Investigation of Gear Surface Topography and Deviations in Gear Skiving Through Advanced CAD Modeling–Based Simulation

Nikolaos Tapoglou

Introduction

Manufacturing high-precision gears has been a key requirement in the automotive, aerospace and wind turbine industries. The volume of gears manufactured is ever-increasing and is expected to reach new limits owing to the drive towards electrification and sustainability. In the aerospace industry, a series of target key performance indicators (KPIs) need to be reached if industry is to meet its sustainability goals (Refs. 1–2). Based on goals set down by the Aerospace Technology Institute that includes the reduction of noise and emissions levels by up to 65% and 90% respectively. The use of high-efficiency gearboxes is crucial for reaching these targets. Looking at the manufacturing processes involved in machining such gears, gear hobbing and gear skiving are the prime candidates for achieving both the throughput and the quality required for such applications. Gear skiving in particular has been in the spotlight of research in this sector owing to the reduced cycle time and the capability to process internal and external gears. The history of the process is well documented and starts in the 18th century (Ref. 3) and is followed by a considerable hiatus during which the advances in machine tool manufacturing made the realization of the process on an industrial scale possible. In recent years, industrial and academic research programs have been focusing on gear skiving processes, including modeling, theoretical and experimental approaches in the study and optimization of this manufacturing process. The research presented in this paper extends the work done on CAD-based simulation approaches with an investigation of the surface topography of gears produced through gear skiving and the investigation of the cutting tool characteristics on the geometry of the produced gear. The study is complemented with the investigation of the cutting forces required in the machining process.

State of the Art

Traditionally, the understanding and optimization of manufacturing processes have been realized with extensive experimental campaigns which result in high operational costs and downtime of manufacturing equipment. Recently, simulation models and digital twins of manufacturing processes are used to increase the understanding of the cutting process and support the decision-making and the selection of the optimal process parameters. Simulation models increase the understanding of a machining process without the cost associated with machining trials. Models can be categorized based on the scale (macro, meso, and micro level) and the method used in the simulation of the process. Finite element, analytical and numerical models have been presented by researchers to investigate the cutting forces, surface quality, and microstructure of the simulated manufacturing process (Refs. 4–8). A review of the dominant simulation approaches used in this domain has been presented by Altintas et al. (Ref. 4) outlining the advantages of each method.

Like more traditional processes, in gear manufacturing a series of models have been developed in order to optimize the cutting processes and predict the developed cutting forces and the gear topography (Refs. 9–15). Since most the gear manufacturing processes have a complex kinematic chain, the simulation models can be a crucial tool in the optimization of the cutting processes in a cost-effective fashion as the results of the cutting process are influenced by a series of parameters. Looking in gear skiving, analytical, experimental, and CAD-based models have been developed to understand the development of cutting forces, the chip geometry and to a lesser extent the quality of the final gear (Refs. 16–17).

The research group of Guo et al. (Refs. 18–21) investigated the cutting mechanism of gear skiving using mathematical modelling with an emphasis on the effect of pose errors on the final gear quality and the design of the tool geometry. The design of cutting tools profiles for machining gears through gear skiving and the design of the machining method on six axis machine tools was the focus of Tsai (Refs. 22–23).

The development of dexel-based models is another contemporary research theme, where researchers have modeled the process using double or triple dexel-based models to predict the gear geometry and the cutting forces of the process (Refs. 24–25). The use of mathematically based models embedded in software has been also presented by Kang et al. (Ref. 26) who presented such a model and embedded the kinematics in Vericut to extract information on the gear characteristics. The work of Jansen (Ref. 27) focused on increasing performance and improving the accuracy of internal gears manufactured through gear skiving. Part of the work he performed also looked at the calculation and measurement of cutting forces.

The remainder of the paper is organized as follows: "Gear Skiving" presents the kinematics of the gear skiving process. The simulative approach developed is presented in "Simulation Model," along with details of the cutting force calculation algorithm. "Simulation Validation" describes the results obtained by the model and the validation of the results with experimental ones. "Investigation of Gear Profile Surface Topography" presents the investigation of the topography characteristics of a skived gear. Finally, "Conclusions" contains summary and ending remarks.

