NVH Potential of PM Gears for Electrified Drivetrains

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Introduction

Electrification has already started to have a noticeable impact on the global automotive industry. As a result, the drivetrains of hybrid (HEV) and full electric vehicles (EV) are facing many challenges, like increased requirements for NVH in high speed e-Drives and the need for performance improvements to deal with recuperation requirements. Motivated by the positive validation results of surface densified manual transmission gears which are also applicable for dedicated hybrid transmissions (DHT's) like e-DCT's, the GKN engineers have been looking for a more challenging application for PM gears within those areas, [1]–[3]. As a result of this, the following case study describes the successful validation of a powder metal (PM) gear for an e-Drive application. Starting with initial engineering discussions on the system requirements, a complete process development of a surface densified PM intermediate gear for an electrified axle gearbox has been executed, followed by system tests related to durability/performance and NVH behavior. Further development insights on ongoing optimizations to increase the benefits in performance and NVH behavior are given, like the improvement of the damping behavior by PM tailored gear bodies and designing an NVH tailored microgeometry for a surface densified PM gear. Finally, the strong need for an early collaboration between customer and supplier to drive future innovations in drivetrain technology efficient and fast will be discussed

High Variety of Electrified Drivetrains

The current transmission developments show, in particular by the different types of hybridizations, a high variety. Figure 1 illustrates this with reference to the arrangement of the electric motor(s) in the drivetrain. Depending on the allocation of the e-motor, the different concepts are classified, from hybrid drive concepts up to the battery-powered vehicle BEV.

In the power-split hybrid drive (PS), the mechanical power of the ICE is split into two paths (mechanical and electrical) and reunited to drive the vehicle. The parallel hybrid powertrains (P) are distinguished by the location of the electric motor (0: belt starter generator, 1: on the crankshaft, 2: at the gearbox input, 3: at the gearbox output, 4: on the axle). The P1 hybrid arrangement is characterized by a relatively low electric power of the hybrid vehicles, in which no purely electric drive is provided. If the electric motor is located at the transmission input with an upstream clutch, this is referred to as a P2 arrangement. In this arrangement, the electric motor can be decoupled from the engine and it is a purely electric ride possible. At the P3 arrangement, the electric motor is located at the transmission output. The power during the electric drive and recuperation must not be passed through the transmission. The e-machine is subject to the transmission output speed and thus a much wider speed range. For the future BEV's favored P4 arrangement, the ICE and the electric motor act on different axes. With this concept a four-wheel drive can easily be realized.

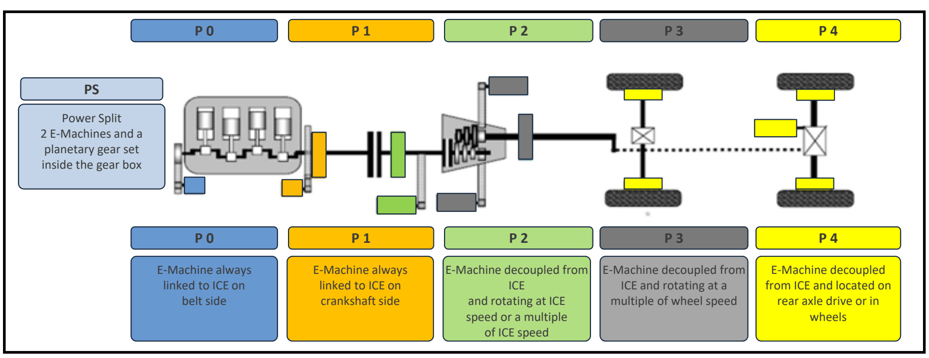

Figure 1 High variety of hybrid and BEV architectures.

