Opportunities for High Performance PM Gears in Automotive Applications

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ABSTRACT

The past decades have seen a continuous growth of use of PM parts in automotive applications. However, the performance requirements future components must fulfill are becoming more and more demanding. Transmission gears for automotive applications are complex in shape and require both very high geometrical accuracy in terms of gear quality and very high mechanical performance in terms of durability of tooth flank and root. PM offers possibilities to produce complex shaped parts in a very cost effective way and by adding a selective densification of the gear teeth both accuracy and mechanical performance requirements can be met at a low added cost.

In this paper a process route consisting of compaction, sintering, surface densification by rolling and finally heat treatment have been studied to assess the feasibility of producing high performance gears for automotive applications by powder metallurgy. Helical and spur gears were used in the study where the densification as well as the resulting gear quality and durability were tested.

INTRODUCTION

Powder metallurgy enables cost effective production of parts with complex geometries such as gears. The amount of waste material is often negligible as a consequence of the minimal necessity to machine the parts and the use of ecologically harmful cutting fluids is avoided.

The growth of the PM market has a long history. In order to continue this growth it is important to maintain the PM strong points, i.e. the net shape capability while performance is improved. In order to expand the PM market new applications could be won by combining the inherent advantages of PM while performance is increased by surface densification.

Gear rolling is a well-known technology for improving the shape and surface finish of solid steel gears [1,6,7,8]. When applied on PM gears, rolling also enhances the fatigue properties since the density and hence the strength in the highly loaded regions, i.e. the surface regions, increases to full density [2, 3, 5, 6, 7]. This technique was first developed more than 20 years ago, but has so far not reached widespread use due to several reasons. The difficulty in obtaining good densification and good gear quality simultaneously has limited the applicability and cost effectiveness of the process. Improvements in rolling machines and increase in knowledge and experience have significantly changed the situation [7]. Several parts producers have after significant and committed development work started to offer surface densified components to the market [5, 9, 10]. Another factor that has limited the use of surface densification technology is the fact that the requirements of more demanding applications have been possible to fulfill by using existing technologies and therefore reduced the driving force for developing the surface densification technology.

This paper aims at pointing out some possibilities in using the combination of powder metallurgy and surface densification. It will be demonstrated that the performance of two surface densified gears can be adequate for highly loaded applications.. The gear quality is also presented and discussed.

GEARS STUDIED

The gears examined in this study are the fifth gear used in a manual gearbox in a passenger car and the planetary gear in the reduction unit in a heavy truck gearbox. The two gears are shown in Figure 1.



Figure 1a. Fifth gear of a manual transmission in a Volvo passenger car.



Figure 1b. Planetary gear of a reduction unit in a Scania heavy truck gearbox

Typical data of the gears are presented in table 1. In this study both gears were manufactured by combining the PM process route with gear rolling. The helical gear was redesigned in order to facilitate testing in a pitting test rig. The clutch gear was removed, the diameter of the bore was enlarged and a keyway was introduced.

Table I. Gear data

	Spur gear	**Helical gear**
Number of teeth Z	20	28
Normal module m_n (mm)	3.650	2
Pressure angle α_n	22.5°	15°
Helix angle β	0°	32°
Addendum modification coefficient x	0.471	0.136
Over ball diameter (mm)	89.350	74.46

EXPERIMENTAL

The investigated gears were pressed and sintered to cylindrical blanks. The cylinders were machined to larger dimensions than on the drawing to have some stock material to compress during surface densification. The work piece was rolled between two dies in order to densify the surface of the tooth flank and root regions. The surface of the component was compressed and the density in the surface increased to full density. The tooth-root-fatigue properties of the gears were tested in an electro-magnetic pulsator.

MATERIALS

Reference gears of wrought steels were manufactured by turning, hobbing, shaving and heat treatment. The materials used for these gears are of similar type (designation) as the material for the gears used in production. The planetary gear is manufactured using the Swedish standard steel SS92506 which corresponds to DIN 20NiCrMo2 and AISI 8620. The helical gear is made in DIN 16MnCr5, which corresponds to AISI 5115 and is very similar to AISI 5120.

