HIGH PERFORMANCE GEARS

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ABSTRACT

The past decades have seen an increased use of P/M components in passenger cars and light trucks. However, only a limited number of applications have been found in heavy trucks. P/M technology have so far not meet the performance requirements of transmission gears. Forging of a blank, followed by turning, hobbing, shaving, heat treatment and finally grinding are the manufacturing steps normally used for the planetary gear of a hub reduction unit of a heavy truck. The large size of the gear means that a lot of material is machined away before the component is finished.
Using a net shape process offers the potential of significant cost savings. Normally conventional cold compaction cannot deliver the fatigue performance and tolerances required, but other techniques can increase these properties to new levels.
Warm compaction improves the density and exhibits an excellent pore size distribution. This means that the fatigue properties improve at a moderate cost increase.
Surface densification is an additional process step in the manufacture of a P/M component. By introducing this step the net shape capability of the P/M technology is utilized while at the same time the highly loaded regions benefit from increased density. Also tolerances of the densified regions can be improved.

INTRODUCTION

Gears are commonly machined from forged billets or bar stock. This manufacturing method generates a significant amount of waste material and machining operations like turning hobbing and shaving are time consuming. By using powder metallurgy (PM) the amount of waste material is radically decreased and the net shape manufacturing method, that includes compaction of metal powder and sintering, ensures that machining operations, in most cases, are avoided. The manufacturing costs can hence be significantly lowered. The simplest way of manufacturing a PM part is by cold compaction, and sintering. By employing warm compaction, the density and hence the performance of the component is enhanced. Warm compaction was developed in the 1990's [1].

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 [2-9].

Gears produced by the three different manufacturing routes, (cold compaction, warm compaction and surface densification) are described in this paper and the performances are compared. The gear presented in this paper is used in a planetary gearbox located in the wheel hub of a Scania truck. The gear is characterized by a moderate module and a positive addendum modification.

EXPERIMENTAL

A planetary gear with the gear data given in Table I was used in this study. The low alloyed powders D.AB and Astaloy 85Mo with the compositions shown in Table II were used as base materials for the gears. The reference material is a case hardening steel with a composition according to Swedish standard 92506, which is equivalent to DIN 21NiCrMo2 and SAE 8620H.

Table I Gear geometry

Number of teeth Z	20
Normal module m_n Diametral pitch	3.650 6.96
Press angle α_n	22.5
Helix angle β	0
Addendum modification coefficient x	0.471
Over ball diameter	89.350

Table II. Chemical compositions of base powders

Base powder	**Cu (%)**	**Ni (%)**	**Mo (%)**
D.AB	1.5*	1.75*	0.50*
Astaloy 85Mo	-	-	0.85**

*Diffusion alloyed, **Pre-alloyed.

Three gear variants were manufactured according to the manufacturing routes outlined in Figure 1. The gears were machined from cylindrical blanks. Gears of variant 1 and 2 were machined to the final shape and gears of variant 3, that were used for surface densification trials, were machined to an over measure functioning as starting material that is compressed during the rolling operation. The characteristics of the sintered gears are summarized in Table III.

Table III. Characteristics of investigated gears

	Base powder	Graphite (%)	Compaction	Sintered Density (g/cm^3)	Surface densification
CC	D.AB*	0.2	Cold	7.01	No
WC	D.AB*	0.2	Warm	7.44	No
SD	Astaloy 85Mo**	0.3	Cold	7.15	Yes

The gears of variant 3 were surface densified by radial rolling. It was carried out in a two-roll burnishing machine commonly used for burnishing of solid steel gears. The case hardening was performed by carburizing at 920 ^{o}C at a carbon activity of 0,9 wt.% followed by quenching in a water/polymer bath at room temperature. The carburizing is followed by a tempering at 160 ^{o}C in air for one hour.
The process parameters were adjusted for solid steel gears. The target case depth is 0.7-1.2 mm. The target surface hardness is 58-62 HRC.

