Surface densified P/M gears made of chromium alloy powder reach automotive quality

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ABSTRACT

A final-drive idle helical gear from a passenger car transmission was made of water atomized and fully pre-alloyed Fe-1.5Cr-0.2Mo powder. The gear samples were cold compacted to 7.1 g/cm^3, sintered, surface densified by radial gear rolling and casehardened. A 3D gear measurement center was used to evaluate profile, alignment, pitch and runout deviations of the gears after the gear rolling and after the casehardening. The gears achieved an overall DIN 7 quality after rolling for all single deviations suggested in DIN 3961 to have general or particular importance for uniformity of rotation, load capacity and noise reduction of gear. After the low-pressure casehardening, the overall gear quality for the deviations as above was DIN 7, except for the total profile deviation F_α, which achieved DIN 10 quality. To achieve DIN 7 gear quality after casehardening, further work should include activities on reduction of the tooth width contraction along the tooth height.

INTRODUCTION

Gear quality DIN 7 or higher is one of main demands which automotive industry put on transmission gears. DIN 7 gear quality may be understood as a compromise between the total gear manufacturing cost and the gear performances including service life, load capability and noise-vibration-harshness properties. The two former gear performances have been improved by better steels and improvements in heat treatment and after treatment, while the latter has been approached using different strategies. The most straightforward is to improve the geometry of the gear itself, meaning better DIN classes.

P/M gears with sintered density of 7.1 g/cm^3 manufactured by using pressing-sintering-hardening routes usually achieve gear quality no higher than DIN 10 [1]. Improvements can be gained by increasing the sintered density by means of warm compaction combined with second pressing [1] or high velocity compaction combined with sinter-hardening [2]. However, one, or a few finishing operations appears to be necessary to achieve DIN 7 gear quality. Soft finishing operations such as rolling or shaving, which are conducted before heat treatment, can be the last machining if followed by a hardening process, which keep the gear quality inside of the gear quality specification. The hardened gears are however often hard finished by grinding or honing to achieve DIN 7 gear quality.

Among a variety of soft-finishing technologies, gear rolling is considered as a forming operation with high productivity, capable to fine tune the gear flank form after hobbing/cutting and reduce the flanks' surface roughness [3]. Considering P/M gears, the gear rolling gains a new dimension – possibility to create a full-dense gear flank from the surface up to a certain depth while the core remains at the base density level [4]. Such densified layer will then be able to carry the high contact pressures at the gear flanks or the high bending stress gradients in the root fillet [4]. A number of reports provide more comprehensive information about gear surface [5-9] Paper [10] shows recent achievements in quality and tooth root load capacity of a spur and a helical P/M prototype gear for P/M automotive transmissions.

The gear quality deviations need to be briefly described before they are discussed. They are grouped into gear flank line, profile, pitch and runout deviations. In fact, the measured flank line is enveloped by two equidistant nominal lines and inspected for the line's form deviation $f_{f\beta}$, angular deviation (slope) $f_{H\beta}$ and total deviation F_β (Figure 1 left). Often, the flank line deviation is called as "helix deviation". Gear flank profile deviations describe how the flank profile deviate from the nominal involute flank profile including profile top correction (crowning). The deviations are analogously defined to the flank line deviations with the difference that the measured profile line is enveloped by two equidistant nominal involutes and inspected for the profile's form deviation $f_{f\alpha}$, angular deviation (slope) $f_{H\alpha}$ and total deviation F_α. Pitch deviations describe variation of the pitch - distance between adjacent tooth flanks (Figure 1 right). The pitch deviations are: the single normal pitch deviation f_u, the difference between adjacent pitches f_p, the total cumulative pitch deviation F_p, and cumulative circular pitch error over z/8 pitches $F_{pz/8}$. Run-out deviation F_r describes eccentricity between the gear pitch diameter and the bore of the gear rim.