Gear Skiving

The complex kinematics of gear skiving allows for the increased processing speed that it can offer due to the continuous generating nature of the process. The main process of kinematics is presented in Figure 1. The tool is traditionally positioned at an inclined position with respect to the axis of the gear, this inclination provides the cutter with the required cutting speed to machine the gear gap. In the case of external gear, the rotation of the cutting tool is opposite to the one of the work gear whereas for internal gears the rotation of the tool is in the same direction as the one of the work gear. Figure 2 presents the cutting velocities involved in the process, visible in the figure is also the side rake angle which plays a crucial role in the chip formation process. The two rolling velocities of the two gears must be precisely tuned for the cutting tool and the work gear to be in mesh. Due to the inclination angle mentioned above, an additional velocity v_c exists which is the cutting velocity of the process.

The kinematics of the process can be influenced by a series of parameters that in turn affect the geometry of the final work gear, the geometry of the chip, and the final gear quality characteristics. Table 1 summarizes the parameters that can be altered during the process. Taking as an example the side rake angle (τ), an increased side rake angle leads to a different approach of the cutting edge on the machined gear gap and allows for the cutting forces to be directed across the axis of the gear thus promoting the stability of the process. Although the increase of the side rake angle does not alter the chip geometry to a great degree, the approach of the tool leads to a change in the cross-sectional area of the chip.

Simulation Model

An accurate model is a key development that would enable an increased understanding of the cutting process, the cutting forces and the final gear topography and gear quality. The development of a simulation model must take advantage of the latest technology in computational geometries and CAD platforms. As such the developed simulation package, presented in this research, was based on a state-of-the-art CAD package that allows the exploitation of the most up-to-date computer modeling platform. The model developed, named *Skive3D*, is embedded in a CAD environment directing

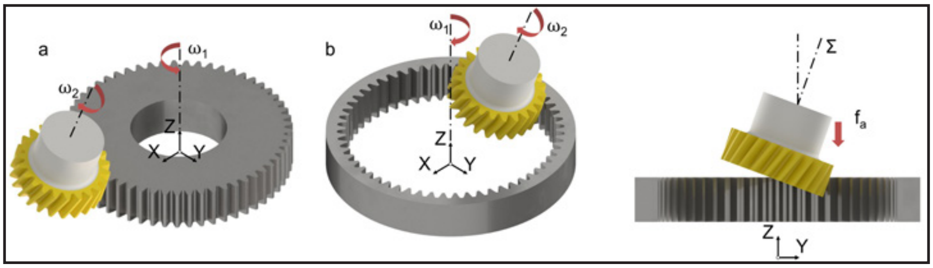

Figure 1 Gear skiving process kinematics for internal (b) and external gears (a).

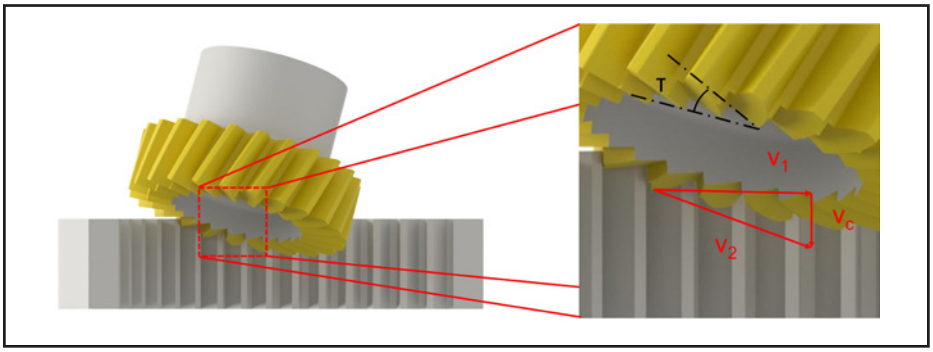

Figure 2 Cutting velocities during gear skiving (v_1 rotation of the work gear, v_2 rotation of the tool, v_c resulting cutting speed).

