Influence of the Contact Conditions in Cold Rolling on the Density Profile of Powder Metallurgical (PM) Gears

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Introduction and Motivation

Powder metal (PM) gears can be an energy and resource efficient replacement for conventional wrought gears (Ref. 1). To illustrate the possible savings in resources and process energy, Figure 1 shows a comparison of the 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 (Ref. 3). Because of the near-net-shape process, PM gears require less raw-material-per-part. Thus, less energy is used per produced part. PM gears are, hence, an economic alternative for conventional gear manufacturing.

Due to production by pressing and sintering, PM gears are porous. Since pores reduce the loaded area and are also probable crack initiators, the porosity determines the strength of the PM component. PM gears can be densified to increase their local density and, therefore, the load-carrying capacity (Ref. 2). PM gears are compacted locally since they are mainly loaded directly at the surface. A common process to densify PM gears locally is the cold rolling process. The contact conditions in the cold rolling process determine the density profile and, therefore, the material properties of the PM component. The influence of the contact conditions in cold rolling of PM gears on the resulting density profile is yet to be investigated.

Analogy Test of Cold Rolling of PM Gears

The meshing of two gears is characterized by continuously changing contact conditions due to changing contact radii as well as different sliding velocities (Fig. 2-left). Each contact point between the meshing gears can be described by

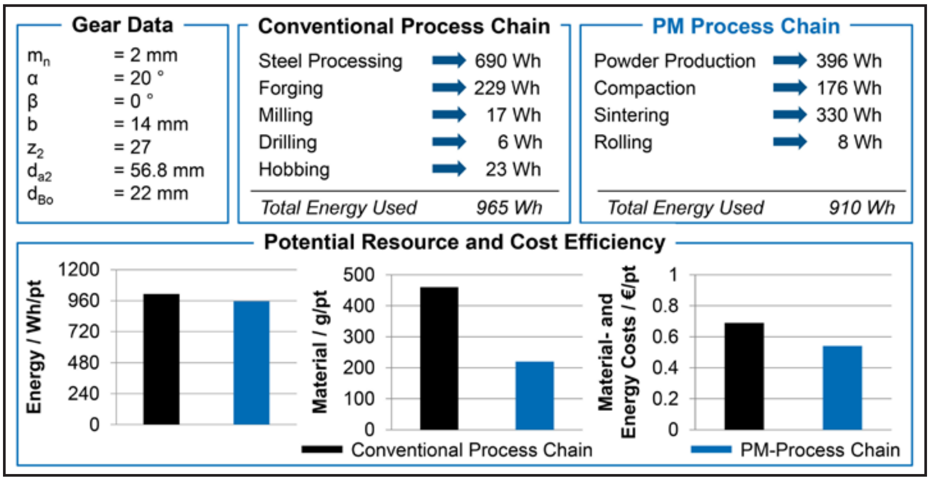

Figure 1 Cost and resource efficiency of PM gears.

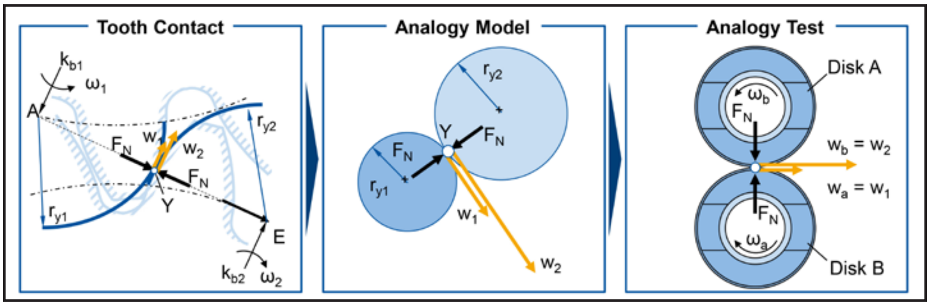

Figure 2 Analogy test for cold rolling of gears.

