P/M Materials for Gear Applications

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Abstract

P/M materials for gear applications have been reviewed based on results of own investigations of gear tooth bending strength of simple spur gears and rolling contact fatigue resistance of rollers. It was concluded that surface densified casehardened P/M gears reached gear tooth bending strength of reference casehardened machined wrought steel gears. Surface densified casehardened P/M rollers reached RCF-resistance of casehardened wrought machined rollers. Surface densification plays the main role in reaching high performance of P/M components. Chromium low alloyed P/M materials show a promising potential for a high performance/cost ratio.

Introduction

Until approximately one or two decades ago, P/M materials have been associated with low cost and low performance gear applications, such as pump– or transmission gears for hobby and household applications. However, introduction of high density technologies improved gear density levels and by this their mechanical strength. Warm compaction [1] improved density levels of parts such as power tool gears up to 7.2–7.3 g/cm^3, and offered a lower cost alternative to double–press double–sinter (DPDS) route. High velocity compaction [2] offered possibilities to cost effectively press large single level P/M parts such as parking gears to densities levels up to 7.2-7.3 g/cm^3. Finally, selective surface densification (SSD) techniques [3] open possibilities to fully dense the part surface to a depth so that Hertzian contact stresses and bending stress gradients are kept inside of it. The selective surface densification techniques include a number of radial and axial rolling techniques even combined with shot peening, and a part's particularity will decide the most appropriate technique.

Demands on gear materials are continuously increasing. This is mainly because of developments in automotive industry toward high performance vehicles with low fuel consumption and low environmental impact. A good example can be to look on car gear transmissions as very demanding ones. In the period from World War II to present, their gear module decreased from between 4 and 5 mm down to between 2 to 3 mm, while effective torque transmitted increased nearly twice. In automatic gearboxes for passenger cars one can even find high effective planetary gear stages with modules between 1.5 and 2 mm.

The gears that meet automotive industry demands are made of case hardening steels such as 16MnCr5, 15CrNi6 or 21NiCrMo2, manufactured by a process route consisting of three principal operation steps: soft machining, case hardening and hard finishing. Soft machining includes a number of machining steps from a forged/cut blank to hobbed optionally hobbed/shaved gear ready for case–hardening. After case hardening it is often needed to compensate for gear hardening distortions by using gear grinding/honing and bore grinding. Gears manufactured in that way achieve more than 1000 MPa in gear tooth bending strength σ_{FE} and 1500 MPa in gear pitting resistance σ_{Hlim} as written in ISO 6336 and DIN 3990.

The reason that case hardening is the main hardening technique today may be illustrated in Figure 1 which shows how specific gear tooth bending strength and specific flank Hertzian stresses depend on gear module respective gear module/flank radius. The trends to more compact and more effective gearboxes lead to smaller modules and that causes higher and higher stresses in tooth root fillet and on tooth flanks. For modules smaller than appreciative 3 mm, the stresses increase sharply and the critical gear stresses shift from the gear flank to the gear tooth root. This phenomenon impact design of P/M gears, and shows that high performance gears need to be surface densified and case hardened in order to meet requirements from automotive industry.

A long life of compact automotive gearboxes demands a stable full fluid film lubrication of gear teeth contact. Two main factors that establish and maintain such lubrication under high loading are oil viscosity and surface roughness. Figure 2 shows viscosity–density curves for three typical oils used in automotive gearboxes, gear oils SAE80W for manual gearboxes, automatic transmission fluid (ATF) according to Dexron III specification and small engine oil SAE10W30. Full fluid film lubrication gets benefits from a high oil viscosity, but commercial oils keep the viscosity as shown in Figure 2 due to several mechanical and chemical reasons. Low surface roughness on other side is beneficial to full fluid film lubrication i.e. the lower roughness the higher film thickness–to–roughness ratio lambda. Gear shaving and gear grinding as two of teeth surface generating operations achieve ten–points–depth R_z lower than 4 µm while P/M gears surface densified by gear rolling/burnishing can achieve lower then 2 µm. For the prototype gears presented later in the paper, gear pitting resistance increases as much as 5% (through the roughness factor Z_R in ISO 6336). This is in fact an opportunity for surface densified P/M gears.