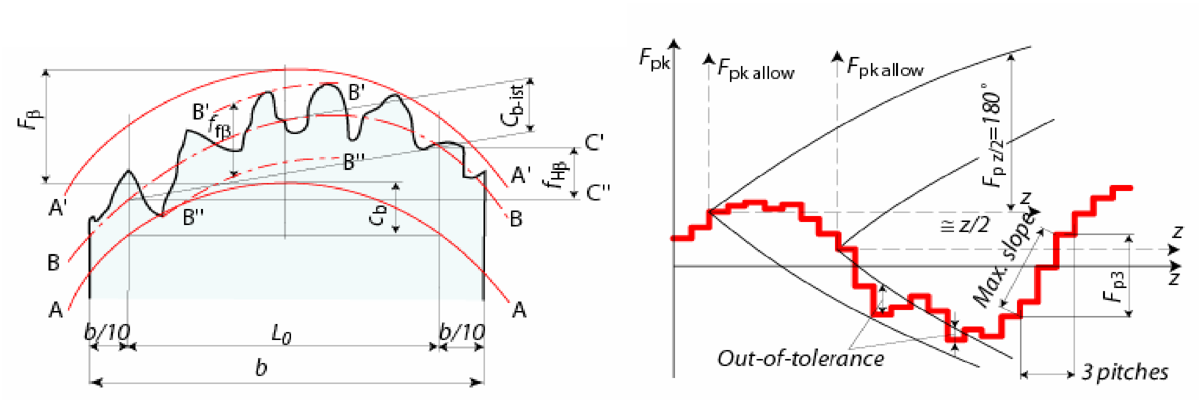

Figure 1 Gear flank line (left) and pitch deviations (right) [11].

The P/M gear-manufacturing route for the commercial variant of the test gears in this investigation will comprise pressing, sintering, rolling, casehardening and bore grinding. Gear pressing is done in dies with a very high geometrical quality. The bore eccentricity caused by the tooling core clearance, sintering and heat treatment distortions is present but is later eliminated by the bore grinding. The gear rolling itself is an involute generating operation so that the pitch deviations of the rolled P/M gears are very small due to a high accuracy of the rolling dies. In the same way, there are good prerequisites for small profile and flank deviations. However, this must be considered together with local inconsistency of the surface material displacement along and across the tooth flank due to local variations in the porosity distributions. On the other side, local flank line and profile deviations, if they exist, may have a minor effect on the profile and flank line slopes, $f_{H\alpha}$ respective $f_{H\beta}$.

A very particular chapter of gear engineering is running-in. The running-in cannot be prevented from happening, and it normally improves the gear quality.

Another aspect of the gear quality is the surface roughness of the gear flanks. In particular, this 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 beneficial to fatigue strength of the tooth root.

This paper focuses on P/M gears with sintered density of 7.1 g/cm^3 which were surface densified by radial gear rolling to achieve the performance level required by the automotive industry but at a lower total cost for the gear manufacturing. The aspects of gear quality will be discussed in some detail.

EXPERIMENT

A final-drive idle helical gear from a passenger car transmission was manufactured by pressing-sintering-machining-rolling-case hardening route. The gear and its manufacturing were described in more details in [10], but the gears need to be briefly described here for the scope of this investigation. The gears were pressed from a mix of Astaloy CrL (Fe-1.5Cr-0.2Mo) with addition of 0.2 wt% carbon and 0.8 wt % amide wax. Astaloy CrL is a water atomized iron powder in which chromium and molybdenum are fully pre-alloyed. The powder is completely nickel–free and provides high compressibility with near-zero dimensional change after sintering. The sintered components made of this powder gain high yield strength and high hardness and are suitable for applications with medium-range demands.

To avoid high tooling cost for this gear prototype manufacturing, simple Ø80x25 mm cylindrical pucks were pressed using a 4 MN hydraulic press. The pucks were sintered in a belt furnace at 1120°C for 30 min. in 90% N_2/10% H_2 atmosphere with carbon potential of 0.2%. Gear blanks ready-for-rolling were then machined by turning of the faces, the OD and ID followed by gear hobbing. The blanks were rolled using a CNC cold rolling machine with two rolling dies (Escofier H20 CN) suitable for forming threads, knurls, splines or other profiles, and burnishing screw threads and gear wheels. Finally, the rolled gears were low-pressure carburized using acetylene at 960 °C for 8 min. exclusive diffusion periods of time, and subsequently quenched using nitrogen gas with a pressure of 10 bars. The heat-treated parts have a martensitic microstructure in the surface and the structure in the core is bainitic with a small amount of low carbon martensite. The case depth achieved after case hardening is 0.55 mm/550 HV0.1 on the flanks.

