Powder Metal Gear Technology: A Review of the State of the Art

Anders Flodin

During the past 10 years, the PM industry has put a lot of focus on how to make powder metal gears for automotive transmissions a reality. To reach this goal, several hurdles had to be overcome, such as fatigue data generation on gears, verification of calculation methods, production technology, materials development, heat treatment recipes, design development, and cost studies.

All of these advancements will be discussed, and a number of vehicles with powder metal gears in their transmissions will be presented. How the transmissions have been redesigned in order to achieve the required stress levels while minimizing weight and inertia, thus increasing efficiency, will also be discussed.

Introduction

Automotive transmissions today are an important machine element for Powder Metal (PM) components. In manual transmissions, the PM synchronizer hubs have gradually replaced machined hubs over a 20-year period. Several other PM parts can be found in manual transmissions, such as synchronize sleeves and shift fingers. In epicyclical automatic transmissions, carriers have been made using PM for many years, in addition to oil pump gears. Recently, powder forged planet gears were introduced in a Ford automatic transmission (Ref. 1), thus opening up the market. Also, Getrag Ford in Cologne has taken PM gears to implementation readiness through an extensive validation program (special interest seminar Euro PM 2014, Salzburg).

Initially, the PM synchronizer hubs in manual transmissions were introduced for the higher gears that were not subjected to that many cycles, typically fourth gear, since there were concerns about durability for the highest gears. The hubs then gradually started to replace machined hubs in the higher and lower gears. Finally, within the last 5 years, PM synchronizer hubs have been introduced in first, second, and reverse gears where abuse is an issue. It took around 20 years for this to happen, and PM gears will likely experience the same cycle with respect to transmission gears. We are now in the introduction phase of PM gears for the least loaded gear stages in car transmissions, where the technology has to prove itself before replacing the more heavily loaded gears. Meanwhile, the PM industry advances their technology to be able to cope with abuse loads and severe driving conditions.

PM Gear Processing

There are several ways to manufacture a PM gear, and the route is dictated by the performance requirements since strength levels can be tailored through material and process changes. For a manual gearbox, some gears, typically fourth to fifth, could be made following this sequence:

- Compaction-Sinter-Case carburize, quench, temper (CQT)
- Hard finish (grinding/honing)

This is a four-step process and could be made even shorter by the introduction of a combined low pressure sintering and CQT process (LPC):

- Compaction-LPC-Hard finish

This three-step process provides strength levels equivalent to approximately 70% of a wrought 16MnCr5 gear, processed using conventional cutting, CQT, and grinding, with respect to tooth root bending fatigue and pitting fatigue. If more strength is required, another sinter and compaction step could be utilized to increase density to 7.4–7.5 g/cc or add a densification process that involves surface rolling of the gear flanks and sometimes in the root. This rolling process flattens out the pores in the surfaces and thus reduces porosity and the number of potential crack initiation points (Fig. 1). This rolling process has been used by Getrag Ford in their validation work; see below.

For gears, the densification takes place in the surface volume, where the highest stresses can also be found. Generally, the performance level of a good densification will give durability similar to solid steel (16MnCr5 for instance), provided all other process steps are done well.

Another method used to increase strength is to powder forge the gears, a technology that has been around since the mid-1970s but never gained popularity due to cost and difficulties with high helix angles. The process steps would be:

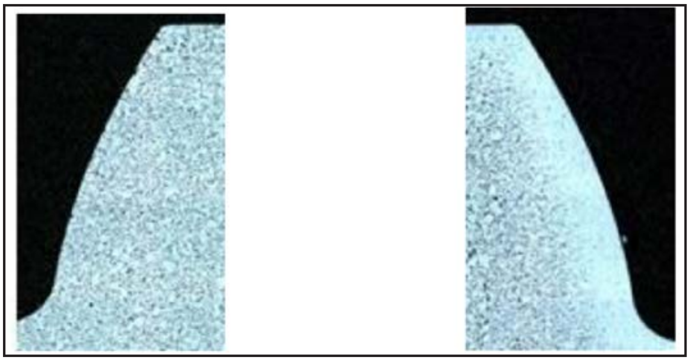


Figure 1 PM gear flanks, cut view, left: non-densified flank; right: densified flank with pore removal.

