PROCESS, QUALITY AND PROPERTIES OF HIGH-DENSITY P/M GEARS

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ABSTRACT

High-performance P/M test-gears made by a high-density manufacturing route and sinter-hardening have been experimentally investigated with respect to dimensional accuracy and mechanical properties. The properties of the gears, compacted to a density of 7.5 g/cm³, were compared to the properties of gears made of heat-treated wrought steel. Dimensional- and surface finish features of the P/M prototypes equal to that of conventionally manufactured gears made of wrought steel. The AGMA and DIN gear quality numbers for profile-, alignment- and pitch deviation of net shape sinter-hardened gears were comparable with hobbed gears. P/M gears can thus offer significant cost savings due to fewer costly machining operations such as turning and hobbing and due to better materials utilization compared to conventional gears. The endurance limit of the sinter-hardened P/M gears at a density of 7.5 g/cm^3 was similar to that of a quenched and tempered (SAE4140) wrought steel material, commonly used for medium-duty gears.

INTRODUCTION

Significant cost savings can be achieved by converting wrought steel transmission gears to net shape or near-net shape P/M gears. Most transmission gears, often running at high contact load, require gear strength, hardness and fatigue resistance that cannot be met by conventional P/M gears at density levels of 6.9-7.1 g/cm³. The density typically achieved by conventional compaction at present, is not sufficient to meet the required mechanical properties for applications with high contact loading.

P/M component manufacturing routes for high density, such as double compaction or warm compaction [1], can produce P/M gears to densities of 7.2-7.3 g/cm³. Several concepts for cost-efficient manufacturing of high-density gears are available or under development. The leanest and most cost-efficient process would be to perform powder compaction followed by sinter-hardening. By surface densification, P/M gears can obtain teeth with a fully dense surface layer that significantly improves the gear load capacity [2-3]. By high velocity compaction, gears with densities up to 7.6 g/cm³ can be produced by a single-press single-sintering (P1S1) operation [4-6]. Similar density levels have been reached by combining warm-compaction, high compaction pressure and die wall lubrication [7].

The tooth strength and pitting resistance must match or exceed the properties of conventional wrought steel gears in order to be fully accepted by the automotive industry. Since the driving force for conversion from wrought steel to P/M is cost reduction, the required gear quality, often expressed as an AGMA or a DIN number, must be reached by processing to net shape or near-net shape in order to keep the number of manufacturing operations down and to maximize materials utilization.

The first aim of this study is to show that the shaping ability of P/M technology can lead to significant cost savings for gears, due to a reduced need for costly machining operations.

The second aim is to determine the performance of high-density, sinter-hardened gears and compare to the performance of conventional quenched and tempered conventional gears for medium duty applications. A performance comparison with case-hardened wrought steel gears representative for automotive transmission applications is also performed.

Sinter-hardened P/M gears made from two materials were produced at the central laboratory of Höganäs AB, Sweden, using High Velocity Compaction. The gears were measured and gear quality was determined according to both AGMA and DIN standards. Gear quality representative for heat-treated wrought steel gears as ground, shaved or hobbed was compared to the quality of the P/M gears.

The tooth root endurance limit of the P/M gears was determined using a pulsator test and a comparison with the performance data of heat-treated wrought steel reference gears was made.

MANUFACTURING PROCESS



Module	m_n	1.5875 mm	(DP16)
Teeth number	z	18	
Pitch diameter	d	28.575 mm	(1.125 in)
Pressure angle	α_n	20°	
Tooth addendum height	h_a	1.25 *m_n	
Tooth height	h_f	1.00 * m_n	
Tooth root fillet radius	ρ	0.4 * m_n	
Gear face width (nominal)	b	10 mm	(0.3 in)
Press area		490 mm²	(0.72 sq.in.)
Mass (7.5 g/cm³)		35 g	
Rim thickness / tooth height ratio	t/h	1.25	

Figure 1. Prototype gear and its geometry data.

The gear used in this investigation is a spur planetary gear from an automotive application. A photo of the prototype gear and its basic geometry data are presented in Figure 1.

