SURFACE DENSIFIED P/M TRANSMISSION GEAR

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ABSTRACT

Progress in development of a surface densified P/M transmission gear is reviewed. The gear is the fifth gear of a manual transmission for a medium sized passenger car. Blanks were produced by hobbing of pressed and sintered slugs. Densification of both the root and the flanks of the P/M gear was achieved using gear rolling technique. The rolled gears were case hardened. At present the development stage, the quality of such the gear is close to AGMA class 10, which is considered to be the required level for automotive manual gearboxes. The surface roughness is better than for the shaved reference gear. The hardness profile in the flank region matches the hardness profile of the wrought reference gear; and finally, the desired density distribution was reached.

INTRODUCTION

Power transmission gears are traditionally manufactured from wrought bar stock or from forged billets by cutting followed by heat treatment. However, in recent years P/M processes have been refined to a level that matches the performance of case hardened steel [see e.g. 1-3].

For high quality gears, e.g. high-speed automotive gears, the rough cutting is followed by a fine finishing in order to improve the quality, see Figure 1. After the heat treatment, the bore and sides of the gear can be ground in order to further enhance the quality. In some cases shot peening of the gear flank and root is performed in order to improve the fatigue resistance. The steels used for these components are usually, relatively low-alloy, low carbon steels, such as AISI 5120, with totally 2% alloying elements and 0,2wt.% carbon. These steels are well suited for case hardening where the surface region is carburized to typically 0,8 wt.% carbon. The result is a component with a high strength in the surface layer that is further increased by the presence of residual compressive stresses generated by the phase transformations during the case hardening. In many cases is the performance of these gears more than what is required; this can be true for both tooth root bending fatigue and for the tooth flank endurance limit. Although this opens an opportunity for P/M technology, there are very few automotive gear applications where a P/M steel with a density of 7,0 g/cm^3 can meet the requirements.

However, a gear is highly loaded in two places; the flank experiences a high contact load and the tooth root region high bending stresses. In general it can be said that for slowly rotating gears it is the bending stresses that are critical for the design and material selection. For fast rotating gears with smaller moments it is generally the contact stress and the degree of sliding that is critical for the gear pair. Both these loads are confined to a shallow layer at and below the surface of the component. This means that it could be sufficient to increase the density in this layer in order to reach the fatigue performance of solid steel [1-5].

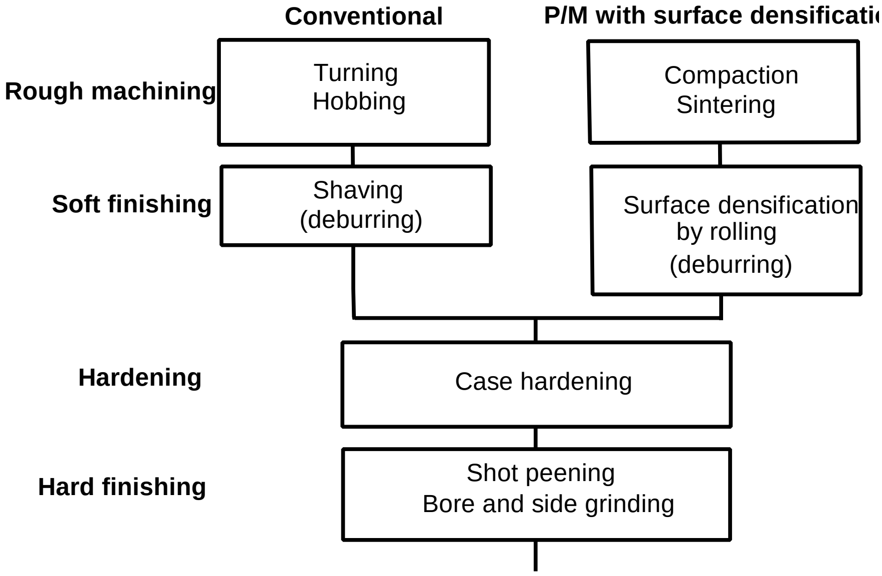

Figure 1. Gear manufacturing sequence for conventional cutting process and for P/M process including surface densification. Washing and transport steps are omitted.

