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EVOLUTION OF GEAR QUALITY IN HELICAL PM GEARS DURING PROCESSING

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ABSTRACT

A helical PM gear for a passenger car gear box was manufactured by pressing, sintering and selective surface densification using transverse rolling. The evolution of gear properties in terms of microstructure, geometry, surface roughness and DIN-quality is monitored at each step of the processing sequence. The geometry of the PM gear is compared to a conventional wrought steel gear being currently used in the gear box. It is shown that PM gears can be manufactured well within the DIN "quality 8" tolerance fields. Furthermore it is demonstrated that alignment and profile errors can be reduced in the sequence of processing. While wrought gears have less alignment and profile errors, PM gears are superior in terms of run-out and pitch errors as well as surface roughness.

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KEY WORDS

PM gear, surface densification, transverse rolling, gear quality

INTRODUCTION

Gears are key structural components in modern driving technology. The main object of a gear is the reliable and silent transmission of torque. Typically, gears undergo pulsating stresses during engagement which peak at or slightly beneath the surface of the component and thus require high strength and wear resistance primarily in areas at or close to the surface. In addition to basic strength requirements low noise is mandatory for many gear applications. The emission of noise is basically determined by (i) dimensional quality of the gear and (ii) topography and surface roughness. Inaccuracies of the gear geometry and/or assembly can significantly reduce service life, load bearing capability and increase noise. Thus a high geometric quality is generally required for gears in gear box applications, typically better than DIN 7. In addition to strength and noise requirements there is also an increasing demand for improved economic performance. It has been shown recently that advanced PM processing has the potential to produce highly loadable gears which are both, cost efficient and sufficiently strong [1-4].

In the past years it has been demonstrated that transverse rolling which selectively increases the density at the surface of sintered gears, yet preserves porosity in the core, is very promising to improve noise properties and, simultaneously, to supply sufficient strength. Transverse rolling can produce a fully densified surface layer, typically up to a depth of ≈ 0.5 [1-4]. The present work is intended to characterize the evolution of microstructure, geometry, and quality of a helical gear along the PM processing route outlined



Fig. 1: PM gear (left) and conventional helical gear (right) with inner spline used as a fixed gear in a standard gear box.

Gear Parameter	unit	finished gear
Number of teeth z	-	31
Normal module m	mm	1.6
Pressure angle α	°	20
Helix angle β	°	30
Helix direction	-	left
Shift coefficient	-	-0.2215
Outside diameter d_a	mm	60.16-60.55
Root diameter d_r	mm	51.31-51.70
Measure over 2 balls (Mdk)	mm	61.567-61.600
Nominal pitch diameter d	mm	57.273

Table 1: Geometric details of finished helical gear from Fig. 1

EXPERIMENTAL

The gear under investigation is the helical gear shown in Fig. 1. The wrought steel version of this gear is presently used as fixed gear in the 5th speed of a passenger car gearbox. This gear features an internal spline and a 30° helix. Its characteristic parameters are summarized in Table 1.

MATERIAL SELECTION

The materials selection was based on previous processing experience (compaction and rolling tests) and on rolling contact fatigue tests [5,6]. From this information a commercial water atomised, pre- and diffusion alloyed powder (Distaloy DC1, Höganäs AB, Höganäs, Sweden), with 1.5 wt.% Mo (prealloyed) and 2.0 wt.% Ni (diffusion bonded), premixed with 0.15 wt.% graphite and 0.6 wt.% Kenolube, was chosen.

PROCESSING AND TOOLING

The processing sequence employed in the present investigation is:

- Pressing of gear with overmeasure
- Sintering to 90-92 % of theoretical density
- Selective densification up to 100% density of regions close to the surface by transverse rolling.

Subsequent processing steps such as case hardening and final surface finishing have as yet not been completed and are the subject of ongoing work. It is important to note that one of the key challenges in producing a surface densified gear is the proper tuning of tools for pressing and rolling. This requires production of a gear with precise overmeasure before rolling such that (i) a sufficient densification depth of > 0.5 mm is obtained and (ii) the geometry of the gear is within the required tolerances after rolling and hardening.