Two powder mixes based on a prealloyed powder containing 0.85% Mo, Astaloy 85 Mo, with slightly different graphite contents were prepared for the two PM gears. The compositions in the sintered condition are given in Table II.

Table II. Chemical composition of sintered and solid steel

Gear	**Material**	C (%)	Mo (%)	Cr (%)	Mn (%)	Ni (%)
Spur gear						
Reference	SS 92506 DIN 20NiCrMo2 AISI 8620	0.20	0.20	0.55	0.50	0.55
PM gear	Astaloy 85Mo Fe-0.85Mo FL4400	0.28	0.85			
Helical gear						
Reference	DIN 16MnCr5 AISI 5115	0.16		0.95	1.15	
PM gear	Astaloy 85Mo Fe-0.85Mo FL4400	0.20	0.85			

MANUFACTURE OF PM GEAR BLANKS

PM gear blanks were manufactured by compaction of cylindrical blanks followed by sintering at 1120 °C for 30 min in a mixture of 90% N_2 and 10% H_2 gas atmosphere. The blank densities were 7.15 g/cm^3 for the spur gear and 7.15 g/cm^3 for the helical gears. The sintered blanks were then turned and hobbed to the desired preform shape. The amount of stock material is estimated using simple calculations of material needed to achieve the required densification.

SURFACE DENSIFICATION BY ROLLING

In the present work a HC20CN rolling machine (Escofier Technologie SA. Chalon. France) was used for the densification trials as shown in Figure 2.

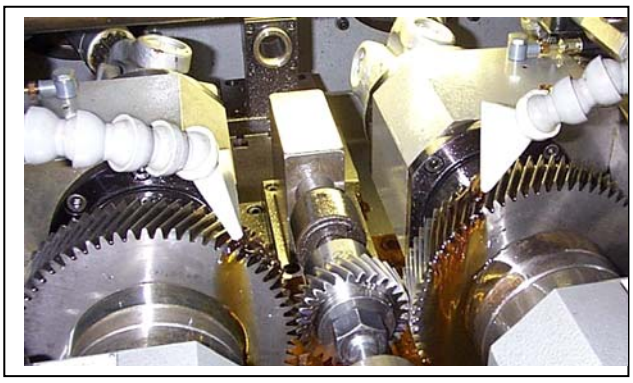


Figure 2. Surface densification of a helical transmission gear

The rolling cycle can be divided into three parts; the initiation where the tool and the gear mesh and make contact. The second phase is when the load is applied and the tools deform the gear until a preset center distance has been reached. The third phase is the tool withdrawal where the tools move outward so that the gear can be unloaded. In a serial production set-up a cycle time including loading and unloading would be 8-15 seconds.

HEAT TREATMENT

The heat treatments selected for the different materials were not the same. The spur gear was carburized at 940 ^{o}C with a carbon potential of 0.8%C followed by quenching in oil. A stress relieving operation was performed at 160 °C for 60 minutes.

The helical gear was gas carburized at 920°C followed by a quench in oil at 80 °C. The stress relieving was performed at 170 °C for 60 minutes in air. The side faces of the gear were masked using a commercial masking paste in order to limit the penetration of carbon through the low-density side faces.

In each case is the carburizing time selected so that the required case depth should be reached for the different gears. The case depth is defined as the depth below the surface where the hardness has dropped to 550HV0.1.

GEAR QUALITY

The geometrical quality of the gears was measured by a Klingelnberg P26 3D measuring center. In all cases were the reference axis defined by the gear teeth themselves. The target gear quality for all the gears was DIN quality 8. Some limited trials were performed in order to assess the consistency of the process. The diameter over balls was measured on the blanks and on rolled gears. The densification of the gears was assessed by using image analysis on polished samples. The response to the heat treatment was examined using etched microstructures of tooth flank and root regions. The heat treatment was further examined using micro hardness measurements. A densification depth was arbitrarily defined as the distance from the surface where the porosity has increased to 2%.

