A Parametric Study on PM Gear Rolling Densification Simulations Coupled with Experimental Results

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Abstract

PM gear rolling densification is a post-sintering process in which the porosity is closed at the surface and at some depth into the flank of the gear. It results in improved mechanical properties such as higher contact strength, but can also be used to improve tolerances. The optimization of the rolling process, the design of the tool geometry, the gear preform and the overall process is time consuming. Therefore, FE simulations are used to optimize the overall process and reduce the development time.

In previous research the simulations were shown to correlate well with experimental results both in terms of gear profile and densification. That investigation focused on gears of one density and rolled with one set of process parameters. In this article a sensitivity analysis will be presented. The same type of gear will be rolled with different parameters, and experimental gear and densification profiles will be compared with simulated results. The experimental accuracy and limitations of the simulations will then be critically examined.

Introduction

PM gears have been produced for many years and for different applications. The principle reason for this is the high productivity rate combined with low material consumption compared to semi-final machining.

The two main failure mechanisms of a gear are bending fatigue of the tooth root and contact fatigue of the flank. The porous nature of the sintered materials is a major factor concerning the strength of PM gears. Secondary operations such as rolling can be used to increase fatigue strength allowing PM gears to be used in automotive gearboxes and other applications with high demands.

As mentioned above, PM gear rolling densification is a post-sintering mechanical process. After rolling a PM gear the porosity is closed at the surface and below the flank to some tenths of a millimeter. This densification coupled with heat treatment has a positive influence upon fatigue strength. The process starts by placing the gear with added stock material between two tools that are free to move in two ways - the rotational and the translational in the horizontal direction. The gear with added stock material can only rotate. The tools rotate and press the gear at the same time until the optimum involute profile is formed and a good surface quality is achieved. Fig. 1 at the the left side shows the principle of gear rolling and at the right side shows the set-up of the tool-gear from inside Profiroll's machine.

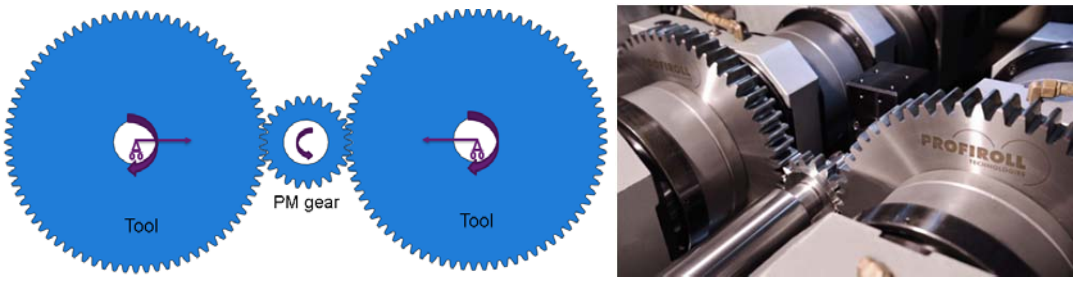


Fig. 1. Left. Boundary conditions of the tools and gear. Right. Photo from Profiroll's rolling machine.

Four phases can describe the rolling process and Fig. 2 shows a diagram with these phases presented schematically. The first phase is called the initial phase and its purpose is to ensure the tool and gear are in contact, from the start to A. The PM gear is then rolled and at the same time it is pressed by the tools, from A to B. This is the infeed phase. The tools then rotate with an opposite motion and remain at their final displacement from the infeed phase, from B to C in the diagram. This is the calibration phase. During the fourth phase the tools are moving linearly outside of the gear, from C to D in the diagram. This is the retracting phase.

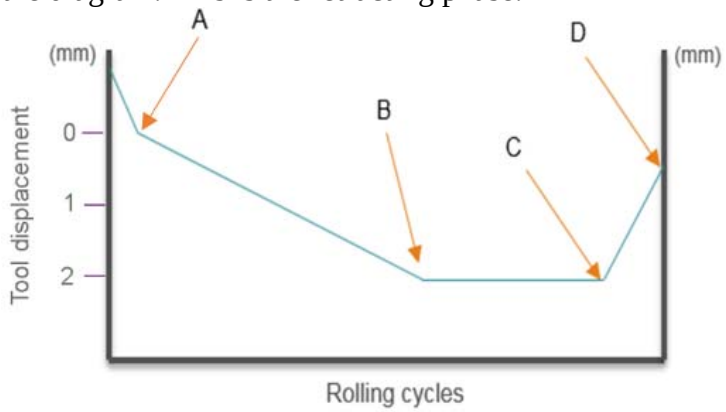


Fig. 2. Phases of the PM gear rolling process.

