Advanced material modelling for gear rolling densification simulations

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Abstract

Gear rolling densification is a post sintering process in which the porosity is closed at the surface and in some depth into the flank surface of the gear. The rolling process improves the mechanical properties such as the contact strength. In order to optimize the gear rolling process and produce more accurate results, FE (Finite Element) simulations can be used for validation and thereafter optimization of tool, gear geometry and overall process. In this paper, FE simulations will be conducted with two plasticity material models to understand their behavior in compression. Moreover, experimental results from an indentation of a wrought steel ball to a PM material will be correlated to FE simulation results for different load levels. Furthermore, gear-rolling simulation results will be compared to experimental results for both material models in involute profile.

Introduction

Powder Metallurgy (PM) is an established technology for manufacturing components for many applications. The reason is the high productivity of highly complex parts with good mechanical properties and tolerances. At the same time, it is an environmentally friendly process.

PM gears have been produced for many years and for different applications. The reason is the high productivity rate combined with less material consumption in comparison to cutting techniques such as hobbing. PM gears can be used in automotive gearboxes and other applications with high demand on fatigue strength. The two loading conditions at which the gears are subjected are the tooth root bending and the Hertzian contact pressure between the contact surfaces. The porous nature of the sintered gears has advantages and disadvantages, the main disadvantage of PM gears is the lower strength. This is the reason why secondary operations can be used, to increase the fatigue strength and if it is necessary for the operation the tooth root strength.

Gear rolling densification is a post sintering mechanical process in which the porosity is selectively closed at the surface and below the flank of the gear to some tenths of a mm. This results in improved mechanical properties due to the non-presence of porosity on the surface. The process starts by placing the gear with added stock material between two tools. The tools during the process have two degrees of freedom, the rotational and the translational in the horizontal direction. The gear with stock added material can only rotate. The tools rotate and press at the same time the gear, until the optimum involute profile is formed and a good surface quality is achieved. Figure 1 shows the production chain of a rolled and sintered gear for highly loaded applications without the extra last step of hard finishing which can be skipped if a good surface can be achieved after rolling.

Figure 1. Production chain for a sintered and rolled component

In order to improve the process and reduce the overall development time, simulations can be used as a tool to predict the tool design, gear with stock geometry and rolling process parameters. Moreover, if the rolling results can be improved through simulations it is possible to skip the hard finishing and introduce the gear rolling as the final mechanical process. The purpose of this work is to investigate how the material modelling can influence the accuracy of the simulation results. Two different material models are compared to each other and to experimental results.

Material modelling

As mentioned above, FE simulations are an effective tool to reduce the development time of the gear rolling densification process and improve the overall result. The simulations should be able to predict the densification and deformation of the involute profile of the gear. To accomplish this plasticity theory should be used and furthermore a suitable material model that can describe realistically the phenomenon of densification of a porous material should be found. The classical von Mises yield criterion that is used to describe the plastic behavior of solid metals cannot be applied in PM due to

the presence of porosity and the volumetric densification that takes place when porosity closes. This is why more complex material models with porosity description are used for porous structures, to predict this kind of behavior.
The most popular plasticity material model is the Gurson [1] model, which was also modified by Tveergard [2-3]. The yield surface combines the von Mises plasticity with the hydrostatic part. One disadvantage of this model is that it considers always the pores to be spherical. P.Ponte Castaneda et al., [4-5] derived a general constitutive theory to model the behaviour and evolution in porous materials with developing deformation in three dimensions. The theory considers a random void distribution that during deformation can change size, shape and orientation. The voids can become ellipsoids, rotate, spin and be loaded in every direction. It is also advantageous that the model considers the change of the Young's modulus every time that the porosity level of the material changes. In this paper, this material model will be referred as the anisotropic material model.
The above two material models are selected to test in FE simulations. The GTN (Gurson-Tveergard-Needleman) model is implemented in many commercial FE softwares and is compatible with an implicit or explicit solver. The elastic-plastic anisotropic material model is implemented as a User MATerial (UMAT) model for ABAQUS [6] with the methodology that is proposed by Aravas and P.Ponte Castaneda [7].
The two material models were compared in uniaxial compression simulations to get an understanding of their behavior. The analysis was conducted with one element, a four-node axisymmetric, isoparametric element (CAX4), in ABAQUS [6] for both material models. The bar is compressed in the y direction driven by displacement. Figure 2 shows the resulting stress-strain relationship of the porous material with both material models. The initial density that is used for the simulations is 7.3 g/cm^3 and the Young's modulus is E= 160 GPa.

