ADVANCED FORMING PROCESS FOR HIGH DENSITY PM GEARS

S. Bengtsson, L. Fordén and P. Skoglund

Höganäs AB, SE-263 83 Höganäs, Sweden

ABSTRACT

Powder metallurgy is a well-established technology for manufacturing a variety of complex shaped parts in the gearbox of a passenger car. However, using standard PM technology it is not possible to reach the mechanical properties necessary for gear components. Combining the net shape capability of powder metallurgy and cold forming by a burnishing operation provides a method of producing transmission gears for automotive gearboxes at a low cost with mechanical properties equivalent to conventionally produced gears. Powder and process selection is discussed, including the influence of core density on densification and quality. The mechanical performance of a helical and a spur gear are compared to their respective reference gears made of case hardening steels. The endurance limit in tooth root bending fatigue testing of the surface densified helical PM gear reaches 94% of the reference material, while the surface densified spur gear reaches 106% of its reference gear. The gear quality of the two gears is DIN class 8 after heat treatment and the surface roughness of the gear tooth and root is R_a=1,2 μm.

KEYWORDS

Surface Densification, Transmission gears, Powder Metallurgy

BACKGROUND

Powder metallurgy is a near net shape process that is very cost effective for mass-produced steel parts. The parts can typically be found in engines and gearboxes in automotive applications. Syncronizer rings, syncro hubs, etc are parts normally manufactured by powder metallurgy. However, the most highly loaded parts have up till now not been manufactured by powder metallurgy. The reasons are twofold, the most important being that the loading of transmission gears and especially the contact loading are higher that what is acceptable for PM parts manufactured by standard process routes. The second factor that limits the use of PM gears in highly loaded applications is that these gears also require a very high geometrical quality. Typical profile shape errors are in the range of 10 μm (DIN

8). Since press dies are of very high quality these requirements can in part be met by standard techniques, but normally a correction must be performed. This correction can be in the form of shaving (soft) or grinding (heat treated). However, both these processes does not improve the strength of the gear. Cold forming in the form of gear rolling is a well-known technology for improving the shape and surface finish of solid steel gears. When applied on PM gears, rolling also enhances the fatigue properties since the density in the surface increases significantly. This technique, commonly termed surface densification, has been developed in order to increase the load bearing capacity of PM gears [1-6].

The driving force in the powder metallurgy community for the development of the surface densification technique is very strong since the number of parts that can be available for manufacture using this technique is very high. Among the more obvious applications are: transmission gears in manual gearboxes, planetary gears for automatic gearboxes, engine balancer shaft drive gears, sprockets and gears for valve timing systems, gears for high-end power tools, heavy duty gears in lawn and garden equipment, etc.

The process chain necessary for a surface densified gear can be slightly different depending on e.g. desired initial density. The most basic process is shown in Figure 1. The competitiveness of the process is very much controlled by the basic PM process step; compaction and sintering. It is these two steps that gives a cost advantage compared to conventional machining of bar or forged blanks. The remaining process steps including the rolling operation are normally also found in the conventional machining process. This means that there is a strong driving force to use simple cold compaction instead of double compaction double sintering or powder forging.

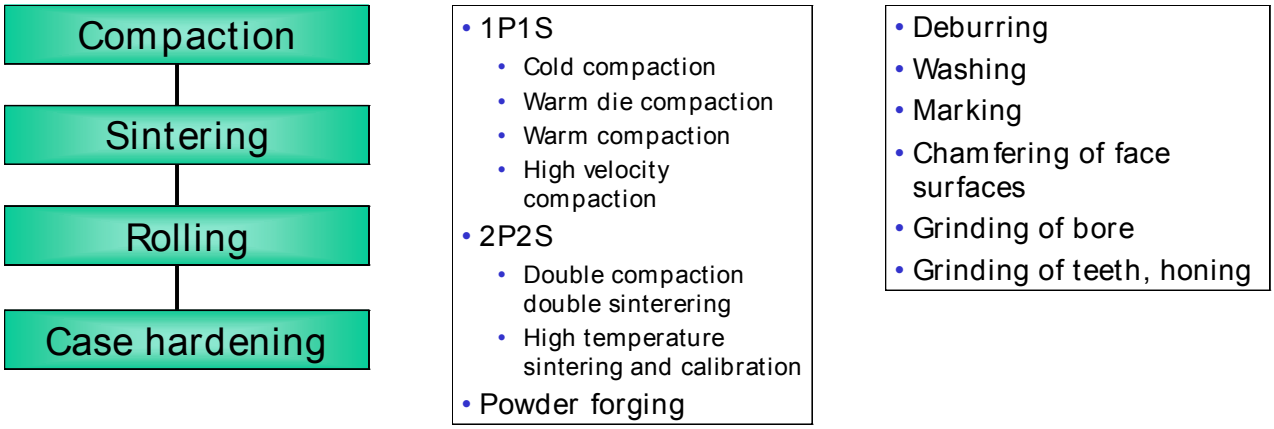


Figure 1. Process steps for the manufacture of surface densified gears. Left: Overview of process chain for surface densified gears. Middle: Different options for the compaction and sintering of preforms for surface densified gears. Right: Additional manufacturing steps normally found in a production scale process chain.

