ABSTRACT

Transmission gears are one of the major growth opportunities for PM in the automotive sector. To succeed with PM helical gears there are challenges in sufficient strength of the material and in the robust compaction of net shape parts. However, there are also benefits from using the PM route for the manufacturing of the gears. The production technology is efficient for making net shape components to save subsequent machining operations and costs. Pressing the parts enables optimization of the gear profile which cannot be made by hobbing and, if conditions are right, weight saving holes can be introduced without adding additional machining operations. This paper presents the work with optimizing the design for PM, selecting the best performing powder concept, tool up and pilot production of the 4th drive gear for a six speed, medium torque transmission.

INTRODUCTION

One of the major growth potentials for PM components is high strength transmission gears. The penetration of PM steels for this group of components is today very limited. In order to demonstrate the feasibility and promote the use of PM in transmission gears, a project has been initiated to replace the original gears for the 3rd to 6th speed in the General Motors M32 gear box with PM gears. This paper covers the solutions and results from compaction of the 4th drive gear.

To take full advantage of the PM process route for manufacturing transmission gears, it is important to not only work with material and process selection, but also with gear design. Some design features that are difficult, and expensive, to introduce with conventionally machined gears come for free with PM. One such feature is the shape of the tooth root. While machined gears are restricted by the motion of the cutting tool, PM does not have these limitations. Instead, by optimizing the shape of the tooth root, the
stresses can be reduced and the fatigue life can be improved [1, 2]. Weight-saving holes is another feature that can be incorporated in a PM component without increasing the number of processing steps.

There are high demands on material performance for transmission gears. High density is required, and in this case where no re-pressing or surface densification is done, it becomes even more important. A highly compressible metal powder mix with good lubrication is crucial to reach high density of the compacted part. In the results presented in this paper, mixes based on diffusion alloyed base iron powders were used with two different lubricants; Intralube® E mix [3, 4] and an experimental high density lubricant in combination with warm die compaction.

Compaction of helical gears adds to the complexity of compaction by introducing rotation of the punches and core rods, assuming the die is not rotating. Furthermore, the upper, outer punch must have a very well-controlled rotational movement to enter into the die without colliding. There are different solutions with passive or active mechanisms that control the rotational movement of the upper punch, for instance cam tracks and lead dies. In the tool used for the trials presented in this paper, an active driven system for the rotational movement of the upper punch was used.

PART DESIGN

An overview of the 4th drive gear is illustrated in Figure 1 and the drawings in Figure 2 indicate some of the main dimensions. Table 1 presents some main gear data. The part features three levels on the upper side and three levels on the lower side.

![Figure 1: 4th drive gear overview](image1)

![Figure 2: 4th drive gear major dimensions and helical angle](image2)

<table>
<thead>
<tr>
<th>Table 1: Gear data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal module (m&lt;sub&gt;n&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Normal pressure angle (α&lt;sub&gt;n&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Helix angle (β)</td>
</tr>
<tr>
<td>Number of teeth (z)</td>
</tr>
</tbody>
</table>
The overall design of the part origins from the currently used wrought steel gear for the M32 gearbox. However, to take advantage of the unique capabilities of the PM production route some modifications to the design have been made. The obvious design feature which has been added is the inclusion of twelve weight-saving holes. The PM process route enables these to be added without adding additional processing steps as would be required in the manufacturing process of a wrought gear. The weight-saving holes decrease the weight and inertia of the gear: something which is of increasing importance considering today’s focus on fuel economy.

Another important design optimization, less obvious by the naked eye, was made in the tooth root geometry of the gear. This geometry of hobbed gears is in general generated by the shape of the hob and is not optimal for the function of the gear. When a gear is pressed from metal powder the tooth root geometry can be designed without some of the limitations that come with conventional gear-cutting processing.

Optimization of the tooth root geometry was done by using the built-in functionality of KISSsoft [5] to make elliptic root profile. In Figure 3 the original and the modified tooth root geometries are illustrated. The original tooth root geometry was replaced by an elliptic segment that is tangential to the tooth flank and root bottom. Figure 3 shows that the elliptic modification adds significantly more material to the tooth root.