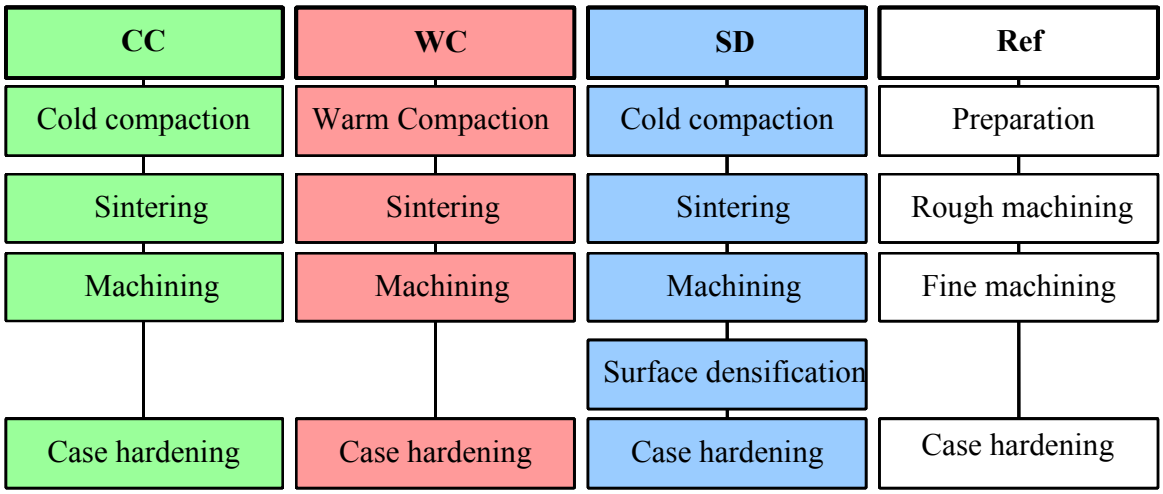
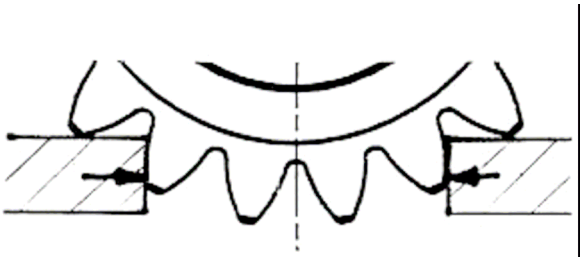


Figure 1. Manufacturing routes for the tested variants

Testing

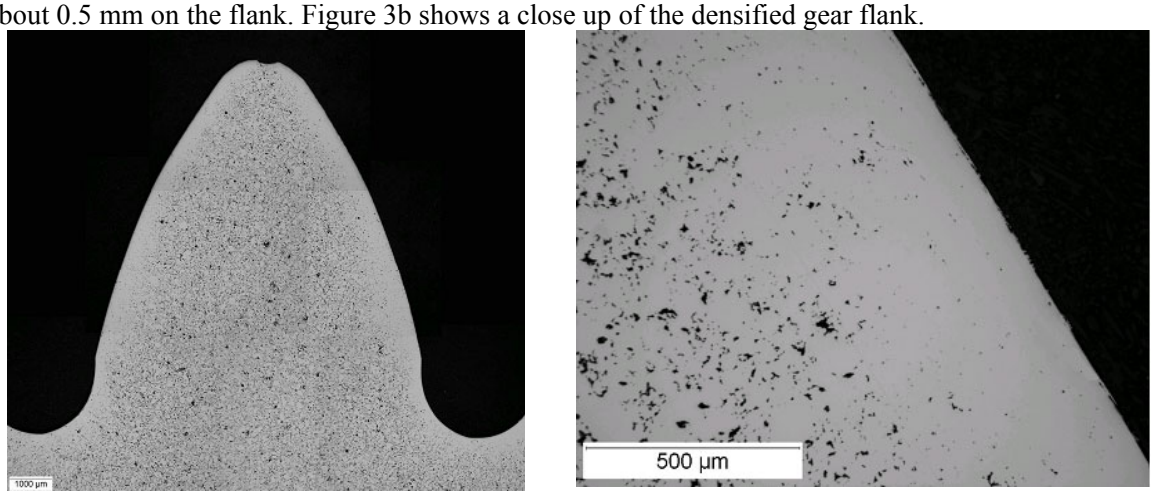
The gears were tooth root fatigue tested in a pulsator rig. Each tested gears were clamped three times with 60 degrees shift with two unloaded teeth between the two loaded teeth as can be seen in the schematic in Figure 2. The R-value has been selected to 0.1 in order to ensure continuous contact between the clamping device and the gear teeth.