The present work aims at showing the possibilities of using surface densification as a secondary operation for improving the mechanical performance and geometrical quality to a level that is required for high performance gears. Furthermore, the influence of the initial density is discussed.

EXPERIMENTAL

Two gears are used in this investigation as shown in Figure 2. A helical gear in a manual gearbox for an automotive transmission and a spur gear in a planetary transmission in a heavy truck gearbox. The gear data are listed in Table 1. Both gears have very high requirements on geometry (gear quality) and fatigue strength.

TABLE 1
GEAR DATA OF THE SELECTED GEARS

Parameters		**Helical gear**	**Spur gear**
No of teeth	Z [-]	28	20
Helix angle	β [^{o}]	32	0
Module	m_n [mm]	2,0	3,65
Press angle	α_n [^{o}]	15,0	22,5
Addendum modicication coefficient	X [-]	0,136	0,471
Diameter over balls	M_e [mm]	74,46 Ball Ø: 4,25	89,350 Ball Ø: 3,5

The gears and rollers were rolled using HC20CN spline-rolling machine from Escofier Technologie SA, France. The machine is shown in Figure 3. It has two synchronized rolling dies that are usually rolled in one direction only. A normal rolling cycle consists of the loading phase, contact phase, force ramp-up phase, force holding phase and parts extraction phase. This means that the force is increased while rolling to a pre-set value and maintained there until the distance between rolling die centres reach a pre-set value or a pre-determined holding time is reached.



Figure 2. Left: Helical gear for manual transmission. Right: Spur gear in a planetary gearbox in the transmission of a heavy truck.

The materials used in this study are listed in Table 2. A high density in the pressed body is favourable for core strength, dimensional control and densification. Furthermore, the density distribution in a complex part like a gear is also improved by using a powder with high compressibility. During the rolling it is important that the yield strength is low and that the strain hardening is limited. A high yield strength means that the elastic deflections will be larger, making tool and gear preform design more difficult. A high strain-hardening rate means that the deformed areas will have a higher yield point, thus effectively increasing the volume that reaches plasticity. The result is a part with a less well-defined densified zone. The gears will be heat treated by case carburizing. This operation requires the ability to carburize to high carbon levels (0,8 wt.%) without oxidation or carbide formation. In this case the gears will be quenched in oil at 60 ^{o}C after the carburization and the hardenability must be high enough to obtain 100% martensite in the loaded/densified regions. The

structure in the core should be strong and tough, but it should have a higher specific volume compared to martensite. Bainite, pearlite and ferrite fulfil these requirements. The selected powder should be pre-alloyed and yet have a high compressibility. The admixed level of graphite should be low in order to maximize the compressibility of the powder mix. The carbon level in the as-sintered preform should also be low in order to provide a soft and formable material for the surface densification, which is in fact a cold forming operation. The powders listed in Table 2 all fulfil these requirements. From these mixes the mix no 1 was selected.



Figure 2. Rolling machine. Left: Overview, Right: Close-up of rolling tools dies with helical gear mounted for trials.

TABLE 2
POWDER MIXES FOR SURFACE DENSIFIED GEARS

Code	Base powder		Graphite	Remark
1	Astaloy 85 Mo	Fe-0,85Mo	0,25 wt.%	Gas carburizing, good compressibility
2	Astaloy Mo	Fe-1,5Mo	0,25 wt.%	Gas carburization, high hardenability
3	Astaloy CrL	Fe-1,5Cr-0,2Mo	0,25 wt.%	Vacuum carburization, Plasma carburization, low strain hardening rate

The powder was compacted into cylindrical slugs, sintered at 1120 ^{o}C for 30 minutes in an atmosphere of 90% N_2 and 10% H_2. The shape of the preformed gears is calculated to give enough material were densification is required as shown in Figure 4. A complication is that the material is not only compressed, but it also moves along the tooth surface as shown in Figure 3. Taking these factors into account the gear preforms were subsequently machined by turning and hobbing. In order to easier calculate the gear preform shape and the tool geometry a simulation of the densification process was developed. The geometry of the gears was measured by a Klingelnberg P26 gear measurement machine. The densification depth was measured by image analysis on metallographic cross section of the rolled gears. The densified layer is defined as the region starting at the surface and to a point were the porosity has increased to 2%. The surface roughness was measured by a Surfacscan 3CS.