P/M test gears were made from two powder mixes: D.DH-1 +0.6 Graphite UF4 +0.2 Amide-wax and Astaloy CrM +0.4 Graphite UF-4 +0.2 Amide-wax (Table 1). D.DH-1 is a water-atomized iron powder containing 1.5% molybdenum (pre-alloyed) and 2% copper (diffusion bonded). Astaloy CrM is a water atomized pre-alloyed iron powder with 3% chromium and 0.5% molybdenum. The powders were selected for their excellent hardenability and by sinter-hardening, they can achieve high hardness and high yield strength [8] in a cost-efficient way.

The P/M gears were high velocity compacted to 7.5 g/cm³ using die-wall lubrication, sintered at 1120°C (2050 °F) for 30 min in $90N_2/10H_2$ atmosphere followed by rapid cooling at 5°C/s (9°F/s) and tempered at

180°C (356 °F) for 60 min in air. A martensitic microstructure with a hardness of 650 HV0.1 was obtained (Figure 2).

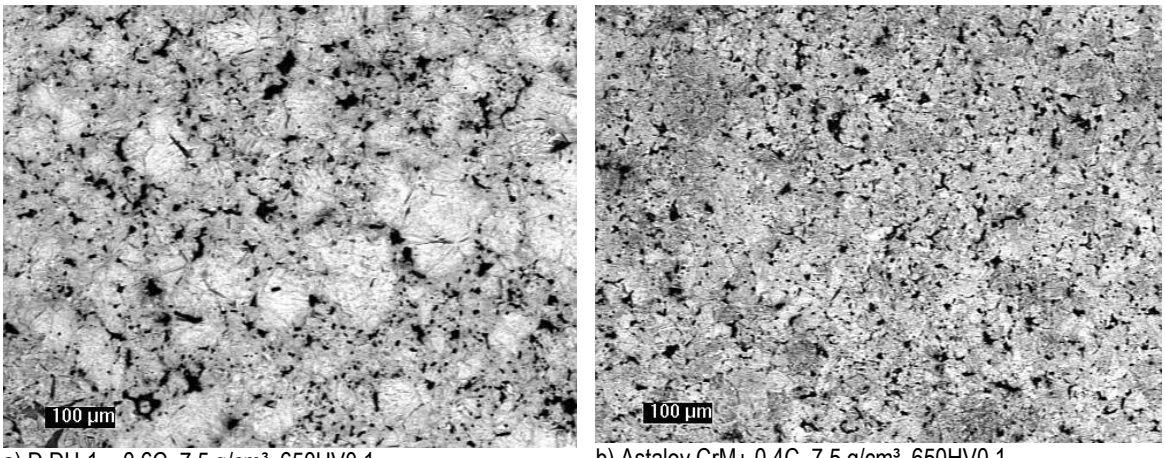
The first reference is a gear made of a trough-hardened material (SAE4140). Gears made of this type of material can be found in medium-duty applications. They typically have a homogenous martensitic microstructure and a hardness of 58 HRC.

The second reference represents a highly loaded application, an automotive transmission gear. The prototype test gears used as reference 2, were machined from a 16MnCr5 steel (SAE5115) and thereafter case-hardened. For the case-hardening, carburizing was performed at 840°C (1544°F) for 30 min with a carbon-potential corresponding to 0.8 wt% C, followed by oil-quenching at 60°C (140°F) and finally tempering at 180°C (356°F) for 60 min in air. The hardness was 750 HV0.1 in the case and 440 HV0.1 (44 HRC) in the core. A case depth of 0.16 mm (0,006") (550HV0.1) was recorded, which according to [9] indicates proper case hardening of the reference gear (Figure 3).

The processing route for the P/M gears in this comparative study is very lean and requires only five operations (Table 2). The processing routes for quenched and tempered or case-hardened conventional gears from wrought steel have at least ten operations and more than half of the material is removed by turning and gear hobbing. For P/M gears the materials waste is less than a couple of percent (Table 3).