Table 1 Gear skiving parameters

Cutting Tool	Process Parameters	Work Gear
Helix angle (h_{at})	Cutting speed (v_c)	Helix angle (h_{ag})
Primary rake angle (γ)	Axial feed (f_a)	Pressure angle (α_n)
Side rake angle (τ)	Depth of cut (a_p)	Module (m_n)
Number of teeth (z_t)		Number of teeth (z_g)

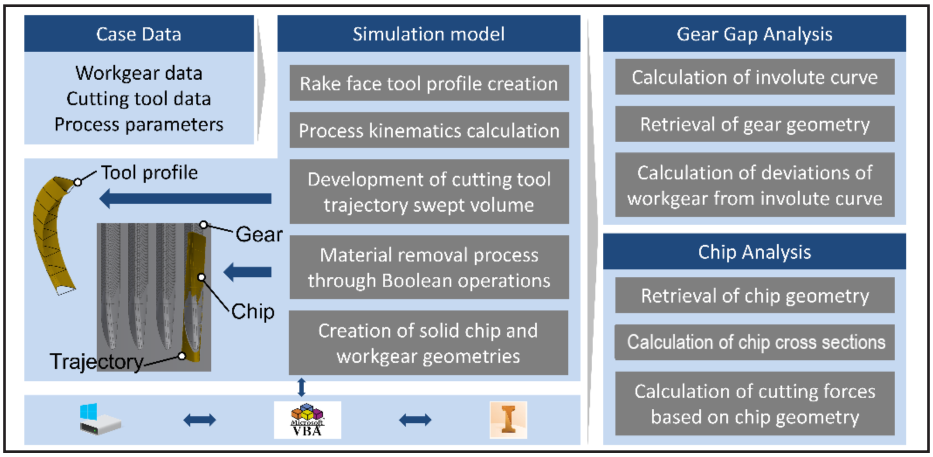

Figure 3 Skive3D flowchart.

commands on the kernel of the software for an increased simulation speed. Figure 3 presents a flow diagram of the information flow of the *Skive3D* model.

As is presented in the figure the initiating step is the input of the simulation data in the simulation model. The data is interpreted by the algorithm which in turn initiates a series of design functions responsible for the creation of the cutting tool profile and the development of a solid model that represents the tool profile trajectory during the cutting motion. Only revolving positions that contribute to the cutting action are created to achieve a lean approach and increase the density of data where they are required. By introducing a series of tool profiles throughout the tooth trajectory, thus ensuring the posture and the shape of the tool, the algorithm can generate high accuracy results. The results of the model are generated through the calculation of the intersection of the toolpath with the respective gear geometry and are stored as 3D solid parts. The results can be further analyzed to extract key data on the cutting process. Analysis of the chip geometry will produce an estimation of the cutting forces during the cutting process whereas the analysis of the flank geometries can provide key data on the resulting gear quality.

In more detail, the cutting force algorithm uses the Kienzle Victor (Ref. 28) equations to estimate the cutting forces from the nondeformed chip geometry characteristics. During the calculations, the ideal tool geometry is considered and any tool wear or defects in the tool geometry are not taken into consideration. As presented in Figure 4, the algorithm of the *Skive3D* model automatically extracts the chip cross-section in all the successive rake face positions. These positions are named revolving positions and are numbered sequentially along the cutting direction. In the top right side of Figure 4, a small subset of these revolving positions is presented. For each one of the cross-sections, it segments the chip geometry in elementary areas in which the Kienzle Victor model can be applied. The resulting forces are subsequently added up and transformed into the relevant coordinate system. For illustration purposes, the cutting force in the Z direction is presented in Figure 4.

The analysis of the flanks is based on the solid geometry of the gear after all the simulation code has been executed. The solid gear geometry includes the machining mark and any form errors due to the cutting tool profile. Systematic misalignment that affects the tool profile, such as run out, tool angle errors or tool wear, can also be included in the model. The algorithm of *Skive3D* can calculate lead and profile deviations. The first step is the creation of the designed involute curve based on the geometrical characteristics of the gear. This curve is used to find the deviations between the ideal and