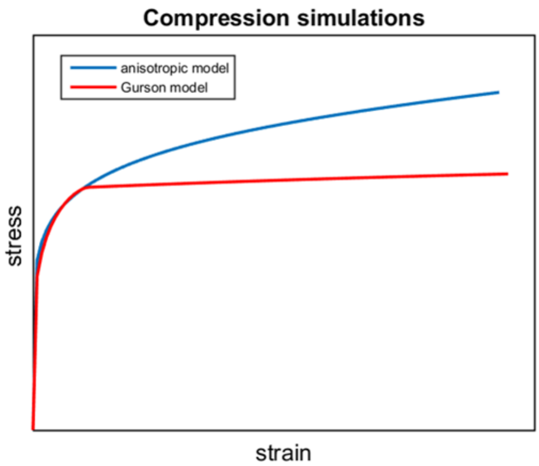
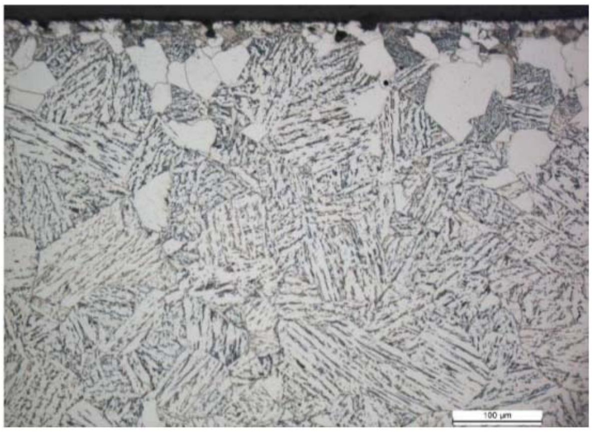


Figure 2 Comparison from the two material models in compression

The simulations show that the GTN model results in a linear behavior. On the other hand, the anisotropic model behaves in a more realistic way and continues to harden. It should be noted that since the orientation of the pores does not change, the hardening of the material depends only on the evolution of the porosity.

Experimental process and simulations

The input parameter for both material models is the stress strain relationship of the matrix material. For the GTN model, three influencing factors have to be determined experimentally in order to calibrate the behaviour of the material model. For both models, tensile tests are used to determine the stress strain relationship of the matrix material. The full dense material was produced by the HIP (Hot Isostatic Pressing) process. Astaloy® 85Mo + 0.3 % C + 0.7 % Lube E mix was pressed in the form of tensile test bars with a density of 7,4 g/cm^3. The specimens were sintered at 1120 ℃ in 90/10% N_2/H_2 for 30 minutes of Höganäs AB in Sweden. Figure 3 shows the microstructure that occurred after the HIP process and the stress-strain relationship from tensile tests. The same material and sintering conditions were used for all the experiments in this paper.



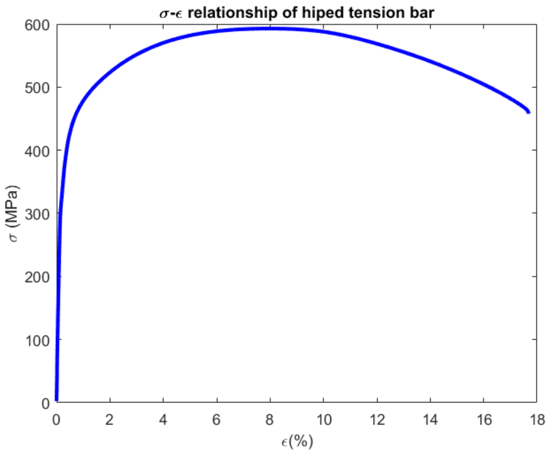
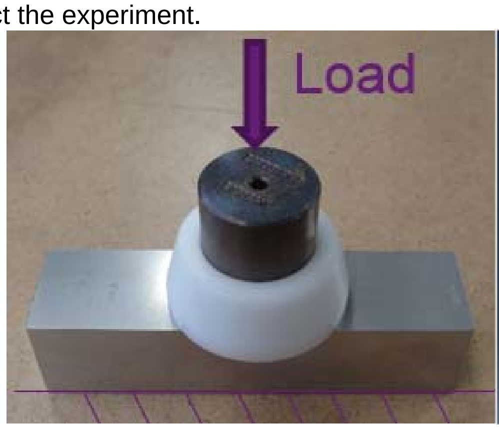


Figure 3. Microstructure and engineering stress/strain relationship from tensile strength test