If the rolling results are improved it is possible to skip the hard finishing. To achieve this and reduce the overall development time, simulations[1,2,3,4,5] can be used as a tool to predict the tool design, the gear preform and the rolling process parameters. The purpose of this work is to investigate the accuracy of the simulations by comparing the simulation results with a series of experiments.

Description of the experimental process

In order to better understand accuracy, a series of simulations and experiments were conducted for a C-PT gear that is the same type of gear. C-PT gears are used to generate contact fatigue data with an FZG back-to-back test. Astaloy® + 0.2% C + 0.6% Lube E pucks were pressed at 6.9 and 7.2 g/cm^3 densities. The pucks were sintered at 1120 ℃ in 90/10% N_2/H_2 for 30 minutes. The pucks were then milled into C-PT gears with stock material at their flank by Profiroll. Table 1 presents the basic data of a C-PT gear.

Table 1. Data for the final geometry of the C-PT gear.

Number of teeth	z = 16
Module	m_n = 4.5 mm
Pressure angle	α = 20°
Face width	b = 14 mm

The gears were rolled with four different rolling process parameters. These parameters concern the penetration and rotational direction of the tool in respect to the gear. Table 2 presents these parameters. The rolling process was designed to achieve the optimum densification on the flank. This rolling parameter is called B1 for the gear with 6.9 g/cm^3 density and B2 for the gear with 7.2 density. C1 and C2 have been used to describe the same process as B1 and B2 by excluding the calibration phase in both density levels. In A1 and A2 the displacement of the tool is 0.2 mm less into the gear in respect to C1 and C2. In D1 and D2 the displacement of the tool is 0.1 mm more into the gear in respect to C1 and C2.

Table 2. Rolling parameters for the CP-T gear at two density levels for penetration of the tools into the gear.

Density (g/cm^3)	**Penetration of the tool into the gear**			
6.9	**A1**: 0.2 mm less	**B1**: Optimum	**C1**: Optimum, no reverse rolling	**D1**: 0.1 mm more
7.2	**A2**: 0.2 mm less	**B2**: Optimum	**C2**: Optimum, no reverse rolling	**D2**: 0.1 mm more

Measurements

After the gears were rolled they were measured in a CMM (Coordinate Measuring Machine) to identify the tolerances and extract the coordinates from the teeth geometry of the densified gears. The tolerance measurements were used to identify accuracy of the deformed shape for different teeth from the same gear. Then one can specify what level of inaccuracy is acceptable in comparison to the simulations. The coordinates were extracted and plotted after rolling the gear. These results will be used to directly compare the deformed shape of the tooth from the experiments and simulations.

One of the principal aims of this research is to identify the repeatability of the experiments and gain an understanding of how accurate the simulations need to be. Then one can understand if the simulation results are acceptable or if improvements should be made, take the next step and design the rolling process based on the simulations. It is also critical to understand the source of the inaccuracies for the experimental results. For this reason an error chain was identified and is presented qualitatively in Fig. 3.

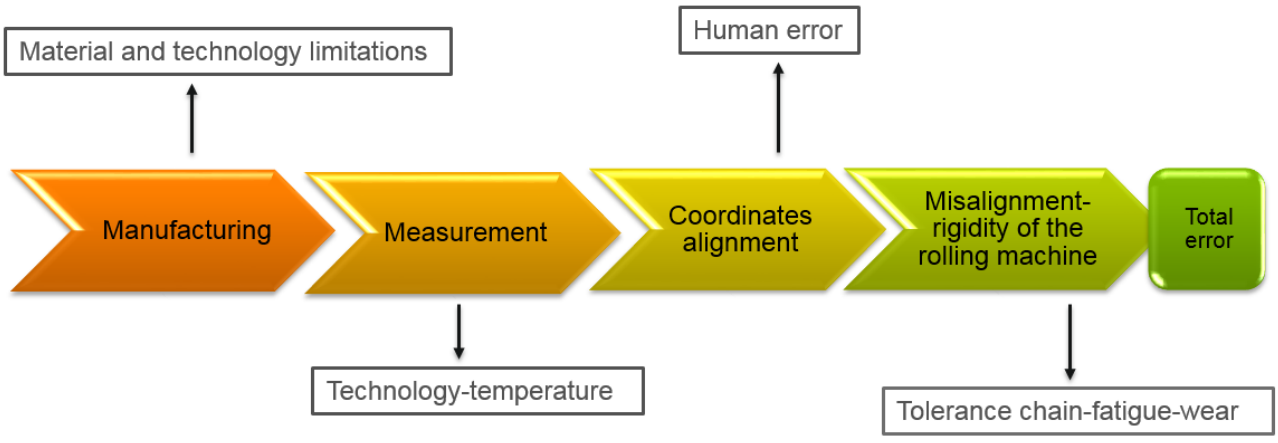


Fig. 3. Qualitative representation of the error chain in gear rolling.

