Validation Approach of PM Gears for e-Drive Applications

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Introduction

Key technical drivers which can be addressed by advanced PM manufacturing technologies are, for example, the need for system downsizing in transmissions and differentials, the need for developing systems with higher power density and the strong NVH (Noise Vibration Harshness) requirements — especially for electrified transmissions or e-axle solutions. In the case of making use of sintered gears in highly loaded applications like automotive transmissions, advanced net shape compaction technology can be applied to produce gears with helix angle above ß = 30°. However, the residual porosity at conventionally pressed and sintered gears requires further density/performance increasing measures. Surface densification technology by transverse rolling is today well known and can be used to increase the density, primarily in the highest loaded volume of the gear teeth, while powder forging technology creates a fully dense component (Refs. 1–4). For surface densification technology, within recent years a strong move from basic research on process simulation (Refs. 5–7) and performance data generation (Refs. 8–11) towards demonstrator applications and PM gear validations on transmissions (Refs. 12–14) could be observed.

This paper gives an overview of the described process technologies and the exemplary results in the case of performance and NVH behavior; the adaption of the surface densification technology for e-drive applications including testing will be shown. Last, but not least, the successful validation of an e-drive gearbox with a PM intermediate gear is the main outcome of this work.

PM Process Routings

Compared to the standard PM process routings for gear production, only routings for highly loaded PM gears — characterized by different density-increasing measures — are described. Especially surface densification by transverse gear rolling and forging powder metal (FPM), both part of GKN's PM process portfolio, are known as the two most important technologies to produce highly loaded PM gears (Fig. 1).

The surface densification (gear rolling) process route starts with the powder manufacture, followed by compaction and sintering of a gear pre-form and a transverse rolling process. Depending on the strength requirements of the gear, different sintered (core) densities can be provided. As dictated by the product application, heat treatment of the surface-densified gears may be required after rolling. If carburizing is applied, the process chosen must consider the specific carburizing behavior of a surface-densified gear (Ref. 5) and, depending on the gear quality requirements, hard finishing like gear grinding or gear honing may be necessary after heat treatment. The forged powder metal (FPM) route creates a fully dense gear product from a compacted and sintered PM pre-form. The single-stroke, hot forging process shapes the component to its forged contour and generates a new metal matrix by metal particle shearing through material flow.

Design Approach and Testing

When driving a customer request for a high-performance PM gear to an engineered product, close collaboration between supplier and customer is crucial. Starting with a drawing and loading situation analysis of the gear application, PM material and process routings are defined. While for gear load calculations conventional design tools like *KissSoft* are used, both for gear rolling and forging powder metal gears unique software solutions have been developed, or existing software codes have been modified to optimize the predictive design tasks for surface densified gears (Ref. 12). In particular, the GKN proprietary software *KinSim* allows modeling of the fi-

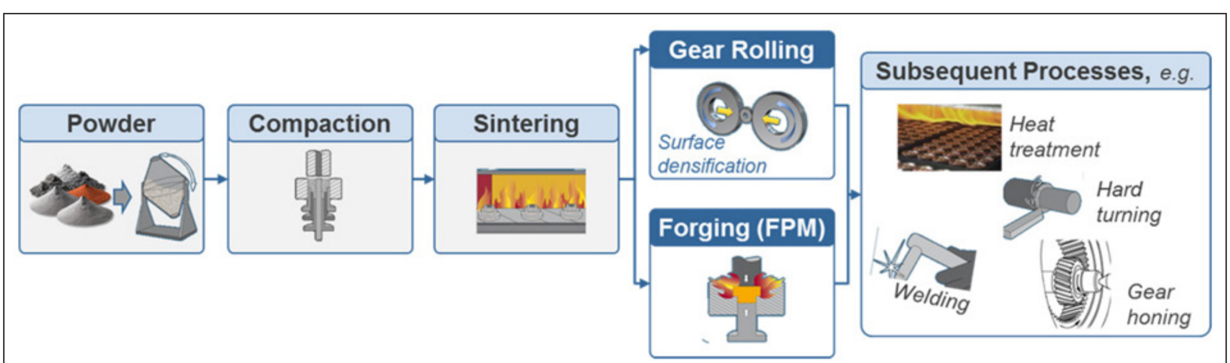

Figure 1 Process routings for high-performance PM gears.

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nal shape and pre-form shape of the PM gear, the rolling tool shape, and to feed the proprietary-developed predictive FEA tools for the surface densification process (Fig. 2).