![Figure 3: Illustration of modified tooth root geometry](image)

The original and elliptic root geometries were both exported to Creo Parametric and Creo Simulate [6] where a stress analysis was conducted to evaluate the effect of the modified tooth root. The calculation was done using a 2D plane stress, finite element model of the tangent plane of the gear. A unit load was applied at the pitch point of the gear, tangent to the base circle and the tooth root stresses were calculated. In Figure 4 the resulting root stresses from the FEA calculation are shown. By modifying the tooth root geometry, maximum stress was decreased to 82% compared to the stress level of the original design.
The risk of tooth root failure can be reduced by optimizing the tooth root geometry and thereby lowering the stresses. This design modification was incorporated in the design of the press tool used for the compaction trials presented in this paper.

PRESS TOOL AND HELICAL DRIVE SYSTEM

To control the rotational movement of the outer upper punch, a helical drive manufactured by Alvier AG (see Figure 5) has been used. This active drive system is a modular system with exchangeable helix modules that enable the system to be adapted to specific components. The gear box converts the linear movement into the required rotation of the upper punch with high accuracy. Large helix angles can be realized with the helical gear system. By high precision top punch entry, the tool wear is minimized and rounding of the edges of the punch faces is avoided.

The other punches and core rods of the tool must be able to rotate and are thus placed on bearings, see Figure 6 for illustration.

Since the centre hole of the part features straight splines, the centre core rod cannot enter into the upper punch. Instead the core rod is pushed back by the upper punch and does not enter into the punch which would be the preferred solution if the centre hole would have been a cylindrical hole. The core rods for the
weight saving holes are of cylindrical shape. However, since these are positioned off-centre they cannot enter into mating holes in the upper punch because the lower punch, through which the core rods go through, and the mating upper punch rotate in opposite directions.

Figure 6: Bearing modules for punches and core rod

EXPERIMENTAL

Powder mixes with different compositions were used to compact gears. These compositions as well as analyses of the powder mixes are presented in Table 2. The mixes were analysed with respect to flow (ISO 4490) and apparent density (ISO 3923). Green density (ISO 3927) was tested at a compacting pressure of 600 MPa. Organic content (lubricant/binder) and graphite content of the mixes were analyzed by solvent extraction and combustion analysis respectively.

Table 2: Composition and analyses of powder mixes

<table>
<thead>
<tr>
<th>Mix</th>
<th>Nominal composition</th>
<th>Flow (s/50 g)</th>
<th>AD (g/cm³)</th>
<th>GD (g/cm³)</th>
<th>Graphite (%)</th>
<th>Lubricant (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD-0105 (E)</td>
<td>D. AQ + 0.4% C-F10 + 0.65% Lube E</td>
<td>31.5</td>
<td>3.02</td>
<td>7.14</td>
<td>0.40</td>
<td>0.66</td>
</tr>
<tr>
<td>FD-0105 (HD)</td>
<td>D. AQ + 0.3% C-UF4 + 0.55% HD lube</td>
<td>29.6</td>
<td>3.03</td>
<td>7.17</td>
<td>0.30</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The press tool was run-in with mix FD-0105 (E) and gears were compacted to a density of 6.9 g/cm³. After metallographic investigations it was confirmed that the as-compacte and sintered gears were crack-free (without any counter measures). At this density level 1,000 parts were pressed at a press rate of 6.5 pcs/min.
Using the same powder mix, the density was increased by increasing the press force to 4,000 kN which corresponds to 690 MPa. The pressure was incrementally increased and the density of sampled gears was measured by Archimedes’ principle. As comparison a compressibility curve of the same mix was also measured according to the standardized method ISO 3927.

At 4,000 kN the density of the gears was 7.2 g/cm³. After increasing the density the press cycle had to be optimized to keep the components crack-free. The press rate after having optimized the press cycle was 5.5 pcs/min. Once the parts were crack-free, a compaction campaign with continuous compaction of 2,000 gears was carried out to prove that the tool and the compaction process were stable by simulating industrial compaction.

To further explore the potential to compact this helical gear to even higher density, a mix named FD-0105 (HD) that contained a high performance, currently under development, lubricant, was tested. The nominal lubricant content was decreased to 0.55% in order to increase the maximum achievable density. The compacting pressure was increased to 4,400 kN, corresponding to 750 MPa, and the tool die was heated to 70°C. A compressibility curve was also generated for this mix, this time during the ramp-up of the pressure. As reference, a compressibility curve was made with tool die heated to 90°C according to the standardized method ISO 3927.