Table 1. Test- and reference gear materials

Name	D.DH-1+0.6C	Astaloy CrM + 0.4C	Reference 1 (Conv. steel)	Reference 2 (Conv.steel)
Code	FLC-4908 (MPIF)	(No MPIF code)	SAE 4140 (42CrMo4)	SAE 5115 (16MnCr5)
Constituents	(Fe-1.5Mo)-2Cu+0.6C	(Fe-3.0Cr-0.5Mo)+0.4C	Fe-1.0Cr-0.25Mo-0.75Mn-0.4C	Fe-1.15Mn-0.95Cr-0.16C
Density	7.5 g/cm³	7.5 g/cm³	7.88 g/cm³	7.88 g/cm³
Heat treatment	Sinter-hardening	Sinter-hardening	Quenching & tempering	Case-hardening
Source of performance data	Prototype test	Prototype test	Standard DIN 3990/5	Prototype test



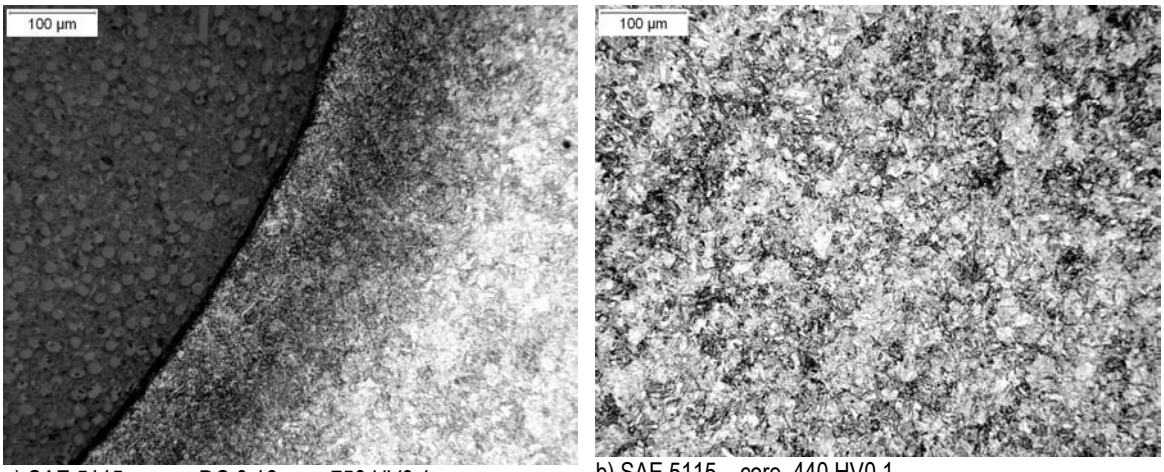
a) D.DH-1 + 0.6C, 7.5 g/cm³, 650HV0.1.

b) Astaloy CrM+ 0.4C, 7.5 g/cm³, 650HV0.1.

Figure 2. Metallographic structure of the P/M prototype gears in the tooth root area.

Table 2. Manufacturing process of P/M prototype and conventional wrought steel gears

P/M prototype gear	*Wrought steel – reference 1*	*Wrought steel – reference 2*
High velocity compaction to 7.5 g/cm³	Cutting off a blank from a rolled bar	Cutting off a blank from a rolled bar
Sintering & rapid cooling	Turning: bore, two faces, topdia and two chamfers	Turning: bore, two faces, topdia and two chamfers
Tempering	Gear hobbing	Gear hobbing
Turning of bore	Austenitization + quenching	Case-hardening
Tumbling	Tempering	Tempering



a) SAE 5115 - case, DC 0.16 mm; 750 HV0.1.

b) SAE 5115 – core, 440 HV0.1.

Figure 3. Metallographic structure of reference 2 prototype gears in the tooth root area.

Table 3. Manufacturing steps and materials utilization of the prototype gears

	P/M gears	Conventional gears
Number of manufacturing steps	5	10
Raw material weight	35.5 g	86 g
Weight of finished gear	35 g	37 g
Materials utilization	98.5%	43%

GEAR QUALITY

Gear quality is a way to describe how a gear and its assembly (gearbox) deviate from their nominal geometry. The production process used determines the geometry accuracy possible to attain in real workshop conditions. The inaccuracy of the gears and the assembly has a significant influence on service life, load capability and noise generation of the gearbox. To enable quantification of the inaccuracy, standardizing authorities established standards [10-12] which determine quality of the gears and gearboxes. The standards mainly follow the same approach but definitions differ for a number of deviation parameters. The different standards agree that there are four principal deviations of unassembled gears; profile-, alignment-, pitch- and run-out deviation; which will be considered on prototype gears in this investigation. These four deviation parameters are illustrated in Figure 4 (left).