The influence of initial density on densification process was investigated by performing densification tests on cylindrical slugs. Cylinders compacted to different densities were sintered and rolled a specific diameteral distance. The density profile and densified layer thickness were measured by image analysis.

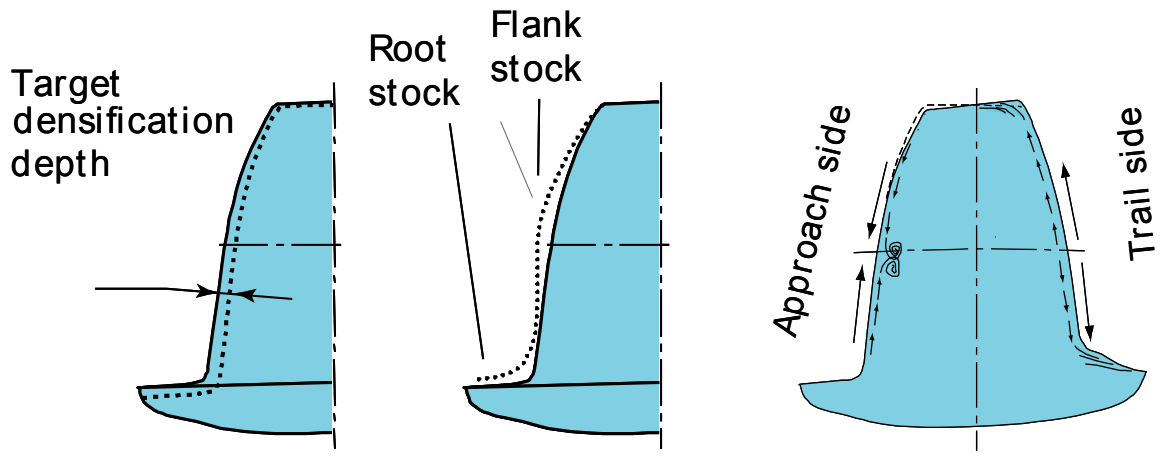


Figure 4. Left: Design of stock material for gear preforms for surface densification. Right: Material movement during surface densification

The heat treatments were conducted by gas carburisation in commercial equipment. The carburization temperature was 920 ^{o}C and it was maintained for 80 minutes at a carbon potential corresponding to 0,8 wt.%C. The material was quenched in a high pressure gas flow followed by a tempering operation at 160 ^{o}C in air for one hour.

The rolled and heat-treated gears were tested by tooth root fatigue testing in a pulsator test. The load ratio was R=0,1 and the run out limit were set to 3 million cycles.

RESULTS

The densified cyclinders are shown in Figure 5. It can be seen that the densified layer thickness is propertional to the initial density.

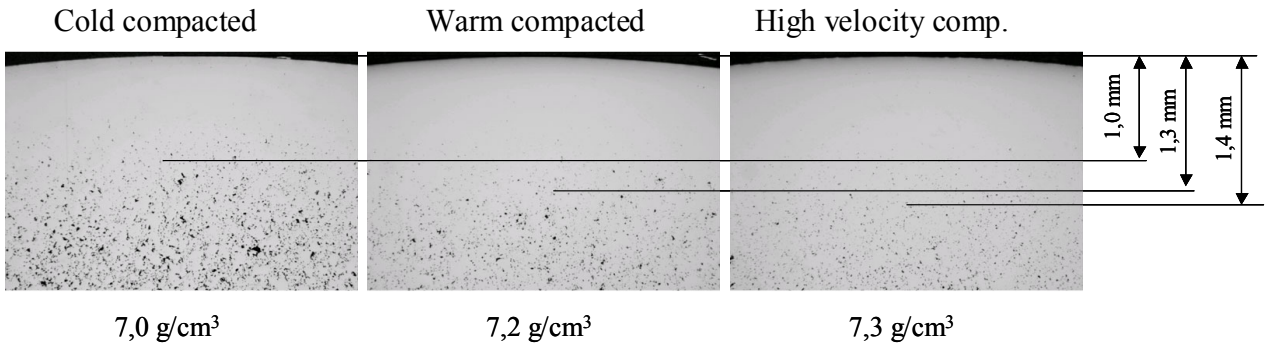


Figure 5. Micrographs of surface densified cylinders rolled to a diameter decrease of 0,3 mm. The densified layer thickness is measured by image analysis and is defined as the distance from the surface were the porosity has increased to 2%.

