Influence of Different Manufacturing Processes on Properties of Surface-Densified PM Gears

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Introduction and Motivation

PM technology offers great opportunities for the reduction of the carbon footprint and improvement of the cost efficiency of gear production. PM gears can achieve flank load-carrying capacities comparable to wrought steel gears if the loaded volume is densified completely. Still, the tooth-root strength is of major concern. The tooth-root stresses can be minimized by optimizing the tooth-root geometry; this usually leads to a target conflict since fully optimized tooth-root geometries cannot be manufactured by generating processes such as hobbing, generating-grinding or rolling. To use the increase in tooth-root load-carrying capacity of a fully optimized root geometry on PM gears, a non-generating method for surface densifying is needed. The shot-peening process is used as an alternative densification process for PM gears. The properties of both shot-peened and cold rolled PM gears are analyzed and compared. To quantify the effect of both manufacturing processes, the tooth root bending fatigue strength will be evaluated and compared to wrought gears.

Today, the reduction of both material and energy consumption gains importance in gear production. A cost calculation of (Ref. 1) shows the potential for the PM process chain to substitute the conventional gear cutting process chain. A more precise calculation of (Ref. 2) specifies the cost distribution of the conventional and the PM gear manufacturing process onto the different manufacturing steps.

Figure 1 shows the distribution of process energy of the PM and the conventional process chain for a gear with the typical size of an automobile gear of module $m_n = 2$ mm. The conventional process chain contains the manufacturing steps of steel processing and forging, machining of the bore, and hobbing of the gear teeth. The PM process chain consists of the usual three steps of powder production, powder compaction, and sintering (Ref. 3). To increase the load-carrying capacity onto a level of conventionally produced gears, the sintered gears must be rolled to densify the surface. The comparison of the two process chains shows the advantage of PM gears, as less energy and material is needed for a single gear. Since the sintering process needs specific process chains, PM gears gain their benefits especially in large scale production. The advantage in energy consumption is mainly gained through the near-net shape production of the PM process chain. The near-net shaping process combines all formative processes, such as machining of the bore and hobbing of the gearing, into one process. Since no material needs to be cut, less material is needed to produce a PM gear than a conventional gear. To summarize, through near net-shape manufacturing PM gears offer an advantage in both material and energy consumption, which results in a cost advantage for this technology if applied in large scale production.

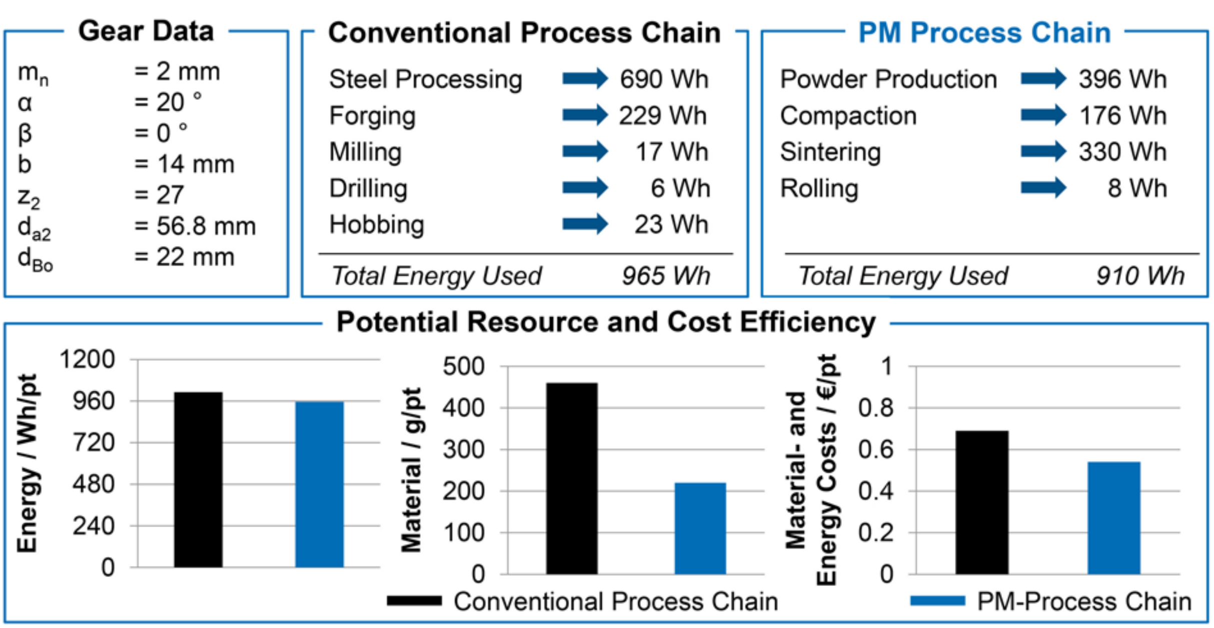

Figure 1 Cost and resource efficiency of PM gears.

State of the Art

The PM process chain offers a cost advantage for gear manufacturing. Furthermore, the process-related porosity of PM gears leads to a weight advantage of about 10% compared to forged and hobbed gears. Nevertheless, the remaining pores reduce the load-carrying capacity of PM parts. Figure 2 shows the density-dependent strength of powder metal, investigated by (Ref. 4). To achieve a strength comparable to normal steel, PM gears are densified at their surface. According to (Ref. 3), the material properties of PM steel can be calculated out of the remaining porosity in the component (Fig. 2, bottom left). Therefore the densified zone at the surface shows the highest Young's Modulus which decreases from the surface to the core. The Young's Modulus, as well as other density-related material properties, can be calculated with Equation 1, (Ref. 3).

$$E_{porous} = E_{\rho max} \cdot \left(\frac{\rho}{\rho_{max}}\right)^m \tag{1}$$

E_{porous}	[N/mm^2]	Young's Modulus of the porous material
ρ	[g/cm^3]	Density
m	[-]	Density exponent
$E_{\rho max}$	[N/mm^2]	Young's Modulus at full density
ρ_{max}	[g/cm^3]	Full density

As can be seen in Figure 2, the rolling fatigue strength of densified PM steels is comparable to conventional steels. Since the tooth root load-carrying capacity of PM gears is outperformed by conventional gears, the bending fatigue strength of the tooth root still needs to be optimized (Ref. 5).

The tooth root bending strength is determined by two characteristics — the nominal strength of the material, and the contact conditions that depend on the strain of the component. The nominal strength is characterized by material parameters such as Young's Modulus, hardness and defect size and quantity and, therefore, by the density of the material. In PM steels, each pore reduces the load-carrying cross-section and can be a crack propagator. The strain is determined by the geometric-functional properties of the gear pair, as well as by the time-dependent load distribution (Fig. 3, left) (Ref. 6).

The tooth root fillet weakens the bending fatigue strength of the gear. According to ISO 6336, the tooth root bending strength due to the geometry is determined by the chordal thickness S_f and the radius of the root rounding ρ_f (Ref. 6). Due to the reduction of the influence of the geometry on two the parameters ρf and S_f, a norm-based optimization of the tooth root is very limited in its design. As can be seen (Fig. 3, top right), the tooth root stress can be reduced by more than 10% when using full rounded standard profiles. Additionally, the tooth root stresses can be reduced further — up to 30% — when optimizing the tooth root free of norm-based restrictions (Ref. 7).

Meanwhile, the free optimization of the tooth root geometry without considering the manufacturing process is not productive. (Reference 7) showed that the optimal tooth root geometry cannot be manufactured by conventional processes. To minimize the notch effect of the tooth root, the highest possible tooth root radius is pursued. This leads to low curvature radii at the bottom of the tooth root so that the mathematical function describing the tooth root geometry cannot be continuously differentiated. Therefore, the tool cannot follow the optimized tooth root geometry in generating processes. As can be seen (Fig. 3, bottom right), already small changes in the tooth root lead to a significant reduction of the tooth root stress.

In addition to conventional densification processes such as cold rolling, further processes that can densify the optimized PM gears regardless of their geometry need to be qualified. The densification process determines not only the material parameters; e.g. — Young's Modulus — but also the surface and gear quality. Hence, the manufacturing process takes major influence on the running behavior and load-carrying capacity of PM gears.