Number of teeth	z_2	28
Module	m_n	2 mm
Pressure angle	α_n	15°
Helix angle	β	32°
Face width	b	18.7 mm
Addendum modif. coeff.	x	0.137
Counter gear number of teeth	z_1	40
Axis distance	a	80 mm

Table 1. Test gear geometry

Figure 2. Test gear

Figure 2 shows a photograph of the test gear and Table 1 lists the test gear geometry.

The quality of the gears in this study was evaluated by measurement of the gear geometry and the surface roughness of the gear flanks. Measurement of the gear geometry deviations was conducted on a commercial 3D CNC gear measuring center according to the according to DIN-standards [11],[12] using a 1.0 mm ruby stylus.

RESULTS AND DISCUSSION

Table 2 lists gear quality single deviations of the gears after rolling and after casehardening. As seen, the quality for single deviations has quite a large variation both between rolled and casehardened gear condition and between single deviations and their groups. The pitch deviations are all in DIN 6 or higher quality class. This is fully in accordance with the gear teeth generating aspect of the gear rolling. The helix deviations vary between DIN 6-9 quality both after rolling and after casehardening. The profile deviations meet DIN 6-7 after rolling but DIN 8-11 after casehardening. Obviously, the profile deviations experienced the largest quality drop.

Deviation	Symbol	After rolling	After case-ardening	General importance	Rotational uni-formity	Load capacity
Profile form deviation	$f_{f\alpha}$	7	8			
Profile angular deviation	$f_{H\alpha}$	7	11			
Profile total deviation	F_{α}	7	10	Yes		Yes
Helix form deviation	$f_{f\beta}$	6	6			
Helix profile deviation	$f_{H\beta}$	7	7	Yes		Yes
Helix total deviation	F_{β}	7	9			
Single normal pitch deviation	f_u	6	6			
Difference between adjacent pitches	f_p	6	6			Yes
Total cumulative pitch deviation	F_p	5	6		Yes	Yes
Cumulative circular pitch error over z/8 pitches	$F_{pz/8}$	5	6			
Tooth thickness variation	R_s	2	5			
Runout tolerance	F_r^*	-	-		Yes	

*The gear measuring centre evaluated the run-out deviation Fr, according to teeth geometry neglecting the real bore eccentricity, which need to be adjusted by using bore grinding or similar machining.

Table 2. Gear quality single deviations of the gears after rolling and after case-hardening according to DIN 3960, 3961 and 3962.

Trying to express a general quality class for such gears could give very doubtful assessments if one try to consider a deviation with the lowest quality class or some kind of mean quality class. DIN 3961 [11] suggests a way to assess how the single gear deviations influence the gear performances. Right part of Table 2 indicates the general and particular influence of single gear deviations on uniformity of rotation, load capacity and noise-vibration-harshness properties of a gearbox.

By assessing in this way, the gear quality after rolling was DIN 7. After case-hardening, the gear quality was still DIN 7 except for four of the measured deviations. The total profile deviation F_{α}, reached quality DIN 10. In the profile angular deviation, $f_{H\alpha}$, also known as profile slope, one can see the quality change from DIN7 to DIN11, the largest quality change among all the deviations. The profile form deviation dropped one quality class from DIN 7 to DIN 8. However, looking at several measurements this may not be a general trend, but rather an isolated event due to debris on the surface. The last deviation to drop after heat treatment is the helix total deviation, F_{β}, which drops two quality classes to DIN 9. However, the helix profile deviation, $f_{H\beta}$, remains in DIN 7, but the average value move from one end of the tolerance band (6,65 μm) to the other (7,5 μm). The tolerance band is ±11 μm for DIN 7.

Such a large flank profile quality decrease needs to be discussed in more detail. Figure 3 shows typical involute profiles of the test gears after gear rolling and after casehardening.

The tooth thickness decreases, especially near the tooth tip. During the rolling, the surface layer is deformed plastically. This material will exhibit compressive residual stresses after rolling. These stresses are balanced by tensile stresses in the core. The tensile stresses in the core are balanced by the compressive stresses in the deformed surface layer. Since the cross section decreases towards the tooth tip and the deformed layer that has approximately constant thickness, the tensile stresses must increase in this direction. During heat treatment, these stresses are released resulting in a shorter (0,015 mm) and thinner tooth. This increase in flank slope is characteristic of the rolling and heat treatment processes used. This means that the deviations can be compensated for during the rolling process.