Figure 2. Tooth root fatigue test. Each gear is tested three times using different sets of teeth with one untested tooth in between tested teeth.

RESULTS

Densification

As can be seen in Figure 3a there is a virtually pore free surface layer along the gear tooth. This layer is about 0.5 mm on the flank. Figure 3b shows a close up of the densified gear flank.



(a) (b)

Figure 3: Cross section of surface densified gear tooth and close up on gear flank.

Case hardening

The micro hardness profiles of the case hardened gears including the solid steel reference are shown in Figure 4. It can be seen that variant 1 with a density of 7.01g/cm^3 was through carburised during case hardening. The hardness is roughly on the same level through the cross section and there is no distinct case depth. The case depth is defined as the depth from the surface were the hardness has dropped to 550 HV0,1. Variant 2 (WC) with a sintered density of 7.44 g/cm^3 has a more pronounced hardness profile with about 650 HV0,1 at the surface and 350 HV0,1 about 3 mm below the surface. The case depth is 1.1 mm, which is within the specification but the maximum hardness at the surface is significantly lower than the solid steel reference. The surface densified gear exhibits a very good case. The hardness in the surface is over 900 HV0,1 while the hardness in the core is 400 HV0,1. The case depth is 1,2 mm which is at the border, but within the limits. The reference gear has a lower hardness in the surface 810 HV0,1.

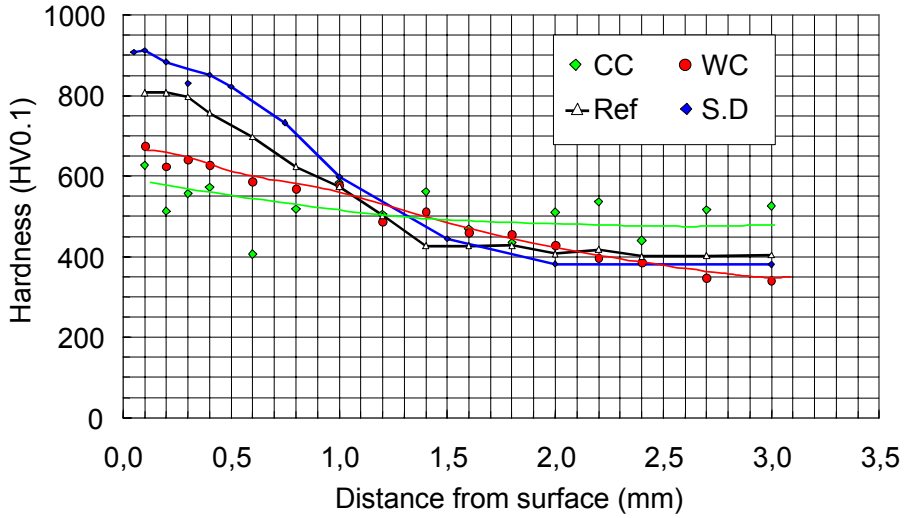


Figure 4. Hardness profiles of the tested variants.