As can be seen (Fig. 3, bottom right), already small changes in the tooth root

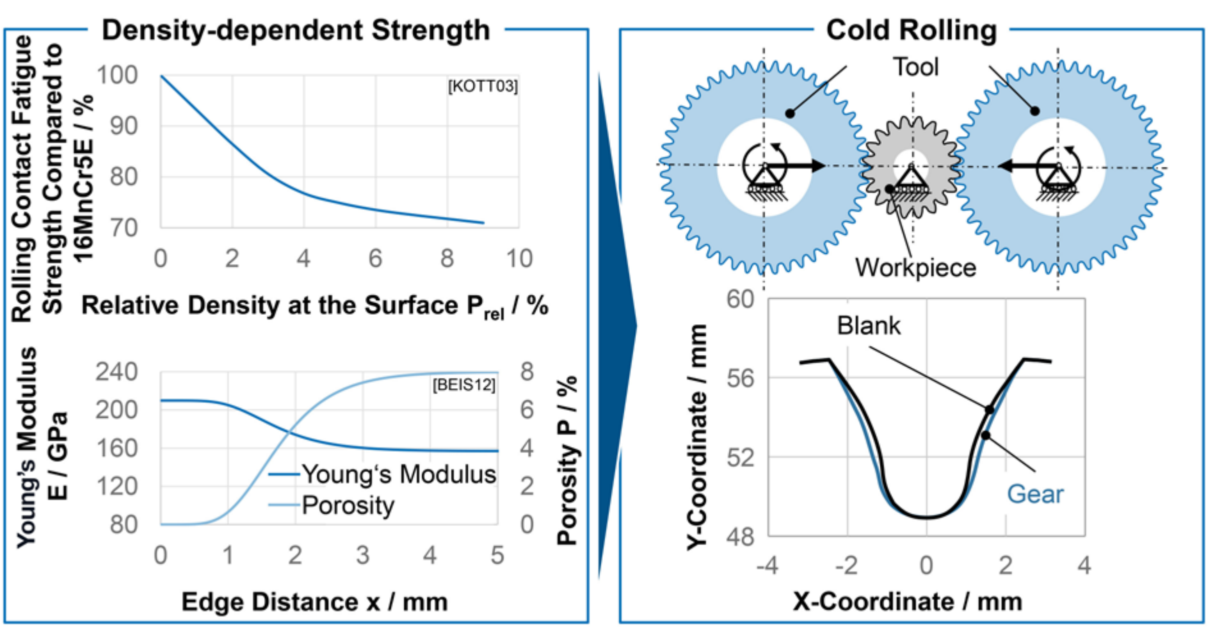

Figure 2 Density dependent material properties of PM gears.

lead to a significant reduction of the tooth root stress.

Densification Processes for PM Gears

PM gears are densified after the sintering process to ensure a proper load-carrying capacity. Furthermore, the densification process determines the density profile and the surface and gear quality and, therefore, the running behavior of PM gears.

Cold rolling. The most common and industrially established process for local densification of PM gears is the cold rolling process. As can be seen (Figs. 2 and 4), the PM gear is placed between two hardened tools and rolled between them to densify a stock on the flanks. The highest stock is located at the pitch circle. In this area the workpiece and the tool mesh with no slip, and so only normal material deformation can be found in this area. In the flank area above and beneath the pitch circle and at the tooth root, the workpiece and the tool mesh with slip. Therefore the material of the workpiece is not only deformed normally, but also tangentially and shoved from the pitch circle to the tip and the root of the tooth. The stock is relieved at the tooth tip and the tooth root to ensure the desired geometry after the cold rolling process. As can be seen (Fig. 4, bottom right), the porous PM gear is densified directly.

Shot peening. In shot peening, a sphere-shaped shot hits the material surface at great velocity. Shot material can be conventional steel-shot as well as ceramic- or glass-shot. The kinetic energy of the shot is transformed into deformation energy at the impact on the component surface. If the induced stress exceeds the yield strength, the material is deformed plastically. According to