Quantitative research can lead to incorrect conclusions and this is due to previous experience showing that gears with a module from 1.5 to 3 provide better accuracy for gears with bigger modules. For the CP-T gear an accuracy level of ±30 μm was identified as acceptable. This value was obtained by comparing the profile deviation between the measured teeth in all the densification experiments. Moreover, the difference between the theoretical root circle and the roots of the

densified gears after alignment was also taken into account. Using these one can identify errors from the first three sources of the error chain. The error from the rolling machine due to wear and misalignment can only be estimated and this is the reason why it is considered a negligible value in this case. Furthermore, the densification at the pitch point at the centre along the face width in both flanks, and on different teeth was measured using optical microscopy. In Fig. 4 from left to right one can see the tolerance measurement and the densification profile.

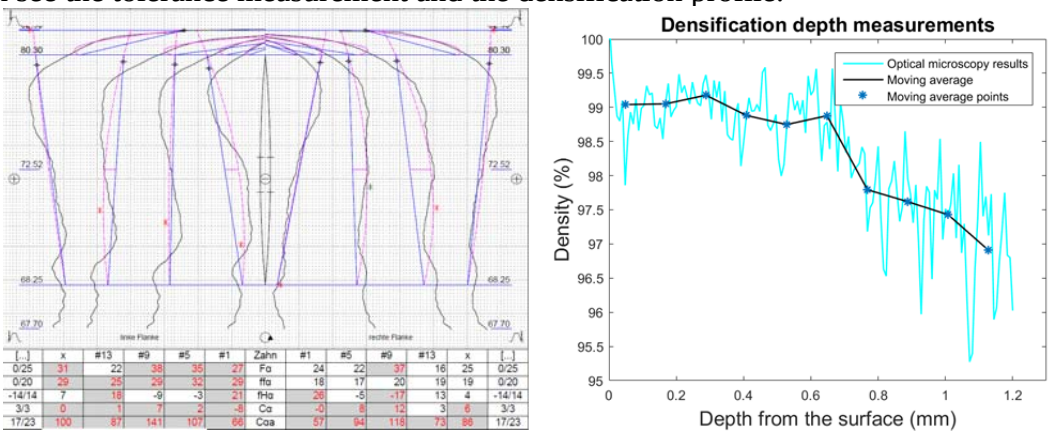


Fig. 4. Left. Tolerance measurements. Right. Densification measurements from optical microscopy.

The densification measurements were made of several teeth to obtain reliable results. This was to check the repeatability of the densification depth at the same gear on different teeth. It was identified after the first measurements showed that the scattering was significant and that in this form one cannot extract useful conclusions when compared with the simulation results. Therefore, the Moving Average method [6] was used to transform the scattered values into an average line.

Simulations

A model was built in the Abaqus FE software[7] to create simulations. These were conducted using the rolling process described in previous work[5,8] and using plane strain conditions so there is no strain in the third direction. The tool was modelled using an elastic material and the gear using an elastic-plastic material model so both are flexible. The model that was used for the elastic-plastic behaviour of the gear was developed by Ponte Castaneda and co-workers[9,10,11,12] . This considers the evolution of the porosity and the development of anisotropy due to the change of shape, size and the orientation of the pores during deformation. The pores are randomly distributed and can have an initial spherical or ellipsoid shape. The material model was implemented in Abaqus using an UMAT (User Material) code with an implicit scheme. The output from the simulations show the porosity for every element that can be plotted during post-processing in Abaqus. In addition, it shows the plastic deformation that can be extracted from the coordinates of the interesting node sets defined during pre-processing.

Results and discussion

Simulations were conducted for all the experimental trials. According to Table 2 there are four rolling parameters at two densities. The densification and deformation levels from every experimental result is presented at the pitch point and inside the surface of the tooth for both density levels.

Deformation results in both density levels

Fig. 5 shows the comparison between the experimental and simulation results in deformation at one tooth. It was selected to show the whole tooth to gain an understanding of the overall accuracy of the simulations at both densities.