As shown (Fig. 2) for rolled gears, in-house-developed FEA tools allow prediction of both the expected density profile as well as the shape of the tooth flank after the rolling process and, therefore, to shorten the development time for the gear pre-form and rolling tool design.

As an initial guideline for selecting the best PM processing route for a given application, GKN has created a gear performance guideline (Fig. 3).

The (Fig. 3) graph builds on tooth flank and tooth root performance tests of sintered gears, and compares the performance values to a case hardened 16MnCr5 reference. With this, a first selection of a PM process and density level for a given gear loading condition can be done without having detailed PM process knowledge.

Furthermore, GKN has developed the "GSM test gear" geometry as a standard test gear for all in-house-available PM process routings, i.e. — standard PM, rolled and forged powder metal (FPM) gears (Refs. 10, 12). Within an ongoing testing program, production tools for all PM processes (incl. rolling/forging) are available. To clearly focus on the performance of the different materials and PM manufacturing routes, test gears are hard finished by profile grinding (Q5, DIN) to a comparable quality and surface structure. For

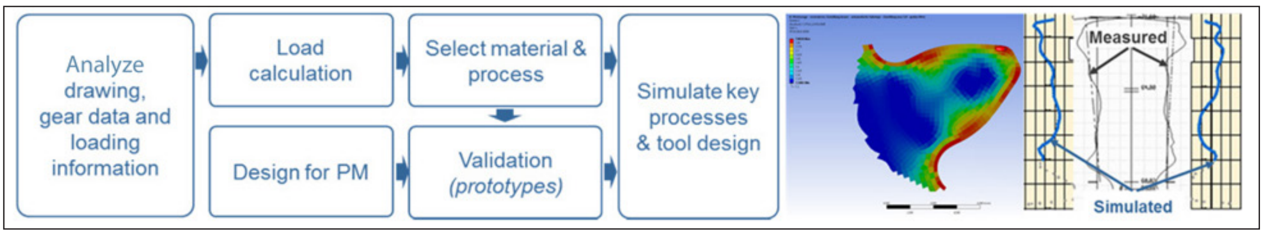

Figure 2 Design approach and state-of-the-art simulation for rolled gears.

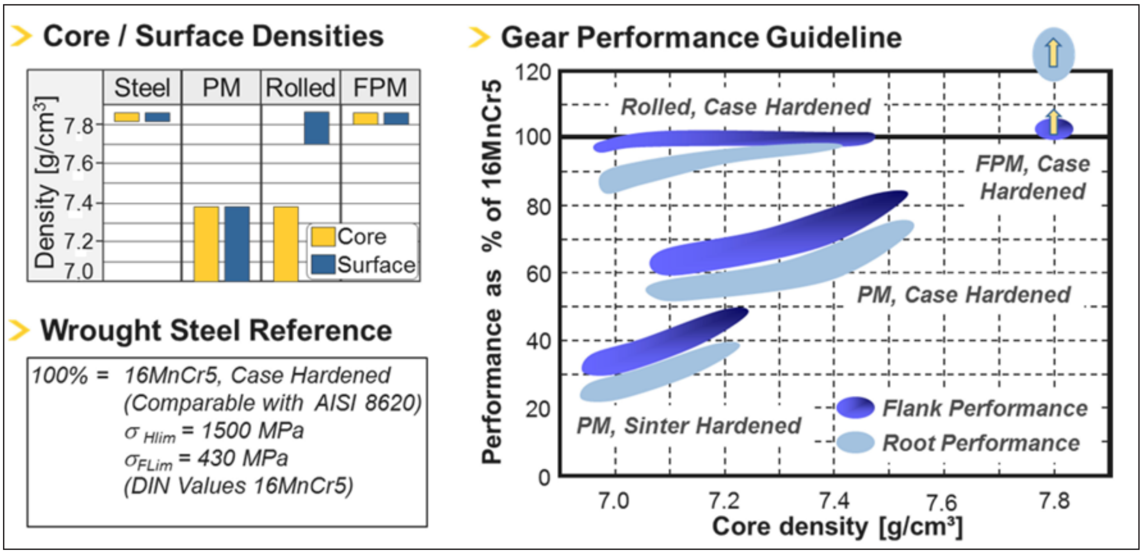

Figure 3 Gear performance map for PM gears compared to wrought steel gears.