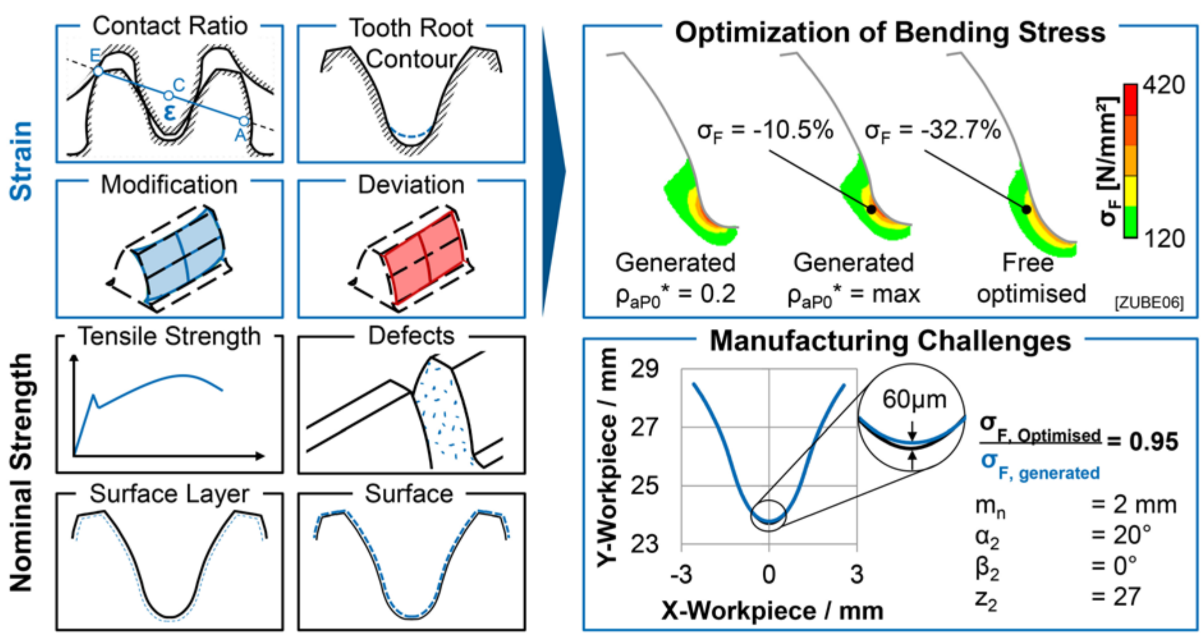

Figure 3 **Challenges in optimizing the tooth root bending strength.**

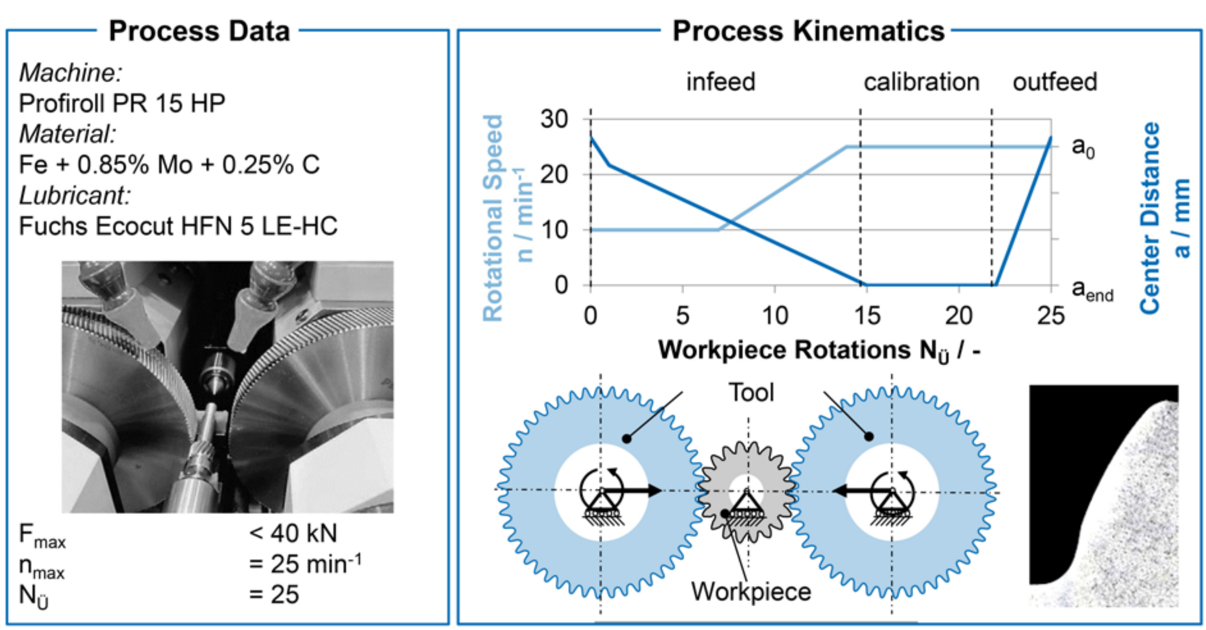

Figure 4 **Cold rolling of PM gears.**

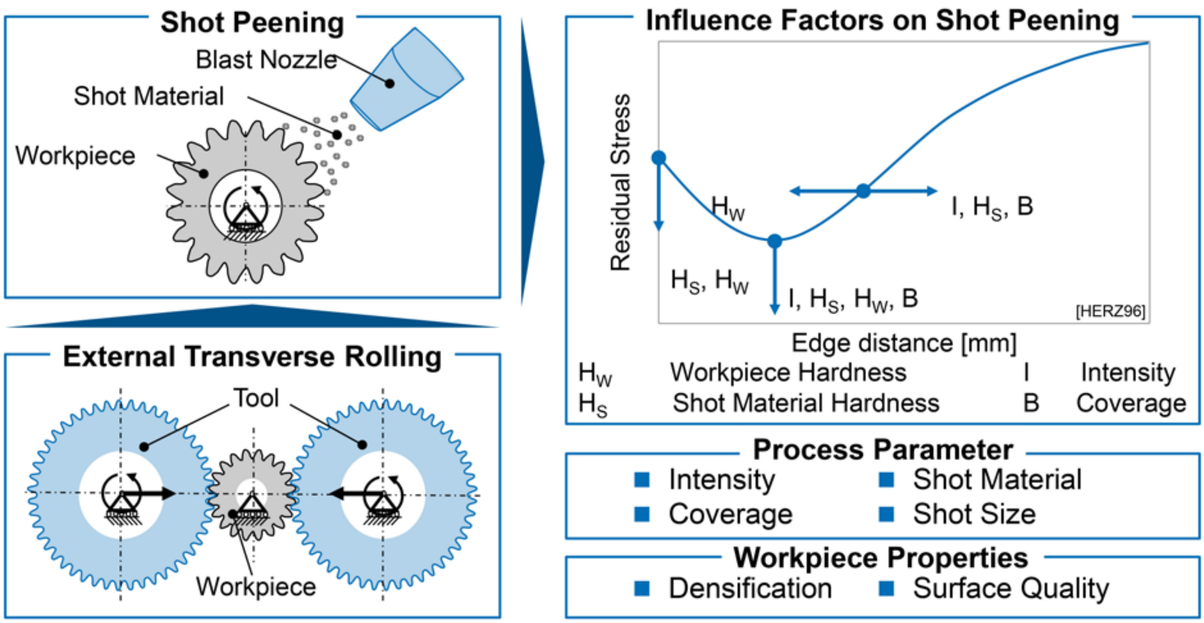

Figure 5 Shot peening of PM gears.

(Ref. 8), two model scenarios for the formation of residual stresses in shot peening exist:

- It can be assumed for low-strength materials that the impact of the shot deforms the surface plastically. Residual stresses build up through the bond of the surface layer to the core material.
- The residual stress in high-strength materials can lead back to the elastic theory according to (Ref. 9). Through the impact of the shot, the material is deformed and, therefore, compressive residual stresses are induced. The maximum of the induced residual stresses is located beneath the surface of the component.

Shot peening in gear production is used for cleaning purposes and to induce residual stresses after the heat treatment to increase the load-carrying capacity. Since residual stresses are induced by a plastic deformation of the material, it can also be used to densify porous materials. The induced stresses in the shot peening process and, therefore, the densification are influenced by the process parameters of the shot peening process (Fig. 5, right). The process parameters intensity, workpiece, and shot hardness — as well as the coverage — influence the induced stress profile in its depth and gradient. Additionally, the surface quality is mainly influenced by the process parameters of the shot peening process.

The shot peening process as a densifying tool was investigated by Iynen, Merkel and Molinari. Depending on the bulk density, densification depths in a range of $50 < t_d < 200\,\mu m$ can be reached (Refs. 10–12). The bending fatigue strength of the investigated specimen was increased by up to 30% (Refs. 11–12).

The achievable densification depths and resulting surface quality, as a function of process parameters intensity, shot material, and Young's Modulus of the shot, was investigated by (Ref. 13). The densification depth of Fe + 0.85% Mo + 0.25% C can be calculated by Eq. (1).

$$t_d = -314.4 + 281.3 \cdot I + 5.763 \cdot H - 0.000127 \cdot E \quad (2)$$

t_d	[µm]	Densification depth
I	[mmA]	Intensity
E	[N/mm^2]	Young's Modulus of the shot
H	[HRC]	Shot hardness

The shot peening process does not rely on specific process kinematics. As long as the shot can cover the whole tooth gap, gears can be machined regardless of their geometry. Therefore, not only normed designs but also optimized tooth root geometries can be densified.

Objective and Approach

The objective of this paper is the qualification of the manufacturing-related properties of surface-densified PM gears. The conventional and established cold rolling process will be compared to shot peening as a densification process. Shot peening allows for a densification without restrictions to the workpiece geometry.

In a first step, PM gears are cold-rolled with a conventional, standards-based tooth root design.

The influence of the tool geometry on the properties of the workpiece are examined and analyzed. Furthermore, the tooth root bending strength of these cold-rolled PM gears is evaluated and compared to conventionally manufactured gears.

Secondly, the tooth root of the PM gears is optimized to increase the bending strength. Since optimized tooth root geometries are not definitely manufacturable by generating processes, two variants are manufactured; i.e. — the first variant is densified by cold rolling while the shot peening process is used as a densification process for the second variant.

The different tooth root geometries can be seen (Fig. 6). The geometry for the cold rolling process can be seen (Fig. 6, left), and the geometry for the shot peening process can be seen (Fig. 6, right). The conventionally designed tooth root geometry is shown in light grey. The optimized variants show a significantly deeper tooth root and are displayed in red lines (Fig. 6). Furthermore, the stock for the different gear design is shown in black lines. For the cold rolling process, a maximum stock of $s = 0.15\,mm$ is used at the pitch circle of the gears. Since the workpiece and the tool are only in rolling contact, with no slip between the contact partners, only normal material flow can be found in this area. In all other areas on the tooth flank and tooth root, sliding occurs between the contact partners. Thus not only normal but also tangential material flow can be found in these areas. The stock is reduced continuously from the pitch circle to the tooth root to a minimum stock of $s = 0.1$ mm.

The contact conditions in the shot peening process are more uniform than in the cold rolling process; additionally, the process forces are lower. Thus a constant stock of $s = 0.013$ mm is used for the shot peened gears; the gears are shot peened at an intensity of $I = 0.3$ mm A at a coverage of B = 200% with ceramic shot Z425.

Manufacturing-Related Properties of Surface-Densified PM Gears

The different gear designs, as well as the manufacturing process, significantly affect the density profile and surface quality and, therefore, the strength of the gears. In the following chapters the surface and gear quality, as well as the density profile of the different gears, will be analyzed and compared. In the end the tooth root load-carrying capacity will be tested on a pulsator test rig to quantify the effect of the tooth root optimization and the influence of the manufacturing process.