- Compaction-Sinter-Forge-CQT-Hard finish

This process would require multiple tools, and the tool wear when forging is normally quite high, making it difficult to maintain tight tolerances. Powder forging would, however, give very good strength in all parts of the gears, which is not the case, for instance, for a densified gear that lacks densification in the bore and has lower ability to redistribute stresses from impact loads. Powder forged gears were referenced in the beginning of the paper; one reason to go with powder forged gears for an epicyclical gear set is that it enables a bearing to be run directly on the powder forged bore surface since it is fully dense, in comparison to rolled gears that have a porous bore. For a manual gearbox, this is less of a problem since there is no load on the bearing while the gear is rotating relative to the shaft. There are even manual gearbox designs with no roller bearings; the gear bore itself is used as a journal bearing rotating directly on the shaft.

Another method of achieving high strength PM gears is by hot isostatic pressing (HIP) of the gear. This has not been done commercially yet, but lab-scale testing shows very good results. The process would be:

- Compaction-Sinter-HIP-CQT-Hard finish

There is also a pending patent on a process where Sinter, HIP, and CQT steps are used in sequence. This three-step processing sequence would produce a gear that is fully dense, with a microstructure qualified for nuclear power plants. So while market introduction for PM gears will be with a process giving lower but still good enough strength for certain gears, more refined processes are being developed that will open up PM for much more highly loaded gears.

Heat Treatment of PM Gears

Heat treatment of PM gears can be performed with the same type of equipment used for processing regular steel gears. Nitriding, CQT, induction hardening, etc. work well with PM, but the process parameters have to be specially tailored for these types of materials and gears. The reason is that the porosity in these gears permits much shorter processing times to be used. This also means that process control becomes much more important. A variance of 5 minutes for a 20-minute soak time for PM material is more significant than a 5-minute variance on a 2-hour soak time that is used for a solid steel gear. Material-wise, it is possible to tailor the alloying and carbon content with respect to cooling rates that can be achieved, or the desired case depth. Another important difference is the method used to measure hardness. For PM, the preferred method is Micro-Vickers (HV 0.1). Using Vickers with a 1 kg indentation weight will render low values, and the part will appear to be out of specification, even though that might not actually be the case.

PM Gear Design

Powder metal manufacturing technology offers and demands a different design approach. Conventionally cut gears are based on rack generation, but PM gears are not limited by that. Instead, the direct gear design method (Ref. 2) is better suited where the functionality of the gear dictates geometry without the influence of how a hob makes its cut.

Micro Design

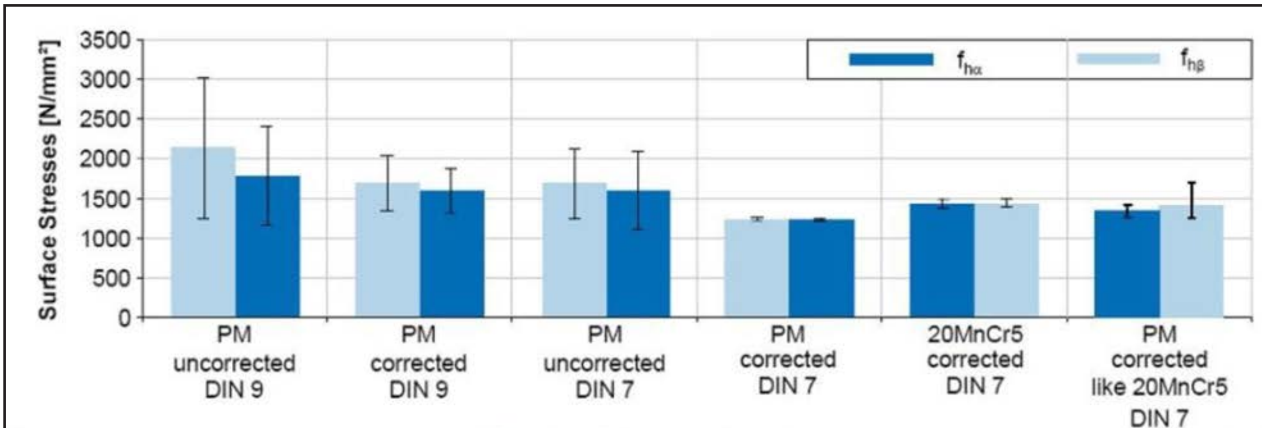
The Young's modulus is dependent on the density of the PM gear. This relationship can be described by Equation 1 (Refs. 3–4).