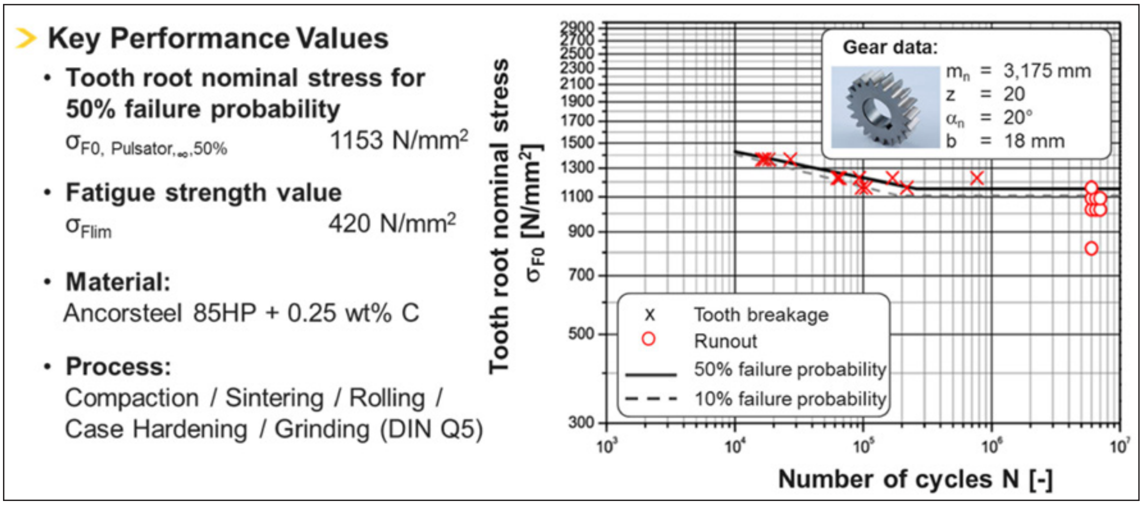

Figure 4 Tooth root strength S/N curve of a surface-densified gear.

investigation of tooth root performance, a resonance pulsator is used; for the flank performance tests an FZG back-to-back test rig is used according to DIN ISO 14635. The endurance limit for tooth root tests is 3 mio. cycles; for the pitting tests it is 50 mio. cycles. At the end of both test methods S/N curves are generated.

A typical data set of a tooth root performance test of surface densified and case hardened PM gears made of Ancorsteel 85 HP (Fe-0,85Mo) + 0.25%C with a tooth root bending stress of 1153 MPa (50% failure probability) is shown (Fig. 4).

Motivation to Apply Surface Densification for e-Drive Applications

Recently, a fourth speed and ß = 34° helical manual transmission gear have been developed completely off-tool towards series production — including the whole package of required, successful customer validation tests focusing on further improvement of rolled gear quality at high helix angles with a tailored heat treatment and gear honing (Refs. 12, 14).

The product shows a high quality before the heat treatment, including the protuberance that is needed for the power-honing process. Some of the key test procedures are shown (Fig. 5).

For gear durability, three out of three tests passed the test criteria, including one test with increased load and longer run times than expected. At the end of the durability test, no wear at all could be detected at the tooth flanks and the profile was comparable to the known profile of the steel gear reference.

How to Apply for e-Drive Applications

Due to the strong move away from the internal combustion engine and conventional transmissions towards electrified drivetrains, future electrified transmissions are also a crucial element of our gear strategy at GKN. Motivated by the positive results of the transmission gears, the engineering team was looking for a more challenging application for PM gears within those areas. Knowing that GKN Driveline is an established development partner for high-performance, electric driveline systems with more than 300,000 electric axle drives produced to date, the GKN powder metallurgy engineers strongly believed that PM technology can make the difference in the future mobile world, being able to provide significant benefits.

The cross-divisional engineering team decided to build the first technical demonstrator of an e-transmission with "PM inside" and to validate the system related to performance and NVH in an already-existing series production, high-performance GKN e-drive gearbox (Fig. 6).