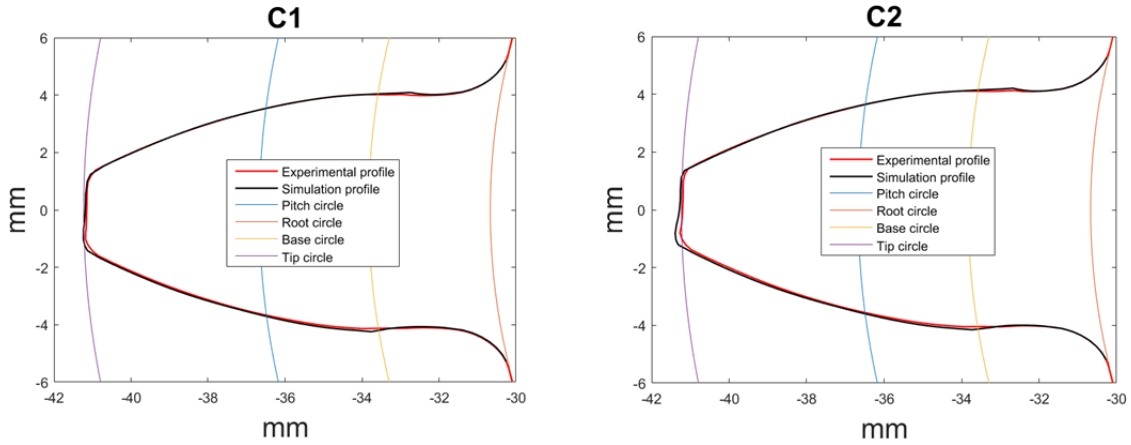


Fig. 5. Deformation results for the optimum process parameters at two density levels.

Fig. 6 shows the deformation at the tip and the experimental results from the simulation at one density level with three rolling parameters. It can be observed that there is a flow of material to the tip in all three situations. This result can be attributed to the fact that the simulation ran with a 2D model in plane strain, therefore there is no material flow in the third direction. On the other hand, it is also observed that there is some flow of the material in the third direction on rolled gears. This phenomenon should be highlighted so future simulations can be improved to become more realistic. The difference at the tip is between 0.1-0.4 mm. It is observed that the flow of the material to the tip increases with more penetration of the tool. This is logical if we consider that the pores are closing and some of the material needs to flow in one direction. Since we are conducting 2D simulations, the material will flow along the x-axis to the tip.

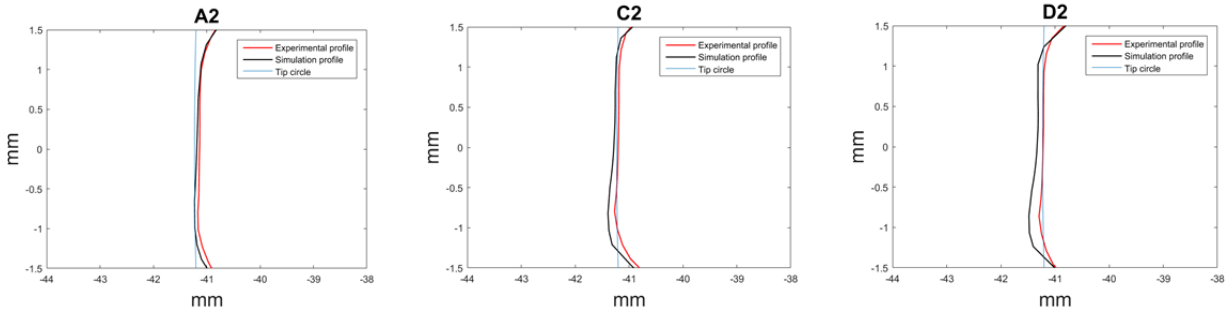


Fig. 6. Comparison in deformation between experimental and simulation results at the tip in 7.2 g/cm^3.

Fig. 7 shows the deviation of the simulation for the experimental results at the pitch point.

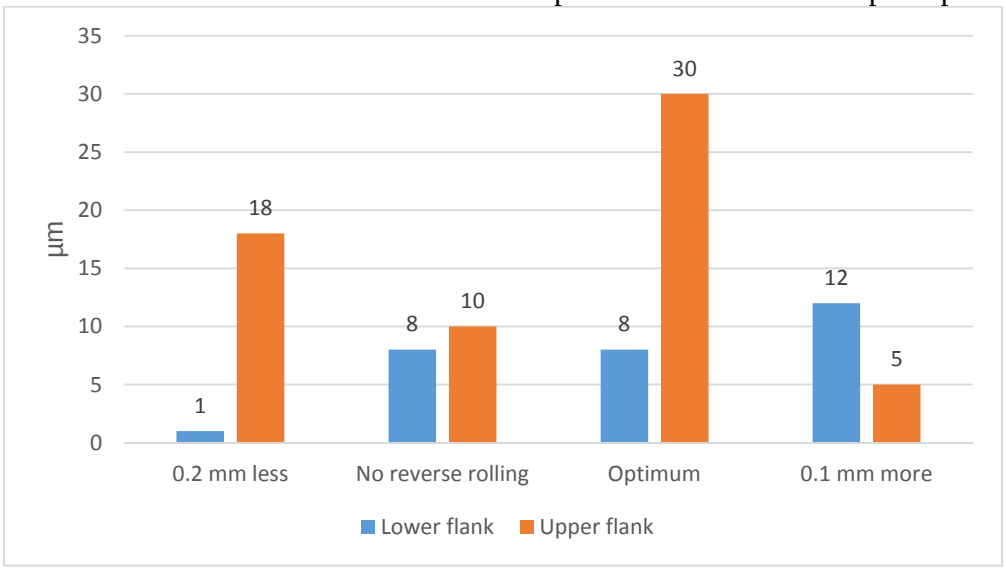


Fig. 7. Deviation of the simulation results with the experimental results measured at the pitch point for deformation.