Surface quality. The surface quality is influenced by the contact conditions of the compaction process. Furthermore, the surface quality affects the strength of the bending and rolling fatigue strength. The surface quality of the cold-rolled gears with, conventional and optimized tooth root geometry, as well as the shot peened gears, are shown (Fig. 7). The measurements of the surface of the conventional cold-rolled gears are shown at the top; the surface measurements of the optimized

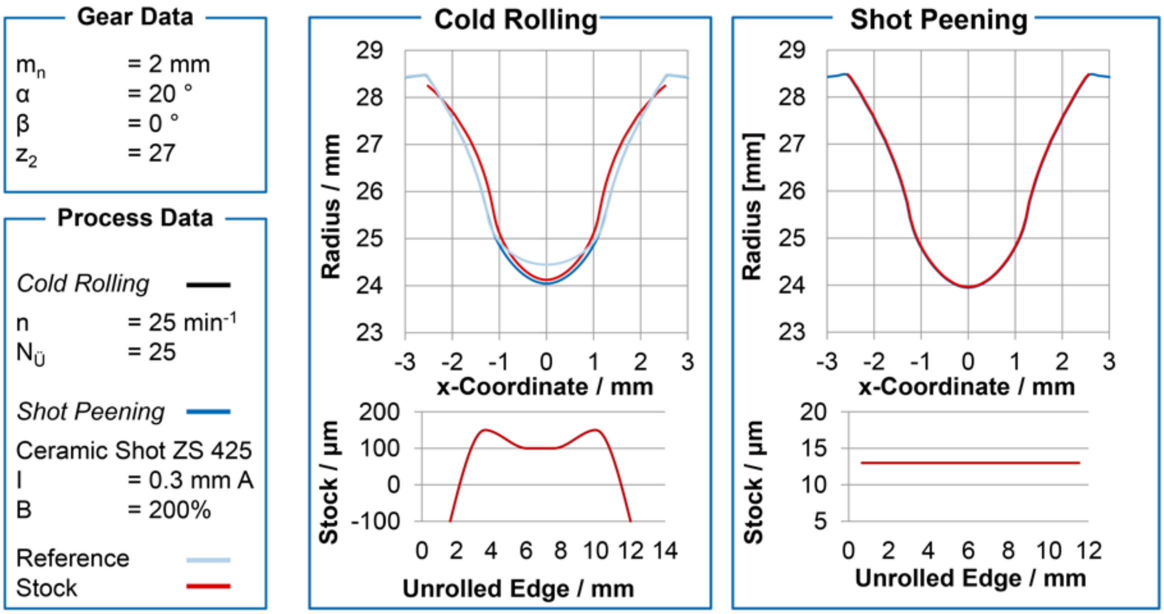

Figure 6 Conventional and optimized tooth root geometries.

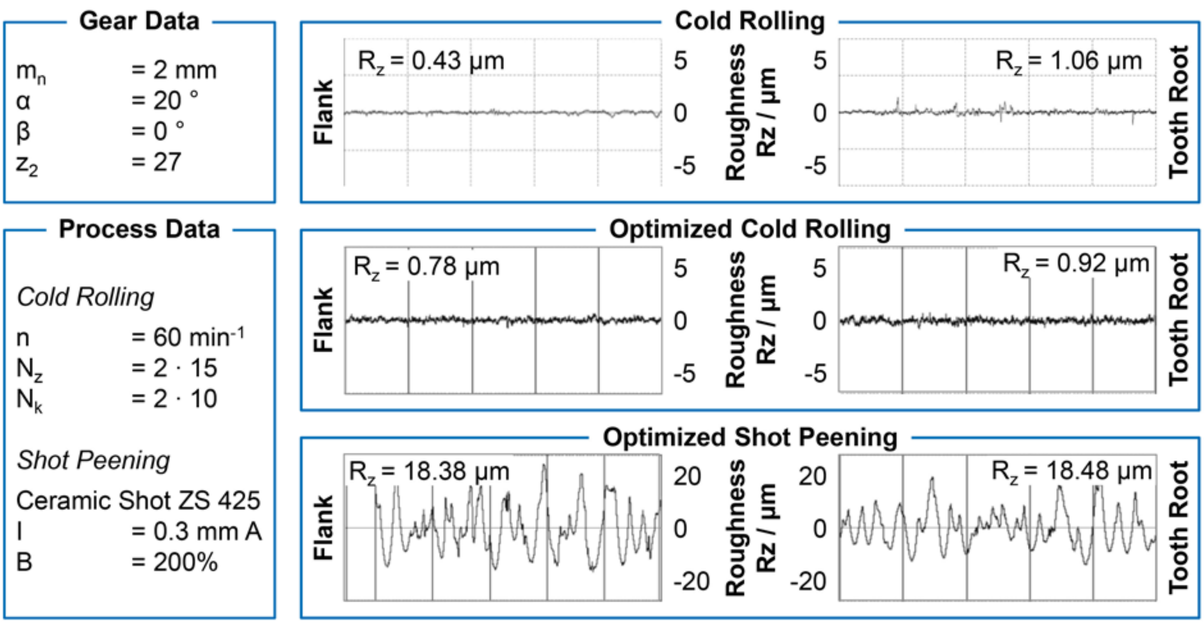

Figure 7 Surface quality of surface densified PM gears.

tooth root geometry that were densified by cold rolling and shot peening are shown in the middle and the bottom of Figure 7, respectively. For all variants the surface quality at the pitch circle, as well as at the tooth root, are shown.

Seen at the top and the middle section of Figure 7, the cold rolling process leaves a surface of high quality. At the pitch circle high surface qualities of $Rz = 0.43\,\mu m$ and $Rz = 0.78\,\mu m$ can be found. For both the conventional as well as the optimized gear, a slight decrease in surface quality can be detected in the tooth root. This can be traced back to the difficult contact conditions at the tooth root during the cold rolling process. The superposition of high slip between workpiece and tool with low contact radii in this area leads to distinctive tangential material flow in this area (Ref. 5). The surface of the shot peened gears is mainly influenced by the shot size and the intensity of the shot (Ref. 13). Since the shot can reach all areas of the tooth gap in the shot peening process, a uniform surface quality of about $Rz = 18\,\mu m$ can be found at the pitch circle as well as in the tooth root.

Density profile. The density profile resulting from the contact conditions of the densification process have a great impact on the load-carrying capacity and are, therefore, of high importance for PM gears. Thus the density profile of the unoptimized as well as the optimized cold-rolled gears and shot peened gears with optimized tooth root geometry are analyzed and compared.

The polished microsection of a tooth of a cold-rolled gear with conventional tooth root design is shown (Fig. 8). Additionally, the microstructure at the pitch circle and the 30° tangent in the tooth root are shown in detail. The densification depth $t_{d,99}$ is labeled in both detail sections and

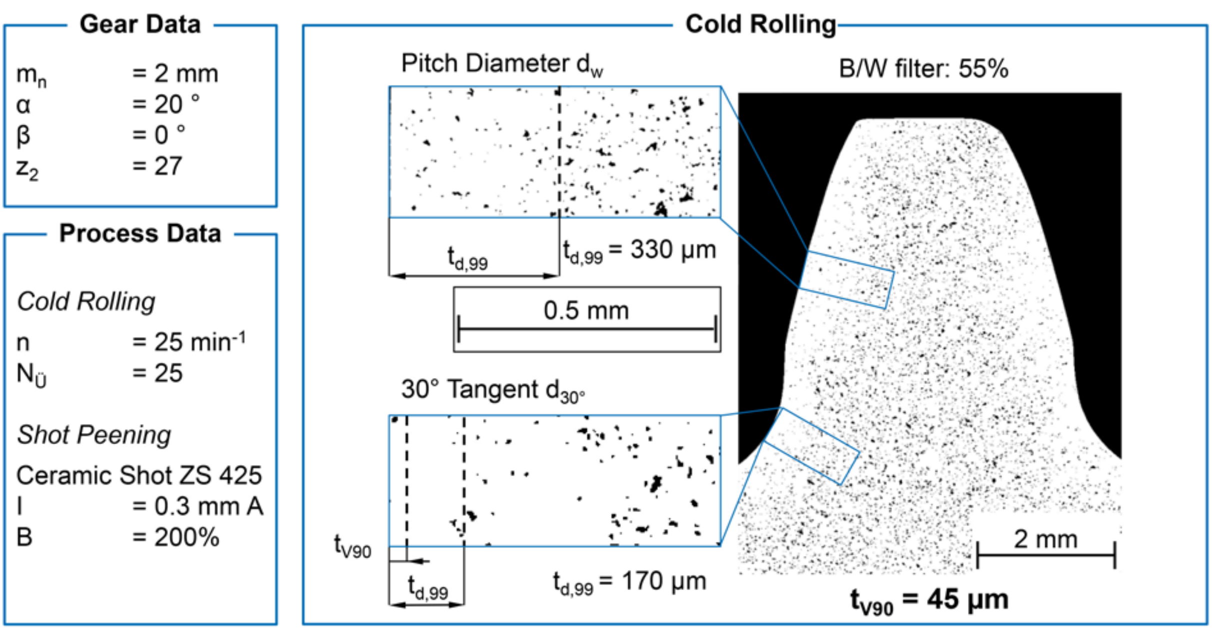

Figure 8 **Densification quality of cold rolled gears with conventional tooth root design.**