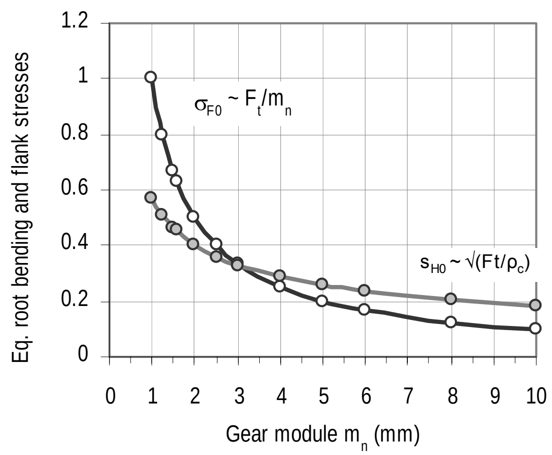

Figure 1. An approximation of equivalent gear tooth root bending and Hertzian flank stresses as a function of module.

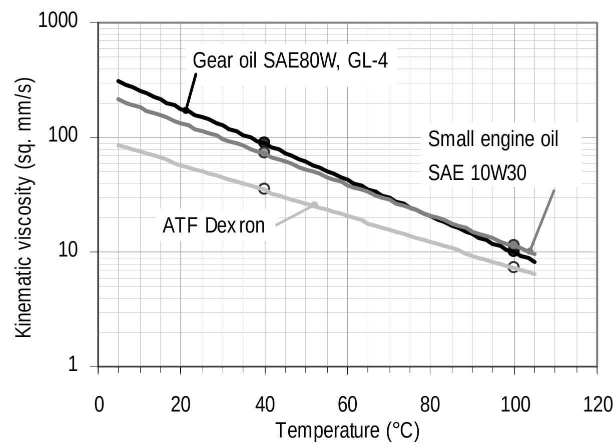

Figure 2. Viscosity vs. temperature for three typical oils in automotive applications.

Prototype gears and RCF-rollers

Performance levels that P/M gears achieve were evaluated on simple spur gears from an automotive application and rollers from rolling contact fatigue (RCF) test defined by ZF Friedrichshafen in 1960'. Figure 3 shows the prototype gear, basic facts about the gear tooth root bending testing and a brief schedule of gear bending stress calculations according to ISO 6336. Figure 4 illustrates rollers' contact of the ZF-RCF test and lists some facts bout the RCF-testing.

Materials and process routes experimentally evaluated

The P/M materials used in this study are the prealloyed powders Astaloy 85Mo and Astaloy CrL, see Table 1 and Table 2. Astaloy 85Mo is prealloyed with 0.85% Mo while Astaloy CrL is prealloyed with 1.5% Cr and 0.2 Mo. The manufacturing process route for each prototype gear and roller is described in Table 1 and Table 2 by using codes listed in Nomenclature chapter. The reference gears and rollers were machined from wrought round bars and case hardened according to common practice for components made of these materials. The reference gears were additionally grind to achieve quality DIN 7. The P/M prototype gears and rollers were first pressed as rings and sintered to achieve the nominal core density, then machined to gear respective roller blanks with rolling–ready–geometry. The gear and roller blanks were then rolled using a radial rolling machine and respective gear and roller die. All P/M prototypes were finally case hardened in order to create compressive residual stresses by creating a hard martensitic surface with a softer core.