The intermediate gear made of conventional case hardening steel was replaced by a PM gear with a core density

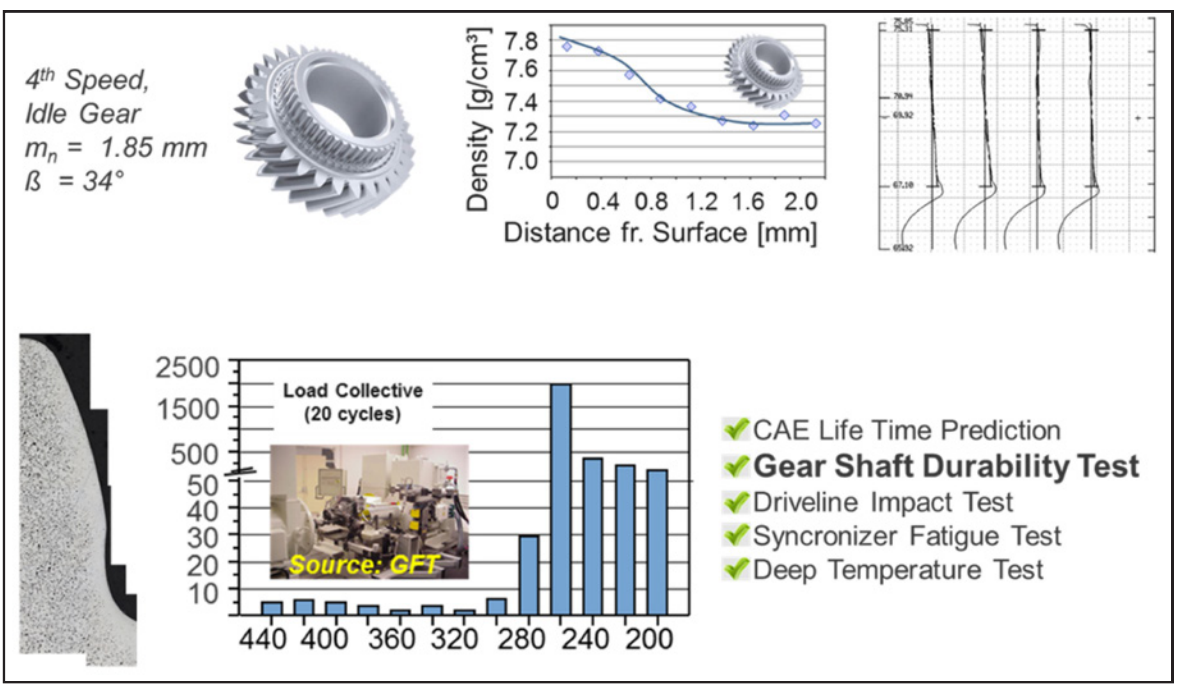

Figure 5 Successful validation of surface-densified transmission gear, ß = 34°.

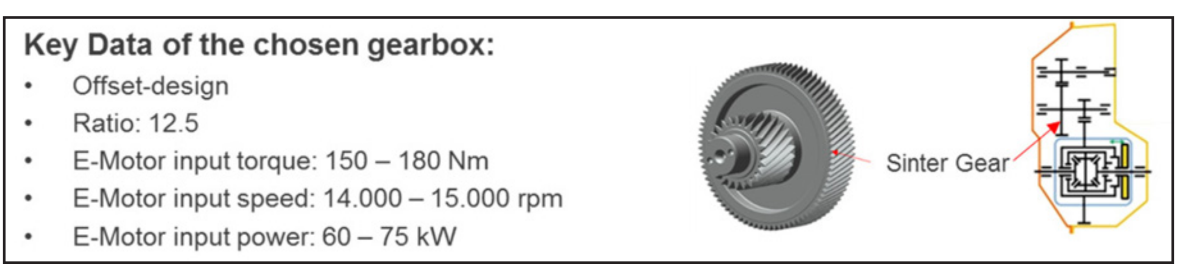

Figure 6 Sinter gear in e-drive gearbox.