The helix deviations have the same origin as the profile deviations described above, the helix tries to unwind, thus decreasing the helix angle. This phenomenon can also be compensated for during the rolling process.

In additions to these systematic deviations, there are of course deviations that can be considered stochastic processes that cannot be compensated for by changes in geometry before heat treatment. These deviations must be limited by proper material and process control.

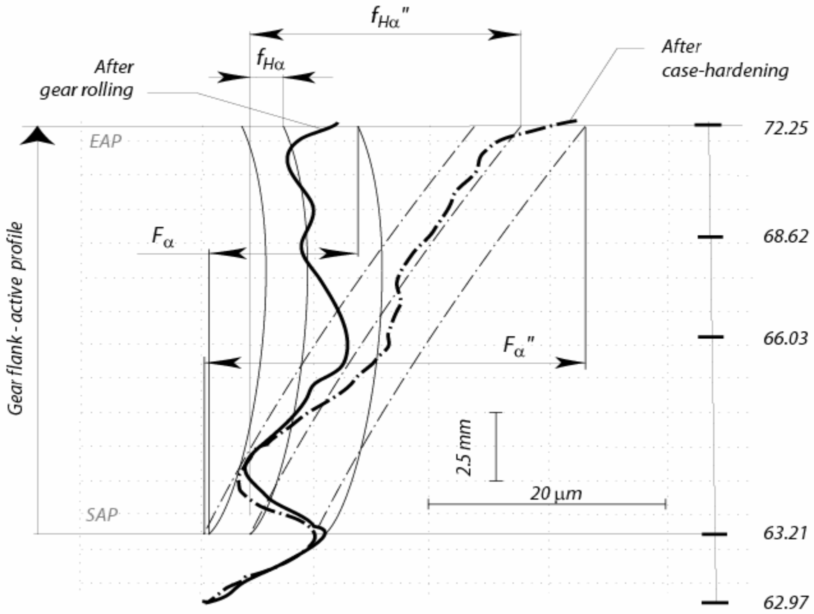

Figure 3. Typical involute profiles of the test gears after gear rolling and after case-hardening. The profile curves belong to the same gear flank, and they were drawn over the scanned profiles from the gear measuring center chart. SAP stands for start-of-active-profile and EAP stands for end-of-active-profile of the gear tooth flank.

This report focused on a quality issue of the P/M transmission gears for automotive applications. The higher gear quality the higher gear performances - it is a widely accepted motto in the automotive industry. However, the investigation [13] showed the load capability of a gear/gear pair might depend more on the gear basic geometry parameters and the particularity of the gear application, than on the single gear deviations. In particular, this was observed on the final drive gears with a large helical angle like the gear in this investigation.

Surface roughness of the test gears.		
Roughness parameter	P/M (rolled)	Wrought reference (ground)
Arithmetic mean profile height R_a (µm)	0.16±0.02	0.25±0.12
Root-mean-square profile height R_q (µm)	0.21±0.02	0.34±0.17
Ten-point-height of the profile R_z (µm)	0.94±0.12	1.47±0.83
Maximum profile height R_{max} (µm)	1.29±0.37	2.40±1.80
Measured with a sliding shoe-type roughness tester, using cut-off filter λ_c = 0.25 mm.		

Table 3. Surface roughness of the test gear flanks

Another aspect of the gear quality is surface roughness of the gear flanks. Table 3 lists surface roughness of the test gears. Both mean, R_a and R_q, and extreme value parameters, R_z and R_{max}, are approximately 30% lower for the rolled P/M gear in comparison with ground wrought reference gear. This confirmed the finding of the previous works [3],[10].

CONCLUSIONS

Surface densified P/M transmission gears were produced by pressing, sintering, machining, rolling and casehardening. The gears were measured according to DIN standard and following conclusions were reached:

- The gears achieved an overall DIN 7 quality after rolling for all deviations suggested in DIN 3961 to have general or particular importance for uniformity of rotation, load capacity and noise reduction of gears.
- After the low-pressure casehardening, the overall gear quality for the deviations as above was DIN 7, except for the total profile deviation F_α, which was DIN 10 quality.
- To achieve DIN 7 gear quality after casehardening, further work should include activities on compensation for or reduction of the tooth width contraction along the tooth height.

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