Profile deviation is the difference between the specified profile and the measured profile of the tooth. Tooth alignment deviation is the difference between the measured tooth alignment and the specified alignment. In other words, alignment is the angle of the tooth flank line to the axis of the gear. Pitch (spacing) deviation is the difference between the measured and the true pitch position. Finally, run-out is the deviation of gear pitch circle measured by inserting a pin or ball between the gear teeth perpendicularly to the bore axis of rotation. Permissible amounts of these four deviations are defined through a number of parameter tolerances in AGMA quality numbers and DIN quality classes. Increasing AGMA quality numbers and decreasing DIN quality classes correlate with a higher gear accuracy.

The quality number of a gear does not only provide information about the gear accuracy. It also allows conclusions to be drawn about the gear's application area, performance level, production route and cost. More accurate gears mean a more sophisticated application area, higher performance level, longer and more sophisticated production route, and consequently higher cost. Quality AGMA 8 (DIN 9) commonly meets demands of low and medium-duty gears for lawn and garden and home appliances. Such gears are commonly finished by gear turning and hobbing. Heavy-duty gears, particularly high speed gears, for automotive transmissions typically require quality AGMA 10 (DIN 7) at least. This gear quality cannot be reached by hobbing or pressing-sintering [13], and one, or a few, finishing operations therefore have to be used. Teeth are commonly finished before heat treatment by operations such as rolling or shaving, or after heat treatment by grinding. Normally, the run-out of the gear has to be reduced by bore turning or grinding.

The quality of the prototype gears in this study was evaluated by measurement of the gear geometry and the surface roughness of the gear flanks. Figure 4 shows measured profile, alignment, pitch and run-out deviation of the gear teeth. A 3D CNC gear measuring center with mechanical probe was used for the determination of the gear quality according to DIN. The AGMA quality numbers were determined using the nearest equivalent DIN parameters shown in Figure 4. The hobbed prototype gears (reference 2) reached quality AGMA 8 (DIN 10) for profile, AGMA 9 (DIN 7) for alignment, and AGMA 13 (DIN 5) for pitch and AGMA 7 (DIN 10) for run-out deviation. The P/M prototype gears reached quality AGMA 9 (DIN 8) for profile and alignment, AGMA 11 (DIN 7) for pitch and AGMA 8 (DIN 9) for run-out deviation. Such high qualities for the P/M prototypes are not unexpected. The pressing tool die has a high dimensional precision, a high surface quality and a high stiffness, which together with high density of the compacted gear give small profile-, alignment- and pitch deviation. However, the run-out deviation of the P/M gears drops to a quality number below the three other.

The second aspect of the gear quality is the surface finish of the gear flanks. This in particular is important for the formation of the separating hydrodynamic oil film between the gear flanks in contact. Furthermore, a smooth surface of the gear tooth root is also favorable with respect to gear tooth bending fatigue performance. Table 4 lists the results of the surface roughness measurements that was recorded by using a roughness tester with mechanical probe. The P/M prototype gears showed 30% lower roughness compared to hobbed gears made of wrought steel. It is worthwhile to note that a significant part of the recorded flank roughness of the P/M prototype gears comes from the surface porosity. However, most of this porosity is narrow in width and shallow in depth and thus has little influence on the surface roughness measurement parameters.