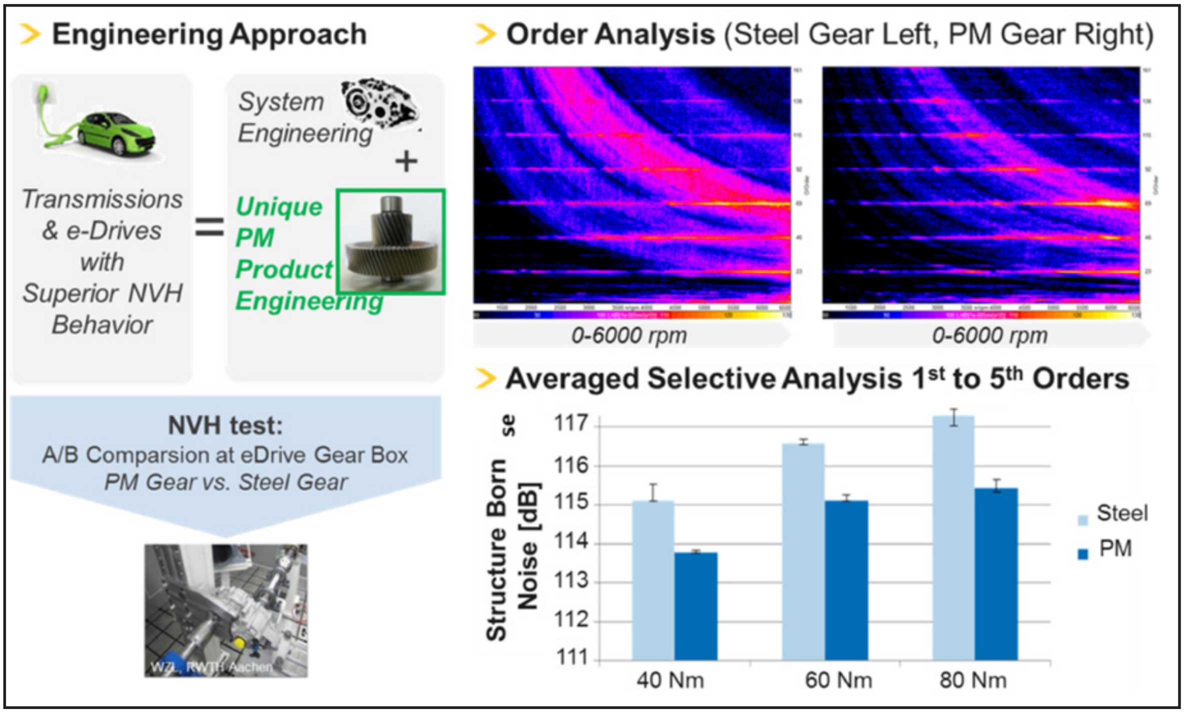

Figure 7 Case study, e-drive gear — NVH A/B comparison.

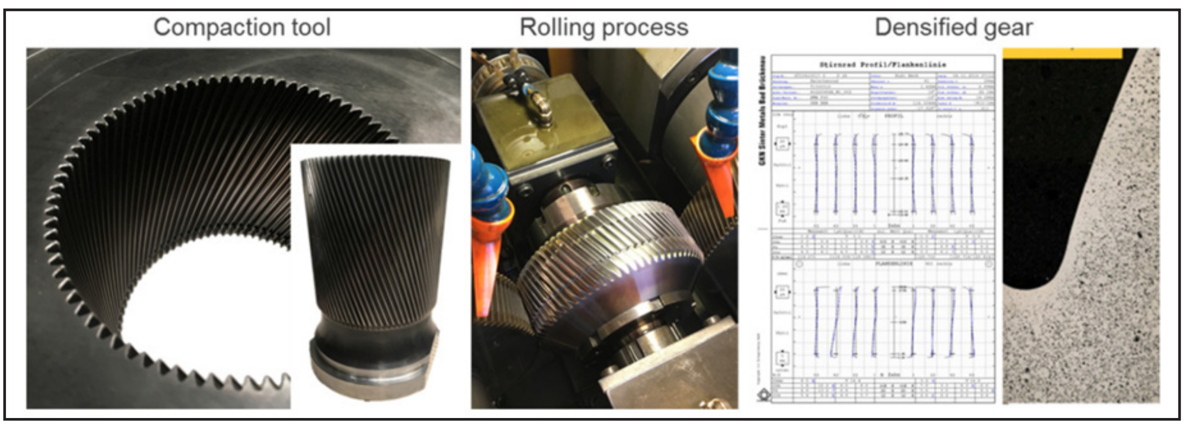

Figure 8 Manufacturing of off-tool parts.