Solid steel gears are usually finished in the soft state by either shaving or burnishing [6]. Shaving is a cutting process that removes very little material and creates a good flank shape and surface finish. Burnishing is a forming (rolling) method that works the surface of the gear tooth in order to achieve the same goals. Both methods are used for e.g. gears for automotive gearboxes. The quality achieved (and required) for these types of gears are in the range AGMA 9-10 [7].

The major steps in the gear manufacturing process chain can be seen in Figure 1 [8]. Compaction and sintering corresponds to the cutting of blanks and rough machining. The surface densification by rolling corresponds to shaving or burnishing. The subsequent steps are similar for the two manufacturing routes. In Figure 1, deburring, washing and handling are not taken into account, albeit they are a necessary step. The reason for this is that the cost for these steps should be similar for the two processing routes, and that large differences exists between components depending on the component itself and on the available machinery.

The surface densification can be performed by several methods. The methods selected here is by radial rolling, i.e. a burnishing machine is used form the work piece by rolling a gear-like tool against it. The flank and the root of the work piece are compressed so that the density increases.

The present activity aims at densifying the flank and root of a helical transmission gear. The densification should result in fatigue performance in the range of the performance for solid steel. The geometrical requirements are around AGMA Class 8-9.

THE GEAR

The gear used in this study is the fifth gear in a manual transmission for a medium sized passenger car. This gear was selected since the contact conditions are less severe compared to the lower gears. On the other hand are the fatigue resistance requirements higher since the car is mainly run in the top gear. The gear is characterized by a high helix angle, moderate module and a positive addendum modification. Selected gear data are shown in Table I. The gear was redesigned in order to accommodate the gear testing. The clutch gear was removed, the bore diameter slightly adjusted and a keyway was placed in the bore.

A gear manufactured by hobbing and shaving was used as a reference in terms of gear quality, surface roughness and hardness profile. The material used for the gear is 16MnCr5 (AISI 5115) a commonly used case hardening steel.

Table I. Selected gear and tool data

Property	**Symbol**	**Gear**	**Tool**
Number of teeth	Z	28	69
Nominal pressure angle	α_{0n}	15^{o}	15
Module	m_n	2 mm	2 mm
Helix angle	β	32^{o}	32^{o}
Pitch diameter	d	66.034 mm	
Addendum modification coefficient	x	0.136	
Top diameter			169.4 mm
Root diameter			156.0 mm

THE MANUFACTURING OF BLANKS

The powder mix used consists of a pre-alloyed base powder, 0.3 wt.% graphite and 0.8 wt.% lubricant. The 4600 (Astaloy A) is a fully pre-alloyed base powder with nominally 1.9 wt.% Ni, 0.5 wt.% Mo, 0.5 wt.% Mn. Blanks were manufactured by compaction and sintering of cylinders 80 mm diameter and a height of 25 mm. The compaction was performed at room temperature to a pressure of 800 MPa. The sintering was performed in a belt furnace at 1120 ^{o}C (2050 ^{o}F) for 30 minutes in an atmosphere of 90% N_2 and 10% H_2. The resulting density was 7,2 g/cm^3. The blanks were turned, a center hole drilled, and the preform teeth were cut by hobbing. The hobbing was performed to a shape that leaves a small over measure (stock) compared to the finished gear. During the preform and tool die design process; the preforms were ground to a new shape.

THE DESIGN OF PREFORM AND TOOL DIES

The design of tool dies and preform shape is performed using simple theoretical guidelines and experience. In most cases it will prove necessary to perform tests in order to fine-tune the shape of the tool dies and the preforms in order to reach high quality.

The gear geometry is fixed. The design process starts by finding a tool profile that can generate the desired gear shape. The tool shape should not only generate the correct shape, it should also have tooth tip and root profiles that will prohibit or minimize any slivering (cutting of fine chips) that can occur. Furthermore, the design should be strong enough to withstand the forces created during the rolling. The shape of the preform is determined by the final shape of the gear and by the desired densification, see Figure 2. Naturally if a thicker densified layer is desired, more stock allowance must be present. The stock allowance for densification of the root and the flank respectively is schematically shown in Figure 2. If both flank and root should be densified, the stock allowance will be a combination of the two.