The results from the manufacturing of the gears are summarized in Table3. The densification is shown in Figures 6 and 7. The densified layer of the spur gear is 0,3 mm, virtually from the tooth top to the root. At the tooth top burr can be found. The densification of the helical gear is somewhat lower reaching a densified layer thickness of 0,2 mm. The teeth of this gear are long and slim giving a more compliant system during rolling compared to the spur gear.

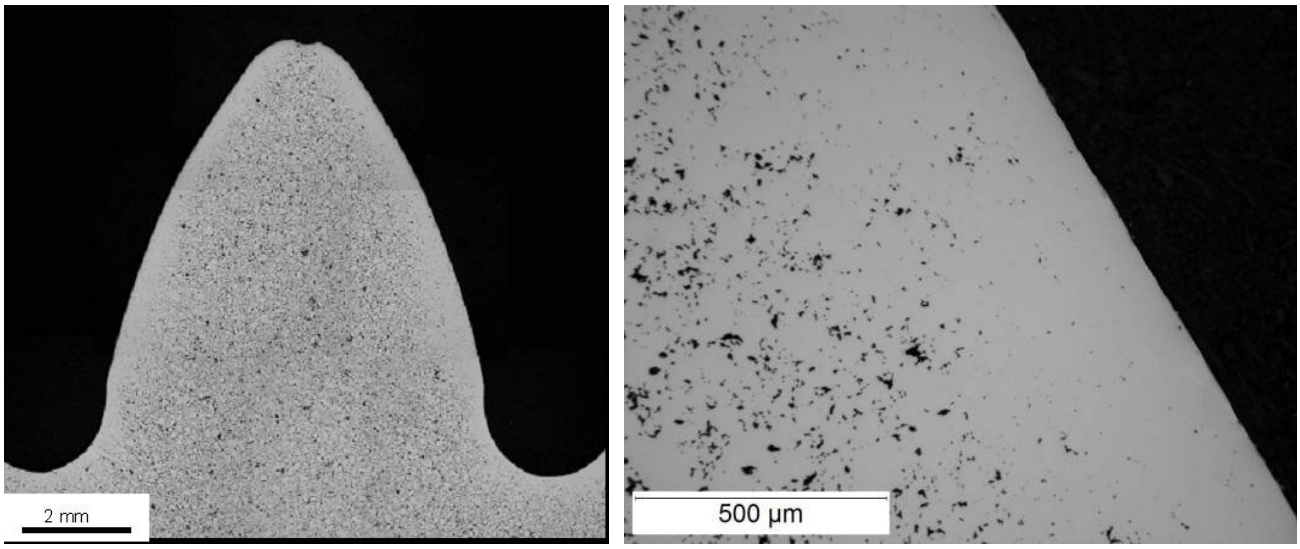


Figure 6. Metallographic cross section of the surface densified spur gear in the as-polished condition. The densified zone is approximately 0,3 mm.

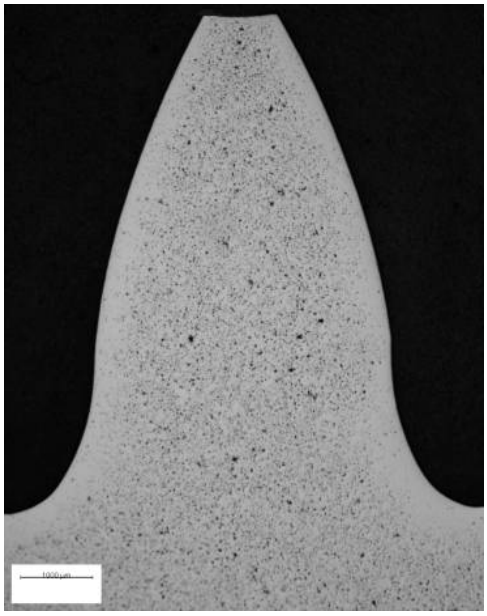


Figure 7. Metallographic cross section of the surface densified helical gear in the as-polished condition. The densified zone is approximately 0,2 mm.

TABLE 3
SELECTED PROPERTIES OF THE PRODUCED GEARS

Base powder	Initial density (g/cc)	Core carbon level (wt.%)	Densified layer thickness (mm)	Case depth (mm)	Surface hardness (HV0,1)	Tooth root bending fatigue limit (kN)
Helical gear						
Astaloy 85 Mo Fe-0,85Mo	7,20	0,22	0,2	0,36	890	9,4
DIN 16MnCr5	-	0,16	-	0,50	820	10
Spur gear						
Astaloy 85 Mo Fe-0,85Mo	7,15	0,27	0,3	1,0	850	33
SAE 8620	-	0,20	-	1,0	800	31

The gear class after rolling is between DIN 7 and 8 (Figure 8) and 8 after heat treatment for the helical gear.