TESTING

The spur gear was tested in a servo-hydraulic testing machine. The load was applied on the flank of the tooth. The load ratio was 0.1. Samples reaching 2 million cycles were considered as run outs. In all 15 tests were performed.

The helical gear was tested in an electro-magnetic pulsator. The test rig was fitted with a special clamping device that applied the load at the top of the gear teeth. Furthermore, a fixture ensured that the gear could not turn or twist during loading. The load ratio was also here kept at 0.1 in order to ensure contact between the clamping device and the gear teeth at all times. As the load is applied at the tooth top and not on the tooth flank and the difference in geometry in the root region it was not attempted to calculate the maximum bending stresses in the root region. In this case the specimens are considered run-outs when they reach 30 million cycles.

RESULTS

DENSIFICATION

The result of the densification of the spur gear can be seen in Figure 3. The densification depth is approximately 0.5 mm on the flank and slightly lower in the root region. For the helical gear the situation is the reverse as can be seen in Figure 4. The deepest densification is in the root region reaching 0.4-0.5 mm for the helical gears. On the flank the densification depth for both gears is approximately 0.2.

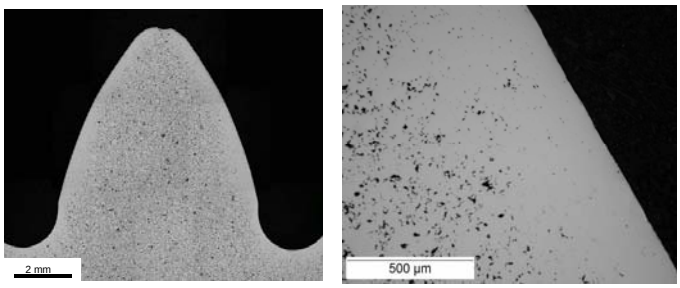


Figure 3. Metallographic cross section in the as-polished condition of the surface densified spur gear.

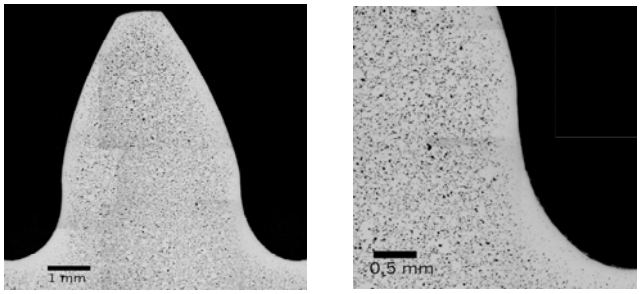


Figure 4. Metallographic cross section in the as-polished condition of the surface densified helical gear.

GEAR QUALITY

The gear quality of the spur gear after rolling is estimated to DIN quality 8. There is one parameter that falls outside DIN 8. The total profile deviation reaches 26 µm and the requirement for DIN 8 is 25 µm. DIN 9 allows 36 µm of total profile deviation.

The gear quality of the helical gear is DIN 8 or better.

Table III. Measured gear quality after rolling

		Spur PM gear	Helical PM gear
ProfileForm deviation	$\mathbf{f_f}$	8	8
Angular deviation	$\mathbf{F_H}$	6	8
Total deviation	**F**	9*	7
Helix Form deviation	$\mathbf{f_f}$	7	8
Profile deviation	$\mathbf{f_H}$	7	7
Total deviation	**F**	8	7
Single normal pitch deviation	$\mathbf{f_u}$	6	6
Difference between adjacent pitches	$\mathbf{f_p}$	7	4
Total cumulative pitch deviation	$\mathbf{F_p}$	5	5
Cum. circular pitch error over z/8 pitches	$\mathbf{F_{pz/8}}$	5	5
Tooth Thickness Variation	$\mathbf{R_s}$	7	4
Runout tolerance **	$\mathbf{F_r}$	6	2

* 1 μm from gear class 8.