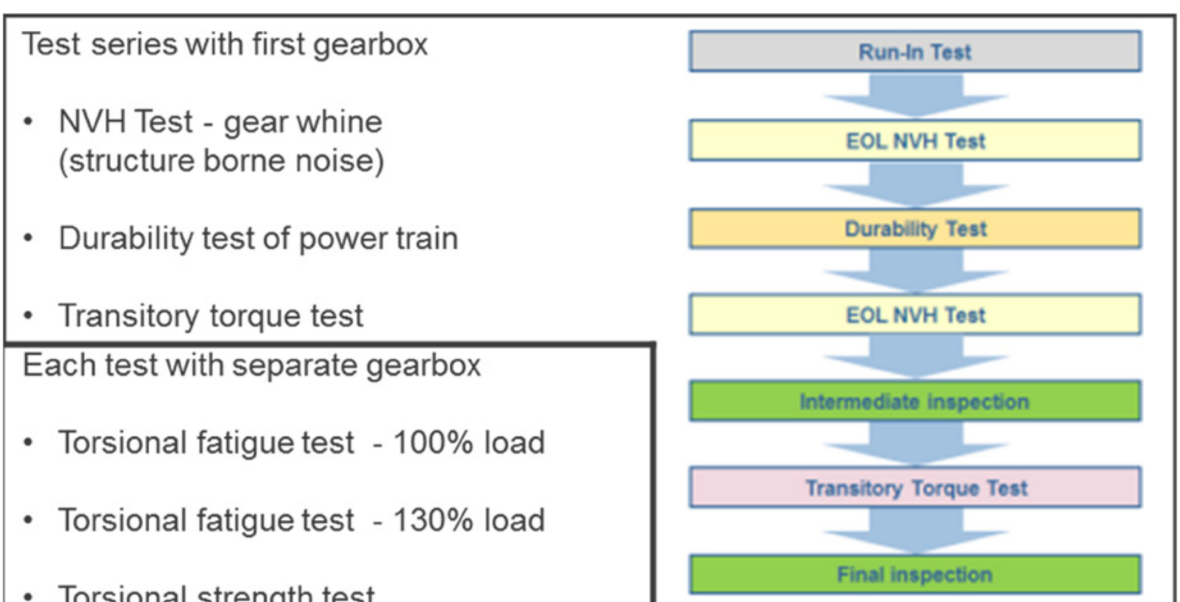

Figure 9 Test and validation program of e-drive gears.

of 6.8 g/cm³, assuming a positive influence from the porosity on the NVH behavior. Hard finishing of the PM gears was identical to the wrought steel version to make sure that profile and lead modification — as well as surface structure — are comparable and only the material and density influence on the NVH behavior could be evaluated. For the investigation, the gearbox has been assembled on an NVH test bench. Test runs have been carried out at three torque levels (40, 60 and 80 Nm) at rotational speeds up to 6,000 rpm, which is comparable to speeds of up to 50 km/h (city mode). Figure 7 shows the result of the A/B structure-borne noise comparison represented by the Campbell diagrams for the steel and PM gear (top right), and the averaged selective analysis for the 1st to 5th orders (Ref. 15).

It is evident from the figures that the PM gears with an overall density of 6.8 g/cm³ show a significant difference in the NVH behavior, and Eigen frequencies are influenced based on the change in material and porosity. Depending on the rotational speed and torque, up to 3 dB lower structure-borne noise could be realized.

Off-Tool Gear Manufacturing and System Validation

Knowing that the performance requirements for this type of transmission gear require surface densification, further investigations of the performance and NVH behavior were carried out. For this, the complete PM process chain was worked on, starting with the material, the compaction of net-shaped parts to a slightly increased density of 7.1 g/cm³, sintering and surface densification. Heat treatment and hard finishing processes have been carried out under serial conditions at GKN Driveline. In the first step, tip relief and crowning are identical to the steel design, knowing that adaptions for the PM design will be needed.

Having the gears produced, a typical GKN Driveline validation program was used to test the parts. The target was that the sintered gears had to pass all tests with same or better performance compared to wrought steel gears; the test program is shown (Fig. 9).

For the NVH test, different high-speed and high-torque steps had to be passed with the structure-borne noise level not higher than customer requirements. After the positive passing of this test the durability test of the powertrain and the transitory torque test were done with the same gearbox.

The durability test (Fig. 10) consists of different steps (high torque with low speed; medium torque with medium speed; low torque with high speed) in a *Multi-Block-Program* (*MBP*). The *MBP* is a condensed program for a defined number of hours that presents the gear damage of a gearbox lifetime. After finishing 100% of the *MBP*, full torque transmission is required, with 20% pitting on teeth surface allowed, but no initial cracks or breaks.