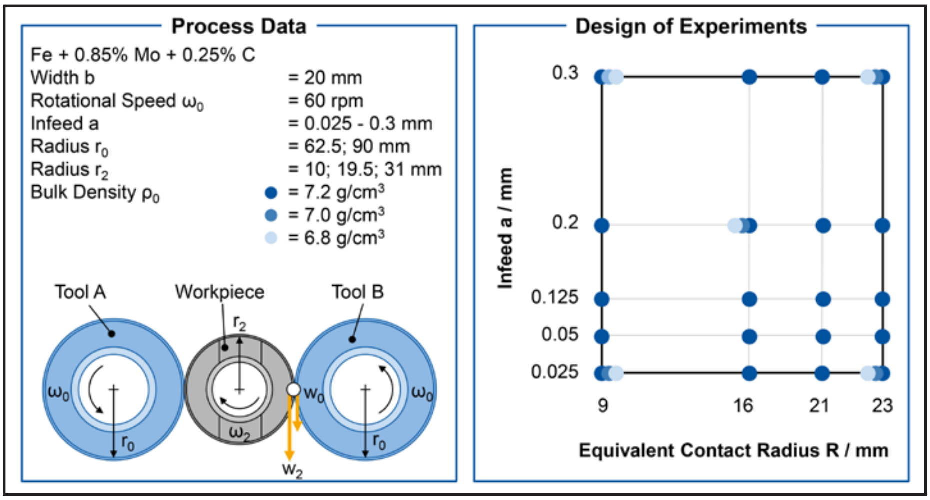

Figure 3 Design of experiments.

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the equivalent contact radius and the relative speed between both contact partners. The equivalent contact radius R can be calculated with the individual contact radii r_1 and r_2 by Eq. 1.

$$R = \frac{r_1 \cdot r_2}{r_1 + r_2} \quad (1)$$

An analogy test was derived to investigate the influence of the contact conditions individually. According to Gräser, the relative speed between the contact partners does not influence the normal material flow and, hence, the densification of PM gears (Ref. 3). Therefore, the contact conditions will be investigated at constant slip of $s = 0$.

Design of Experiments

The design of experiments of the analogy tests for rolling of $Fe + 0.85\%\ Mo + 0.25\%\ C$ is shown in Figure 3. The infeed will be varied in a range of $0.025 < a < 0.3$ mm and represents typical infeeds of the cold rolling of gears. The used cold rolling machine Profiroll PR15HP allows to construct contact radii $R > 9$ mm. In the cold rolling of PM gears, contact radii of up to $R = 20$ mm can be found. Hence, the contact radii are varied in a range of $9 < R < 23$ mm.

The bulk density is varied in the range $6.8 < \rho_0 < 7.2\ g/cm^3$. Since the highest bulk density is most relevant for highly loaded applications such as gears, the influence of the process parameters is investigated full factorial. The lower bulk densities are investigated at the corners and the central point of the experimental plan.

The influence of the different process parameters is investigated numerically. The analogy process is modelled as a dynamic-explicit model in the FE program *Abaqus*. The model is validated experimentally for the reference test parameters with existing material models that have been validated in previous investigations (Ref. 6). The FE model uses the flow curve determined by Kauffmann to calculate the yield strength of the material as well as the Gurson-Tveergard-Needleman model to describe the influence of hydrostatic and deviatoric stress states on the material deformation (Refs. 4–6). Since friction does not influence the normal material flow, friction is not considered in the FE model (Ref. 3).