The simulation results are quite accurate for the measurements. It should also be noted that the deviation from the measurements is similar across the whole length of the flank. If we see the resulting deformation of the entire tooth we can conclude that the results at the flank are very good but at the tip we have some significant differences. This difference will influence the design phase since the preform of the gear is always designed to take into account the flow of the material to the tip. Usually one designs the preform with the tip of the tooth lower for the targeted tip circle. Therefore it is critical to have accurate simulation results at the flank and at the tip area.

Fig. 8 shows the deformation at the tip from the simulation and the experimental results for 6.9 g/cm^3 density with three rolling parameters. In comparison to Fig. 6 the results show that at a higher density the flow of the material at the tip is less. The difference in this density is between 0.1-0.2 mm. There is certainly an influence from the designated porosity upon the material model that is used in simulations on the deformation results.

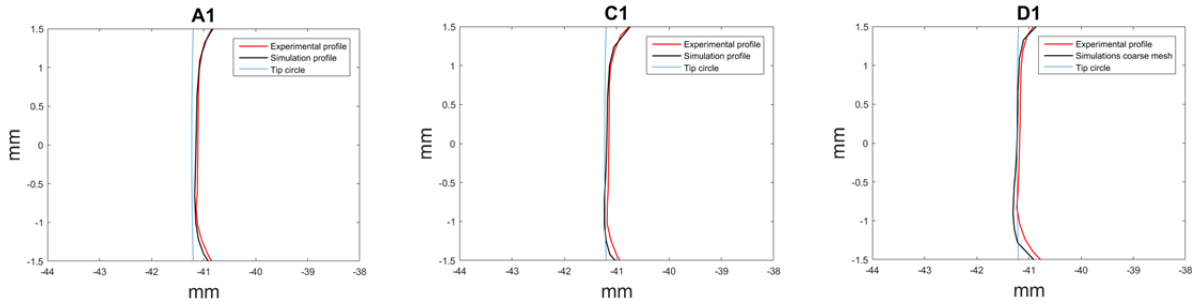


Fig. 8 Comparison in deformation between experimental and simulation results at the tip in 6.9 g/cm^3.

Fig. 9. shows the deviation of the simulation for the experimental results at the pitch point for the 6.9 g/cm^3 density.

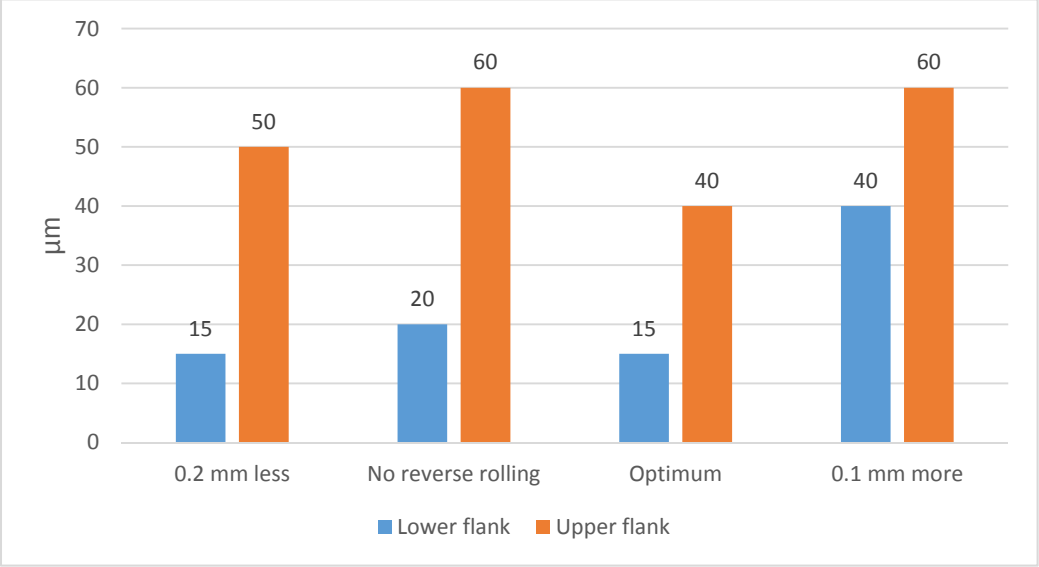


Fig. 9. Deviation of the simulation and measured experimental results at the pitch point for deformation.