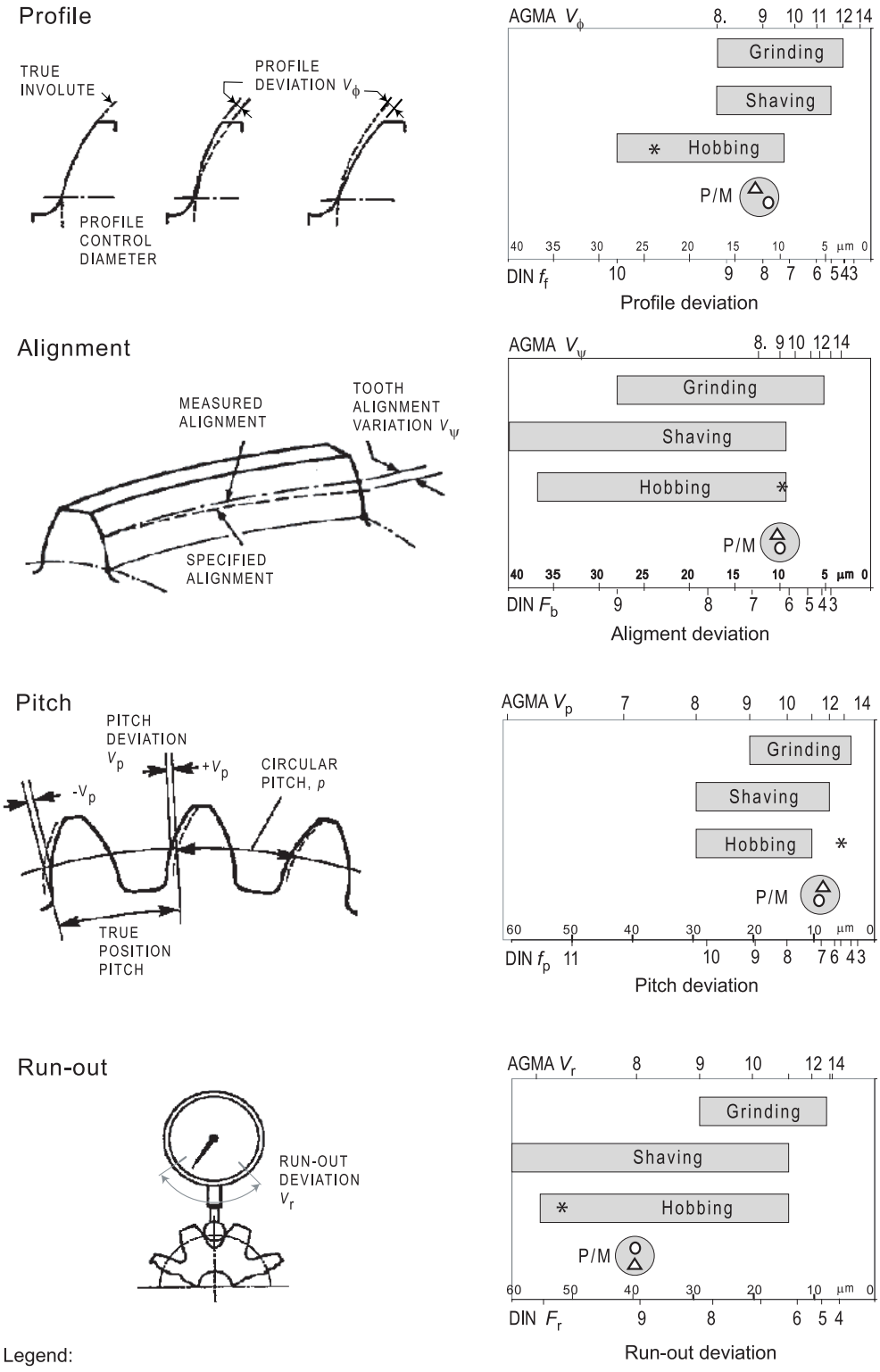


Figure 4. Profile, alignment, pitch and run-out deviations of pressed and sinter-hardened prototype gears according to ANSI-AGMA 2000-A88 /DIN 3961-3962, together with a comparative guide to achievable qualities for ground-, shaved- and hobbed gears.

Table 4. Surface roughness of the prototype gears flanks.