The numerically and experimentally obtained density profiles are shown

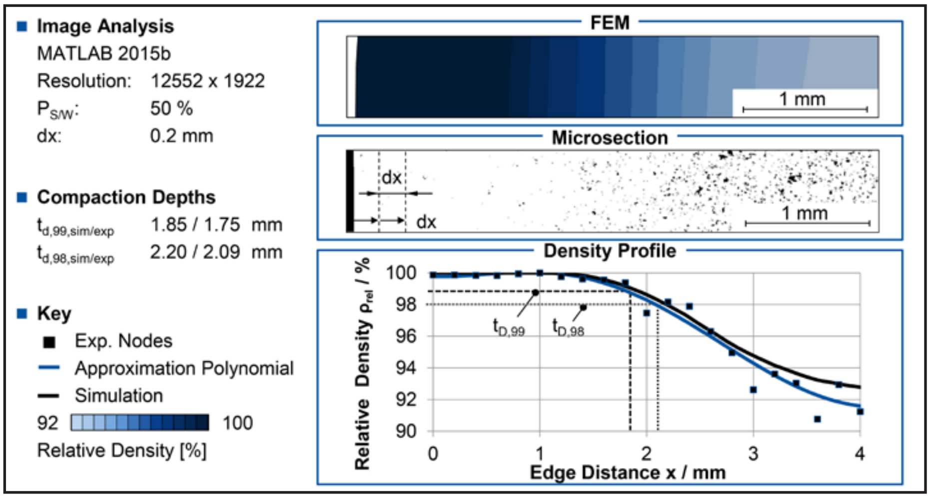

Figure 4 Validation of the FE model.

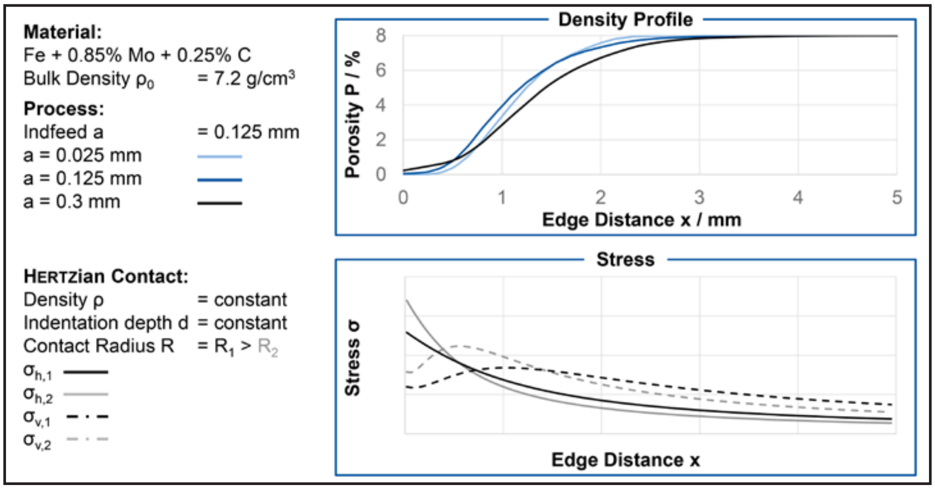

Figure 5 Influence of the equivalent contact radius on the density profile.

(Fig. 4). The simulated cross section of the analogy test component is shown on top while the experimentally obtained micro section is shown (Fig. 4-middle). To get a more quantitative comparison between both cross sections, the density profile of both sections is shown (Fig. 4-bottom).

Since the simulated density profile shows a qualitatively and quantitatively good fit to the experimentally obtained density profiles, it is expected that the simulation provides an appropriate image of the reality.

Influence of the Process Parameters on the Density Profile

To analyze the effect of different process parameters on the density profile, the different process parameters are varied individually while other process parameters are kept constant.

The influence of the equivalent contact radius R is shown on the left side of Figure 5. The equivalent contact radius is varied between $9 < R < 23$ mm while the infeed is $a = 0.125$ mm at a bulk density of $\rho_0 = 7.2\ g/cm^3$.

The equivalent contact radius influences the fully densified edge area as well as the gradient of the density profile. A low contact radius R leads to deeper densification at the surface but also to a steep decrease onto the bulk density when compared to higher contact radii R. The different depths of full densification as well as the different gradients can be explained with the Hertzian theory (Ref. 7). On the bottom of Figure 5, the stresses in the workpiece for two different contact radii are shown qualitatively while $R_1 > R_2$. The indentation d as well as the density ρ_0 are constant. The von Mises stresses calculated from the deviatoric stresses are shown in dashed lines. While it is assumed that conventional parts with full density are only deformed plastically by the Von Mises stresses, PM parts are also influenced by the hydrostatic stresses. It can be seen that both the hydrostatic stresses $\sigma_{h,2}$ and the von Mises stresses $\sigma_{v,2}$ of the lower contact radius R_2 are high directly beneath the surface with a steep gradient into the core of the workpiece. Because of their gradient, the stresses $\sigma_{h,1}$ and $\sigma_{v,1}$ of contact radius R_1 rise above $\sigma_{h,2}$ and $\sigma_{v,2}$ deeper under the workpiece surface. Therefore, low equivalent contact radii R result in a deeper full densified area beneath the surface but also in a steep decline of the density. The reason for the different density profiles at different equivalent contact radii R can be found in the resulting stress profile of the different contact conditions.