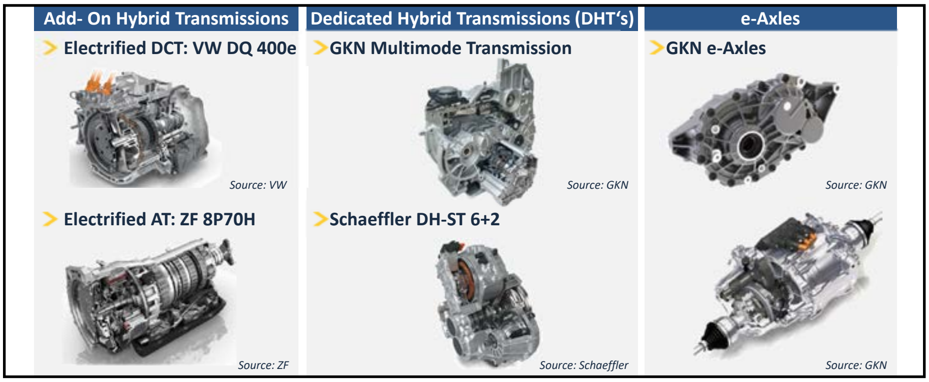

Figure 2 Electrified transmissions with potential for PM gears.

Figure 2 shows some transmission designs for HEV's and BEV's. The so-called "Add-On Hybrid Transmissions" are a combination of an e-machine with existing transmission concepts, like "Dual Clutch Transmissions" (DCT's) or Automatic Transmission (AT's). These transmissions have full functionality even without the operation of the electric motor. Furthermore, "Add-On Hybrid Transmissions" offer the advantage for both OEMs and transmission manufacturers that the majority of the transmission components used today can continue to be used.

The so-called "Dedicated Hybrid Transmissions" (DHT's) are transmissions with a fully integrated the power source for the electric drive. Their functionality depends entirely on the integrated electrical components. Figure 2, middle, shows some actual examples of electrified DHT's. Finally, the Figure 2, right, shows electrified axles which are available on densified PM transmission gears could be applied. The arrangement of the transmissions on the second vehicle axle allows e.g. the realization of a four-wheel drive without the use of a prop shaft. However, high rotational speeds up to 16.000 rpm, up to 30.000 rpm are already under development, lead to challenging requirements related performance and NVH (Noise Vibration Harshness) behavior.

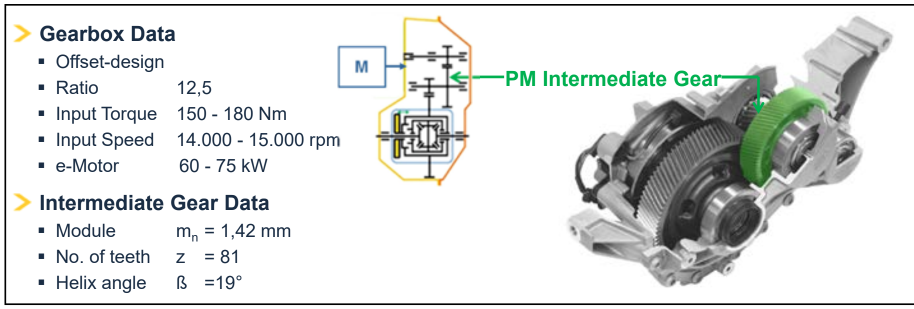

Figure 4 **Selected E-Axle gearbox for PM technology validation.**

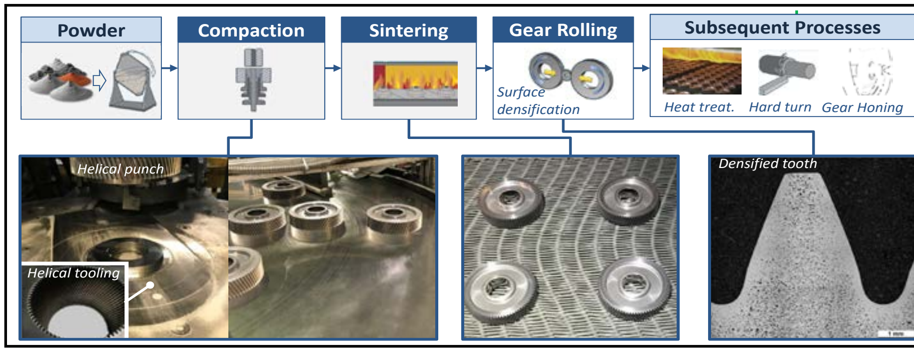

Figure 5 **Off-tool production of PM intermediate gears.**

Validation of Surface Densified PM-Gears for E-Drives

While surface densification technology of PM Gears has been validated with a ß = 34° helical transmission gear for 6-speed manual transmission [1], [2], the motivation of our engineers was high to proof the technology and implementation readiness also for e-Drive applications. However, one main challenging requirement is the increased sensitivity related to the NVH behavior needed to be addressed and answered positively as part of a product validation program, Figure 3.