The microstructure of the pore free material is bainitic and ferritic. The target after the HIP process is to obtain the same microstructure as the porous material that is used in the following experiments. The above stress-strain relationship was used as an input to the material model in simulations. In Figure 3, the material is presenting a behavior that can be wrongly interpreted as some softening. In reality the material does not soften; this behavior is due to local instability and necking during the tensile test.
The next step is to compare simulations with experimental results for both material models. The target is to gain a deeper understanding of the material behavior and the accuracy of the simulations that can be achieved. Furthermore, since the target is to model the gear rolling densification process, contact should be added between surfaces in multiple loading conditions to gain an understanding of how the material deforms plastically in contact pressure loading conditions. Moreover, with the indentation test one can investigate better the input parameters to the material model and tune them to achieve the best result in the loading sequence that is described below.These are the reasons why an indentation test is chosen, as a representative test.
The same material that was used for the tension bars is compacted in cuboids of 120*30*30 and with a density of 7.0 or 7.2 g/cm^3. Figure 4, at the left, shows the apparatus and the fixation method to conduct the experiment.



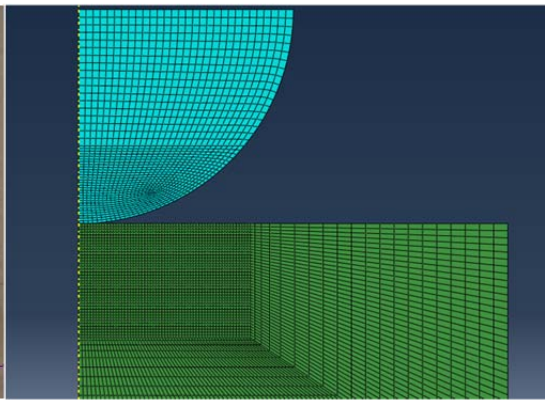


Figure 4 a, Apparatus and fixation for the indentation test at the left. FEM model of the indentation test at the right

The solid steel sphere that is used has a diameter of 15 mm and is a ball bearing part. This ensures high hardness and very good surface quality, to avoid phenomena such as high friction between the sphere and the cuboid. The high hardness of the sphere ensures that it will not deform plastically in these loading conditions. The sphere is fixed into a cylinder that allows applying load on the cylinder instead of on the sphere directly. Load is applied to the cylinder, the sphere presses and deforms plastically the cuboid. The load levels are three, first 5 kN then 10 kN on the same spot and finally 15 kN also on the same spot of the cuboid. The indentation on the cuboid was measured with a surface profiler machine.

Two contact surfaces are required to setup the FE model. The sphere is modelled as an elastic body and the cuboid is modelled with the above described plasticity material models. The Young's modulus for the elastic body is E=200 GPa and the poison's ratio v=0.3. The input parameters to the plasticity material models are the same as described above. For the elastic part of the PM component the Young's modulus is E=160 GPa and the Poison's ratio is v=0.27. Figure 4, at the right, shows the FE model and the mesh. The FE model is built as a 2D axisymmetric model because symmetry around y axis can be considered. The quarter of the sphere is force controlled vertically; the load is applied on top of the sphere and the sphere presses the cube, which is constrained in space. The coordinates from the deformed elements are exported and plotted together with the experimental results. 5840 axisymmetric, isoparametric linear quadrilateral elements (C4X4) were used for this analysis.
Finally, simulations were also conducted for the gear rolling densification process. Figure 5 shows the models schematically.

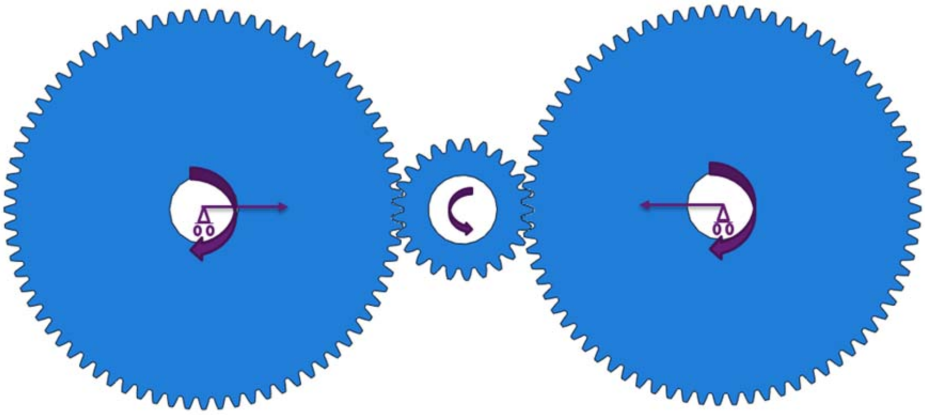


Figure 5. Schematic of the gear rolling densification process

Finally, cylindrical blanks with 100 mm in diameter and 7.3 g/cm^3 in density were pressed. A C-PT gear with stock was grinded from the pressed blanks. The gear was rolled and grinded in the facilities of Profiroll Technologies GMBH. After rolling, the gear was measured with a Coordinate Measurement Machine (CMM) to extract the coordinates of the deformed shape.