	D.DH-1 + 0.6C (Fe-1.5Mo)-2Cu+0.6C	Astaloy CrM + 0.4C (Fe-3.0Cr-0.5Mo)+0.4C	Reference 2 SAE 5115 (16MnCr5)
Roughness average R_a (µm)	0.50	0.53	0.71
Mean roughness depth R_z (µm)	2.69	3.00	3.76

*Probe tip radius 5µm, cut-off wavelength λ_c = 0.25 mm, evaluation length l_m = 1.5 mm

To recapitulate the gear quality issue, the quality of the prototype P/M gears matches the quality of hobbed wrought steel gears in respect of tooth profile, tooth alignment, pitch and surface finish. The run-out deviation could easily meet quality AGMA 9 (DIN 8) by performing common machining operation such as bore turning. For many gears in agricultural- and household appliances, industrial medium speed gear drives and medium-duty automotive transmissions the sinter-hardened high-density P/M gears meet the quality requirements as pressed and sinter-hardened. This opens up for cost savings thanks to fewer manufacturing operations and better materials utilization.

FATIGUE PERFORMANCE

The service life of a medium or high-performance gear is commonly limited by its fatigue strength against tooth root bending failure or tooth flank pitting. A tooth root bending fatigue failure occurs suddenly and as a rule leads to failure of the whole transmission. In contrast, the tooth flank pitting develops more gradually and can be detected by an increase in the noise level. Experimental evaluation of the tooth bending strength is often carried out using pulsator- or gear transmission rig tests. The pulsator tests are conducted on standard fatigue material testing machines, with simple test design and low cost. They are therefore often used for evaluation of geometry-, manufacturing- and materials effects.

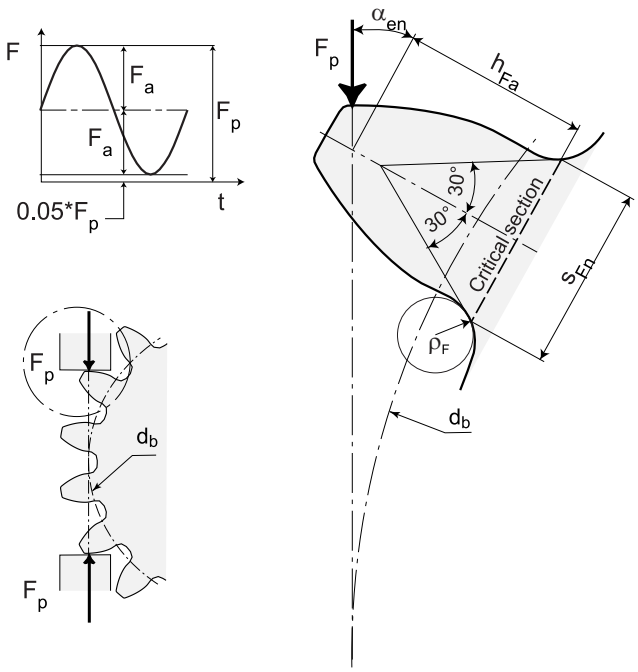
The prototype gears in this study were tested by means of a tooth bending fatigue test. The tests were conducted on a standard servohydraulic material testing machine (Figures 5-6), with dynamic load capacity of ±20kN (4500 lbs). Test load frequency and test nominal (maximum) force ranged from 10kN (2250 lbs) at 15Hz to 2 kN (450 lbs) at 60 Hz. The loading profile was sinusoidal with $R = F_{min}/F_{max} = 0$, but a 5% pre-load was applied to prevent slipping between the load anvils and the gear flanks. Three to five tests were conducted on each test gear.

S-N curves were determined based on approximately 20 test runs. Test runs that experienced more than $3 \cdot 10^6$ load cycles without tooth failure were considered as run-outs. The tooth bending fatigue limit was evaluated using ArcSin√P method [14] for 50% probability of survival for the purpose of ranking these three gear materials and respective manufacturing processes.

The prototype gear was set up between the pulsator anvils in such a way that the load was applied near the tooth tip and the load direction tangentially to the gear base circle (Figure 5). The critical bending section in the tooth root was determined according to DIN3990 / ISO6336 [15] and so was the the calculation of the tooth bending stress. The tooth bending strength σ_F was calculated as the nominal tooth bending stress σ_{F0} at which 50% of the tested teeth failed / experienced run-out.