The profile measurement trace has a typical appearance with tip and root relief as shown in Figure 7. The lead trace is also typical showing the intentional crowning. The reference axis used for the measurement was constructed using the best fit of points measured on the gear flanks. By using this procedure it is assured that any influence of bore concentricity (run-out error) is removed from the profile, lead and pitch measurements. The run-out error obtained using this reference axis is of no practical value. The real run-out error must be assessed separately.

The gear class of the measurement on the spur gear is DIN 8 or better for profile, lead and pitch errors in the as-rolled condition.

The case depth obtained for the helical gear was 0,36 mm which is inside the required range of 0,15 – 0,20m_n (0,3 –0,4 mm). The surface hardness is 890 HV0,1 and no carbides or oxides associated with the hardening procedure can be found. The microstructure is martensitic at the surface and it changes to bainitic in the tooth core.

The result for the spur gear is similar, except that the larger module. The case depth achieved was 1,0 mm, slightly above the required range of 0,55 – 0,73 mm The surface hardness is 900HV0,1 and residual stress measurements confirm that significant compressive stresses exits in the region near the surface.

The surface roughness measurements are virtually identical for the two gears. The roughness in terms of R_a is 0,12 μm measured on the helical gear compared to 0,28 for the shaved reference gear, see Figure 9. The smooth surface extends all the way into the root region.