The results at the flank from the 6.9 g/cm^3 density are less accurate, which is clearly seen if one compares the results in Fig. 7 and Fig. 9. On the other hand, at the tip the results are more accurate for the 6.9 g/cm^3 density, as can be observed in Fig. 6 and Fig. 8. One of the reasons for this is the porosity level applied to the material model because more porosity allows less material to flow to the tip. Moreover, the initial shape for the pores in all cases is ellipsoid and this allows less material to flow because the pores will close at an earlier densification stage in respect to the spherical pores. For simulations it is clear that porosity is a significant influence upon the deformation results.

Densification results for both density levels

Fig. 10 at the left side shows the densification of one tooth from the densified gear at the density of 7.2 g/cm^3 and rolled with the optimum process parameters. The right side shows the simulation

results. The light grey area has a percentage of porosity corresponding to 7.2 g/cm^3 density and the dark grey area is the area with no porosity. Optically, the shape and the densification between the measured teeth and the simulated teeth matches very well. The same applies for the other results.

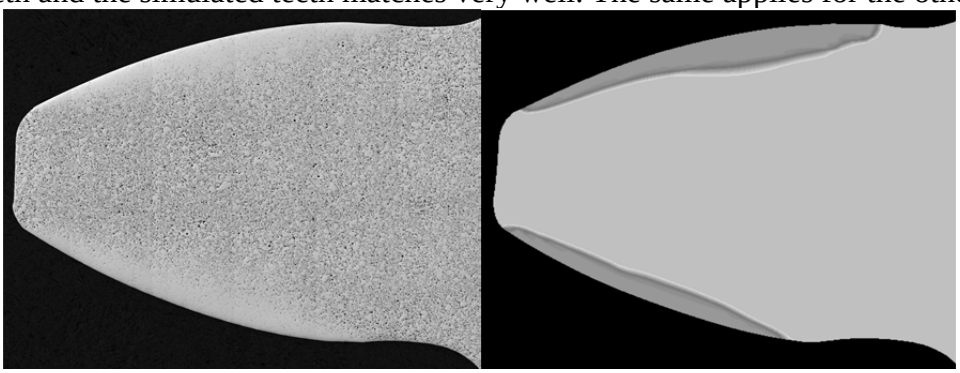


Fig. 10. Left picture from optical microscopy, right simulations with densified area, dark grey area.

An optical representation of the results as the one above gives a qualitative result but cannot provide a quantitative comparison between experiments and simulations. Therefore, the densification profile was investigated at the pitch point and inside the surface at some depth in both flanks for every experimental run. The methodology is also described in the measurements subparagraph above. The porosity level from the simulations at the pitch point and inside the surface has been exported and plotted with the experimental results. Fig. 11 shows the densification results from the rolled gears at 7.2 g/cm^3 density at the pitch point and for the lower flank.