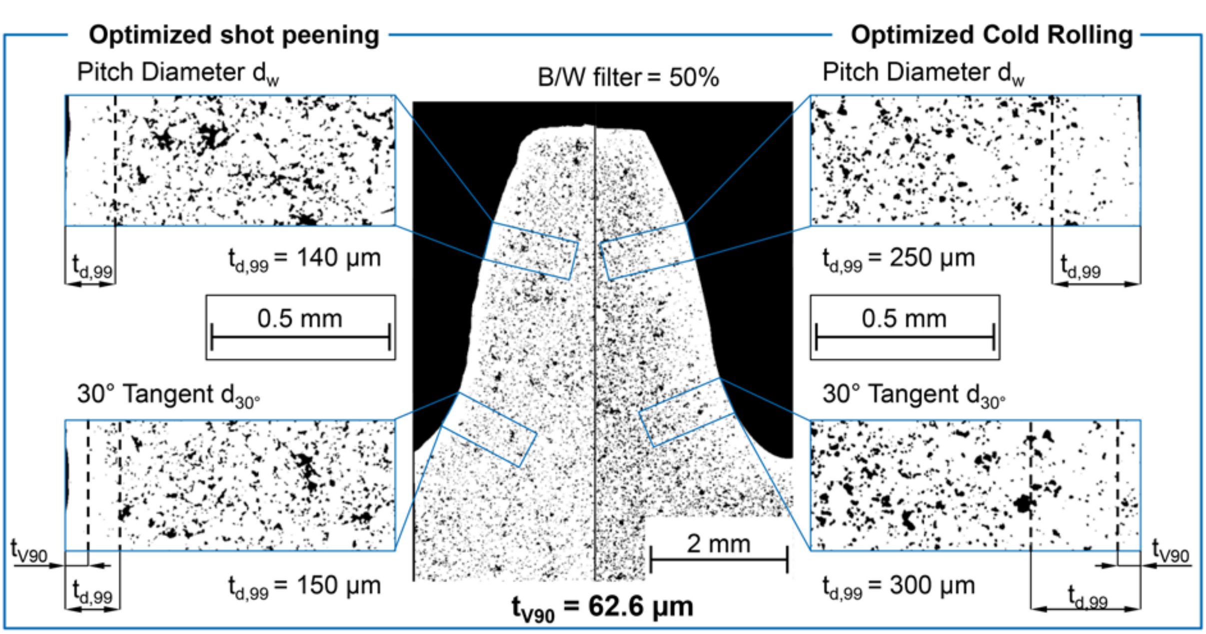

Figure 9 **Densification quality of cold rolled and shot peened gears with optimized tooth root design.**

marks the distance from the surface where at least 99% density can be measured.

At the pitch circle, a densification depth of $t_{d,99} = 330\ \mu m$ can be measured at the pitch circle while the tooth root shows a lesser densification at $t_{d,99} = 170\ \mu m$. When meshing, the gear must withstand the abrasive contact as well as the stresses induced by the Hertzian contact at the pitch circle. Furthermore, the gear tooth needs to withstand the tensile stresses due to the deflection of the gear tooth under load. Therefore a full densification is needed in the highly stressed volume V_{90} in the tooth root. The highly loaded volume V_{90} is defined as the volume in which more than 90% of the stresses can be found. The highly loaded volume V_{90} reaches a depth of $t_{V90} = 45\ \mu m$ in the tooth root for the shown tooth root geometry, and is also labeled in the detail microsection at the tooth root. As can be seen (Fig. 8), a full densification of V_{90} can be measured. It can therefore be expected that the tooth root bending fatigue strength is not influenced by the porosity.

Figure 9 shows the metallographic sections of cold-rolled and shot peened gears with optimized tooth root geometry. The cold-rolled gear can be seen on the right, while the shot peened gear is shown (Fig. 9, left); as before, the microstructure at the pitch circle and the 30° tangent are shown in detail.

The cold-rolled gear shows a densification depth of $t_{d,99} = 250\ \mu m$ at the pitch circle and a densification depth of $t_{d,99} = 270\ \mu m$ at the tooth root. Since the shot peening process provides uniform contact conditions over the whole tooth, the densification depth for the shot peened gear can be measured to about $t_{d,99} = 140\ \mu m$. The highly loaded volume is located in a depth of up to $t_{V90} = 63\ \mu m$ for this optimized tooth contour. Thus both the cold rolling process, as well as the shot peening process, are able to provide a proper densification of the highly loaded volume V_{90}; the greatest difference can be noticed in the density profile resulting from the different densification processes. The shot peening process causes a uniform densification over the whole tooth gap, with a sharp transition to the bulk density. The cold rolling process results in a more variable profile over the tooth height. The absence of slip between workpiece and tool causes a high normal material flow and, therefore, a high densification depth. The reduced densification depth in the tooth root results from higher slip between cold rolling tool and workpiece and, thus, in a more tangential than normal material flow.

Residual stress and hardness profile. The residual stress and hardness profile are other characteristics that are influenced by the manufacturing process, and affect the fatigue strength of the component. Therefore the residual stress profile, as well as the hardness profile of the case hardened gears, are measured and shown (Fig. 10). The profile of the shot peened gears is shown in blue while the profiles of the cold-rolled gears are shown in black.

The residual stress profile of both variants follows a comparable trend. At the edge, both residual stress profiles show a significant drop onto about $\sigma = -300$ MPa. The shot peened gears show a slightly higher drop, but less compressive residual stresses between the edge of the component and the core of the tooth.

The cold-rolled gears show a hardness plateau of about 850 HV 0.1 into a depth of about 200 µm, while the hardness of the shot peened gears decreases earlier at about 100 µm distance from the edge of the component. The hardness is mainly determined by the remaining porosity; therefore the different hardness plateaus can be explained by the different density profiles presented previously.

Both densification processes affect the porosity and, therefore, the hardness as well as the residual stress profile of the PM gears. Especially in edge distances of more than 100 µm, greater differences in the hardness and residual stress profile of the differently densified gears can be detected. The highly loaded volume V_{90} is located at depths of up to $t_{V90} = 63\ \mu m$ (see previous). In this depth, both variants show a comparable hardness and residual stress profile. As such, the effect of