Tooth root fatigue performance

The results from the tooth root fatigue testing are shown in Figure 5. The endurance limit for the solid steel reference is approximately 31 kN. The cold compacted and warm compacted variants were only tested in the finite life region. The results are significantly lower compared to the reference material and it was not considered necessary to establish the 50% endurance limit. However, it should be noted that the performance in the finite region is not the same for the two variants. The warm compacted variant exhibits a 50% fatigue load of 82% of the reference at 10 000 cycles while the cold compacted reaches 59% at the same number of cycles. From the measured data it is not possible to state if this relation will be the same at the endurance limit (2000 000 cycles). The slope of the curve in the finite life region is similar for the two P/M materials and the reference material.

Nine data points were generated for the surface densified gear. It is not enough to accurately establish the fatigue behaviour at both high loads and loads near the endurance limit. However, two run-outs were encountered which means that the 50% endurance limit can be estimated. One run-out occurs at a load of 33 kN and the other at 34 kN. The 50% endurance limit is estimated to 33 kN. Failed teeth were encountered at 33, 35, 36 and 37 kN. All the points are above the line for the reference material except one. However, the points indicate that the slope of the curve in the finite life region could be lower than the other materials as indicated in Figure 5.

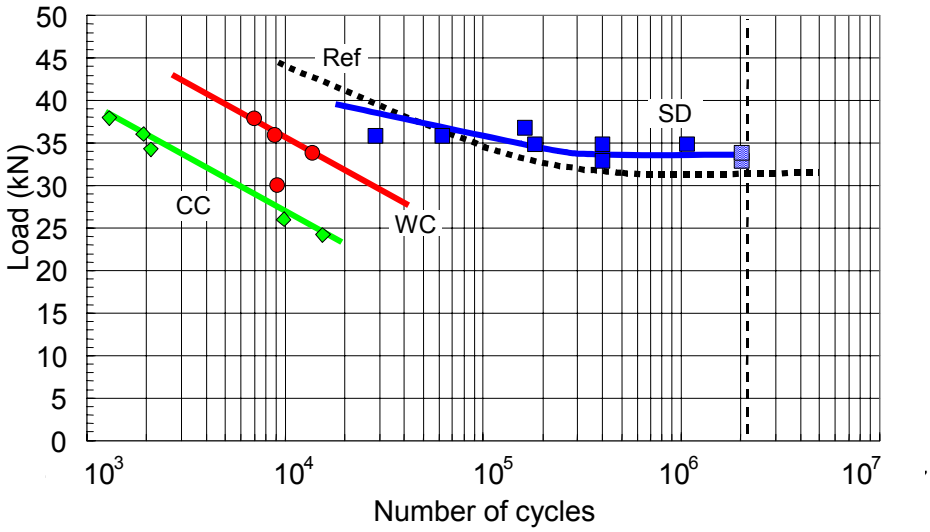


Figure 5. Tooth root fatigue results of the tested variants.

Residual stresses

Residual stresses have been evaluated for CC, WC and the reference materials. Highest compressive surface stress was found for the warm compacted (WC) material. The cold compacted (CC) material show residual stresses close to zero in the surface and 7 and 15 µm below the surface. The reference material show tensile residual stress in the surface. All other measured values between the surface and 80 µm into the gear are in the interval –100 to –250 MPa.