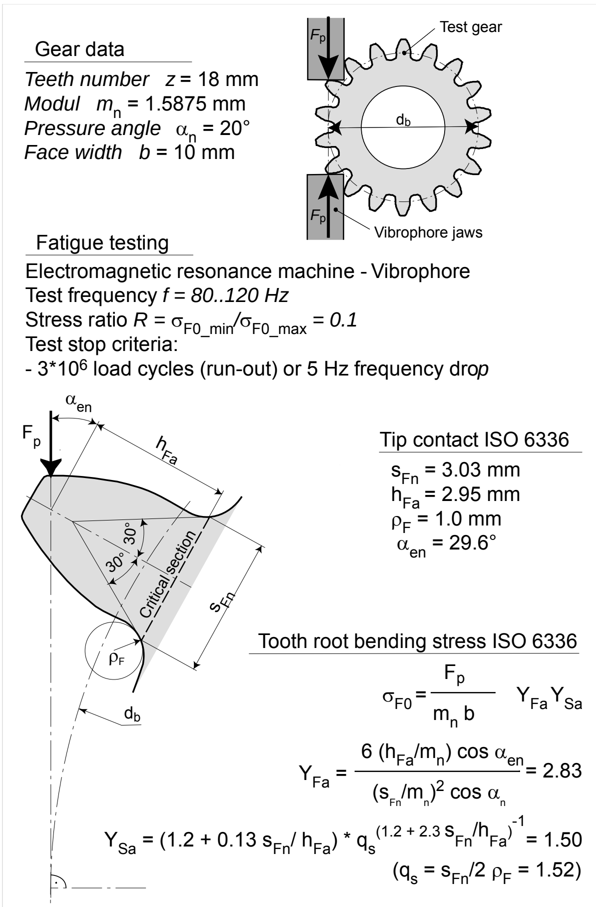

Figure 3. The prototype gear, basic facts about the gear tooth root bending testing and a brief schedule of gear bending stress calculations according to ISO 6336

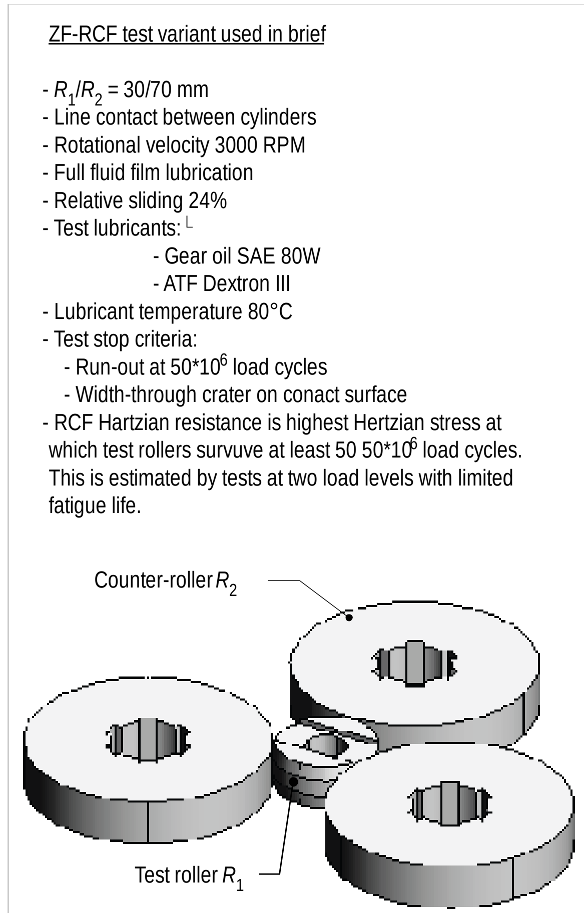

Figure 4. Illustration of the rollers' contact of the ZF-RCF test and some basic test data.

Figure 5, top row, shows the microstructure in case hardened Astaloy 85Mo materials. The microstructure is plate martensite that has high carbon content at the surface and in the core it is lath martensite with low carbon content. Between the surface and the core there will be a gradient of the carbon content were the martensite gradually will have lower carbon content.

Figure 5, bottom row, shows the microstructure in the case hardened Astaloy CrL. The microstructure is plate martensite with high carbon content at the surface and further in the material the carbon content will decrease and the plate martensite will be mixed with more and lath martensite. Eventually the lath martensite will be mixed with more and more bainite so in the core the microstructure will be bainite mixed with lath martensite. The gears made from Astaloy CrL were low pressure carburized but this process was not optimized for the gears.