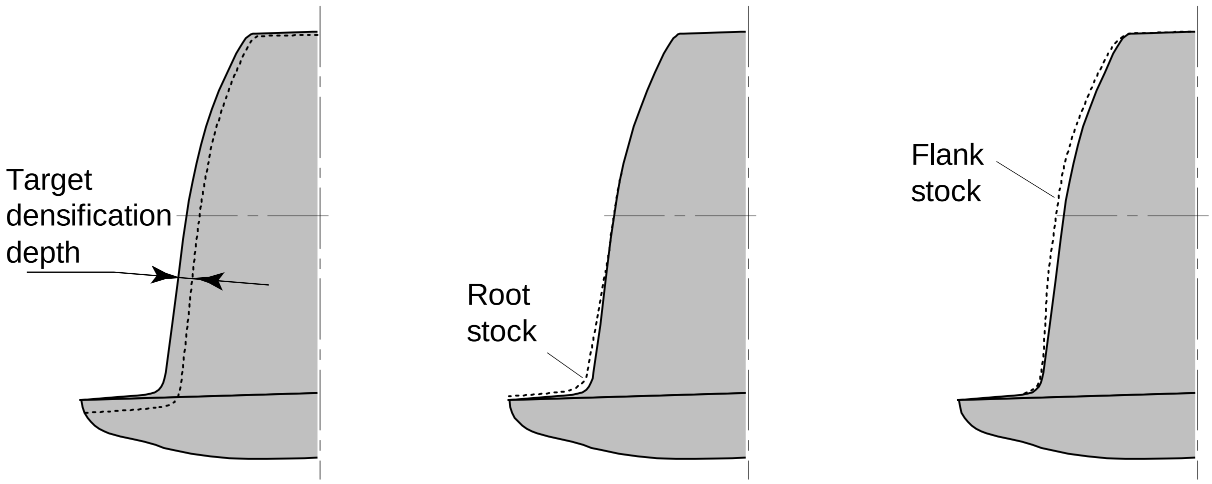

Figure 2. Schematic view of preform. *Left:* Required densification depth. *Center:* Root stock allowance. *Right:* Flank stock allowance.

A schematic overview of the design parameters can be found in Table II. The gear parameters are considered to be fixed, even if especially the root radius may have to be changed. The main variables for the tool design are the addendum modification and the tip and root profiles. The preform must have the correct shape in order to reach the desired densification and shape. This means that it is sometimes difficult to express the preform shape in the standard terms of module, addendum modification, pressure angle, etc.

Table II. Selected design parameters.

<table>
<tr><th>Parameter</th><th>Preform (blank)</th><th>Tool dies</th><th>Finished gear</th></tr>
<tr><td>Module m_n</td><td>fixed</td><td>fixed</td><td rowspan="9">Fixed by gear drawing</td></tr>
<tr><td>No of teeth Z</td><td>fixed</td><td>free</td></tr>
<tr><td>Helix angle β</td><td>fixed</td><td>fixed</td></tr>
<tr><td>Addendum modification x</td><td rowspan="6">design parameter</td><td rowspan="6">design parameter</td></tr>
<tr><td>Tooth tip relief and root profile</td></tr>
<tr><td>Pressure angle a</td></tr>
<tr><td>“Tip” Radius r_{a0}</td></tr>
<tr><td>“Root” Radius r_{f0}</td></tr>
<tr><td>“Root” Clearance c</td></tr>
</table>

<u>THE SURFACE DENSIFICATION PROCESS</u>

Figure 3 shows the rolling machine with the work piece in the center and the two adjacent movable and rotating axes. The load and position of the axes can be used for control of the process. The rotation, movement and load are programmed to follow a selected pattern during the rolling operation. The surface densification by rolling can be divided into three stages. The first is the penetration stage where the tool and work piece make contact, the preform is compacted and its flank and root shape is changed. The second stage is the calibration where the overall size of the gear is “calibrated” by rotating with at a constant center distance. The work piece is made round at this stage. The last stage is the decompression, where the elastic stresses in the tool and work piece are released.