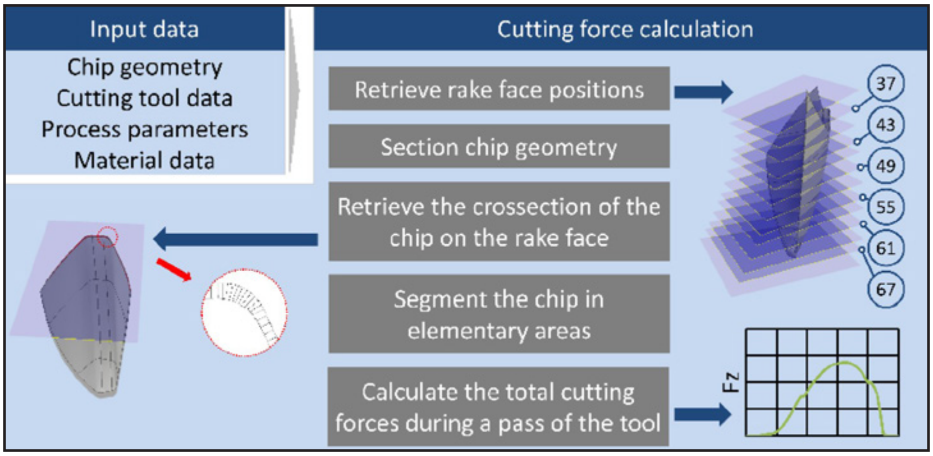

Figure 4 Cutting force calculation algorithm.

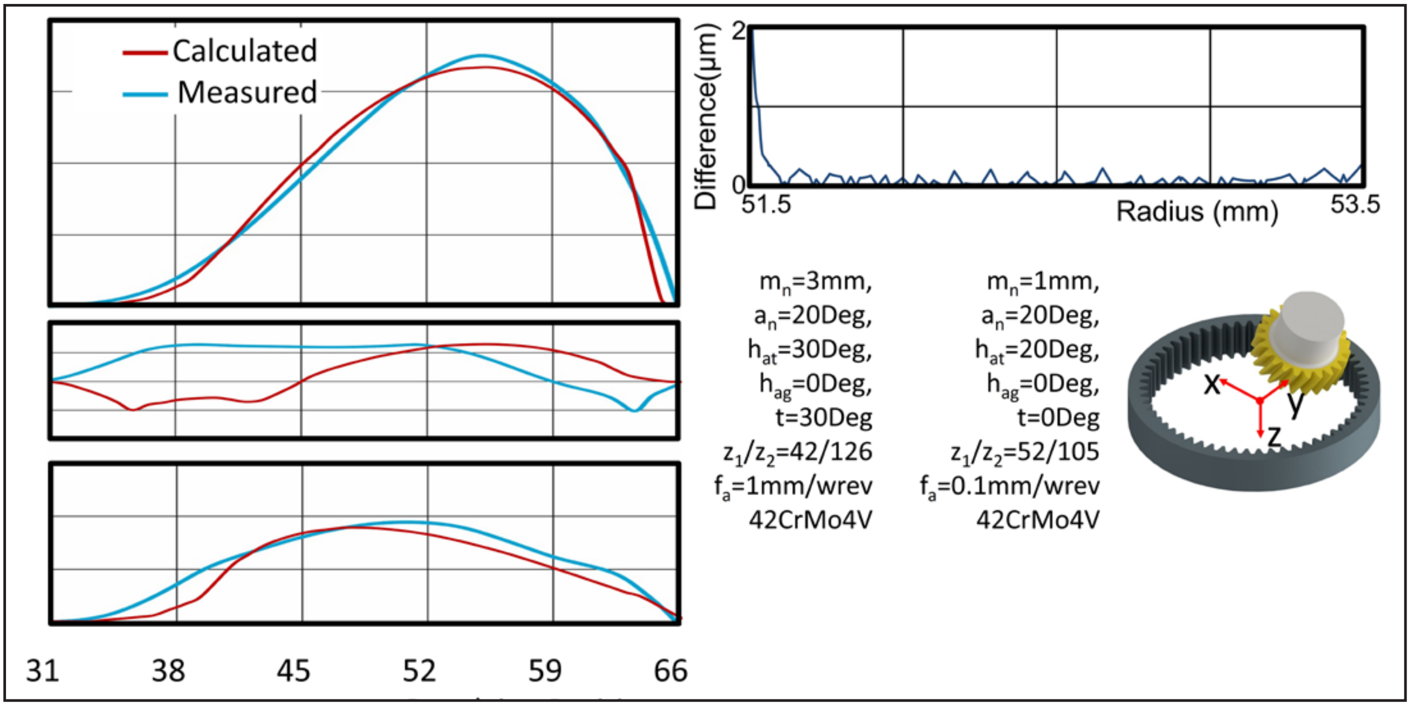

Figure 5 Cutting force (left) and surface topography validation (right).

machined geometry. The curve is also used to calculate the plane on which lead deviations can be measured. The algorithm can extract point cloud data that can be further analyzed to understand the spatial variation of the deviations in a gear.