Additional to the investigation of the contact radius, the influence of the infeed a is also investigated. Different density profiles for different infeed a are shown (Fig. 5). The contact radius as well as the bulk density are constant at $R = 16$ mm and $\rho = 7.2$ g/cm^3 respectively. Furthermore, the stresses in the material resulting from the Hertzian contact are shown at the bottom Figure 6.

As it can be seen at the top of Figure 6, the densification depth rises when increasing the infeed. The reason for the higher densification can be seen (Fig. 6, bottom) as the stresses out of the Hertzian contact increase at higher infeed. Therefore, the higher densification depths at higher infeed can also be traced back to the stresses out of the contact conditions.

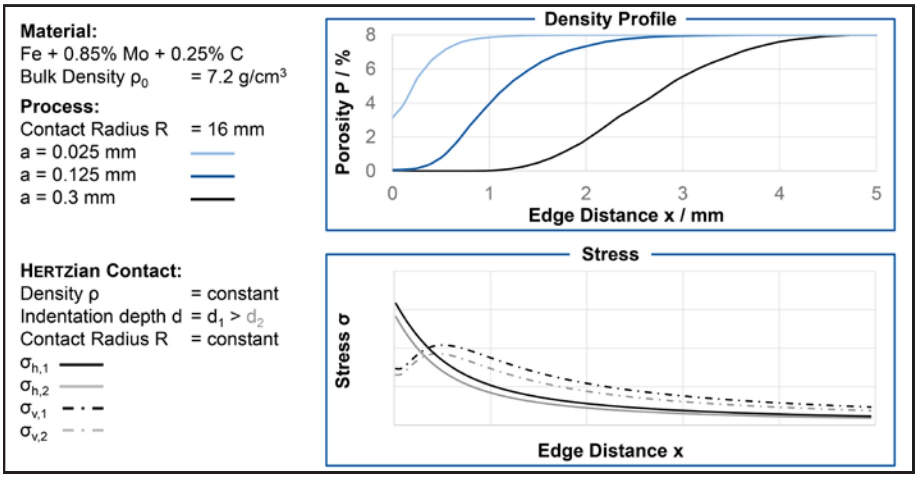

Figure 6 Influence of the infeed and the bulk density on the density profile.

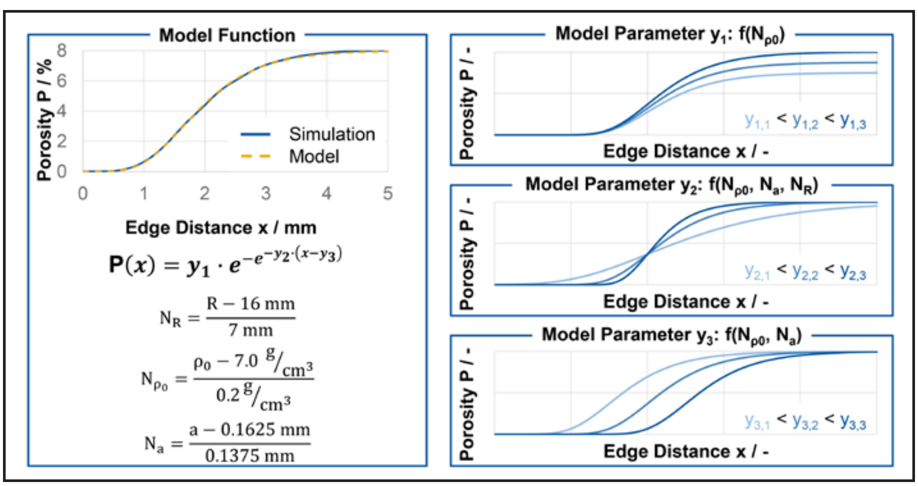

Figure 7 Modelling approach.