$$E = E_0\left(\frac{\rho}{\rho_0}\right)^{3.4} \tag{1}$$

where

E Young's modulus of PM part
E_0 Young's modulus of solid steel
ρ Density of PM part
ρ_0 Density for solid steel

This means that PM gears will deflect more than steel gears as long as they are not the same density as steel. The deflection will have to be accounted for in the micro design of the



Optimized Geometry [µm]					
$f_{h\alpha,1}$ / $f_{h\alpha,2}$	0 / 0	-2,5 / -2,5	0 / 0	-37 / -37	-30 / -30
$f_{h\beta,1}$ / $f_{h\beta,2}$	0 / 0	-2,5 / 2,5	0 / 0	-37 / 35	-15 / 15
$c_{\alpha,1}$ / $c_{\alpha,2}$	0 / 0	6 / 6	0 / 0	2 / 2	4 / 4
$c_{\beta,1}$ / $c_{\beta,2}$	0 / 0	7 / 7	0 / 0	5 / 5	6 / 6

Figure 2 Surface stress of PM with different modifications.

gears in order to maintain a good mesh and low transmission error (TE).

Figure 2 shows an example of how the micro design affects the stresses on the gears. The bars are the average value of the variation $((Max+Min)/2)$ when a gear pair is run within the allowable tolerances (i.e., DIN 7–9). The different colors indicate which error, $f_{h\alpha}$ or $f_{h\beta}$, is varied, while the other is kept at 0. In the far right bars of Figure 2 the modifications are optimized for steel, and those modifications are applied to PM. The result is that PM mean stresses increase slightly; but more importantly, the maximum stress the PM gear may be subjected to is 50% higher (1,200 MPa to 1,800 MPa), leading to a higher failure probability of the PM gears using a copied steel design. Instead, the micro design values in the black frame under "PM corrected DIN 7" should be used for a more robust design.

This type of analysis will determine if it is possible to use an existing micro design, or if that design is sub-optimized. The same type of analysis can be performed to predict TE, for instance.

Macro Design

PM manufacturing technology allows, to a certain extent, material to be put where it is needed. And where it is not needed, efforts can be made to remove it. Figure 3 shows the 4th drive gear in a six-speed manual transmission; it is compacted into the shape in the picture with lightening holes, bore spline, and a 32-degree helix angle. The remaining operation — setting the final shape — is teeth grinding after heat treatment. This gear is operational in a demo car and is driven every day; it is 15% lighter than the original solid steel gear. Half of the weight reduction comes from the lower density, the other half from the holes in the web.

PM Gear Materials

The choice of PM material is dependent upon the process and size of the gears. Smaller gears can utilize a leaner alloy, while larger gears typically require more alloying content due to the slower cooling rate of a larger-mass gear. If surface densification by rolling is used, low-carbon, chromium-alloyed materials seem to give better results under repetitive yielding than molybdenum alloys. Larger gears (modules around 2 mm) typically need 1.85% molybdenum or 1.8% chrome. But chrome is sensitive to oxygen content, so not all heat treatment equipment can handle it. For very fine module gears, heat treated with conventional gas carburizing and oil quenching, a leaner- alloyed material may be used since the case layer is thinner, requiring less cooling speed to avoid the bainite nose in the CCT diagram. If induction hardening is used, an alloy with 3% chrome and 0.5% molybdenum with admixed graphite, around 3%, could be a good selection. In PM gear production the choice of lubricant of the powder will play an important role. It affects productivity, surface finish and density distribution in the gear and can be the source — and remedy — to many issues in manufacturing.

Root Optimization

Another feature of direct gear design is that the root can be freely formed to reduce the bending stress. This also widens the design window and enables a different balancing of the root stress and contact stress. In Figure 3 the original gear (left) has fewer teeth and a larger modulus, compared to the PM redesigned gear (right). This increases contact ratio, reduces contact stress, and for a conventional gear, increases bending stress. However, since the root could be optimized for the PM gear, bending stress did not increase with this design change; it still decreased, compared to the bending stress of the original gear.

Figure 3 Original gear to the left and weight reduced PM design to the right.