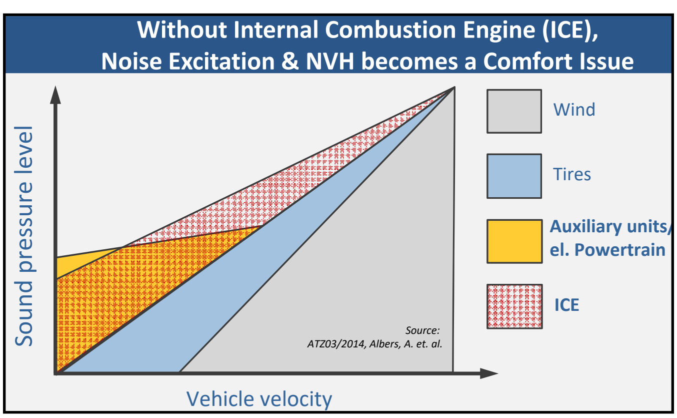

Figure 3 **Sound sources depend on vehicle velocity.**

Looking back into 2016, the potential of the NVH improvement has been shown on a generic e-axle system as used currently in serial production by changing the steel intermediate gear into a PM gear. At that time, the PM gear was machined from blanks with a core density of 6,8 g/cm³ and has been tested on a test bench up with rotational speed to 6,000 rpm, which is comparable with car speeds up to 50 km/h (city mode), [1]. Having shown the potential of NVH improvement within this first test of machined blanks, it was clear to the team that the performance of the PM intermediate gear needed to be proven, while at the same time working on measures on improving the NVH behavior of surface densified gears in a systematic approach. The gearbox, as it is used for the current system validation of the PM intermediate gear, is shown in Figure 4.

Consequently, the development of off-tool and surface-densified (rolled) gears has been carried out in order to execute a complete system validation based on a customer defined load-collective test. The core density of the PM gear had to be moved up to ~7,15 g/cm³ to be on the safe side regarding durability. The production steps of the off-tool and surface densified PM Gears are shown in the following Figure 5.

The process route starts with the powder manufacture, followed by compaction and sintering of a gear preform, a transverse rolling process and finally a case hardening and gear honing operation. A GKN owned design for the helical compaction tooling was applied. On the bottom right, the picture shows a cross sectional cut of a surface densified tooth with the performance tailored densification zone. The densified layer is quantified after metallographic preparation of a cross sectional cut of the teeth, Figure 6. In order to properly quantify the densification depth, an approach similar to the hardness curve evaluation has been applied. The surface densification depth SDD 98%, describes the depth with 98% density of the "fully dense PM material" and is 0.36 mm on the flank and 0.19 mm in the root section.

Following to the surface densification by gear rolling, the PM intermediate gears have been heat treated. Figure 7 shows the results of the heat treatment runs. From the experience on the densified manual transmission gears it was known that no specific heat treatment process needed to be developed. This is beneficial e.g. if a densified PM gear shall be heat treated and hard finished within an existing production environment. Two serial case carburizing programs for steel gears have been applied and the program *CONV2* was selected for the carburizing of the gears to be validated in the system tests.