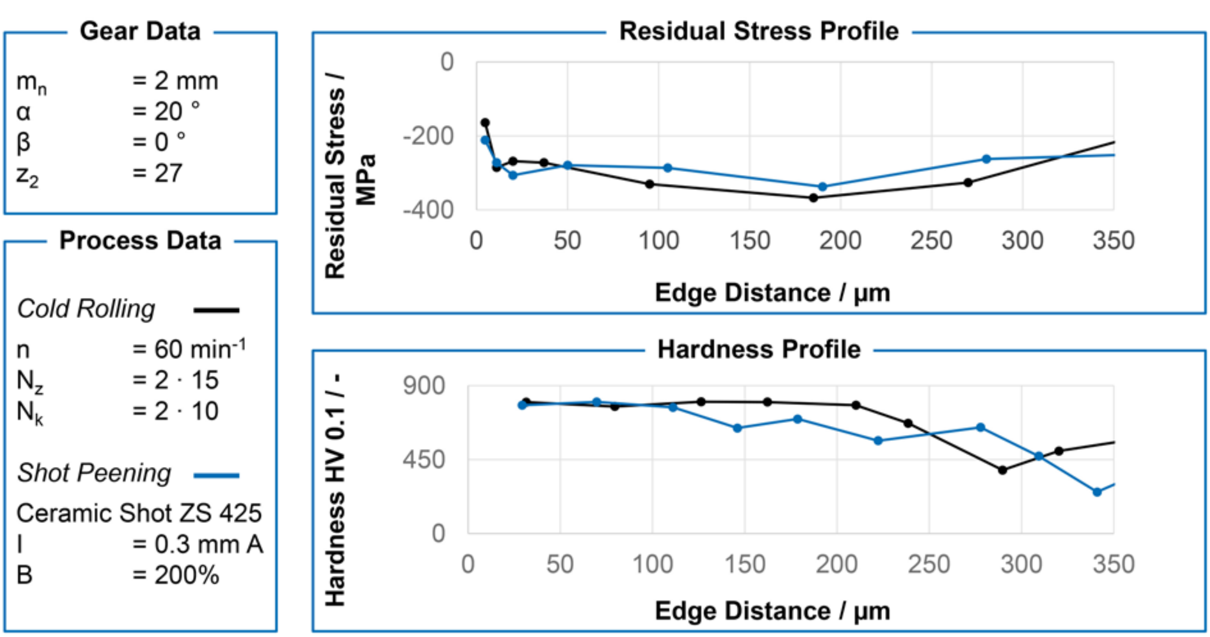

Figure 10 Residual stress and hardness profile of surface densified PM gears in the tooth root.

the hardness and the residual stress profile onto the tooth root bending fatigue strength is comparable for gears of both densification processes.

Tooth Root Load-Carrying Capacity of PM Gears

To study the effect of the different surface and structure qualities, as well as the different densification depths, the tooth root load-carrying capacity of the different tooth root designs and densification processes are tested on a pulsator test rig (Fig. 11). The gear is clamped between two clamps; force is applied from the right clamp and measured at the left clamp. These tests are not as application-related as trial runs, but faster and more economical (Ref. 14). The tests are evaluated using the staircase method by (Ref. 15) and are tested to load cycles up to $l_c = 3{\cdot}10^6$.

The bending fatigue strength of the different process and gear designs are shown (Fig. 12).

At the top of Figure 12, the test evaluation by (Ref. 15) is shown for the shot peened gears as an example. If the gear tooth reaches more than $l_c = 10^6$ load cycles, the load is increased, while the load is decreased when the tooth breaks before reaching the desired number of load cycles. Out of the spread in the test results, the mean bending fatigue strength can be calculated. Besides the PM gears, the test results of conventionally made gears are also shown.

The mean bending fatigue strength of the conventional cold-rolled gears can be calculated to μ = 6.63 kN; the optimization of the tooth root reduces the notch caused by the tooth root radius.

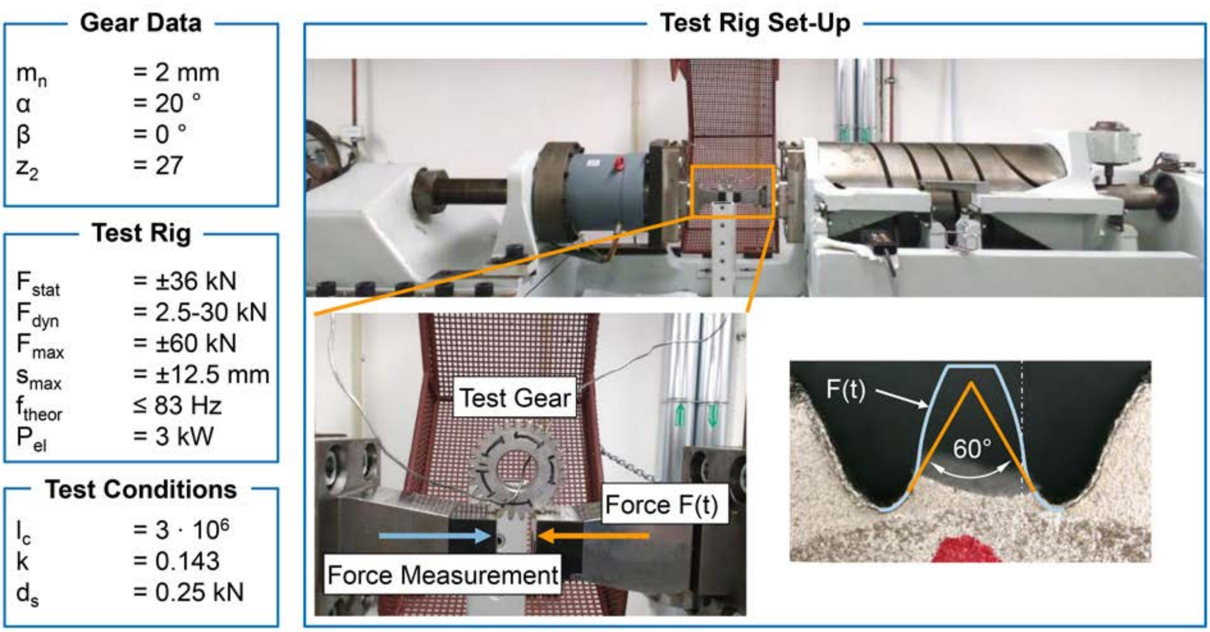

Figure 11 Pulsator test rig.

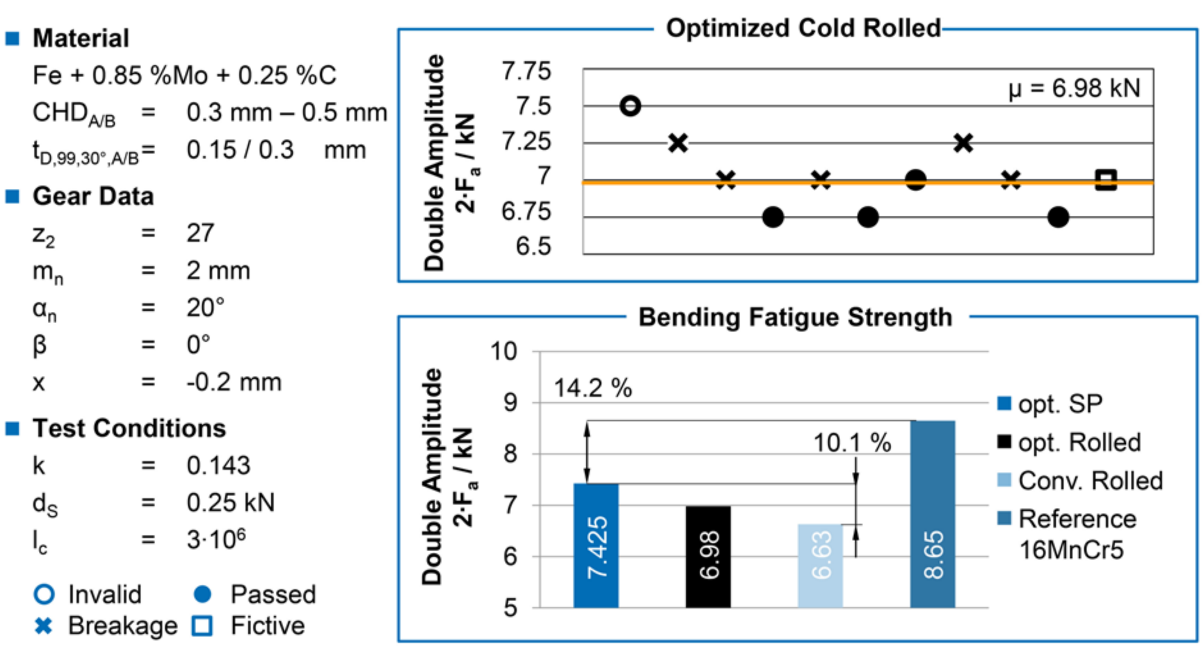

Figure 12 Bending fatigue strength of surface densified PM gears.

Therefore, lower tensile stresses are induced when the tooth is deformed, and so the bending fatigue strength of the optimized gears can be calculated to $\mu = 6.98$ kN for the cold-rolled gears and $\mu = 7.3$ kN for the shot peened gears. Hence, the optimization of the tooth root geometry leads to an improvement of the bending fatigue strength of up to 10%.