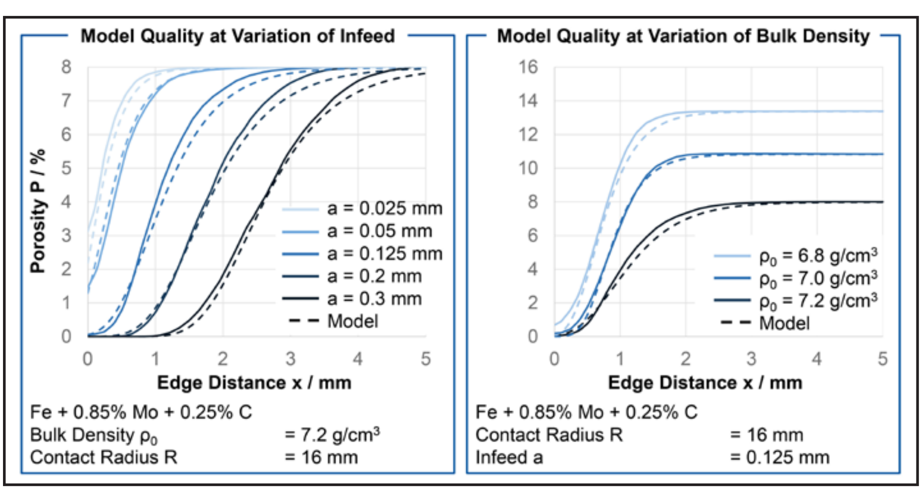

Figure 8 Modelling the density profile in cold rolling.

Modelling the Density Profile

To describe the density profile not only qualitatively but also predict it quantitatively, a model function needs to be found. As it can be seen on the left side of Figure 7, the density profile can be described with Eq. 1. The numerical obtained density profile is shown in solid lines while the fitted profile of Eq. 2 is shown in dashed lines.

$$P_x = y_1 \cdot e^{-e^{-y_2 \cdot (x - y_3)}} \tag{2}$$

To ensure the comparability of the influence among each other, the different process parameters are scaled on values ± 1 and can be calculated with Eqs. 3–5.

$$N_{\rho 0} = \frac{\rho_0 - 7.0\,\mathrm{g/cm^3}}{0.2\,\mathrm{g/cm^3}} \tag{3}$$

$$N_R = \frac{R - 16\,\mathrm{mm}}{7\,\mathrm{mm}} \tag{4}$$

$$N_a = \frac{a - 0.1625\,\mathrm{mm}}{0.1375\,\mathrm{mm}} \tag{5}$$

The influence of the different model parameters y_i can be seen (Fig. 7-right). Model parameter y_1 defines the threshold value of the model function. Model parameter y_2 influences the rise while parameter y_3 shifts the abscissa section of the model function.

Based on the density profiles in the previous section, the influence of the process parameters on the model parameters y_i can be analyzed statistically. Model parameter y_1 influences the threshold value of the model function. Hence, it is only influenced by the bulk density and can be calculated by Equation 6 with a coefficient of determination of $R^2 = 0.99$.

$$y_1 = 0.1 - 0.03 \cdot N_{\rho 0} \tag{6}$$

Model parameter y_2 determines the gradient of the model function. As discussed in the previous chapter, the gradient is influenced by contact radius and the infeed as well as by the bulk density. Since the process parameters are scaled (Eqs. 2–4), the weight of each process parameter can be determined out of Eq. 7.

$$y_2 = 2.6 - N_a \cdot (1{,}4 - 0.8 \cdot N_a - 0.3 \cdot N_{\rho 0} - 0.3 \cdot N_R) - 0.4 \cdot N_{\rho 0} - 0.3 \cdot N_R - 0.4 \cdot N_{\rho 0}^2 \tag{7}$$

The main influencing factor is the infeed a. The weight of the parameters contact radius R, bulk density ρ_0 as well as interdependencies between the different process parameters are nearly similar in Equation 7, therefore showing the same influence. By Equation 7, model parameter y_2 can be calculated with a coefficient of determination of $R^2 = 0.97$.