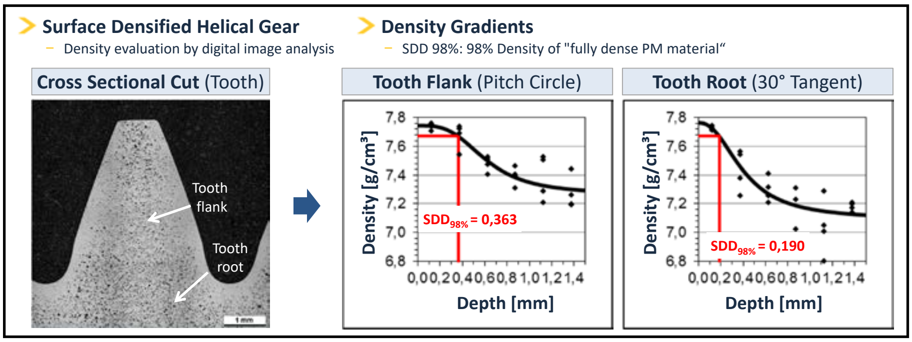

Figure 6 Result of surface densification.

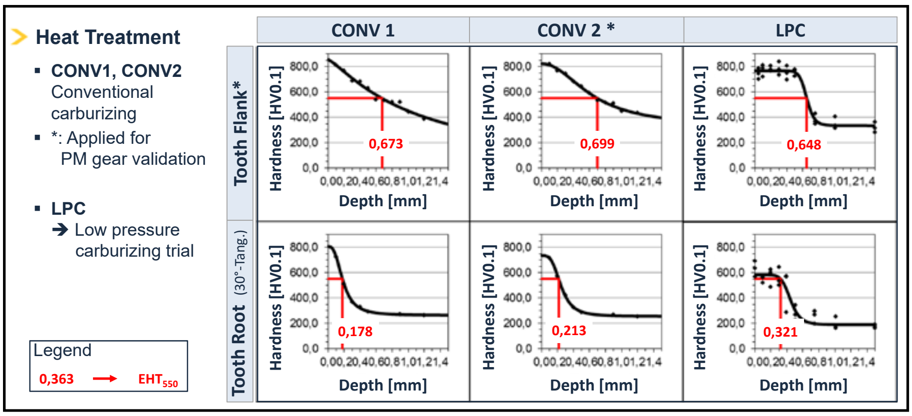

Figure 7 Result of heat treatment runs.

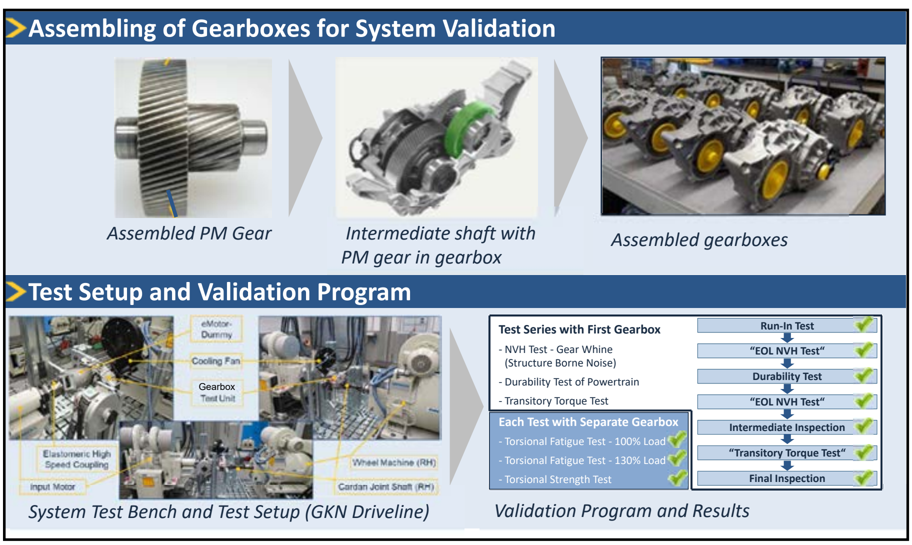

Figure 8 Assembling of gearboxes, test bench setup (GKN Driveline) and results.