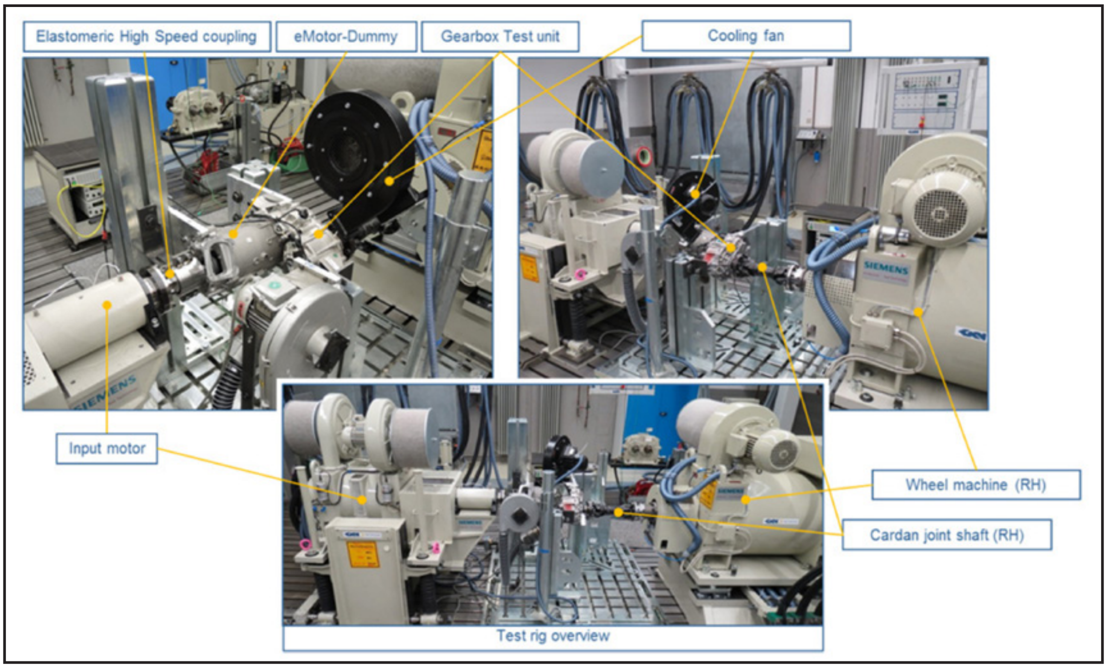

Figure 10 Typical test rig set-up of durability test.