Results

The experimental and simulation results from the indentation test with both material models are plotted in a x-y coordinate system. Figure 6 and Figure 7 show the resulting profiles in two different densities. The loading condition of 5-10-15 kN was chosen to be shown due to the fact that in gear rolling densification the PM gear is densified many times. The loading condition of 5 kN showed a good result for the Gurson model but in 5-10 kN the anisotropic model was more accurate.

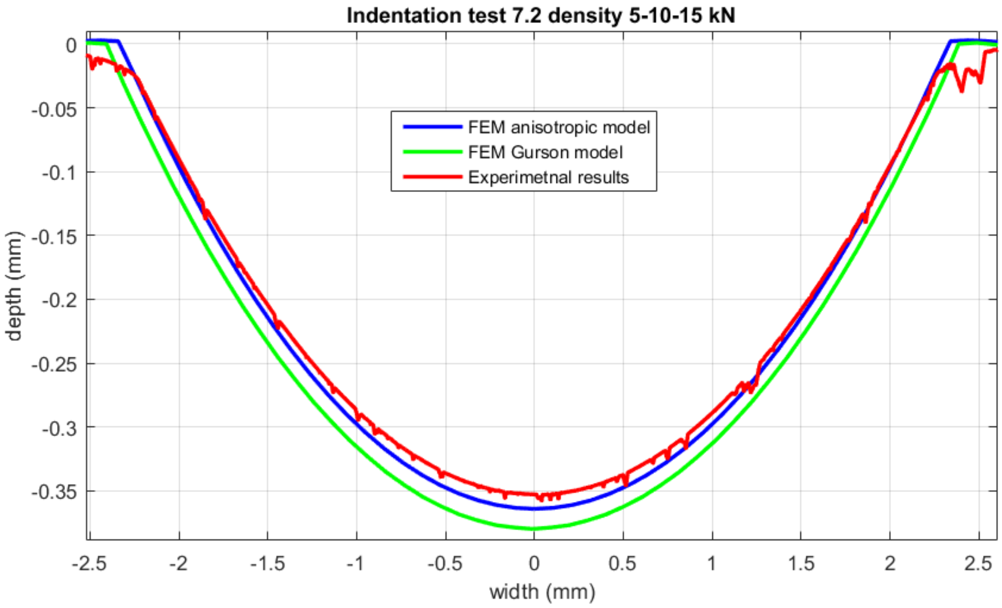


Figure 6. Experimental and simulation results for the indentation test in 7.2 g/cm^3 density

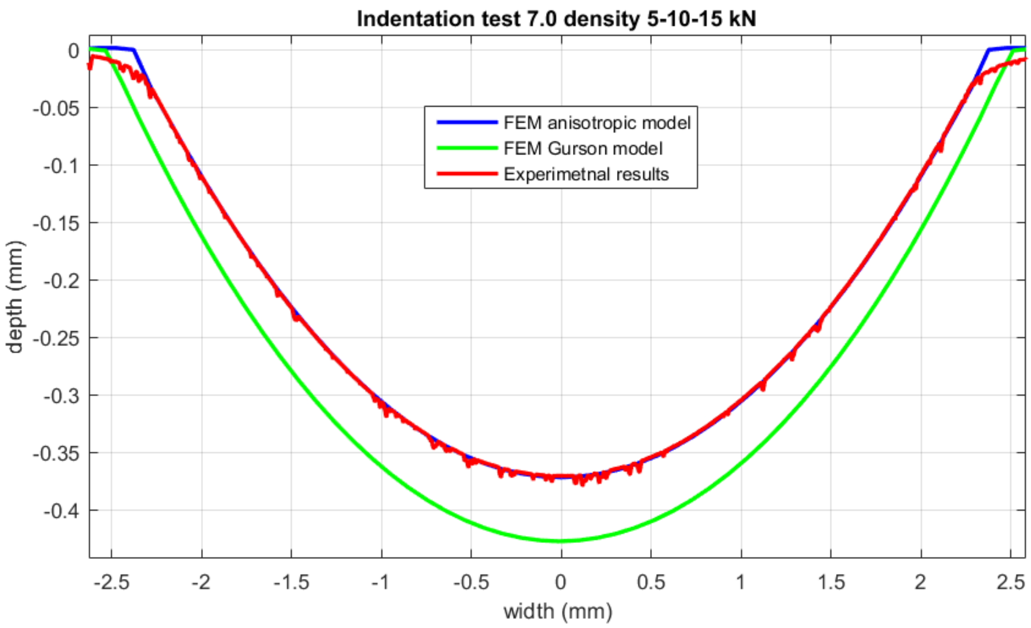


Figure 7.Experimental and simulation results for the indentation test on the cuboid with a density of 7.0 g/cm^3