No	Material	Density (g/cm³)	Process route	$SDD_{0.98}$/ Eht_{550HV}
1	16MnCr5 (SAE5115)	7.9	M, CQT,GG	- /0.19
2	Astaloy CrL+0.2C (Fe-1.5Cr-0.2Mo+0.2C)	7.1	P,S,M,GR, CQT	0.20 /0.25
3	Astaloy CrL+0.2C (Fe-1.5Cr-0.2Mo+0.2C)	7.4	DPDS,M, GR, CQT	0.20 /0.25
4	Astaloy 85Mo+0.2C (Fe-0.85Mo+0.2C)	7.1	P,S,M,GR, CQT	0.20 /0.30
5	Astaloy 85Mo+0.2C (Fe-0.85Mo+0.2C)	7.4	DPDS,M, GR, CQT	0.20 /0.32
6	Astaloy 85Mo+0.2C (Fe-0.85Mo+0.2C)	7.6	DPDS,M, CQT	- /0.25

Table 1. Material and process route of tested prototype gears.

No	Material	Density (g/cm³)	Process route	$SDD_{0.98}$/ Eht_{550HV} mm/mm)
1	21NiCrMo2 (JIS NCM220H, SAE8620)	7.9	M, CQT	-/0.8
2	Astaloy CrL+0.2C (Fe-1.5Cr-0.2Mo+0.2C)	7.1	P,S,M,R, CQT	0.7/0.7
3	Astaloy CrL+0.2C (Fe-1.5Cr-0.2Mo+0.2C)	7.6	P,S,M,R CQT	1.4/0.9
4	Astaloy 85Mo +0.3C (Fe-0.85Mo+0.3C)	7.0	P,S,M,R, CQT	1.0/1.0
5	Astaloy 85Mo +0.3C (Fe-0.85Mo+0.3C)	7.0	P,S,M, CQT	-/1.0

Table 2. Material and process route of tested ZF-RCF rollers.