Simulation Validation

A model validation is a critical step in the development of any simulation algorithm. *Skive3D* has been therefore validated with experimental data through literature for the cutting forces and through analytical relations governing the involute curve in terms of the flank geometries. Figure 5 presents the validation of the simulation results. As can be seen on the left side of the figure the simulation results on the cutting force magnitude closely match the experimental results of Jansen (Ref. 27). The predicted cutting forces show good agreement with the relevant experimental values especially in the Z and Y direction in terms of magnitude and form. In the X direction, there is good agreement in terms of magnitude. As the simulation model is based on the nondeformed chip geometry dynamic phenomena in the cutting process like collisions between chips coming from different flanks, chatter, etc., are not considered in the calculation. The X direction is more prone to such phenomena due to the nature of the cutting process. On the right side of the figure, the simulated flank geometry is compared against the involute curve profile. In the case of the gear profile validation the ideal flank profile, based on the involute curve equations, is generated as a 3D curve and the difference between the curve and the solid geometry produced through *Skive3D* is measured based on the radial direction.

Investigation of Gear Profile Surface Topography

Sections of the gear flank like the one present in Figure 5 provide an understanding of the quality of the gear, however, the spatial variation of that section is not clearly understood. A novel algorithm was introduced in the *Skive3D* model that is responsible for the extraction of data across the length of the gear, therefore giving a spatial image of all the deviations in the resulting gear geometry.

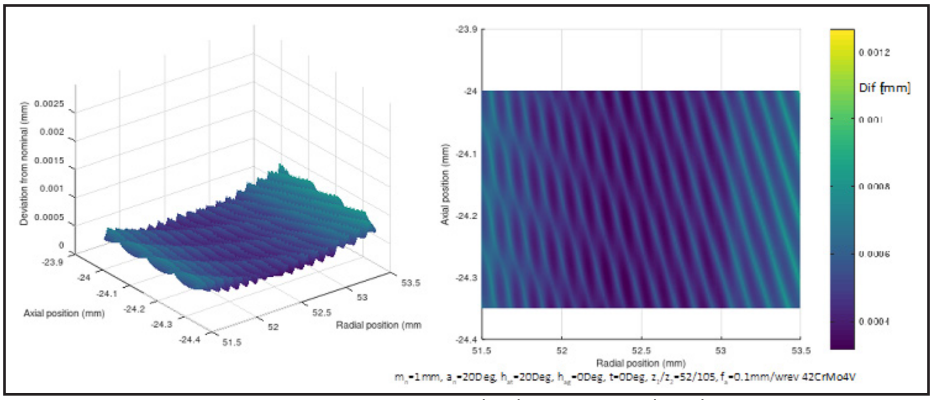

Figure 6 Work gear topography deviation 3D view (left) and top view (right).

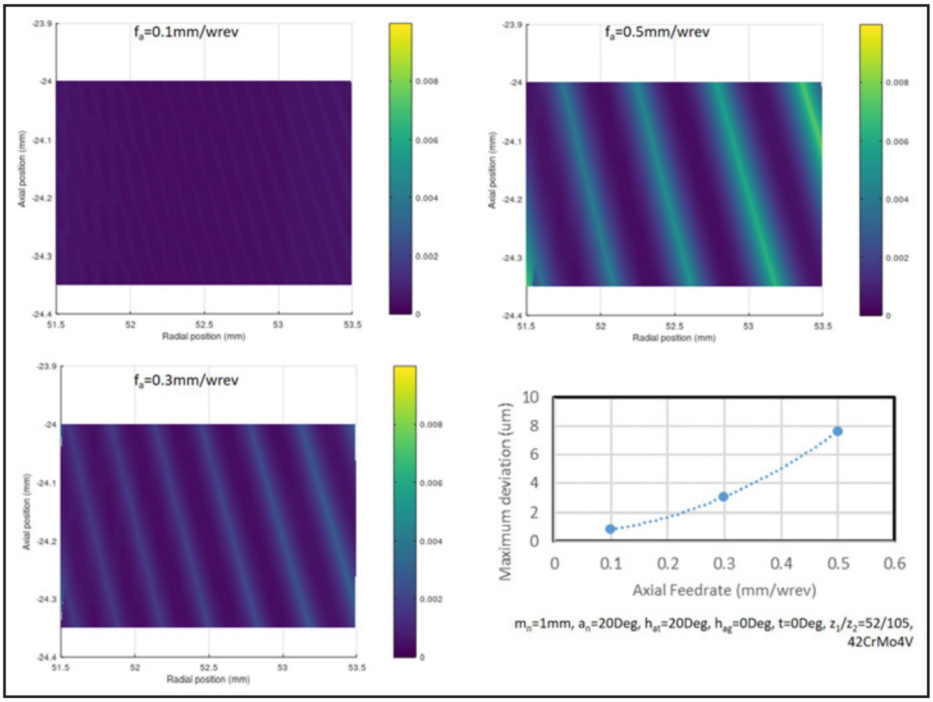

Figure 7 Influence of feed rate (f_a) on the gear topography.