The profile from simulations with the anisotropic material model correlates well with the experimental results. For both presented densities, the difference of the experimental and simulated profiles is 2-10 µm for the depth of the deformed profile, measured in the y-axis and 20-30 µm measured in the x-axis. The profile from simulations with the Gurson material model results in a bigger deformation for both densities. For both presented densities, the difference between the Gurson and the experimental result is 20-40 µm for the depth of the deformed profile, measured in the y-axis and 80-120 µm for the width measured in the x-axis. Some material flowed at the end of the identity in simulations with both material models, this was compensated for optical reasons. This phenomenon was not observed in experimental results.

The results show that Gurson model predicts a higher deformation than the real one. It should be noted that both models do not account for strain hardening.

A C-PT gear rolled to achieve a good involute profile and simulations in 2D, in plane strain condition conducted with the anisotropic material model. The tool is modelled as a rigid body; the gear is modelled with the anisotropic material model and by assuming initially spherical voids. The simulation follows the real rolling cycles from the experimental process. Figure 8 shows the resulting simulation and experimental profiles. The tip, pitch and base circles are plotted to provide a better overview of the involute profile.

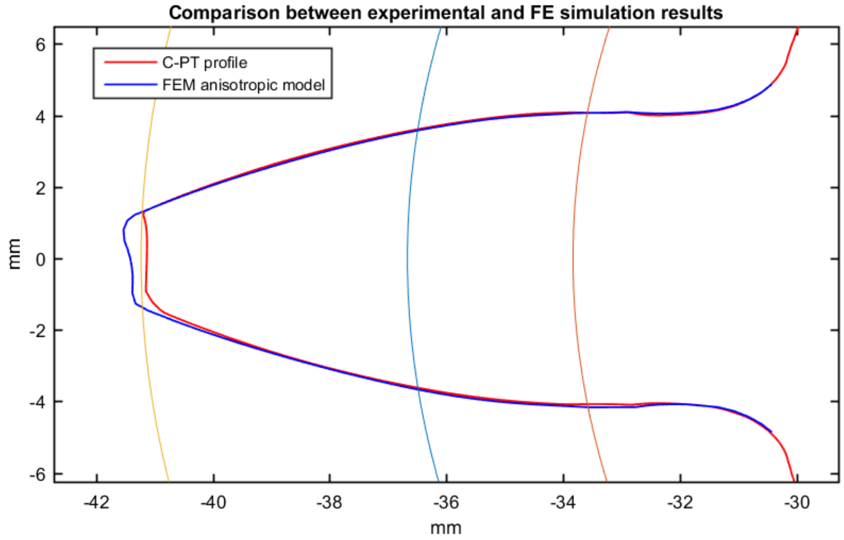


Figure 8. Comparison of the deformed profiles obtained from the experiment and FE simulation

The gear rolling simulation results correlate well with the experimental results. The accuracy on the involute is between 20-50 µm; it should be noted that the rolled gear has some level of inaccuracy since the C-PT gear is not the optimum design to be rolled. The simulation profile from the 2D FE model is more extended at the tip area than the real profile. This shows that many elements have deformed towards the tip area during the rolling simulation. It is expected that in a 3D simulation the elements will also deform in the z direction because the pores will deform in that direction forming ellipsoids and changing their orientation.

Conclusions

Two plasticity material models were used for comparison reasons to simulate the plastic behavior of a PM material at different density levels, the Gurson model and the anisotropic model. Results from both material models in uniaxial compression were compared to get an understanding off their behavior under simple loading conditions. The two material models were used to simulate an indentation experiment in samples with different densities and the results were compared. Finally, the anisotropic model was ran to simulate a gear rolling test, the simulation results of deformation were compared with the experimental results. The simulations showed:

- The anisotropic model behaves realistically in compression loading.
- The indentation test comparison showed that the anisotropic model behaves well in monotonic loading and gave very good results in samples with different density levels.
- The Gurson model gave an over densified profile at both density levels.
- The gear rolling simulation with the anisotropic material model correlated well with the experimental results for the involute profile.
- The tooth form that resulted from simulations is extended at the tip area in the 2D model in comparison to experimental results

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