The gear preform, i.e. the gear geometry *before* rolling, which includes the overmeasure at flank and root, was determined by calculation, see also [7]. Furthermore tests were performed prior to pressing and sintering, to evaluate the dimensional changes due to pressing (spring back) and sintering (shrinkage). Finally, all shape changes exerted by pressing, sintering and rolling were combined to define the dimensions of the pressing and rolling tools. Pressing was performed at 600 MPa on a hydraulic 350 to press which is equipped with a gear-box driven adapter to rotate the die components. Using a 30° helix angle (Table 1), pressing is close to the self blocking condition, such that careful set-up of the punch moving unit is required. With this set-up, very uniform components were obtained as illustrated by a weight scatter of less than ±0.5% (measurement of 50 gears).

Sintering was subsequently performed at 1120 °C for 30 mins. on ceramic plates in a standard belt furnace under endogas. The carbon potential in the furnace was closely controlled to keep the carbon content of the gears close to its initial level. All gears were slowly cooled from sintering temperature at a cooling rate of ≈ 0.2 Ks^{-1}. The average density of as-sintered gears is very uniform, i.e. 6.96-7.0 g/cm³ in the core region. After sintering, the gears were selectively densified on a circular force controlled rolling machine. In this process, an as-sintered gear with overmeasure is put into the centre between two mating rolling tools until the tool and the gear get into contact. Subsequently, the load is applied and the tools densify the gear surface until a pre-set centre distance has been reached.

CHARACTERIZATION

The microstructure of the materials was studied on as-polished and etched microstructures by light microscopy. A 3 vol.% alcoholic solution of nitric acid was used as etchant. The hardness was measured according to DIN ISO 4498 (part 1) using a 2.5 mm Brinell ball at a load of 62.5 kg. The gear quality was measured according to DIN 3961/3962 [8,9]. All measurement were performed on a Zeiss measuring machine. The helical gear was fixed in the measuring unit by clamping on the inner diameter and subsequently aligned along the inner spline. The following data were assessed:

(1) Total profile error, F_a
(2) Profile angle error, f_{Ha}
(3) Profile form error, f_{fa}
(4) Total alignment error, F_b
(5) Tooth alignment error, f_{Hb}
(6) Long alignment error, f_{fb}
(7) Radial run-out, F_r
(8) Cumulative pitch error, F_p

RESULTS

MICROSTRUCTURE

Consistent with the slow cooling rate and the low carbon content (≈ 0.15 wt.%, Table 2), the major microstructural constituents are ferrite and upper bainite, although some Ni-rich austenite areas are also detected (Fig.2). The microstructure after sintering is fairly homogenuous, which is reflected by the constancy of hardness and carbon-content distribution as shown in Table 2.