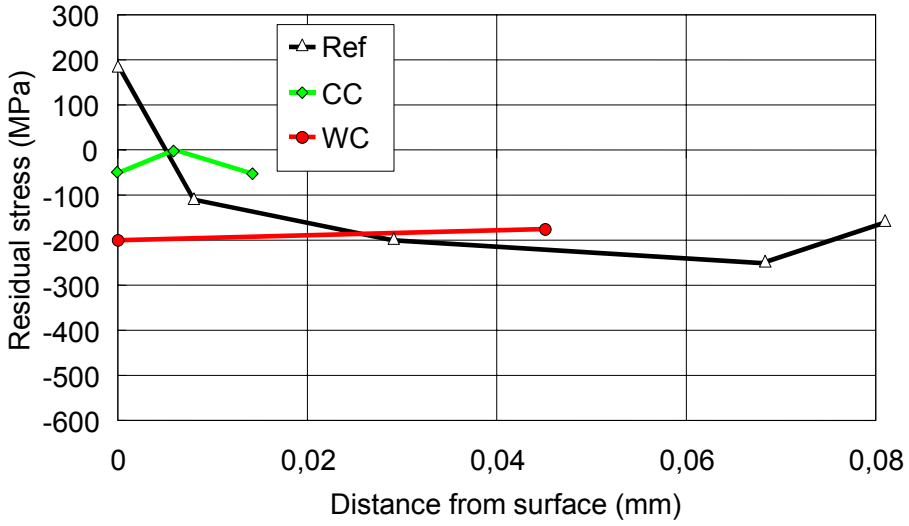


Figure 6. Residual stresses measurements on the cold compacted (CC), warm compacted (WC) and reference materials (Ref).

DISCUSSION

Residual compressive stresses from the case hardening are an integrated part of high performance gears. Compressive residual stresses are generated due to the different lattice parameters of surface martensite and non-martensitic core. These stresses are superimposed on the stresses from the loading and have a

significant influence on the ability to withstand the loading. Through hardened material show no or very small residual stress.

The investigated PM gears were case hardened with the same process route as conventional solid steel gears. The cold compacted PM gears (non-surface densified) were carburized completely and no hardness/microstructure profile was obtained. The residual stress profile of the warm compacted material show about –200 MPa to a depth of 45 µm. This is close to the residual stress for the reference material. The lower Young´s modulus of the P/M steel compared to the homogeneous materials should imply a correspondingly lower residual stress, There is a close relation between the microstructure gradient and the compressive residual stresses. Since the residual stresses of the surface densified gear was not measured one can only speculate as to the value and magnitude of the residual stresses present in the material. However, hardness at the surface is very high (900 HV0,1) and it drops to approximately 400 HV0,1 1,5 mm below the surface. The microstructure is fully martensitic from the surface to a depth of 0,7 mm as shown in Figure 7. At this depth bainite starts to appear and at approximately 1,5 mm below the surface the structure is fully bainitic. These observations indicates that the residual stresses formed by the martensite transformation in the surface should be fully developed. The successful hardening of the surface densified gear is one of the reasons for the good tooth root fatigue performance.

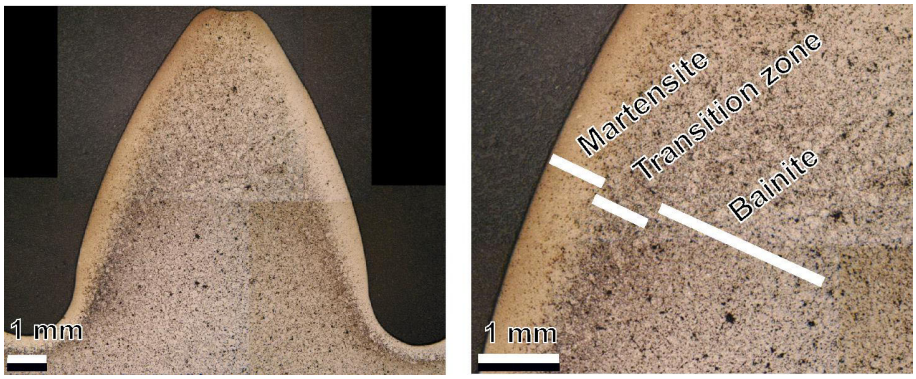


Figure 7. Etched microstructure of the surface densified (SD) gear. Left: Overview of whole tooth. Right: Detail of tooth flank showing surface densified and case carburized layers.

CONCLUSION

- Increasing the density from 7.01 g/cm^3 to 7.44 g/cm^3 by employing warm compaction improves the tooth root fatigue performance.
- At densities above 7,44 g/cm^3 the material have the ability to form a case carburized layer, thus providing a hard martensitic surface region and a non-martensitic core.
- The fatigue performance of the surface densified material is equal or better than the reference material.

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