** The gear bore is not used as reference. The rotation axis is calculated by measurements on the tooth flanks.

CONSISTENCY OF GEAR QUALITY

Measuring the diameter over balls before and after rolling makes it possible to assess the consistency of the rolling process. After hobbing of the helical gear, the scatter in diameter over balls was approximately 0.0225 μm as can be seen in Figure 5. After rolling the standard deviation dropped to 0.0031 mm.

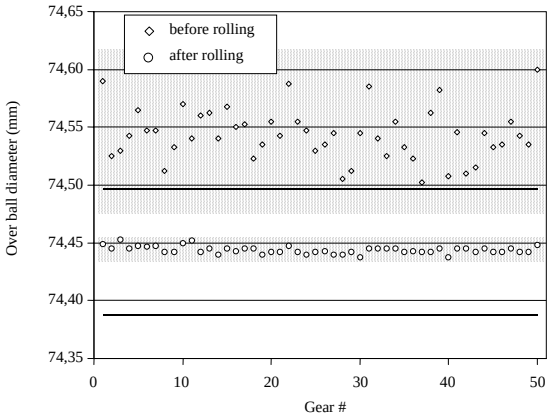


Figure 5. Scatter in diameter over balls measurement before (diamonds) and after rolling (circles). Scatterband ±3μ is indicated by shadowing. Upper and lower tolerances are shown as solid lines.

The helical gear was also used to assess the consistency in gear profile. Four teeth were measured for each gear and the results are plotted in the scatter diagram in Figure 6.

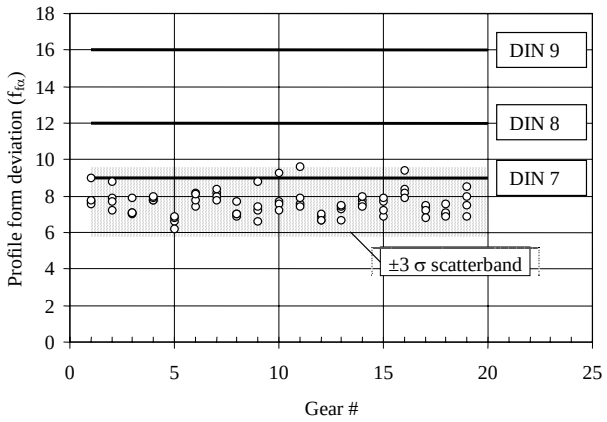


Figure 6. Scatter in Profile form deviation. Four teeth are measured on each gear.

CASE HARDENING

The hardness profiles for the tested gears are shown in Figures 7 and 8. The target case depth on the flank was 0.7-1.2 mm for the spur gear while the profiles for the helical gears have a target of 0.3 – 0.4 mm. The case depth for the spur gear is 1.0 mm which is well within the target range. The helical gear obtained a higher surface hardness than the reference gear. The case depth obtained was approximately 0.35 mm.

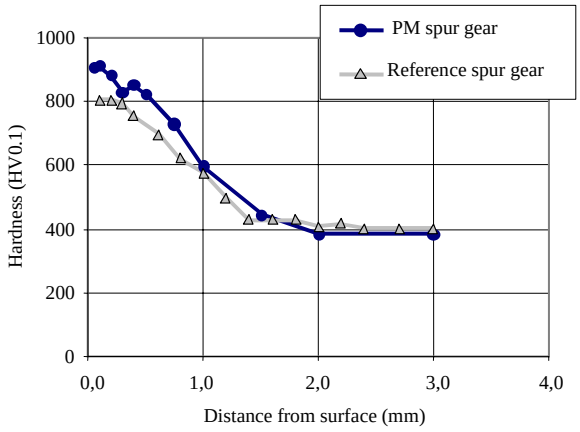


Figure 7. Micro hardness profile for the spur gear (SG).