Figure 6 presents the deviation map that is produced from the algorithm. On the left-hand side of the figure, the 3D view of the surface is presented whereas the right side of the figure presents a top view of the deviations of the flank when compared with the ideal involute curve. As it can be easily noticed the simulated surface appears to have a series of feed marks in a periodic fashion that are inclined with respect to the axis of the gear and match the axial feed. The total overall deviation is sub 1 μm which is expected due to the relatively small axial feed rate and module of the gear.

As it can be seen the simulation model is able to predict the feed marks that are generated from the cutting process and can be used to verify the feed rate used in the process. These maps were used to understand the influence of key parameters in the deviations in the topography of the gear. As part of the investigation, two key parameters were investigated, namely the cutting feed rate and the tool inclination angle.

Influence of Feed Rate on Gear Topography

Cutting feed is a deciding factor in terms of the quality of the produced gear and the production time of components. Like other processes, in gear skiving, the increase in feed rate leads to an increase in the maximum deviation of the flank geometries. Figure 7 presents the effect the cutting feed has on the resulting gear topography. As it can be seen the maximum deviation is increased with the increase of feed rate in a nonlinear manner as fewer tool teeth are passing through the gear gap. It can also be observed that the angle of the feed marks is constant for all three feed rates examined.

Influence of the Inclination Angle on Gear Topography

Another crucial factor in the cutting process is the inclination angle of the tool. As the tool inclination angle is increased, the tool-workpiece contact is extended. Figure 8 presents the effect the inclination angle has on the resulting gear topography. As it can be observed, the result of the increased contact between the tool and the workpiece at higher inclination angles leads to an improvement in the quality of the produced gear. At a higher inclination angle, the feed marks also appear at a steeper angle when compared to lower inclination angles.

Using *Skive3D* a broader investigation of the influence of all the factors that affect the cutting process can be performed. Other parameters of the cutting process including the cutter profile, the number of the teeth of the gear and the tool micro geometry can be investigated to achieve an optimal work gear profile for each application. The direction and magnitude of feed marks can be used to understand their impact on the transmission quality, vibrations, and acoustic emissions during operation.

Conclusions

The research presented in this paper focuses on the study of deviations in gear topography in the gear skiving process. The study was based on the development of surface deviation graphs through a novel simulation software that was developed as part of this research. The CAD-based simulation model was developed using the programming interface of the CAD software and can accurately simulate the cutting process through a solid modeling approach. The results of the model were validated through analytical and experimental data from the literature. The results of the model show that both the feed rate and the inclination angle influence to a large degree the quality of the final surface with the feed rate having a nonlinear effect and influencing the gear quality in a larger effect compared to the inclination angle. The use of simulation models, like the one presented, has the potential to reduce overall costs in the development of manufacturing methods for complex gear forms and lead toward optimized manufacturing processes. The optimization of the cutting process could lead to gears with improved quality characteristics that have lower noise emissions during operation. The research presented extends current research efforts in the modeling of the gear skiving process through accurate CAD-based models. Further expansion of the experimental data to assist with