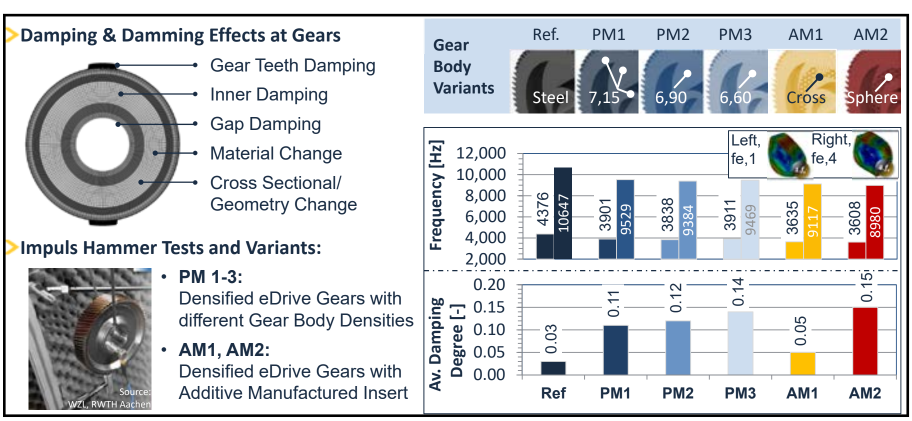

Figure 9 Potential of PM technology to tailor the damping behavior of gear bodies.

In addition, the potential of low pressure carburizing was analyzed within the heat treatment development. The low pressure carburizing tests show that a more flexible adaption of the hardness curves is possible, Figure 7 right. Further evaluation on this process is ongoing.

Following the successful manufacturing of the surface densified intermediate gears, the PM gears have been assembled on the intermediate shafts and the test gearboxes have been built for the validation tests and adapted on the system test bench, Figure 8.

In summary, the PM gear successfully passed all steps of the extensive validation program, achieving at least the same level of reference gear in terms of strength, wear and NVH [4]–[6].

NVH Potential of PM E-Drive Gears

Damping and damming effects

As PM Technology gives a high freedom with regard to the design of the gear body, a series of basic investigations related to the influence of the gear body on the structure-borne noise transfer has been started. In order to get a basic understanding of the influencing factors related sound damping and damming, differently produced steel and surface densified PM gears have been manufactured and experimentally tested by impulse hammer tests, carried out with the GKN parts at the WZL of the University of Aachen, Germany, Figure 9.

With regard to the fixed shaft hub connection of the gear, only the first and fourth Eigen mode (fe,1; fe,4) of the free oscillating behavior are relevant. The experimentally measured Eigen frequencies of these modes show a decrease in the range of 460 Hz for fe,1 and more than 1.000 Hz for fe,4 while decreasing the gear body density. In addition, the damping degrees of the different variants have been determined using the peak-picking method of the first five Eigen modes. In summary, an increased degree of damping while decreasing the gear density is observed — with an additional increase of the damping while decreasing even further the ring segment density or combining the PM densified gear with additively manufactured inserts.

Tooth microgeometry effects

Another important topic within the design process is the noise emission which is initiated by the gear mesh excitation. Target of these basic investigations was first to model the density gradient as input for the simulation and second to compare the measured and simulated transmission error of a densified PM and a steel intermediate gear ($z_2 = 81$). Due to setup conditions of the available test bench, instead of the original gear box input gear a modified input gear was designed, resulting in a test gear set of $z_1/z_2 = 41/81$, Figure 10, [7].

A good comparison between tested and simulated transmission errors of the test gear set could be observed. Following, the micro geometry of the densified PM gear has been simulated for the original gear set ($z_1/z_2 = 23/81$), considering the displacements of the real gearbox and targeting a reduced excitation at medium and high torques, Figure 10, right.

In summary it can be stated, that applying a copy of the original steel geometry to the PM gear ("original PM") leads to a higher excitation, while the optimized geometry shows a lower excitation at the targeted torque range. As a result of this, the micro-geometry optimization should be part of the design process for surface densified PM e-Drive Gears.