Table 1 shows a comparison of stresses between the original gears of a six-speed manual with full fillet radius in the root, compared to the PM gears with optimized roots. The comparison has been normalized with the original steel gear stress set to 1. As can be seen, the elliptical root shape shows the best results.

There are different algorithms for constructing the root; in this case, the elliptical roots were designed using an available function in the *KISSsoft* software. Finite element models were used to cross-check the results.

Table 1 Normalized root stress for different root designs in a 6-speed manual automotive gearbox

Root form	1st input	1st output	4th input	4th outputill	6th input	6th output
Original	1	1	1	1	1	1
Spline	1	1	0.96	0.94	0.93	0.93
Elliptic	0.92	0.96	0.82	0.76	0.83	0.70

Figure 4 Left: Smart fortwo; right: Mitsubishi EVO × in WRC competition.

The lower Young's modulus for PM does not reduce the bending stress; however, it does reduce the contact stress. Contacting surfaces, if Hertz's theory is used, will have a wider semi-contact width and lower contact stresses. If two 7.25 g/cc density gears mate, the reduction in max contact stress is 14%. If a steel gear mates against a 7.25 g/cc PM gear, the reduction is 8%. Therefore it is favorable to run PM against PM since contact stress is reduced the most.

Efficiency studies have been conducted (Ref. 5) where PM and solid steel FZG type C gears were used in a dedicated back-to-back gear tester built by Strama machines in Germany. This machine has the capability to measure frictional losses in gear contacts when using different oils, for instance. In Sosa's work, no conclusive results were found, regarding a difference in efficiency between PM and steel gears; what *was* found was that the scatter in the results was less for PM. The reasons for this are still under investigation. It could be caused by the machine dynamics, assembly errors of the gears, or difference in frictional behavior between the two materials.

Application Examples

A Smart Fortwo (*Ed.'s note: The Smart Fortwo is a rear-engine, rear-wheel-drive, 2-seater, 2-door hatchback city car manufactured and marketed by the Smart division of Daimler AG, introduced in 1998*) was used as a test platform for a redesigned and rebuilt PM transmission. Seven gears were made in PM and put in the transmission, which is of the AMT type. The transmission was run for more than 180,000 km (112,000 miles) without failures or noise issues; see Figure 4. The process for making these gears was:

- Compaction-Sinter-CQT-Hard finish

The max contact stress for these gears is around 1,000 MPa, and the max bending stress varies from 380 MPa to 500 MPa, or within reach for PM. The transmission remains in service and the car is driven every day.

A rally car was also rebuilt with PM gears to prove that the strength of PM is a matter of material and process know-how. The car was in competition for three years, and in the final year, all gears were made using PM. No problems were ever recorded with the PM gears in this extreme application.

The process used for the rally car dog-box was:

- Compaction-Sinter-HIP-CQT-Hard finish

During these three years, several track cars (Mitsubishi EVO IX Rally edition) were equipped with a PM transmission where the 4th gear stage was made in PM, using the same process route as for the smart car (no HIP), and was test driven over 1,000 km (620 miles) on racetracks with this non-synchronized race box. After 1,000 km the gearbox was disassembled and the gears inspected; there were no visible damages.

The smart car and the rally car represent two opposite types of vehicles. To close the gap a Saab 95 six-speed manual was redesigned from scratch, keeping only the housing and final drive

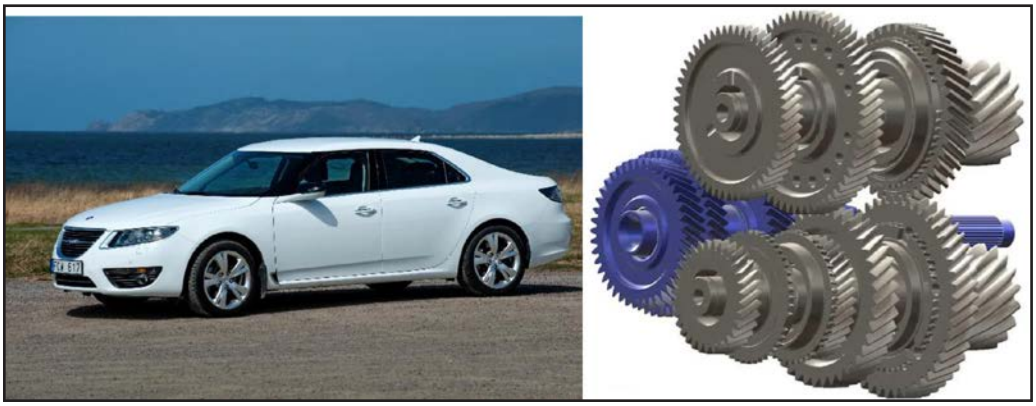


Figure 5 Left: Saab 95 demo vehicle; right: CAD model of transmission.