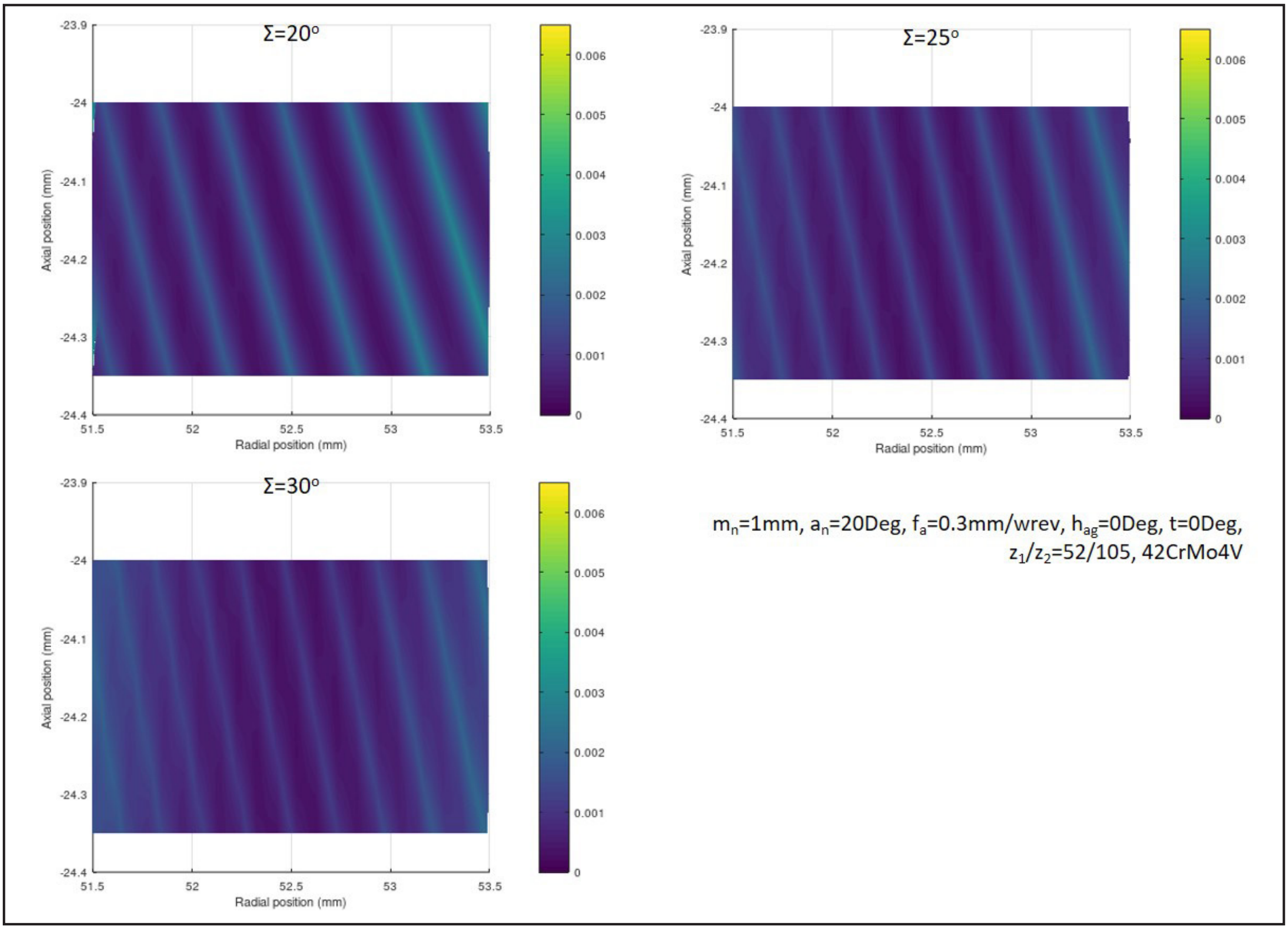

Figure 8 Influence of inclination angle on the gear topography.

further validation of the program, as well as the development of an optimization backbone, are the next steps in the development of the simulation platform. The study of the effect of the tool micro- and mesogeometry on the resulting gear is also a considerable research strand that the work will be expanded on.

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Asst. Prof. Dr. Eng. Nikolaos Tapoglou is assistant professor in the department of Industrial Engineering and Management department of the International Hellenic University, Greece. Prior to joining IHU, he led the emerging machining technology team in the Advanced Manufacturing Research Centre (AMRC) of The University of Sheffield as a Technical Fellow. He has developed substantial research in the field of simulation technologies for gear manufacturing processes. His current research focuses on the simulation of gear manufacturing processes, emerging machining technologies, sustainable lubri-cooling techniques for metalworking, additive manufacturing, optimization of advanced manufacturing processes, manufacturing simulation focusing on the calculation of in-process characteristics and manufacturing informatics. He is a member of several international organizations including the ASME, IMechE and the HEA. He has co-authored over 40 journal and conference publications and has worked on more than 20 research projects.