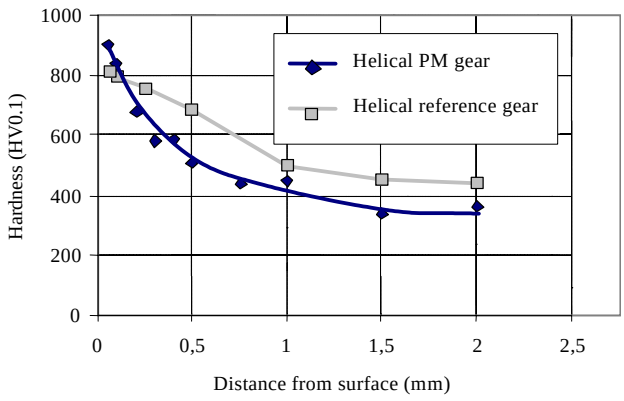


Figure 8. Micro hardness profile for the helical gear.

DISTORTION AFTER HEAT TREATMENT

The profile and lead traces of the helical gear is shown in Figure 9. The hobbed gear has a quality of DIN 10 regarding the profile form deviation, while e.g. the profile angular deviation is quite good at DIN 7. The lead errors are better between DIN 7 and 9. After rolling some improvements can be seen. The profile form deviation has decreased to DIN 8 near DIN 7, while the profile angular deviation is a DIN 8 near DIN 9. In the lead trace the chamfering can be clearly seen. After heat treatment it can be seen that the profile form deviation is virtually unaffected, while the profile angular deviation and the profile total deviation changes significantly. The lead trace shows a similar behavior in that the helix form deviation is unaffected while the helix total deviation and helix angular deviation changes slightly.

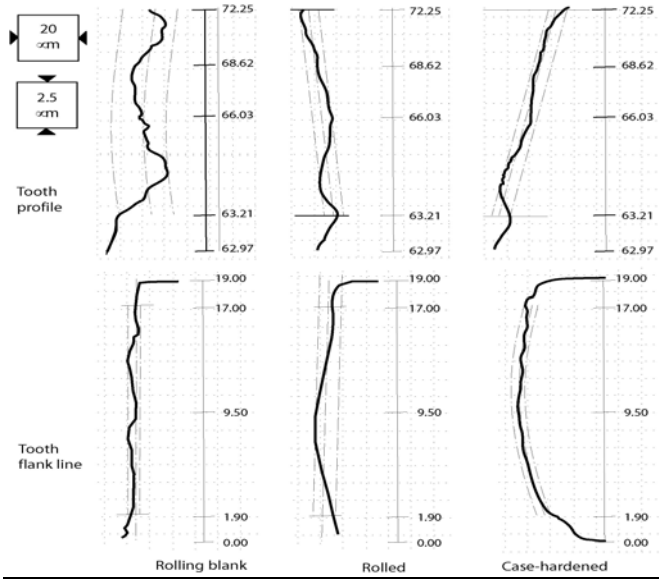


Figure 9. Profile trace in the helical gear in hobbed, rolled and heat treated state

DISCUSSION

DENSIFICATION

Ideally a larger densification depth would be preferred. However, especially in the flank region it is difficult to reach deeper densification depths without too severe deformations. If too hard densification is attempted, the work piece may break due to fracture of teeth near the top. This may lead to breakage of the rolling dies. In the present investigation we have reached a densification depth of 0,5 mm for the spur gear and 0,2 mm for the helical gear. However, the densification depth is arbitrarily defined as the depth where 2% porosity is reached. From a case hardening point of view it is sufficient to reach a state of closed porosity (around 7.2 g/cm^3) were the material starts to behave like solid steel. This region is significantly thicker in fact it is in the same range as the target case depth. This means that the carburizing process will be controlled by diffusion in the solid state. Naturally the diffusion will be a combination of bulk, grain boundary and surface diffusion, but these densities, bulk and grain boundary diffusion will dominate and mass transport in gas phase will not be possible. This means that the case hardening process will be more robust compared to a case where the porosity is higher in the region where carburizing is to take place.

If the case is not developed and the entire tooth is carburized it is likely that the entire tooth becomes martensitic on quenching. If this happens the compressive residual stresses that are normally formed by the martensite transformation will not occur. This means that the performance of the gear will be significantly lower.