The differences of the achieved bending fatigue strength between the shot peened and cold-rolled gears cannot be traced back to the spread of the experiments alone; thus the differences in the density profile must be considered. The shot peened gears show a much lesser, but more even, densification when compared to the cold-rolled gears. Since the highly loaded volume V_{90} is densified completely, the lesser densification depth of the shot peened gears remains sufficient. The bending fatigue strength of the wrought gear is calculated to $\mu = 8.65$ kN. While the conventional PM gear has a 24% lesser bending fatigue strength, the strength of the optimized PM gear still remains more than 14% behind the unoptimized wrought gears. To provide a better understanding of this result, the influence of the density profile on the tooth root stresses is analyzed in detail.

Influence of the Density Profile on the Tooth Root Stress

The three-dimensional density profile in the surface zone of PM gears, as well as the material stiffness due to the porosity of the material, lead to a different tooth root load-carrying capacity of PM gears compared to steel. For the calculation of the tooth root load-carrying capacity of PM gears, it is necessary to consider

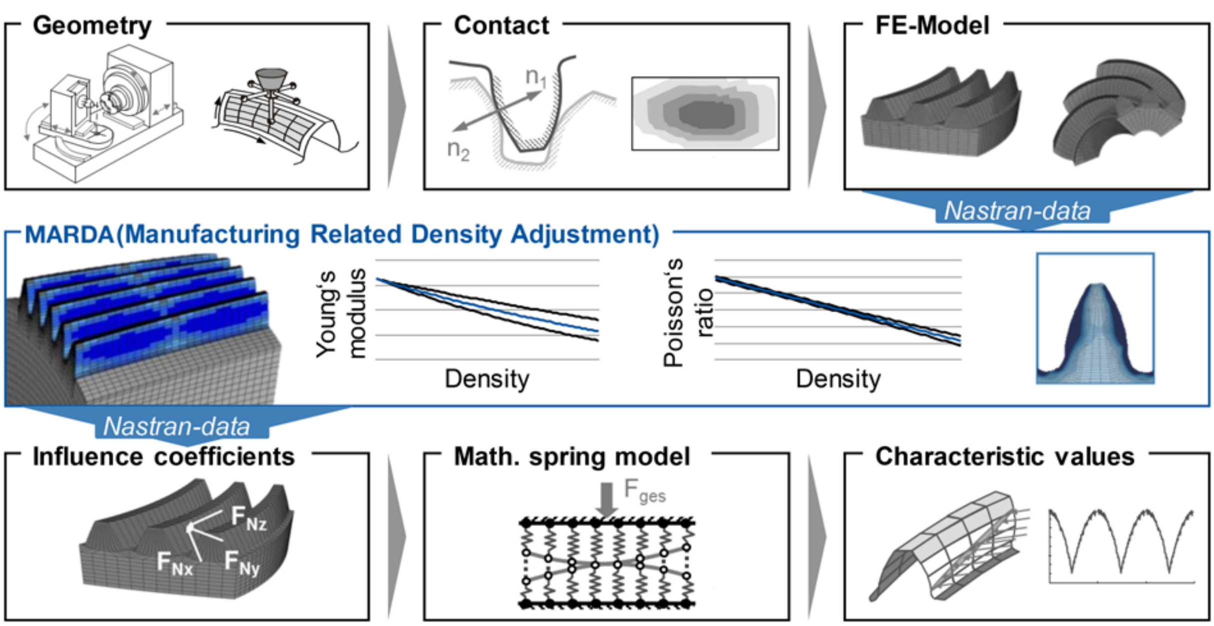

Figure 13 Consideration of the density profile in the FE-based tooth contact analysis.

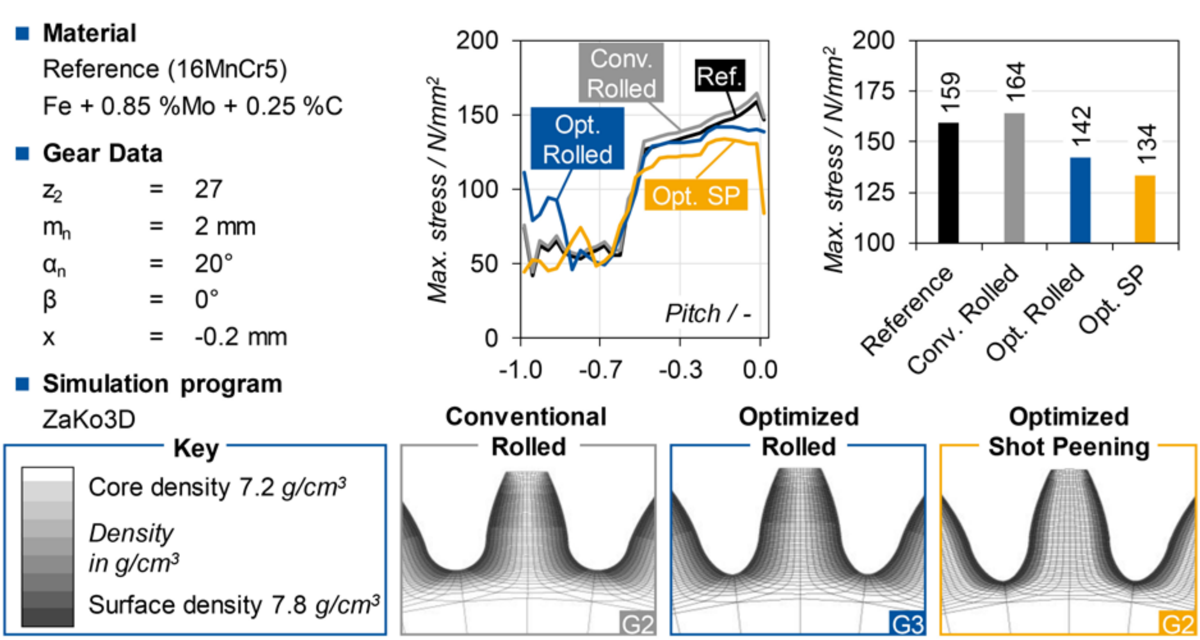

Figure 14 Simulation results: Tooth root stress of surface densified PM gears.

the density profile in the tooth contact analysis. Therefore the calculation program *MARDA* (*Manufacturing Related Density Adjustment*) was developed and integrated in the FE-based tooth contact analysis *ZaKo3D*. The general approach of the FE-based tooth contact analysis and the integration of *MARDA* are shown (Fig. 13).

The first two steps are the definition of the gear geometry and the calculation of the load-free characteristics of the running behavior. In the next step, the FE structure generator creates the FE model necessary for the loaded tooth contact analysis. The influence coefficients define the displacement of each FE node for the successive loading of the FE nodes with a unit force. Finally, the characteristics of the operational behavior of the gear set are calculated with a mathematical spring model.

The FE model generated by the FE structure generator contains all of the information needed for the loaded tooth contact analysis. According to (Ref. 3), the Young's Modulus and the Poisson's Ratio are functionally related to the density of powder metallurgical materials. This allows for the conversion of the density of PM materials into Young's Modulus and Poisson's Ratio and the adjustment of the FE model with regard to a defined density profile. Therefore, new materials are added in the Nastran file and assigned to the respective elements of the FE model. Regarding the adjustment, the material data of the FE elements successively change and the density profile of the PM gear is mapped for each layer.

Figure 14 shows the densified FE models and the simulation results of the tested surface densified PM gears. For the simulation the core density of the PM gears is $\rho_{core} = 7.2$ g/cm^3, while the surface density is $\rho_{surf.} = 7.8$ g/cm^3. To model the density profile in tooth height direction, the density profiles shown in (see previous) are used. The density profile of the material is defined by an s-curve density gradient. The result of the simulation is the maximum tensile stress in the tooth root over one pitch for $T_{Drive} = 10$ Nm normalized torque (Fig. 14, left). To compare the different variants, the maxima of the curves are shown (Fig. 14, right).