The abscissa section of the model function is shifted by model parameter y_3. The statistical significant process parameters are the infeed a and the bulk density ρ_0. The contact radius R does not show a significant influence on model parameter y_3 (Eq. 8). Due to the scaled process parameters, it can be seen that the infeed a has the greatest weight in Equation 8, while the bulk density ρ_0 and the interdependencies between both process parameters display a lower weight. Equation 8 allows to calculate model parameter y_3 with a coefficient of determination of $R^2 = 0.98$.

$$y_3 = 1.0 + 0.2 \cdot N_{\rho 0} + 1.0 \cdot N_a + 0.2 \cdot N_a \cdot N_{\rho 0} \tag{8}$$

With Equations 6–8, the model parameters for the model function in Equation 2 can be determined. This allows for a calculation of the density profile of cold rolled cylindrical PM components and, therefore, the determination of the density-dependent material parameters such as Young's modulus.

Quality of the Modeled Density Profile

To determine the quality of the mathematical model, the simulated density profiles are compared to the calculated density profiles. Figure 8 (left) shows the model quality at a variation of the infeed, and the variation of the bulk density on the right side. The density profiles obtained by simulation are shown in solid lines, the calculated density profiles are shown in dashed lines.

Both sides of Figure 8 show a very good match between the model and the simulation. Therefore, the model approach is an appropriate approach to calculate the density profile of PM components in the cold rolling process based on the contact conditions.

Summary and Outlook

The powder metallurgic process chain offers advantages in resource and energy consumption in mass production when compared to conventional 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 mainly stressed locally at and directly beneath the flank, gears are suitable for local densifying processes such as cold rolling.

The knowledge of the local density is of high importance when determining the mechanical properties and, therefore, the load-carrying capacity of powder metal components. The density profile is determined by the densification process and its process parameters or contact conditions respectively. Based on the Hertzian theory as well as on previous research, the process parameters infeed, equivalent contact radius and the bulk density were identified as relevant process parameters. The contact conditions of the cold rolling process of gears were transferred to an analogy test. This analogy test allows separation of the different and constantly changing contact conditions of the gear rolling process from each other so that the influence of each parameter can be determined individually. The infeed was varied in the range of $0 < a < 0.3$ mm, the equivalent contact radius in the range of $9 < R < 23$ mm while the bulk density was varied in the range $6.8 < \rho_0 < 7.2$ g/cm^3. The influence of the different process parameters was determined by FE simulations. The simulative results are qualitatively as well as quantitatively an adequate match to experimentally obtained density profiles.

The densification of PM steels is influenced by the Von Mises as well as the hydrostatic stresses in the material. An increase of the bulk density increases, due to the density-dependent Young's modulus, the stresses at constant infeed and equivalent contact radius. Additionally, a lower pore volume needs to be densified. Therefore, materials with higher density can be densified deeper. Due to the higher material deformation, a higher infeed also increases the stresses in the material and, hence, the densification. The equivalent contact radius of the workpiece-tool contact affects the slope of the density profile but not its depth.

To predict the mechanical properties of densified PM components, the density profile was modelled based on the contact conditions of the cold rolling process. The density profile of cold rolled PM components can be predicted with an appropriate model function. Therefore, the influence of the process parameters on the different model parameters was analyzed qualitatively. Then, this analysis was used to calculate the model parameters quantitatively.

The review of the model quality showed that the calculated density profiles show a good match to the simulated density profiles. Therefore, the determined model is capable to predict the density profile of cold rolled PM components based on the contact conditions.

The obtained results allow determination of the local density and, therefore, the mechanical properties based on the contact conditions of the cold rolling process. On the one hand, the information about the material properties of the PM workpiece allows a calculation of the local process forces. On the other hand, the results obtained from the analogy tests need to be transferred to the actual cold rolling process of gears. The constantly changing contact conditions of this process need to be considered to determine the local density profile at the tooth flank as well as in the tooth root.

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