The tool data are shown in Table I. The tool is designed together with the over measure of the preform. During the rolling process there are three mechanisms active; material compaction, material movement, and elastic deformation. It is only the first mechanism that contributes to the densification. A kinematic simulation can be performed that shows the interference between tool and preform at different stages of the rolling process. If all the material in the interference zone was compacted the tool shape could be easily constructed. However, the latter two mechanisms call for the use experience and of trial and error methods.

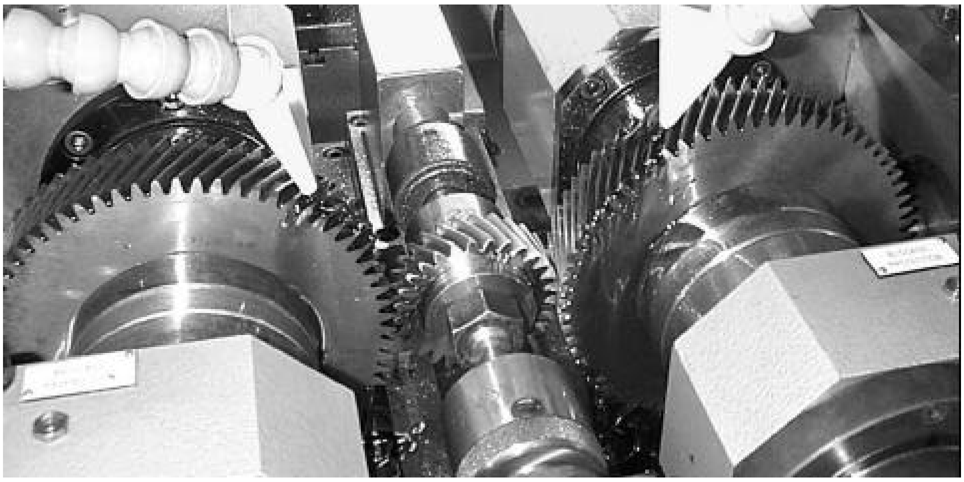

Figure 3. Surface densification of a helical transmission gear using a standard burnishing equipment.

The movement of material during the rolling is schematically shown in Figure 4. On the approach side the material moves towards the "middle" (pitch circle) of the tooth. This means that two moving "waves" of material meet there and this may cause a problem by creating a "seam". On the trail side the situation is reversed, the material is moving away from the pitch circle and towards the root and top regions. This too can cause problems by slivering in the root region and slivering and burr in the top region. The top of the tooth will have a characteristic tilted appearance due to the excess material on one side and the removal of material on the other. By rotating the tools in one direction and then reversing, the problem of asymmetric material movement can be minimized.

The material selected for surface densification must meet a number of requirements [9]; it must allow compaction and sintering to close tolerances, it must be relatively soft in the as-sintered state in order to allow densification it must also perform well during case hardening and service.

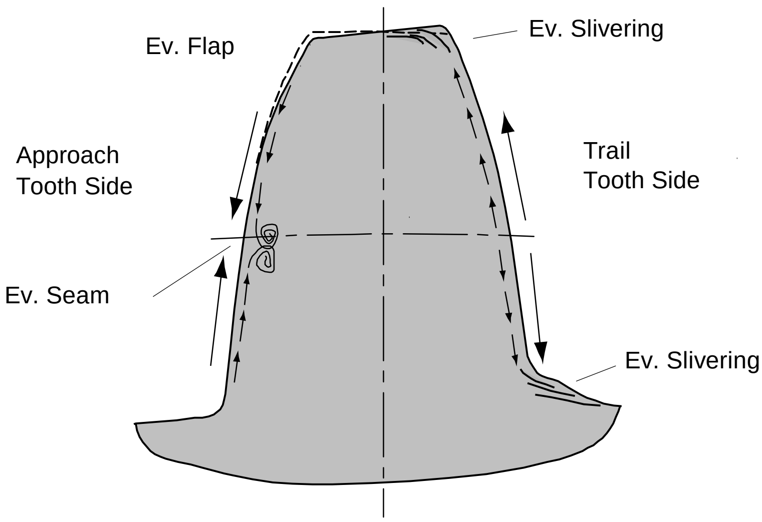

Figure 4. Schematic view of material movement during surface densification [6].