During the setup of each trial the density distribution was checked by cutting the gears in various sections:

- Pie slices: front, left, back and right
- Concentric segments: gear, web and hub
- Horizontal slices (upper and lower) of the gear and hub segments

During the compaction trials, the press control system logged the maximum press force, peak force of the lower ram and weight of each part. Part temperature, total green density and height of the different segments of the gears were measured at regular intervals during all press campaigns; the sampling frequency differed between the trials depending on the total number of parts made in each respective trial. Higher sampling frequency was used during the shorter runs.

After compaction of 4,000 parts the press tool was disassembled and inspected.

Sample gears were sintered at 1120°C for 30 minutes in 90 N₂/10 H₂ atmosphere. Case hardening was carried out with a carburizing temperature of 920°C. Carbon potential was set to 1.2% for 30 min and then decreased to 0.8% for another 30 min. The parts were quenched in oil from 920°C. After the quenching the parts were tempered for 60 min at 180°C in air.

The dimensions of the green, sintered and heat treated gears were assessed by measurement in a Zeiss DuraMax 5/5/5 VAST-XXT coordinate measurement machine. Diameters, axial and radial run-out, flatness and roundness of the gears were measured.

**RESULTS AND DISCUSSION**

**Trials with mix FD-0105 (with 0.65% Lube E)**

The parts were initially crack-free when running in the tool with the mix FD-0105 (E) at a density of 6.9 g/cm³. At this stage no specific counter measures other than using a top punch hold down of 250 kN
during withdrawal had been used. The pressure was then incrementally increased until the green density reached 7.2 g/cm³. In Figure 7 the compressibility of gears is plotted versus the compressibility of cylindrical specimens according to ISO 3927. It can be seen that the compressibility was 0.06 to 0.03 g/cm³ lower for the helical gear compared to the standardized cylindrical specimen.

![Figure 7: Compressibility of FD-0105 (E) measured on gears and specimens according to ISO 3927](image)

The desired density of 7.2 g/cm³ was reached with a press force of 4,000 kN corresponding to 690 MPa. After increasing the density, cracks were found in the cross section of the gears and adjustments to the settings were made in a number of iterations to eliminate the cracks and to obtain a better density distribution in the teeth. The following modifications were made to the press cycle:

- Decompression time was increased from 0.5 to 0.9 s.
- Counter pressure during ejection increased from 250 to 350 kN
- Synchronization of die motion relative to upper punch was increased from 62.5% to 67% (to improve density distribution)
- Punch deflection compensation of punches 2a and 1a (gear section) was set to 0.20 mm

These modifications resulted in gears free from press cracks. The vertical cross section of the gear can be seen in Figure 8.

![Figure 8: Vertical cross section through the gear](image)
After modification of the press cycle to eliminate the micro cracks, the press rate was 5.5 pcs/min. However, no attempts to optimize the press cycle for maximum productivity were made at this stage and by further optimizing the settings it should be possible to increase the potential of productivity.

Densities of concentric cut segments are presented in Figure 9. It can be seen that the density of the gear segments were slightly lower compared to the hub segment. In the gear section there was a tendency to higher density in the upper half. This could be further improved by optimizing the synchronization of the movement of the upper punch and the die during compaction. In the hub section the vertical density distribution was the opposite, thus density was higher in the lower part. This is explained by the tool design where the upper punch pushes back the core rod and in principle causes local single action compaction of this segment.

![Figure 9](image)

**Figure 9:** Green density measured on concentric segments

Density distribution was also measured on “pie slice” segments, see Figure 10. There were only small density differences between these four segments. Figure 10 also presents the height of the gear segment measured in four positions. The largest difference in height between these positions was 0.03 mm.

![Figure 10](image)

**Figure 10:** Green density measured on “pie slice” segments and height of the gear segment

To investigate the density distribution in the gear teeth, horizontal cross sections were made through the top, centre and bottom of a tooth, see Figures 11 a-c. A cross section was also studied along a tooth, see Figure 12. In the horizontal cross sections, high and even density was found at the three levels.
investigated. In Figure 12, it can be seen that the neutral zone was somewhat below the vertical centre of the cross section. This was also indicated by the sectional density measurements in Figure 9.