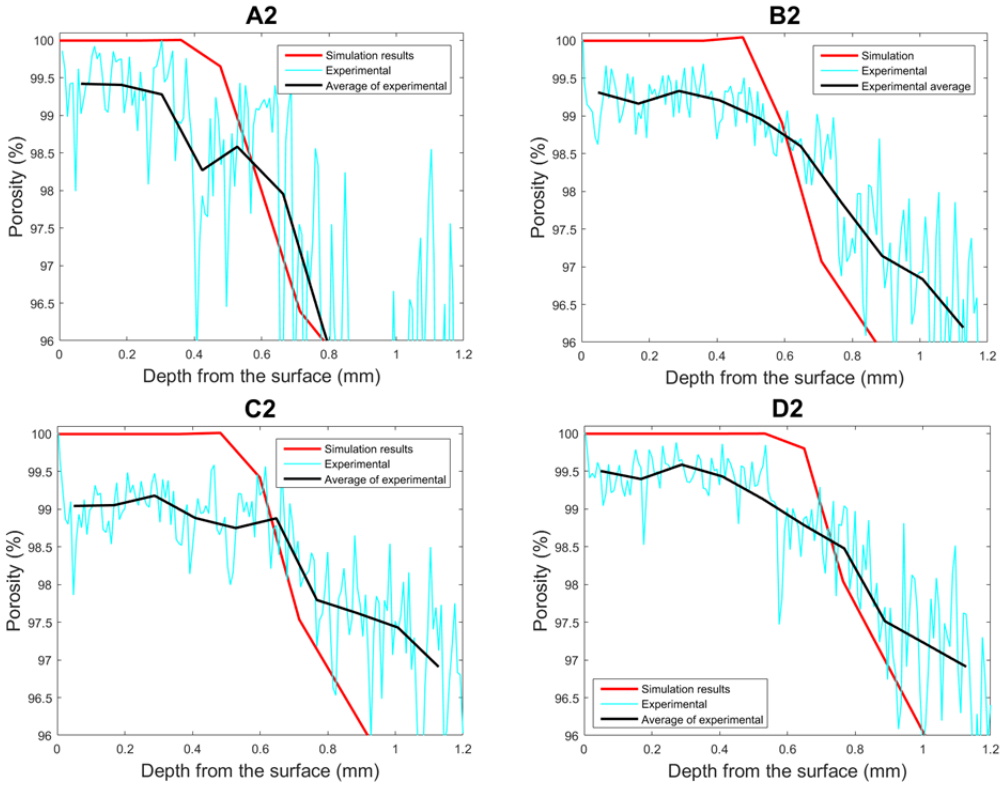


Fig. 11. Porosity level for experimental and simulation results at the pitch point from the lower flank with 7.2 g/cm^3 density.

It can be clearly seen that the simulation and experimental results match well. Even though the scatter from the measurements is significant, a good representation has been achieved with the MA method. Fig. 12 shows the densification results from the rolled gears at 6.9 g/cm^3 density at the pitch point and for the lower flank. By comparing the results between the two densities one can see that the level of accuracy is good. Even though the measurements were repeated for more than one tooth, the scatter is big for both density levels. Therefore, they cannot assess the accuracy of the

simulations with confidence. One can see in Fig. 11 and the A1 rolling parameter, at the upper left that the scatter is very big.

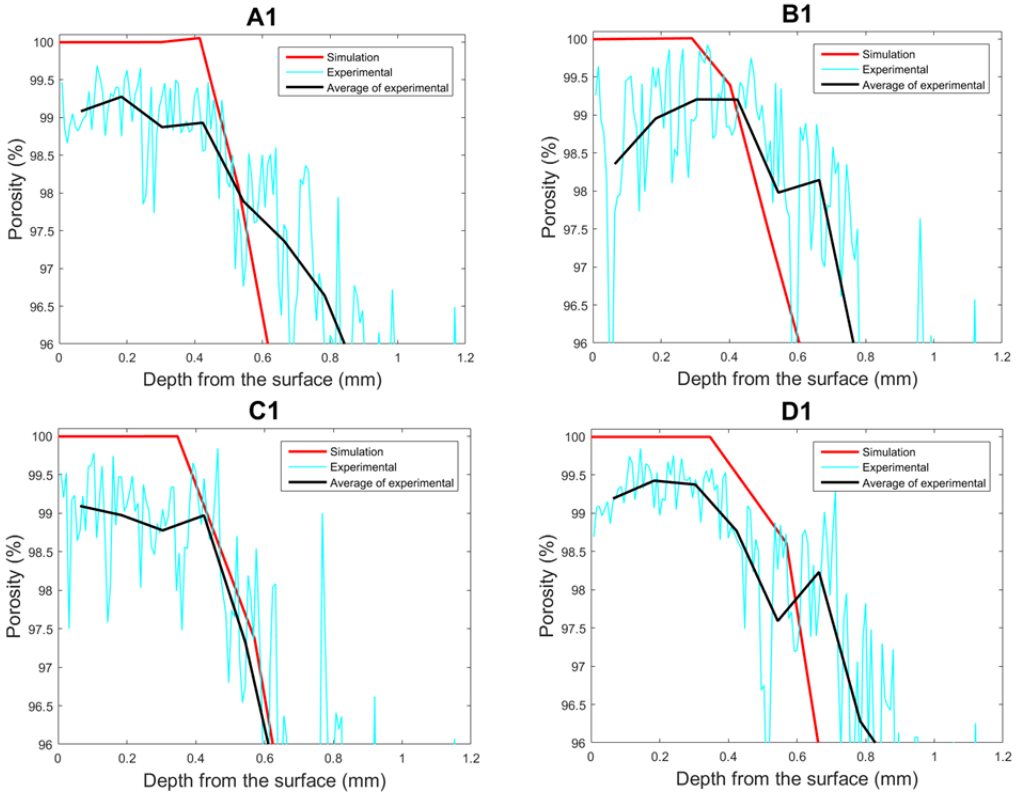


Fig. 12. Porosity level for experimental and simulation results at the pitch point from the lower flank with 6.9 g/cm^3 density

It should also be noted that some measurements were repeated on the same gear on different teeth to compare the scatter and accuracy. Overall, the experimental results are consistently the same but with slightly different scatter and porosity. It can be said that the resulting densification profile depends on the size of the pores on the measured surface. The software of the microscope detects the porosity automatically. Several images are taken, and each has a length of some micrometers. The light area in an image is the pore free area and the porosity is identified by the dark area which is material free on the plane and pore. The software calculates the percentage of porosity from this image. Then all the spots are plotted together and create the densification profile. It is clear that the densification profile depends on the pore size and since the pores are randomly distributed with unequal size it is inevitable to see scatter on the measurements. It should be emphasised that several measurements were taken to optimize the length of the image and provide a reliable representation of the result.