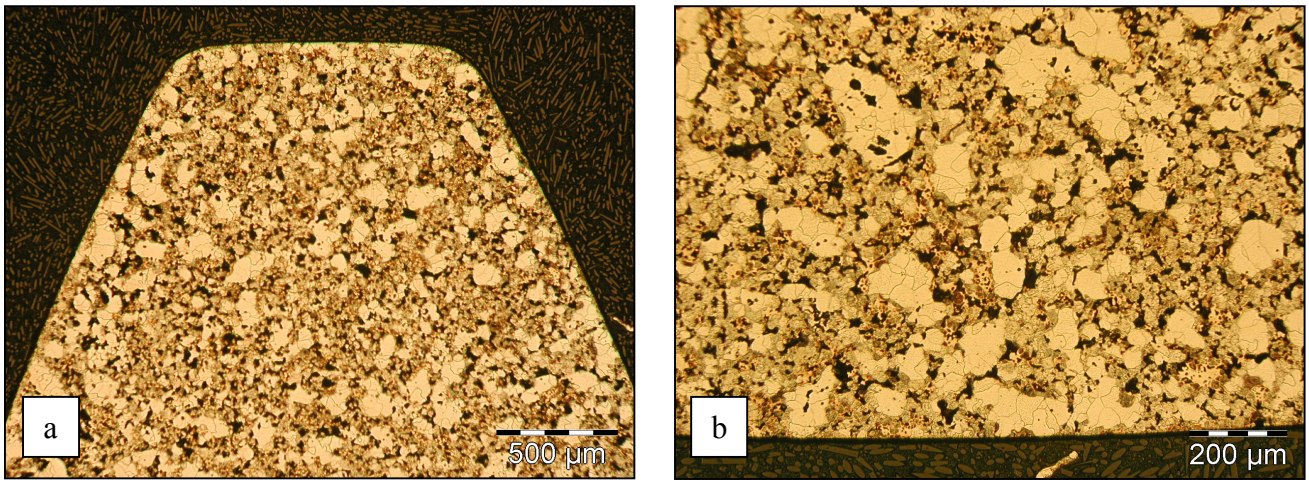


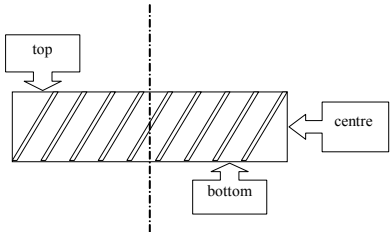
Fig. 2: Microstructure of sintered gears: ferrite (light), bainite (dark) and small fractions of Ni-rich austenite: (a) tooth tip region, (b) flank region

GEAR QUALITY

After each processing step the typical dimensions and gear errors were measured as described in section 2. Typical data records for tooth alignment and tooth profile of as-pressed gears are displayed in Figs. 3 a,b. The tooth geometry and the tooth quality were evaluated in the as-pressed, as-sintered and as-rolled condition and compared with data from a finshied conventional wrought gear. Detailed results are shown in Tables 3 a,b. It should be noted that all data are referenced to the *final* gear geometry. Furthermore decreasing DIN quality numbers and decreasing deviations in Table 3a indicate increasing gear accuracy.

Table 2: Hardness and carbon content after sintering with definition of measuring point

Location in the gear	Hardness HB 2,5/62,5	C-Content, wt. %
top	122	0.14
centre	116	0.16
bottom	122	0.15



GEAR PROFILE AND ALIGNMENT

The pressing tools have a quality of DIN Q5. After pressing the gear has the following characteristics: while small errors are observed for run-out and pitch, which essentially reflects the die quality, errors corresponding up to DIN quality 10 are discovered for the gear profile and alignment (Table 3a). Though on first sight this finding seems to be alarming, it should be recalled that the quality specifications in Table 3a correspond to the *final* gear geometry rather than to the geometry of the pressing tool. In fact gear quality after sintering would be on the order of Q6 when referenced to the geometry of the pressing tool.

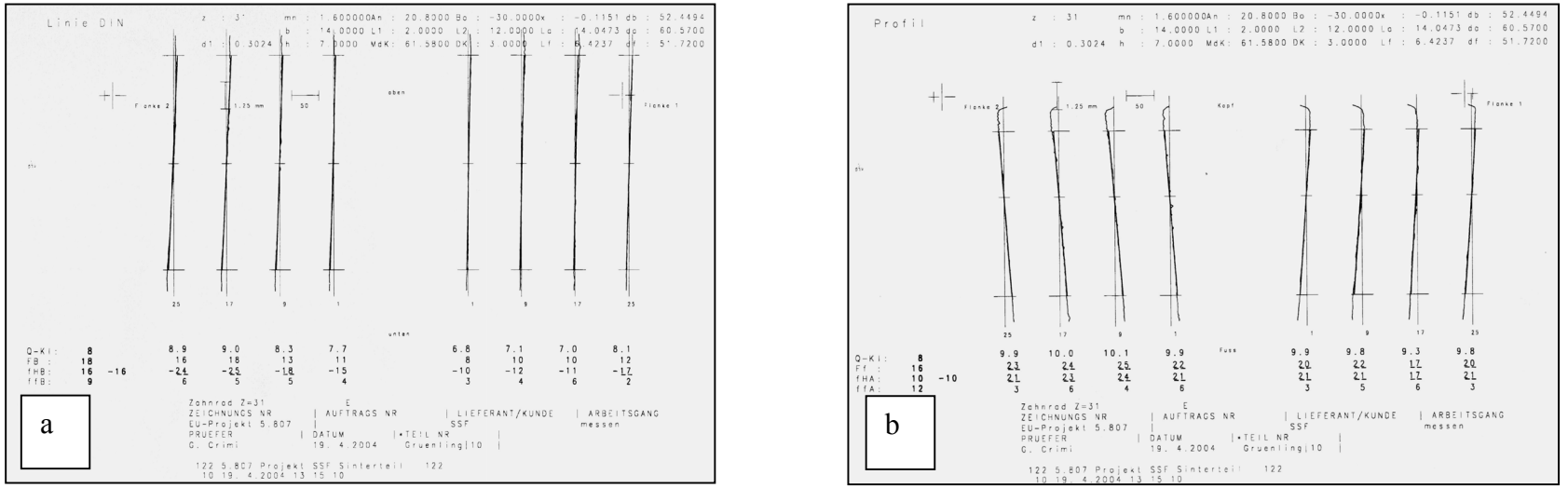


Fig. 3: Gear quality measuring protocols: (a) alignment inspection, (b) profile inspection

Table 3a: Gear error data after pressing, sintering and rolling compared with quality of finished conventional wrought gear.