S-N curves showing the performance of the P/M prototype gears are presented in Figure 7. The sinter-hardened gears made from Astaloy CrM +0.4C reached an endurance limit of 700 MPa (101 ksi) and the sinter-hardened gear made from D.DH-1 +0.6C reached 630 MPa (89 ksi). Figure 6 shows a close-up of the test set-up and a typical appearance of a tooth fracture. In Figure 7, right, the durability of the P/M gears are compared to the durability of reference 1, a quenched and tempered wrought steel gear typically used for medium-duty applications. The performance of the tested P/M gears is similar to the performance of the quenched and tempered reference gear of wrought steel. Sinter-hardened P/M gears with high density can be a cost-efficient alternative to conventional gears made from quenched and tempered low-alloy wrought steel. Reference 2, represented by the case-hardened prototype gears made from 16MnCr5,

reached an endurance limit of 1270 MPa (184 ksi). This is almost twice the performance of the through hardened gears. The surface residual compressive stresses and the higher surface hardness achieved by case-hardening have a very positive effect on the gear durability. Therefore, case hardening and other surface hardening processes will play an important role in the development of P/M gears for the most demanding applications, such as automotive transmission gears.



Geometry data (tip contact)

s_{Fn} = 3.03 mm

h_{Fa} = 2.95 mm

ρ_F = 0.76 mm

α_{en} = 29.6°

Tooth root bending stress according to DIN 3990 / ISO 6336

$$\sigma_{F0} = \frac{F_p}{m_n\, b}\, Y_{Fa} Y_{Sa}$$

$$Y_{Fa} = \frac{6\,(h_{Fa}/m_n)\cos\alpha_{en}}{(s_{Fn}/m_n)^2 \cos\alpha_n} = 2.83$$

$$q_s = s_{Fn}/2\,\rho_F = 1.99$$

$$Y_{Sa} = (1.2 + 0.13\, s_{Fn}/h_{Fa}) * q_s^{(1.2 + 2.3\, s_{Fn}/h_{Fa})^{-1}}$$

$$Y_{Sa} = 1.63$$

Figure 5. Details of the prototype gear set-up between the pulsator's load anvils and calculation of the tooth root bending stress in the critical section when the pulsator load was applied near the tooth tip.

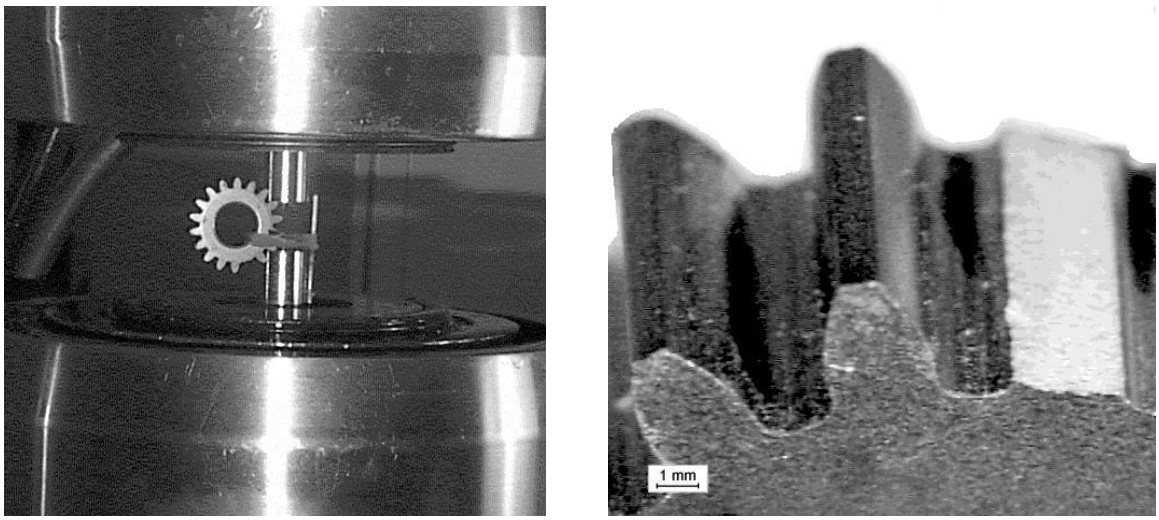


Figure 6. Close-up of test set-up (left) and tooth failure surface on the gear rim (right).