The reference gear (Ref.) and the conventional rolled gear (Conv. Rolled) do not differ in the geometry, but in the material and the density profile. Nevertheless, the maximum tooth root tensile stress of the conventionally rolled gear is higher than the maximum tooth root tensile stress of the reference steel gear. The optimization of the tooth root geometry for cold rolling and shot peening leads to a decrease of the tooth root stress by 13.4% (Conv. Rolled to Opt. Rolled) and 18.3% (Conv. Rolled to Opt. SP). While the calculated maximum stress is lower for the optimized geometries (Opt. Rolled and Opt. SP), the tested bending fatigue strength of both gears is lower than the reference steel gear. To explain the results, the nominal strength resistance of the PM gears needs to be lower than for homogeneous steel.

The increased tooth root stress of a conventional rolled gear compared to the steel reference gear with the same geometry can be explained by the inhomogeneous material stiffness of densified PM gears. In the analogy view of the tooth bending by a bending beam, the densification of the surface layer of PM gears can be correlated to the resulting bending stress of a sandwich beam.

Figure 15 shows the stress distribution of two bending beams that differ in material stiffness and structure. On the one hand, the bending stress of a homogeneous (brighter line) and a sandwich beam (darker line) are plotted over the beam thickness (Fig. 15, top). On the other hand, the percentage deviation of the tensile stress of both variants is shown (Fig. 15, bottom). For the homogeneous bending beam, the resulting stress by shear force is divided and distributed linearly in the beam. It can be seen that the material stiffness of a homogeneous bending beam has no impact on the calculated stress distribution.

If a sandwich beam is loaded by a shear force, the inhomogeneous material

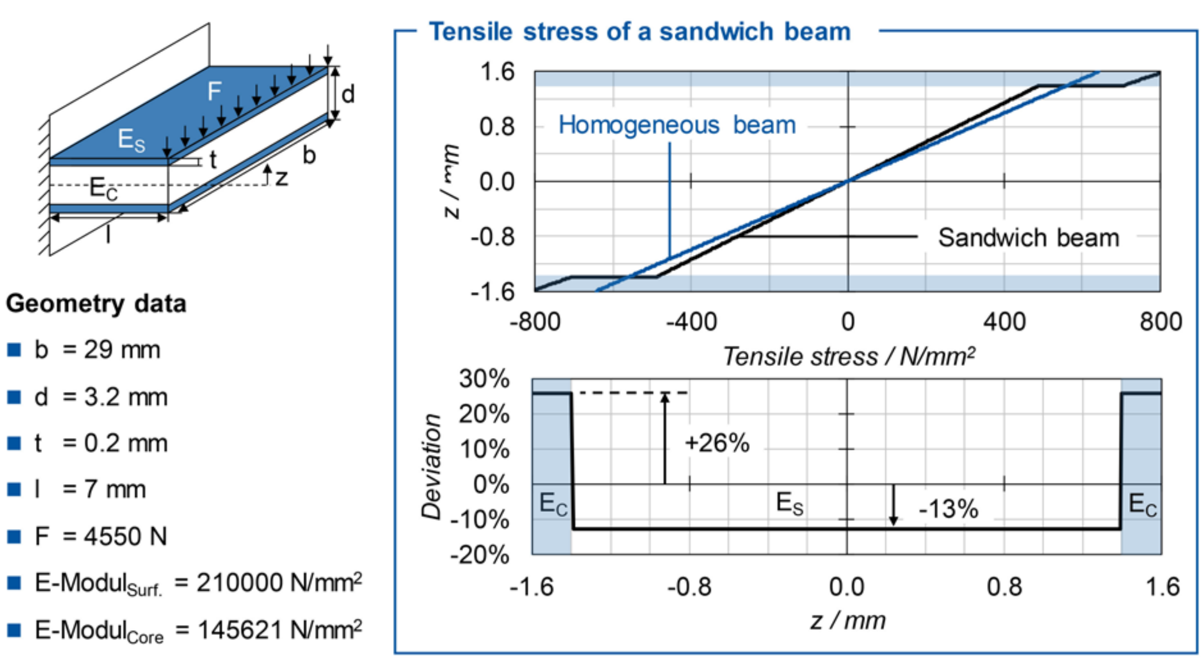

Figure 15 Stress distribution of a sandwich beam.

stiffness leads to a stress jump of the tensile stress distribution. If the material stiffness of surface layer of the beam is higher than the material stiffness of the core, like for PM gears, the bending stress in the surface layers increases during the material change. The percentage comparison of the resulting stresses of both variants shows a reduction of the tensile stress of the sandwich beam core by −13%, while the tensile stress of the surface layer increases by 26%. Hence, the analytical calculation results of the tensile stress in bending beams confirm the simulation results in the case of the increase tensile tooth root stress of Gear 2 compared to the steel reference gear. Due to the higher material stiffness of the surface layer of PM gears resulting from the densification process, the maximum tensile stress in the tooth root increases while the load is constant.

The comparison between the experimental results of the tooth root load-carrying capacity and the calculated tooth root stress of the gear variants show good correlation for the densified PM gears. While the calculated tooth root stress of the optimized PM gears (G3 and G4) is lower than the tooth root stress of the reference gear (Ref.), the experimental test shows a higher tooth root load carrying capacity. This deviation can be explained by a lower bearable tooth root stress of PM gears compared to steel (16MnCr5), which needs to be investigated in further research projects.

Summary and Outlook

The powder metallurgic process chain offers advantages in resource and energy consumption in mass production when compared to conventionally wrought components. The components are produced by compacting and sintering powdered metal into shape. After sintering, PM components show a process-related and unavoidable porosity. Since the pores reduce the load-bearing cross-section, while also being internal notches in the material, the mechanical properties of porous components are inferior to parts of full-dense material. Therefore highly loaded components are densified to increase their load-carrying capacity. Since gears are only stressed locally at and directly beneath the flank, gears are suitable for local densifying processes such as cold rolling.

Due to the densification in the cold rolling process, the flank load carrying capacity can be improved at levels of conventionally wrought gears. Still, the tooth root strength of PM gears must be improved. Therefore, the tooth root is optimized to reduce the stress in this area. Since optimized tooth root geometries cannot be densified by the industry-established cold rolling process in general, the shot peening process is an alternative. The densification process, either shot peening or cold rolling, has a major influence on the properties of the manufactured gears. The influence of the densification process on the surface quality, as well as the density profile, is analyzed in this report. Furthermore, the influence of the tooth root optimization, as well as the influence of the manufacturing process on the tooth root bending fatigue strength, is evaluated.

The contact conditions of the different manufacturing processes have a great impact on the surface quality. While the cold rolling process leaves high surface quality at $Rz = 1\,\mu m$, the indentations of the shot in the peening process cause a coarse surface at $Rz = 18\,\mu m$. The density profile is also affected by the different densification processes. In the cold rolling process, the contact conditions between workpiece and tool are changing over the tooth height and are, furthermore, influenced by the stock on the workpiece. Hence, the highest densification can be found at the pitch circle, while the densification in the tooth root is reduced. The even contact conditions over the tooth height in the shot peening process cause a constant densification depth over the tooth height. Since the highly loaded volume is completely densified for all process variants, the remaining porosity does not affect the bending fatigue strength. Furthermore, the residual stress and hardness profile for shot peened and cold rolled gears were evaluated after the heat treatment and are comparable for gears of both process variants.

To quantify the effect of the tooth root optimization and the different densification processes, the tooth root bending fatigue strength was evaluated and compared to optimized gears of both PM and wrought steel; optimization of the tooth root leads to 10% improvement of the tooth root bending fatigue strength. Nevertheless, the strength of the PM gears is 14% lower than the tooth root strength of conventional gears. To analyze these differences further, tension in the tooth root due to the different tooth root geometries and the density profile are evaluated.

In order to determine the influence of the density profile on the tooth root tensile stress, the calculation program *MARDA* was developed and integrated into the tooth contact analysis *ZaKo3D*. Due to the densification process, the resulting inhomogeneous density profile leads to a different tensile stress distribution in the tooth root that can be correlated to the stress distribution in a sandwich beam. The tensile stress in the densified surface layer of PM gears increases, while the tensile stress in the core material decreases. Still, due to the deviation between the calculated tooth root stress and the tested tooth root load capacity of densified PM gears, the bearable tooth root stress of PM gears needs further investigation and research.

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