Gear Error	Dimension	Max. dev. for DIN Q8	as-pressed	DIN Quality	as-sintered	DIN Quality	as-rolled	DIN Quality	wrought gear*	DIN Quality*
total profile error F_a	µm	16	25		10		14		21	
profile angle error f_{Ha}	µm	± 10	24	10	-4	6	-11	8	-14	9
profile form error f_{fa}	µm	12	6		9		5		17	
total alignment error F_b	µm	18	17		28		16		26	
tooth alignment error f_{Hb}	µm	± 16	-25	8	-41	10	-21	8	34	9
long. alignment error f_{fb}	µm	9	6		9		10		11	
radial run-out F_r	µm	32	16	6	17	7	12	5	25	8
cum. pitch error F_p	µm	50	15	5	19	6	13	4	41	8

*) wrought gears are phosphatised

During sintering the tooth alignment deteriorates slightly while the profile improves, basically due to improvements in profile angle error. Taking these deviations into account, a set up for the rolling operation can be developed which compensates both alignment and profile errors, without declining the pitch and run-out properties. Specifically, the profile adjustment can be influenced by the geometry of the rolling tool and the rolling parameters. In fact, as documented in Table 3a, proper set-up of the rolling process allows improvement of alignment without loosing much in profile errors.

Further progress is expected from a systematic improvement of rolling parameters and rolling tools. It must be remembered, however, that case hardening as the final processing step will most likely deteriorate the gear quality. It is the goal of ongoing development to characterize the distortions associated with hardening, and to account for these effects already during rolling such that finished gears with high quality can be obtained. As can be seen from Table 3a, gear qualities in the range of DIN 8 can be expected.

DISTORTION

As shown in Table 3b, there is a considerable deviation of as-sintered gears from the final dimensions. It should be recalled that this is due to the intended overmeasure required for balancing the volume loss which occurs during surface densification. After rolling, the geometry of the gear is a little off the final dimensions, but it is presumed that these shortcomings can be accounted for by adapting the geometry of the press tooling.

Table 3b: Major gear dimensions after pressing, sintering and rolling

Gear Dimension	Dimension	Specification	pressed	sintered	rolled	wrought
Measure over 2 balls (Mdk)	mm	61.567-61,600	61.679	61.533	61.401	61.457
Root diameter d_f	mm	51.310-51.700	51.854	51.712	51.622	51.524
Tip diameter d_k	mm	60.160-60.550	60.711	60.534	60.612	60.369

SURFACE ROUGHNESS

The surface roughness of PM gears after rolling is significantly better than for finished wrought steel gears, c.f. Table 4. There is a little increase of roughness from pressed to sintered part followed by a decrease of roughness after rolling..

Table 4: Surface roughness of PM gears and conventional wrought steel gears

Roughness parameter	Dimension	as-pressed	as-sintered	as-rolled	wrought gear after shaving
R_a	µm	0.38	0.41	0.20	0.46
R_z	µm	2.08	3.35	1.35	2.55
R_k	µm	1.30	0.72	0.64	1.19
R_t	µm	3.02	5.94	1.79	3.32

CONCLUDING REMARKS

In this investigation, the evolution of gear quality as a function of processing has been investigated for helical PM gears and compared to the quality and properties of a conventional wrought steel gear. Though the investigation of the total process line has as yet not been finished, i.e. the

evaluation of gear quality after case-hardening is the subject of ongoing development, the following conclusions can be drawn:

- After rolling, the quality of selectively densified PM gears reaches a quality level of DIN Q8, which is comparable to the quality of shaved conventional gear made from wrought steel.
- PM gears are comparable in terms of tooth profile and tooth alignment, yet obtain better quality in radial run-out und cumulative pitch error.
- The surface roughness of as-rolled PM gears is better then for conventional gears.

The impact of case hardening has yet to be assessed. It is expected that adaption of the rolling process will suffice to account for distortions due to case hardening. The results of this investigation will be addressed in a forthcoming paper.

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