Figure 11 a-c: Unetched metallographic horizontal cross section through top, centre and bottom of a tooth

Figure 12: Unetched metallographic cross section along a tooth

A production run of 2,000 compacted gears (1 ton of powder) was carried out to ensure that the process was running stable. In Figure 13a, green density of gears sampled during this production run is presented. The density of the gears was very stable: around 7.22 g/cm³ throughout this production run. Figure 13b presents the temperature of the parts after ejection: after 500 parts the temperature was stable around 62°C.
Figure 13 a – b: Green density (left) and part temperature after ejection (right) from production run of 2,000 gears

In Table 3, measured dimensions of 10 sample gears measured as green, sintered and case hardened are presented along with the dimensional specification of the gear after final heat treatment and grinding. It can be seen that inner and outer diameters were well centred in the specification as case hardened. Roundness of inner and outer diameter was well within the specifications. Axial run-out measured on ø40 mm (hub) and ø84 mm (gear) were close to the upper tolerance limits. It can be noted that both the flatness and axial run-out at ø84 mm increased during case hardening and some optimization of the heat treatment process is required in order to improve this characteristics. Radial run-out is measured between the inner spline and the outer gear. Measured values of the radial run-out were on the upper specification limit of the pressed part, after grinding the radial run-out is specified to maximum 22 µm. The radial run-out was not influenced by the sintering and heat treatment.

Table 3: Dimension of 10 sampled gears measured by CMM in green, sintered and case hardened state

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Specification</th>
<th>Average dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal</td>
<td>Upper tolerance</td>
</tr>
<tr>
<td>Inner diameter of splines</td>
<td>32.8</td>
<td>0.075</td>
</tr>
<tr>
<td>Outer diameter of teeth</td>
<td>103.6</td>
<td>0</td>
</tr>
<tr>
<td>Two balls measurement average</td>
<td>103.60</td>
<td>103.50</td>
</tr>
<tr>
<td>Roundness of inner diameter</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Flatness at ø40 mm</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Flatness at ø84 mm</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Axial run-out at ø40 mm</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Axial run-out at ø84 mm</td>
<td>0.1</td>
<td>0.07</td>
</tr>
<tr>
<td>Radial run-out</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Trials with mix FD-0105 (with 0.55% experimental HD lubricant)

The following results were generated from compaction of gears from the second mix: FD-0105 (HD). The objective in this part of the investigation was to further increase the density of the gears by utilizing a highly efficient lubricant in combination with heated tool die.

In Figure 14, the compressibility of FD-0105 (HD) for gears as well as standardized compressibility specimens are plotted. Compressibility of gears of the FD-0105 (E) mix from the previously presented trials is also included in the graph for comparison. It can be seen that higher density was achieved by combining the better lubrication performance of FD-0105 (HD) with lower lubricant content and higher tool die temperature. The density improvement increases with increasing compacting pressure. Comparing the difference in compressibility of the gear and standardized specimen, the difference was bigger for the FD-0105 (HD) mix compared to the corresponding case in Figure 7. In the case of FD-0105 (HD) there was a difference in tool die temperature. For the standardized specimens the tool die temperature was set to 90°C which is the optimum temperature for this lubricant. In the case of the gears, the set value for the
tool die temperature was limited to 70°C to be on the safe side and to avoid problems with clearance between tool members due to temperature differences.

**Figure 14**: Compressibility of gears versus specimens according ISO 3927

Densities of concentric cut segments are presented in Figure 15. Again, there was a tendency to higher density in the upper half of the gear segment. In the hub section the vertical density distribution was improved compared to the results presented in Figure 9. Measured density of the cut segments of the green components tends to be slightly lower than the overall density due to the rougher surfaces generated by the saw.

**Figure 15**: Green density measured on concentric segments

Next study is from a continuous production run of 400 gears from mix FD-0105 (HD). Figure 16a presents green densities of gears sampled throughout this production run. The density was stable around 7.3 g/cm³. Compared to the first study the temperature stabilized faster with the pre-heated tool die and was around 67°C after 200 parts, see Figure 16b. The higher temperature was a consequence of the pre-heated tool die and can thus not be used as a direct indication of the efficiency of the lubrication.