THE HEAT TREATMENT

The case hardening parameters were selected to ensure that the hardness profile at the flank should match the hardness profile of the reference gear.

The gears where carburized for 160 min at 920 ^{o}C (1688 ^{o}F). Just before quenching the temperature is lowered to 870 ^{o}C (1598 ^{o}F) in order to minimize distortions. The quenching is performed in oil heated to 60 ^{o}C (140 ^{o}F). The quench was followed by a stress relieving treatment at 160 ^{o}C (320 ^{o}F) for one hour in air.

GEAR DIMENSIONS

Table III shows the scatter in diameter measurements before and after rolling. The measurements of diameter over pins and the root diameter decrease its scatter by 60-70%.

Table III. Diameter measurements

Measurement	**Standard deviation before rolling**	**Standard deviation after rolling**	**% Change**
Root diameter	33	9	-73%
Diameter over pins	20	8	-60%

SURFACE ROUGHNESS

The surface roughness was measured on the gear tooth flanks. Table IV shows the measurements that were made on the rolled and hardened gears as well as on a shaved and hardened reference gear. It can be seen that the surface roughness is significantly lower for the surface densified gear.

Table IV. Surface roughness measured on a 1.0x2.6 mm area on the gear tooth flank.

Gear	**R_z (mm)**	**R_a (mm)**	**R_t (mm)**
Surface densified gear	1.13	0.168	1.53
Shaved gear	2.26	0.366	3.11

DENSITY DISTRIBUTION

Metallography of the densified and case hardened gears was performed in the as polished condition to reveal the level of porosity. Figure 5 shows parts of the cross section of a densified P/M gear tooth. The densification depth (here defined as porosity < 2 %) is approximately 0.4-0.5 mm in the part of the flank with the highest loading. In this cross section the densification depth in the root region is slightly lower.

HARDNESS DISTRIBUTION

The micro hardness was measured on polished and lightly etched cross sections using a Vickers indenter with a load of 100g. The indents are placed in martensite were phases can be identified and pores are avoided. This means that the effect of increasing porosity towards the core of the tooth is not shown in Figure 6. The indents where placed in rows from one side of the tooth to the other. The distance between the measurements was small in the case carburized zone where the hardness is high and the indents are small. Further into the tooth the spacing between indents is wider as the size of the indents increase with decreasing hardness. Hardness profiles were measured on the flank, the root and in the top regions. These profiles were used in order to create “iso-hardness” curves as shown in Figure 6.

The hardness is a function of local carbon level and density. Near the surface the material is fully martensitic (with some retained austenite) and the hardness is proportional to the carbon level. Further into the material, when the cooling rate drops, bainite is formed. The presence of the dens layer slows the carbon penetration, but increases the cooling rate. This means that the fully dens layer is almost without exception fully martensitic. At the top of the surface densified gear tooth, the densified layer is not very thick and carbon penetrates quicker during the carburization treatment. This results in a fairly deep layer of very high hardness.