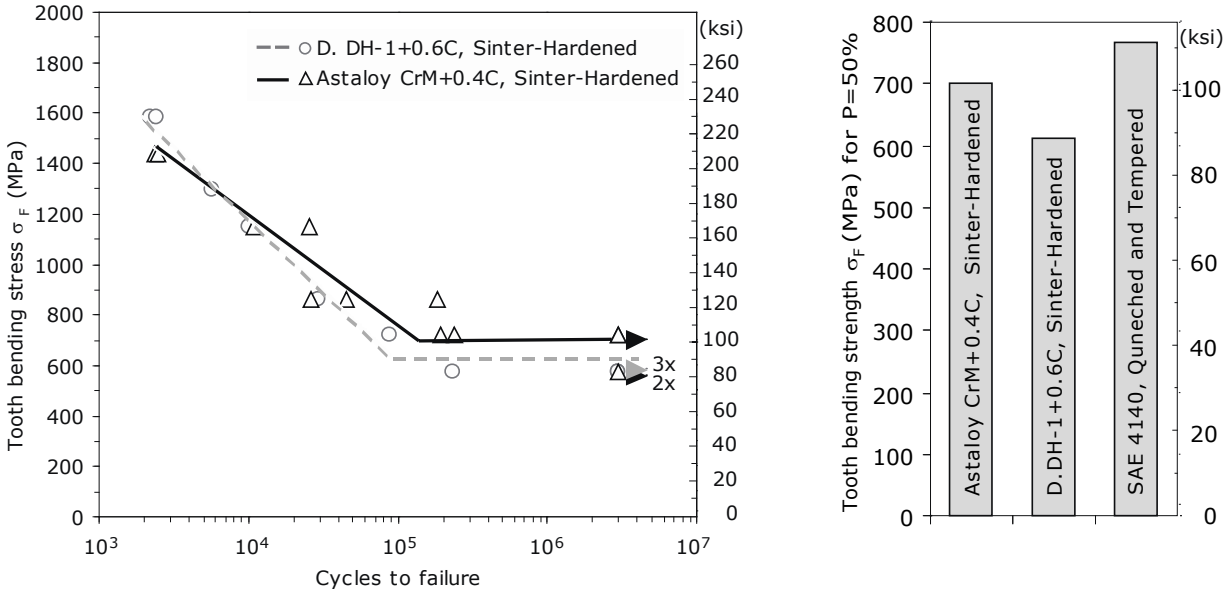


Figure 7. S-N curve for tooth bending fatigue testing of P/M prototype gears (left) and tooth bending fatigue limits for the prototype P/M gears and quench and tempered gears from low-alloyed wrought steel (this according to DIN 3990/5) (right).

CONCLUSIONS

In this investigation, the process, quality and performance of high-density sinter-hardened P/M gears and conventional wrought steel gears have been tested, evaluated and compared. It was concluded that:

- P/M gears can offer significant cost savings due to fewer manufacturing steps and better material utilization compared to conventional gears made of wrought steel.
- The quality of gear-profile, alignment and pitch of the high-density P/M prototype gears, as pressed and sinter-hardened, matched the gear quality of hobbed conventional gears from wrought steel.
- The surface roughness of the P/M prototype gears was about 30% better compared to wrought prototype gears as hobbed.
- The tooth root bending fatigue strength of sinter-hardened high-density (7.5 g/cm³) P/M prototype gears made from Astaloy CrM +0.4 C reached 92% of the corresponding gear-fatigue performance of a quenched and tempered low-alloy steel (SAE 4140).
- The tooth root bending fatigue strength of sinter-hardened high density (7.5 g/cm³) P/M prototype gears made from D.DH-1 +0.6 C reached 82% of the corresponding gear-fatigue performance of a quenched and tempered low-alloy steel (SAE 4140).

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