The peak force of the lower ram of the press was similar (800 kN) between FD-0105 (E) and FD-0105 (HD) even though the lubricant content of the latter mix was 0.1% lower and the compacting pressure was 50 MPa higher. This, in combination with the observation of the same shiny component surface conditions with both mixes, indicates that the lubrication of FD-0105 (HD) is very efficient.
Figure 16 a – b: Green density (left) and part temperature after ejection (right) from production run of 400 gears of FD-0105 (HD)

In Figure 17 the weight stability of the gears of mix FD-0105 (HD) is presented. The weight stability is a good indication of the filling performance of a mix. It can be seen that the weight of the compacted gears was very stable, indicating consistent filling of the tool die. No adjustments of the fill depth were made during the run of these 400 gears. A standard deviation of 0.11% for the weight scatter is a very satisfactory and good result.

Figure 17: Weight scatter from production run of 400 gears of FD-0105 (HD)

In Figure 18a-d data from height measurements of gears from follow up during the compaction campaign are presented. The blue lines are the specification limits for the measured dimensions. Process capability numbers (Pk) are also indicated in each diagram. In the calculation of these numbers the first three data points were omitted to not include the start-up. As can be seen, some of the measured heights were not centred in the specification. However, no actions were taken to correct this since the main objective was to assess the stability of the process rather than making useful parts. What is more interesting is that high numbers of the process capability were achieved and production of this gear with good process capability would be possible if the settings were adjusted to centre these dimensions in their specifications.
Figure 18 a–d: Height of gears from SPC follow-up during a production run of 400 gears

Density distribution in the gear teeth is presented in Figure 19 a-c as horizontal cross section through top, centre and bottom of a tooth and 20 as cross section along a tooth in Figure. Also in this case it can be seen that the neutral zone was shifted somewhat towards the bottom side of the tooth. In the horizontal cross sections, high and uniform density was found in the cross sections at the three levels. In the cross section along one tooth shown in Figure 20, it can be seen that the neutral zone is somewhat below the vertical centre of this section, this in accordance with the density measurements presented in Figure 15.

Figure 19 a-c: Unetched metallographic horizontal cross section through top, centre and bottom of a tooth
Figure 20: Unetched metallographic cross section along a tooth (bottom side of the gear is to the left)

Table 4 presents the measured dimensions of 10 sample gears measured in green condition along with the specification for the dimensions of the gear after final heat treatment and grinding operation of the gear profile. Comparing the green dimensions of the of the gears of FD-0105 (HD) in Table 4 with the gears of FD-0105 (E) in Table 3, it can be concluded that dimensions, roundness, flatness and run-out is more or less identical.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Specification</th>
<th>Average Green dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of splines</td>
<td>32.8 0.075</td>
<td>32.79</td>
</tr>
<tr>
<td>Outer diameter of teeth</td>
<td>103.6 0</td>
<td>103.66</td>
</tr>
<tr>
<td>Two balls measurement average</td>
<td>0.03 0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Roundness of inner diameter</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Flatness at ø40 mm</td>
<td>0.03 0.00</td>
<td></td>
</tr>
<tr>
<td>Flatness at ø84 mm</td>
<td>0.1 0.02</td>
<td></td>
</tr>
<tr>
<td>Axial run-out at ø40 mm</td>
<td>0.03 0.01</td>
<td></td>
</tr>
<tr>
<td>Axial run-out at ø84 mm</td>
<td>0.1 0.04</td>
<td></td>
</tr>
<tr>
<td>Radial run-out</td>
<td>0.08 0.09</td>
<td></td>
</tr>
</tbody>
</table>

In total, more than 5,000 gears have been compacted with the tool for the M32 4th drive gear, whereof 4,000 have been compacted to a density of 7.2 g/cm³ or higher. Except for a broken bolt for the core-rod, the press tool have been working very well and no scoring or damages have been found on the tool parts. Some brown deposition can be seen on the surface of the lower punch. This is formed by friction and can easily be removed by light polishing. However, a friction reducing coating of the lower punch should be considered for a production tool.
CONCLUSIONS

In total more than 5,000 M32 4th drive gears have been successfully compacted.

By utilizing the benefits of the PM manufacturing technology, weight-saving holes were introduced and the tooth root geometry was modified resulting in lower weight and lower stresses in the tooth root.

An active helical drive system was used to control the rotational movement of the upper punch with high accuracy.

An overall density of 7.3 g/cm³ was achieved with an experimental “high density” mix under development.

Good filling consistency and small weight scatter was achieved. Height tolerances can be met with high process capability.

Most of the requirements on dimensions and precision have been met.

REFERENCES


[6] PTC, Creo 2.0