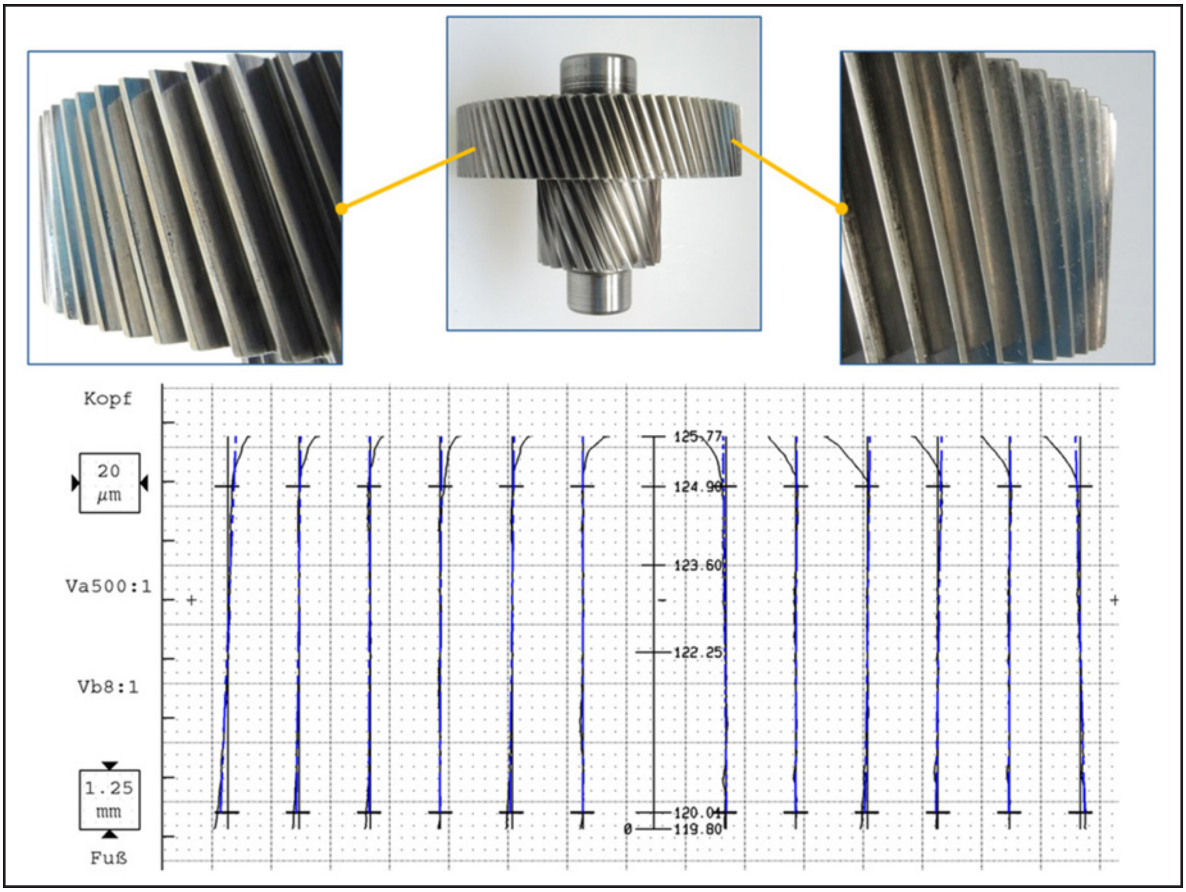

Figure 11 Sinter gear after durability test.

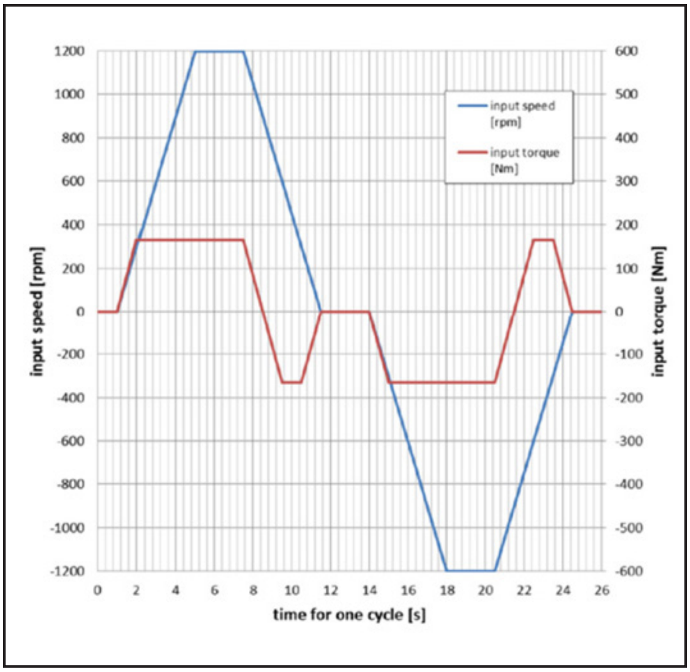

Figure 12 Alternating load under revolutions.

Figure 13 Sinter gear after torsional strength test.

During the last test with this gearbox an alternating load with frequency 0.5 Hz was put on one tooth flank with double the nominal load and customer-agreed number of cycles. No initial cracks or breaks are allowed. All three tests were passed with the same gearbox; the wear was within the specification (Fig. 11).

The torsional fatigue tests (Fig. 12) with alternating loads of 100% and 130% of the nominal torque with a defined number of cycles were passed with two additional gearboxes without initial cracks or breaks.

The last step within the validation program was the torsional strength test, where the torque was increased (twist angle at gearbox output shaft: 15°/minute) on a blocked gearbox until one component of the system failed, which was *not* the PM intermediate gear (Fig. 13).

As an overall test summary, it can be stated that the PM intermediate gear in the e-drive gearbox passed all steps in the required validation program. Regarding strength, wear and NVH performance, the sinter gear is at the same level as the replaced steel gear.

Outlook

It was shown that the holistic approach for design and performance positions PM technology with the potential to be used in e-drive applications. GKN continues to work on different optimizations in order to further increase the benefits in the area of the NVH behavior in comparison to wrought steel gears. First simulations with a new FEA-based modeling approach indicate that the excitations of a surface-densified PM gear can be further optimized by applying a tailored microgeometry. Along with validation tests to confirm the model-based approach, further tests on gears with optimized gear bodies are planned and will help to build an even stronger basis and design guide for the product and application engineers. **PTE**

Questions or comments regarding this paper? Contact Bjoern Leupold at *bjoern.leupold@gknpm.com*.

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