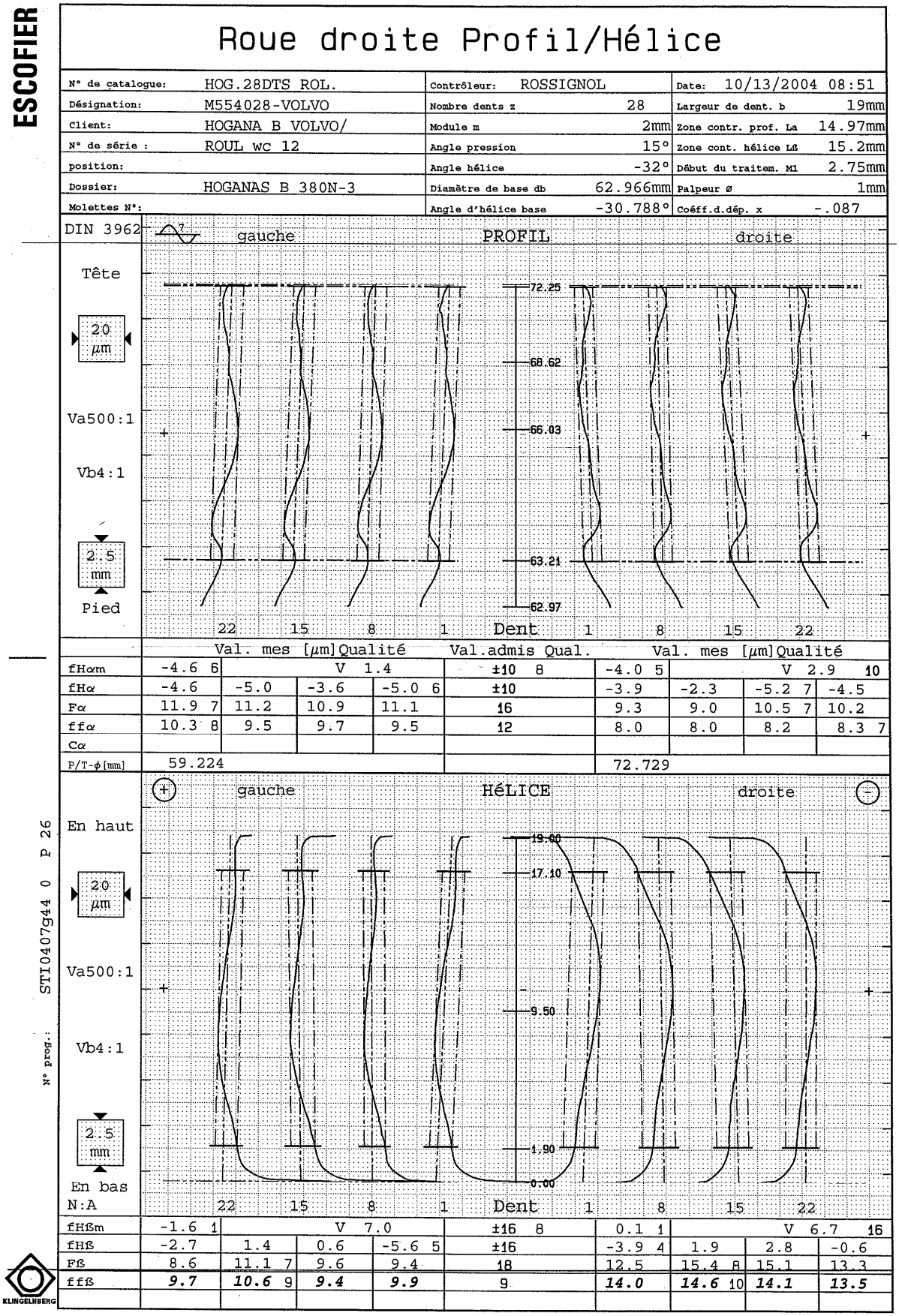


Figure 8. Gear quality measurement in the as-rolled condition. The gear class is DIN 8 or better for

profile and helix (lead) parameters. Pitch errors were excellent at DIN 7 and better while real run out was not measured, since an artificial reference axis was used for the measurements.

The results from the tooth root fatigue tests are shown in Figures 10 and 11. The spur gear exhibits a fatigue limit of 106% of the solid steel reference gears, while the helical gear exhibits a lower result at 94% of the reference gear.

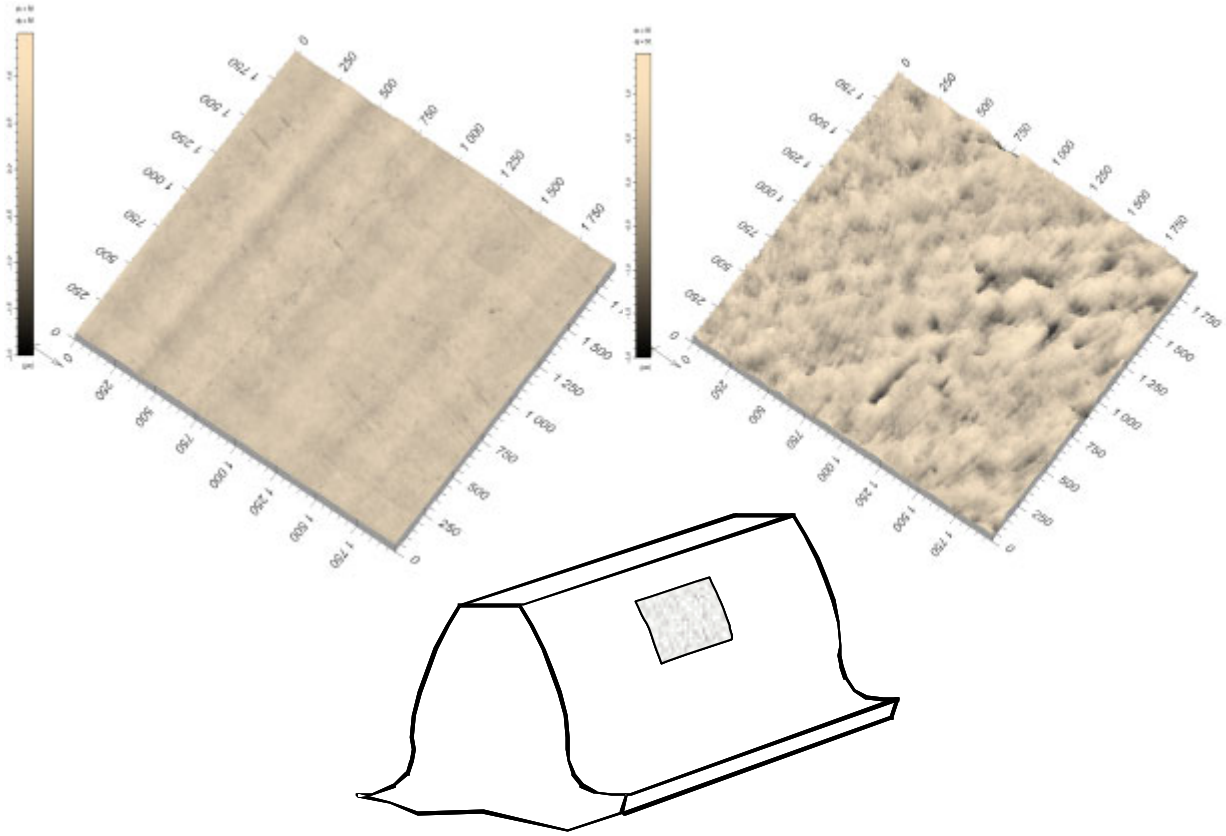


Figure 9. Three-dimensional surface roughness measurement of the helical gear in the rolled condition. The two dimensional parameter (linescan) R_a is extracted from the 3D-measurement. (left, R_a=0,12 μm) and in the shaved condition (right R_a=0,28 μm).