Piece costs (total cost)

Cost in Euro	Steel gear 4:th gear Fixed	Steel gear 4:th gear Loose
Forged Rough Part		
Material Cost	0,65	0,65
Manufacturing Cost & Profit	0,75	0,75
Soft Machining Costs		
Turning, Hobbing	2,5	3,3
Subtotal	**3,9**	**4,7**

Includes direct and indirect labour
Manufacturing costs (variable and fixed)
Overhead
Manufacturing conditions
Green Field
Manufacturing in Western Europe

Cost in Euro	PM gear 4:th gear Fixed	PM gear 4:th gear Loose
PM rough part		
Material Cost	0,5	0,6
Manufacturing Cost & Profit	3	3
Packaging & Transportation	0,2	0,2
Subtotal	**3,7**	**3,8**

400 000 parts/year
2 derivatives:
Diesel and gasoline

Figure 6 Cost breakdown comparison between steel and PM — before CQT and hard finishing (with permission from Dr. Strehl at Getrag Ford).

(Fig. 5).

The Saab has made it through several OEM test drive sessions with flying colors. The gears have 35, 000 km (21,748 miles) of usage without problems. The analytical work behind the design predicts 300, 000 km (186,400 miles) with 99% reliability. In order to cope with the high stresses on first, second, and reverse asymmetric gears, (2nd gear stage) and Convoloid gears (1st and reverse) are used. A total reduction of 1.1 kg of material was achieved, thanks to PM technology. This car is also in service and driven every day.

Cost

The cost reduction often associated with PM technology is one of its major benefits. For gears, that is most often true as well; however, it is a case-by-case scenario. Sometimes, gears are bundled in a package, and the cost of one of the parts subsidizes another. In addition, depreciation of the machines and how the cost is calculated in-house versus by an external supplier will also serve to influence the overall cost comparison. There are union issues, supplier base issues, investment decisions, policies, etc. that play an important role rather than just the techno-commercial facts. Getrag Ford made an interesting presentation (Ref. 6) on cost analysis (Fig. 6), where cost was compared between in-house production and buying a PM gear as sintered. The PM gear came out cheaper, even though the process with roll densification was used. PM gears will likely be the choice when capacity has to be increased for existing platforms or when new plants have to be built. The investment cost can then be reduced by around 30%, since much of the soft machining equipment and the floors pace do not have to be part of the investment (Ref. 7).

Another untapped opportunity is the ring gear in automatic transmissions, where PM has an even greater potential to reduce cost and improve performance. This will be the next step in the development of PM gears where the isotropic material behavior will reduce scrap-rate from CQT, and the roll forming process can shape the gear teeth in the lead direction, creating very smooth surfaces.

Summary

- This paper has addressed both the technical aspects of PM gear technology as well as some of the commercial question marks. Today PM gears can replace many existing gears in automotive applications, and it is in the starting blocks for a few future transmission platforms, which is a great breakthrough. The technology will gradually gain ground as it develops and as confidence is built up in the automotive gear community. This has been the pattern for timing gears in engines, synchronizer hubs, and other high-end components in PM steel.
- Some design aspects that the gear designer needs to keep in mind in order to get the most out of PM gears has been presented, together with implemented designs in different types of demo vehicles.
- Process and materials have been discussed, where fewer process steps and shorter processing times with PM have been presented.
- OEM cost reduction has been demonstrated by examples referenced from Getrag Ford.
- Also, PM gear strength is material and process dependent. The material and process for making gears or parts can be tailored to suit the intended application requirements to match any solid steel part. The choice then becomes dependent on total cost and what supply chains are available. **PTE**

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Anders Flodin is manager for application development at Höganäs AB Sweden. His background is in mechanical engineering, having received his PhD in 2000 on the topic of simulation of wear on gear flanks. Since 2000 Flodin has worked on various gear-related assignments in the fields of aerospace, ship propulsion and automotive drivelines.