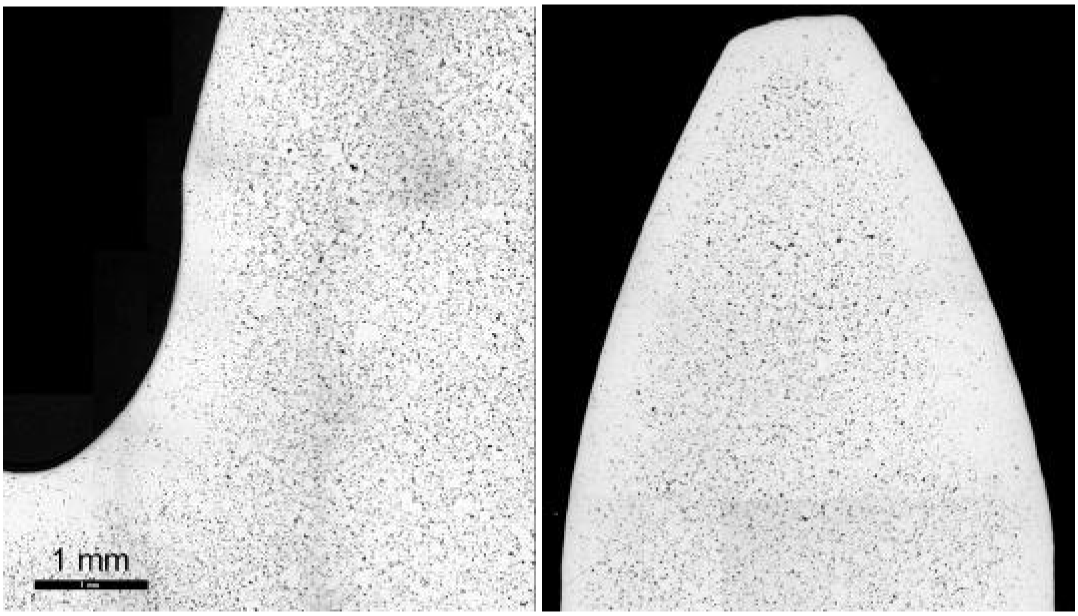

Figure 5. Cross section of a surface densified P/M gear tooth in the as-polished condition. *Left*: Tooth root section. *Right*: Flank and top of tooth. The scale marker is 1 mm.

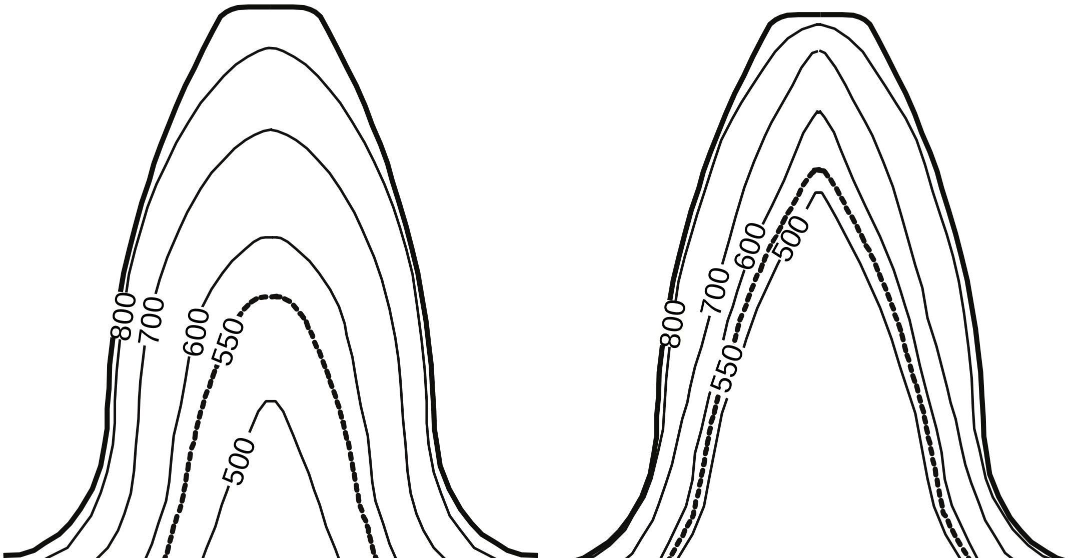

Figure 6. Micro hardness measurement mapping. *Left:* A surface densified P/M gear. *Right:* Reference gear 16MnCr5. The cross section is located in the center of the tooth.

CONCLUSIONS

- The scatter in vital gear dimensions improves by the rolling process.
- The surface roughness of the surface densified gear is better than the shaved reference gear.
- The desired densification distribution was reached.
- The hardness profile in the flank region matches the hardness profile of the solid steel reference gear.

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