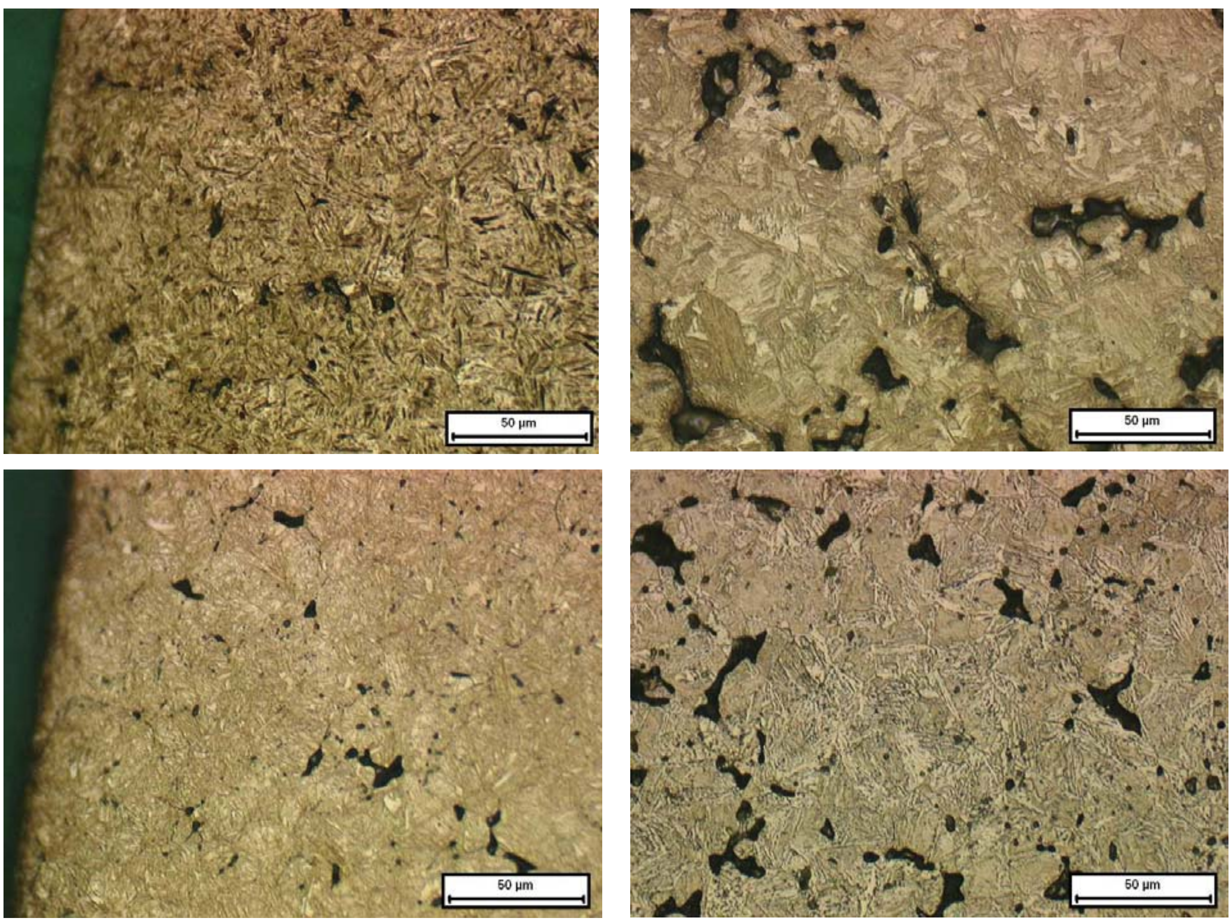

Figure 5. Case and core microstructure photographs of case hardened Astaloy 85Mo (top row)) and Astaloy CrL materials (bottom row)

Results

The results of the gear tooth bending respective RCF-testing are summarized in Figure 6 and Figure 7. Figure 6 shows high gear tooth bending performance of case hardened surface densified gears made of Astaloy 85Mo +0.2C. Those with core density of 7.4 g/cm^3 have even higher performance than reference case hardened wrought machined 16MnCr5 gears. The Astaloy CrL+ 0.2C gears have a bit lower performance but the case hardening for this material was not optimal and is at present under optimization. Surface densification and increased core density 7.1 to 7.4 g/cm^3 gained 100 MPa in gear tooth bending strength. However, absence of the surface densified layer lowers the gear tooth bending strength down to 850 MPa level despite a high core density of 7.6 g/cm^3.

When comparing gear tooth bending strength of different gear sizes i.e. modules, one has to note for so-called size effect. Figure 6 includes gear tooth bending strength levels evaluated on larger wrought gears with module 3-5 mm depending on core hardness level and Ni content according to ISO 6336. The test gears in this investigation had a relatively small module of 1.5875 mm. Their gear tooth bending strength exceeded ISO 6336 levels for 3-5 mm module gears. The same phenomenon was previously reported by e.g. Jeong in 1992 [4], who found a difference in casehardened gear tooth bending strength of 22% between modules of 1.5 and 5 mm. Simply dividing 1350 MPa in gear tooth bending strength of casehardened 16MnCr5 gears with the core hardness of 440 $HV_{0.1}$ by 1100 MPa for casehardened wrought gears with core hardness of 40 HRC (≈400 HV), one gets a difference of 23%. This is an additional evidence of validity of the results shown here.

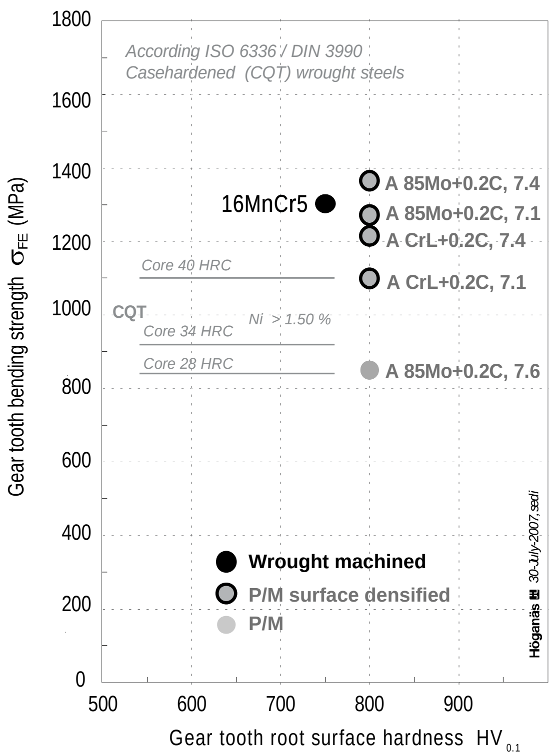

Figure 6. P/M gear tooth bending strength σ_{FE}.