GEAR QUALITY

The gear quality in the rolled condition is quite satisfactory in most aspects. However, as with all PM gears it is difficult to control the run out of the bore. The root cause of this difficulty is the play between die and punches and between punches and core rods. Since the filling of powder is not perfect, the side with more powder will push the core rod to one side. Many procedures have been developed to minimize this problem and although partly successful, it remains a problem. In some cases it is not a severe problem sine the bore can be ground after heat treatment. But if the bore contains e.g. splines internal grinding is not possible and instead the teeth have to be corrected by grinding or honing. In the present work this problem has been ignored and all gear measurements have defined the rotational axis based on the gear teeth themselves. By doing so it is possible to isolate the influence of the rolling process on the gear quality from the run out problem.

The most difficult part of the development process for surface densified gears is to achieve a good gear profile and sufficient densification at the same time. A more severe deformation will lead to higher forces and larger deflections. This in turn leads to more difficult design of rolling tools.

GEAR QUALITY CONSISTENCY

By observing the gear quality for a significant number of gears the scatter can be estimated. In the present case the diameter over balls and the profile form error have been selected for observation. The result for the diameter over balls is very good, but it is easily explained by the fact that the rolling process is controlled by this diameter, although indirectly. The machine is run until a pre-set centre distance between rolling dies is reached and then the process is stopped. In the ideal case this means that the pitch diameter of the gear is reached at this point and that the pitch diameter is equal to the point where the balls make contact during the diameter over balls measurement. However, in practice there will be small aberrations from this, but the fact remains that the rolling process is very much in control of this measure.

The profile form error is on the other hand the consequence of a very complex process involving the entire process, the plastic behavior of the work piece material and the quality of the gear blanks. A conclusion from the above discussion is that the scatter in diameter over balls depends mainly on the repeatability of the machine, while the profile form error depends on the robustness of the entire process, including quality of materials and blanks. Some improvements can be expected here since the quality of the gear blanks is in the range DIN 12-11 and after a press and sinter operation a quality of 10-9 can be expected. The width of the scatter band is of the same range as the difference between DIN 7 to DIN 8.

CASE HARDENING

The case hardening of the spur gear was successful as has been shown in [11]. The surface hardness is high and the case depth is in the required range. Furthermore, the residual stresses have been measured and they reach 300 MPa in compression. All taken together indicates a very good case hardening process. This is also reflected in the very good tooth root bending fatigue behavior of this gear [11].

The case hardening of the helical gear that was conventionally gas carburized reached a surface hardness of 850 HV0.1 and a case depth in the required region (0,4 mm).

DISTORTION AFTER HEAT TREATMENT

The fact that the profile form deviation and the helix form deviations change very little with heat treatment shows that it could be possible to correct the shape of the rolled gear in order to let the heat treatment change the shape into the desired one. By introducing an intentional profile angular deviation it would be possible to counteract the change in profile angular deviation introduced by the heat treatment. This change requires either a change in blank dimensions so that the target diameter over balls after rolling will be different or a change in rolling tool profile in order to change the geometry of the gear teeth after rolling. A similar correction could be made for the helix angular deviation. This error can be decreased by a simple adjustment of the rolling machine.

TOOTH ROOT FATIGUE

Tooth root fatigue tests have been reported for the spur gear in [11] and for the helical gear in [7]. The surface densified PM spur gear obtained an endurance limit of 33kN while the solid steel reference gear reached 31kN. The helical PM gear reached an endurance limit of 9.4 kN compared to 10 kN for the solid steel reference of 16MnCr5. The reason the surface densified spur gear reaches a relatively higher endurance limit compared to the surface densified helical gear can be attributed to a number of factors. Among the more important factors are: changes in root radius, surface roughness in the root, densification profile, reference material and quality of heat treatment.

CONCLUSIONS

The densification is in all cases sufficient to allow successful case hardening and the development of a defined case depth.

The gear quality of the as-rolled gear has reached a level where it is possible to compare the quality to automotive transmission gears.

The robustness of the rolling machine is very high. The robustness of the whole process including influences from process, material and blank quality, also appears to be high.

The systematic distortion during heat treatment of the rolled gear can be compensated for in the rolling process.

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