure 6. Bending Fatigue SN curve for material F

CONCLUSIONS

The conclusions that can be drawn from this study are the following:

- The highest tensile strengths levels for the new Distaloy AQ material were achieved at carbon content in the range of 0.5% and 0.6%.
- Depending on density level tensile strengths of 800 MPa to1300 MPa could be achieved.
- Plane bending fatigue performance of Distaloy AQ was slightly higher compared to the more highly alloyed Distaloy AB material. Plane bending fatigue limits of 381 MPa (σ50%) and 358 MPa (σ90%) were achieved at a density of 7.16 g/cm^3.
- Tooth root bending fatigue limit of quenched and tempered gears made of Distaloy AQ was slightly lower than for the Distaloy AB based material, 554 MPa versus 587 MPa (σ90%). However, a higher tooth root bending fatigue limit was obtained compared to the Distaloy AE material, 554 MPa versus 503 MPa (σ90%).
- Tooth root bending fatigue limit of case hardened gears was slightly lower for Distaloy AQ material compared to the Distaloy AB based material, 695 MPa versus 710 MPa (σ50%) but higher compared to the Distaloy AE material, 695 MPa vesus 658 MPa (σ50%).

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