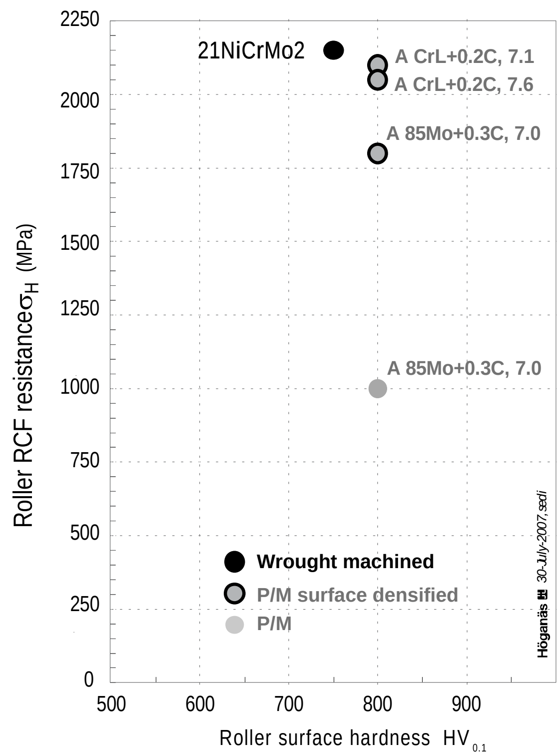

Figure 7. Roller RCF resistance (Hertzian stress).

Figure 7 shows that RCF-resistance of the case hardened surface densified P/M rollers reached 2150 MPa RCF resistance level of the case hardened wrought 21NiCrMo2 steel rollers. The best P/M rollers that reached 2100 MPa level were made of Astaloy CrL+0.2C with core density of 7.1 g/cm^3 and both surface densification– and case depth of 0.7 mm. Next to them, at nearly the same level of 1950 MPa, came Astaloy CrL+0.2C rollers with core density of 7.6 g/cm^3, and surface densification/case depth of respective 1.4/0.9 mm. Both rollers had very similar profiles of residual compressive stresses down to 0.5 mm depth. The reasons for this 150 MPa difference in the RCF-resistance can be therefore searched for in other aspects of case hardening quality, uniformity of surface densified depth, ratio of case hardened and surface densified depth and core density/hardness differences.

Further, Astaloy 85Mo+0.3C with density of 7.0 g/cm^3, case hardened but not surface densified reached only about 1000 MPa. Equally manufactured rollers but surface densified, reached 1800 MPa and that clearly illustrates how surface densification increases the RCF-resistance.

Conclusions

P/M materials for gear applications have been reviewed based on results of own investigations of gear tooth bending strength and rolling contact fatigue resistance. Following conclusions were reached:
(1) Surface densified case hardened P/M gears reached gear tooth bending strength of reference case hardened machined wrought steel.
(2) Surface densified case hardened P/M rollers reached RCF-resistance of case hardened wrought machined rollers.
(3) Surface densification plays the main role in reaching high performance of P/M components.
(4) Low alloyed chromium P/M materials show a promising potential for a high performance/cost ratio.

References

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Nomenclature

Symbol	*Stands for*	*Symbol*	*Stands for*
CQT	*Case hardening i.e. carburizing, quenching and tempering*	*S*	*Common sintering, 1120°C, 90N2/10H2, 30 min.*
E_{ht550}	*Case depth i.e. depth with 550HV hardness*	$SDD_{0.98}$	*Surface densification depth – depth with 98% relative density*
DPDS	*Double–pressing double–sintering*	*R*	*Rolling for surface densification of prototype rollers*
M	*Machining*	*GG*	*Gear grinding after CQT*
P	*Pressing*	*GR*	*Rolling for surface densification on prototype gear tooth flanks.*