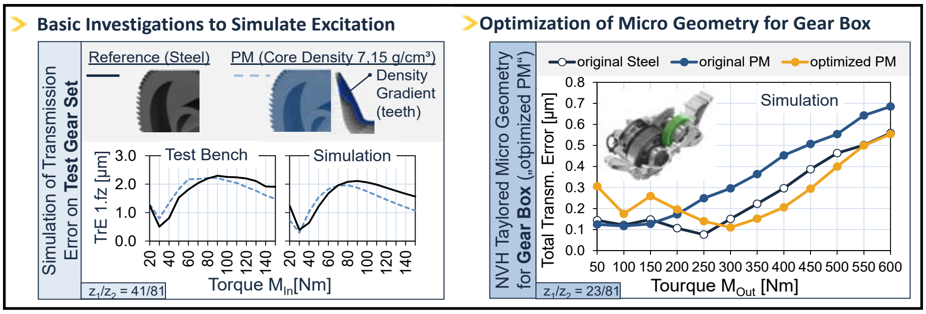

Figure 10 Approach to simulate the excitation of densified PM gears.

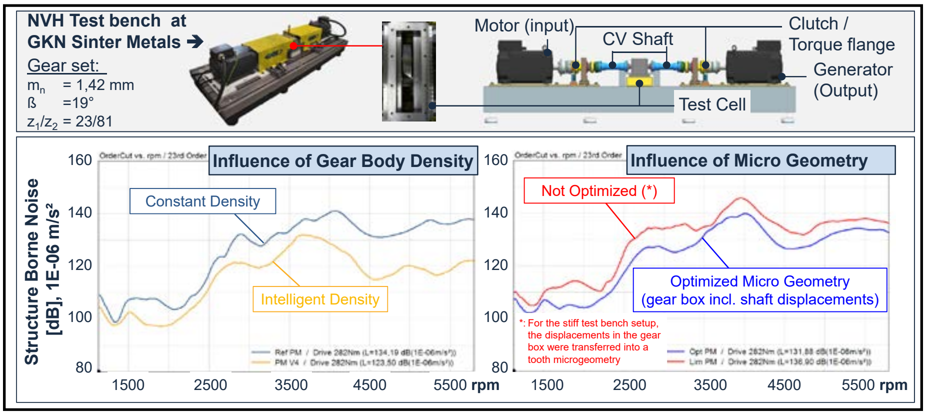

Figure 11 Influencing the NVH by gear body density and tailored microgeometry.

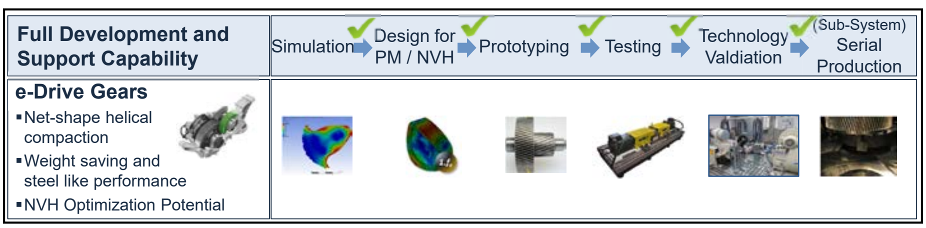

Figure 12 Driving product and system innovation with full development capability.

Quantifying the effects on component level

As part of the ongoing project, NVH tests on component and system level are carried out, e.g. at the NVH test bench at GKN Sinter Metals Innovation Center, Germany. Initial test results show the potential of the PM technology to improve the NVH behavior, considering the above mentioned effects, Figure 11.

Figure 11, left indicates the reduced structure borne noise emission for the surface densified intermediate gear by creating a gear body with a tailored density variation. Figure 11, right, shows the positive effect of a tooth micro geometry optimization. In order to evaluate the potential of the micro geometry optimization on the "ideal stiff" test cell, the displacements in the real gear box have been transferred to a modified micro geometry, characterized by a significantly increased crowning and reduced tip relief. It can be stated that these results just start to open more NVH optimization potential of PM Gears. However, in order to maximize the added value for a transmission system, a collaborative engineering approach on component and system level will be crucial.

Summary

The e-Axle PM Gear case study shows the potential to apply technological differentiated powder metal (PM) gears for electrified transmissions. Starting with a system engineering discussion on the eDrive application, a complete process development has been successfully executed, being now ready to apply PM Gears for eDrive applications. Additionally a holistic testing approach on component and system level to improve the NVH behavior opens further potential to integrate PM Gears in current and future transmissions. Figure 12.

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