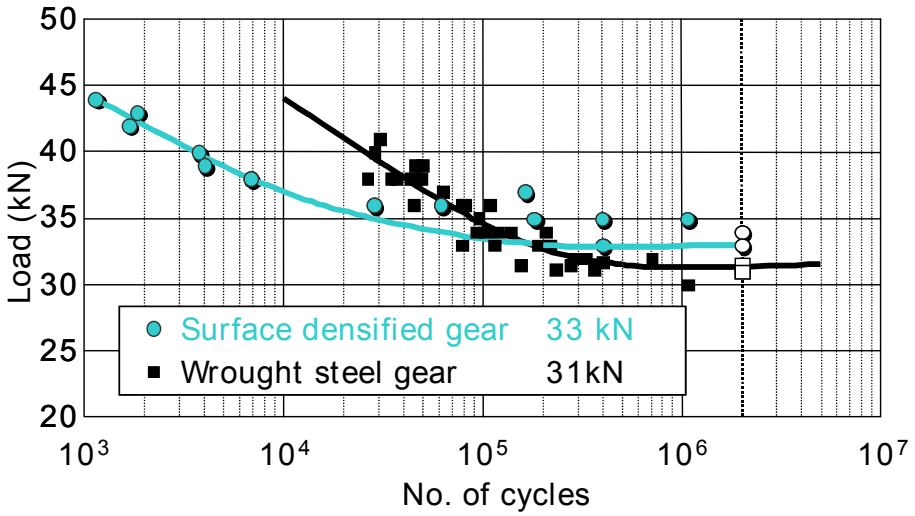


Figure 10. Pulsator test of the spur gear. Surface densified gear reaches 106% of the solid steel reference material.

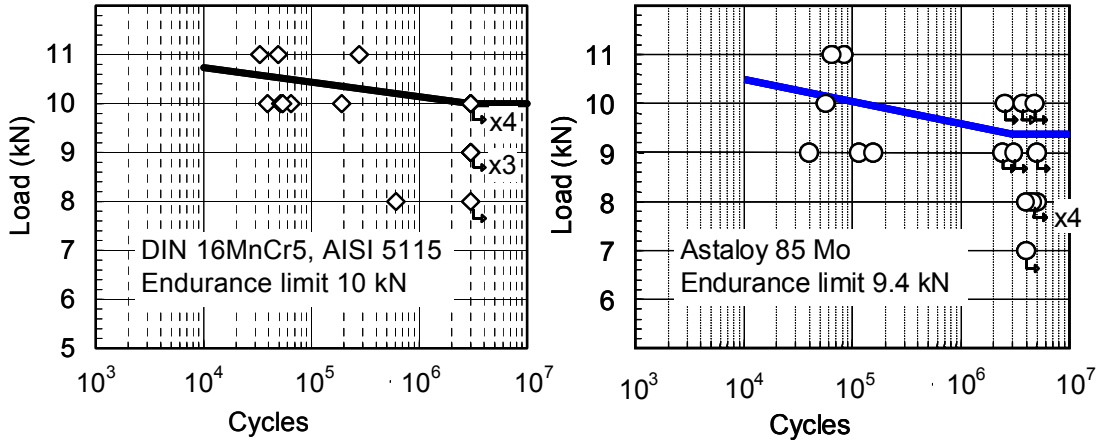


Figure 11. Pulsator tests of the helical gear. The surface densified gear reaches 94% of the solid steel reference material.

DISCUSSION

The way a porous material behaves under compressive loads above the compressive yield point is controlled by the material and the level of porosity (density). A material with a high hardness and yield point must deflect (elastically) more compared to a material of a lower yield point. Furthermore, since the deformation takes place by pushing a tool against the gear, the stresses are localised to near the surface of the gear. The most loaded regions will yield and the pores will be compressed. In a material with a strong strain hardening behaviour, the material that have reached the yield point will actually have a higher yield point at the next load cycle. This means that more and more material must reach the yield point for each load cycle. It also means that a significant porosity can remain near the surface after several load cycles. If on the other hand the strain hardening behaviour is very weak, the material next to the surface will reach the yield point again and again and a more complete pore closure will be achieved. In this context it does not matter what the starting density is. However, in practice it is found that the starting density is an important parameter. A higher starting density means

that the deformation necessary to achieve a certain degree of densification decreases. This fact can be explained by the following chain of arguments:

Consider a cube of material with side lengths l_0 and starting density ρ_0. It is assumed that the densified zone reaches the theoretical full density (ρ_1), while the rest of the material remains at the starting density. The distance the surface is compressed is Δt_1 and the thickness of the densified layer is d_1 as defined in Figure 12. The mass of the system is constant:

$$m = A_0 l_0 \rho_0 = A_0 (l_0 - d_1 - \Delta t_1)\rho_0 + A_0 d_1 \rho_1 \quad (1).$$

Solving for the distance needed to compress the surface in order to achieve the densified layer thickness d_1:

$$\Delta t_1 = \frac{\rho_1 - \rho_0}{\rho_0} d_1 \quad (2)$$

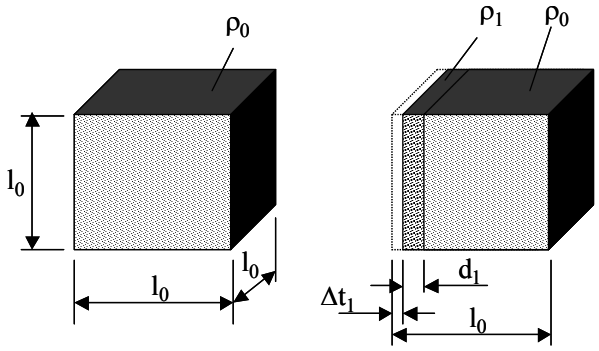


Figure 12. Schematic view of the densfication model.

Assuming that a gear needs a densified layer thickness of 0,25 mm and further assuming that the theoretical full density is 7,85 g/cc and an easily achievable density is 7,0 (cold compaction), 7,3 (warm compaction) and 7,6 (2P2S – high temperature sintering), the following table can be constructed (Table 4):

TABLE 4
DISTANCE NECESSARY TO COMPRESS THE GEAR TOOTH FLANK IN ORDER TO REACH A SPECIFIED DENSIFIED LAYER THICKNESS.

d_1 (mm)	ρ_0 (g/cm^3)	Δt_1 (μm)
0,25	7,0	36
0,25	7,3	19
0,25	7,6	8

The implications of this simple discourse are pointing in two directions. The first is that it is easier to densify material with a higher core density since the deformations involved are smaller, thus making it easier to design rolling tools and gear preform shape. The other implication is that with a higher

starting density the geometrical requirement on the gear preform is higher, due to the fact that small errors in gear preform shape will give large differences in densified depth.

In practice it is the diameter over balls that is used as the control parameter and not Δt_1 or d_1. This means that aberrations in density and shape will not show up as errors in gear geometry (class), but as errors in densified depth (d_1). This parameter can only reliably be assessed by metallography, which is both costly and time consuming in production.

The surface densified gears have a smooth surface not only on the active flank, but also in the entire root region. The absence of surface defects improves the fatigue performance [7]. The solid steel reference gear is manufactured by forging, hobbing and shaving. The active flank is shaved giving a surface roughness of Ra=0,28 μm, but the surface in the root is in the hobbed condition with an unknown, but most likely more rough surface condition. It is difficult to estimate how much the improved surface roughness contributes to improvement in fatigue endurance limit. Another factor that has influence on the tooth root fatigue behaviour is the root radius or curvature. Although nominally the same it can be noted that the surface densified gear has a very shallow undercut, since it does not need shaving.

The core density and the material selection are factors that must be considered also from a heat treatment point of view. During carburization a material with a lower density will normally pick up more carbon compared to a more dense material. In a gear, and especially in a gear tooth it is required to have martensite in the surface region and bainite in the core. If the carbon level is too high in the core due to fast influx of carbon at low core density, the microstructure can be martensitic. The residual compressive stresses in such a material will be much lower and may even be tensile. The fatigue limit of such a material will be much lower compared to a material with correct microstructure and optimum residual stress distribution.

FUTURE WORK

In the present work it has been shown that two of the most critical requirements on high performance gears can be met by surface densifying P/M gears. What remains to be shown, in order to cover all important aspects of manufacture and performance, is the pitting resistance of the gears and the cost for the manufacture of surface densified P/M gears. The pitting resistance have been covered by rolling contact fatigue tests [8] and by gear pitting tests [9]. The conclusion of these tests is that it is very likely that the pitting resistance of these gears is sufficient. The production characteristics of the surface densification process are also not known for P/M gears. However, the performance of the process for burnishing of solid steel gears, which is very similar to the surface densification of P/M gears, is a very economical process with low cost and high quality.

CONCLUSIONS

- The most cost effective production sequence is found by carefully selecting compaction, sintering and heat treatment process to fit with the requirements. The material (powder) must be selected so that it will perform well in all the manufacturing process steps as well as in service.

- It has been shown that the tooth root fatigue limit of the surface densified gears match the levels of the reference gears. Also the gear quality in terms of gear quality fulfils the requirements.

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