Conclusions

The principle reason for conducting this research was to identify the accuracy of the simulations and their limitations in a series of experiments. By using the results one can begin to model the PM gear rolling densification process through simulations, thereby reducing the development time and cost. The time and cost can also be reduced by limiting the number of experimental trials and avoiding repeated tool geometry and gear preform adjustments. The conclusions of this work can be seen below in bullet form.

- The error chain contributed significantly to identifying the sources of inaccuracy for the experimental results. It can also be used as a tool for improving the overall process.
- The deviation of the C-PT gear flank is ±30 µm and this result was achieved by comparing the profile deviation of different teeth on the same gear.

- The deformation accuracy from the the 7.2 g/cm^3 density simulation is between 1-12 μm for the lower flank and 5-30 μm for the upper flank at the pitch point. At several points measured on the flank the deformation accuracy was found to be within this range.
- The deformation accuracy from the 6.9 g/cm^3 density simulation is between 15-40 μm for the lower flank and 40-60 μm for the upper flank at the pitch point. At several points measured on the flank the deformation accuracy was found to be within this range.
- The densification profile from the simulations for the 7.2 g/cm^3 density was an indicator of what followed with the experimental results.
- The densification profile from the simulation for the 6.9 g/cm^3 density was an indicator of what followed with the experimental results.
- The scatter of the measurements cannot provide a clear picture of the densification profile so it is not possible to evaluate how accurate the simulation results are. It is clear that the simulations provide a good indication for the densification profile.
- From the experimental data it can be seen that there is a difference in deformation and densification between the upper and lower flank. This difference can also be seen in the simulation results and shows that the computer model is sensitive to these changes.

References

[1] Kraft T., Y. B. A., R. H., Finite element modelling of PM surface densification process, Powder Metallurgy Vol.51 No.3 (2008), pp. 211-216.

[2] Kauffmann Philipp, F. K., T. S.: Fundamental study of surface densification of PM gears by rolling using FE analysis, German Academic Society for Production Engineering (WGP), International Journal of Mechanical and Production Engineering Research and Development. (2007) pp. 113–120.

[3] Roshan Kumar D., Andrew Denise V. Krishna Kumar R., Simulation of Surface Densification of PM Gears, SAE Technical Paper 1999-01-0334 (1999), DOI: 10.4271/1999-01-0334.

[4] H. Cho, Y. Shin, S. W. Hwang, J. H. G., J. H. B., J. H. K., S. T. C., S. H. C., S. J. P., Finite element simulation of PM gear rolling process, Institute of Materials, Minerals and Mining, Powder Mettalurgy 2015 Vol.58 No.3, DOI 10.1179/1743290115Y.0000000011

[5] V. Angelopoulos, Improved PM gear rolling simulations using advanced material modelling, Journal of Advanced Mechanical Design, Systems, and Manufacturing Vol.11, No6, 2017, DOI: 10.1299/jamdsm.2017jamdsm000x.

[6] Information on https://en.wikipedia.org/wiki/Moving_average

[7] ABAQUS , Dassault Systèmes, Providence, RI, USA.

[8] V. Angelopoulos, M. Hirsch, PM gear rolling simulations using advanced plasticity material model and improved initial conditions, proceedings of VDI conference on gear production 2017, Munich

[9] P. Ponte Castaneda, M. Zaidman, Constitutive models for porous materials with evolving microstructure, J. Mech. Phys. Solids, Vol. 42, No 9, pp.1459-1497, 1994

[10] M. Kailasam, P. Ponte Castaneda, A general constitutive theory for linear and nonlinear particulate media with microstructure evolution, J. Mech. Phys. Solids, Vol. 46, No3, pp. 427-465, 1998

[11] Kailasam M., Ponte Castaneda P., Willis J.R., The effect of particle size, shape, distribution and their evolution on the constitutive response of nonlinearly viscous composites – I. Theory, Philosophical Transactions of the Royal Society of a Mathematical, Physical and Engineering Scienses, vol. 355, Issue 1730 (1997), pp.1835–1852, DOI: 10.1098/rsta.1997.0092.

[12] N. Aravas, P. Ponte Castaneda, Numerical methods for porous metals with deformation induced anisotropy, Comput. Methods Appl. Mech. Engrg, Vol. 193, pp.3767-3805, 2004