The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-018-2790-3

ORIGINAL ARTICLE

Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation

Nikolaos Tapoglou [1]

Received: 23 April 2018 / Accepted: 28 September 2018

Abstract
Power skiving is a new machining process that allows the manufacturing of external and internal gears while achieving high throughputs. Although the process was first described during the nineteenth century, it is not until lately that advances in machine tool technology allowed for the process to be implemented on an industrial scale. This paper presents a novel simulation model that enables the accurate prediction of the non-deformed chip geometry, the form and dimensions of the chips produced during the cutting process as well as the characteristics of the gear gap. The simulation model is embedded on a CAD environment in order to take advantage of their increased accuracy. Through the simulation code, the virtual simulation of the manufacturing process is realised. The simulation model was verified with the use of analytical equations regarding the form of the gear. Chip geometry and dimensions for internal and external gears machined with different conditions are also presented.

Keywords Gear · Simulation · Power skiving

1 Introduction

Manufacturing of precision internal and external gears is one of the most critical and complex applications in industry. The gear manufacturing industry market value is hard to estimate, but in any case, it is a multi-billion industry producing millions of gears with approximately half of the production dedicated in high precision external and internal gears [1]. With advances in electric drives amongst others, the demand for high precision gears is increasing. Traditional manufacturing processes, especially for the manufacturing of internal gears, are time-consuming and use dedicated platforms for the machining of the final geometry. In the modern manufacturing environment, the need for agile processes has led in the implementation of novel machining methods in gear manufacturing.

The selection of the appropriate manufacturing process for a given gear geometry is a critical stage in the manufacturing cycle and can vary based on the type, tolerances and geometrical characteristics of the gear. The manufacturing process can influence the quality of the gear as well as the time needed for manufacturing the gear geomentry [2]. Bouzakis et al. [3] discussed the technological problems and analysis methods in the most common cylindrical gear manufacturing processes. The focus of their paper was on processes with a geometrically defined cutting edge, whereas Karpuschewski et al. [1] focused on finishing gears by abrasive processes.

Power skiving is a manufacturing process for generating internal and external gears. The process was first described in a patent by Wilhelm von Pittler in 1910 [4]. The process did not find industrial application until the 1960 when the first power skiving machines where introduced. The main factor limiting the industrial adoption of the process was the need of a high degree of synchronisation in the cutting tool-workgear pair and the large requirements in terms of motor power. The process itself is based on a shaper-like cutting tool, which is in mesh with the gear and the cutting action is generated due to the difference in speeds between the gear and the cutting tool. Spath and Huhsam [5] presented one of the first models for the simulation of the skiving process for machining periodic structures. Klocke et al. [6] presented an analysis of the power skiving process using technological and simulative approaches. Guo et al. [7] studied the cutting mechanism for machining gears with power skiving. In further research, they focused on the design of the cutting tool in power skiving for machining involute gears [8, 9].

Manufacturing processes have been simulated with a variety of methods, including the development of numerical models, drexel-based simulation as well as solid modelling

✉ Nikolaos Tapoglou
n.tapoglou@sheffield.ac.uk

1 AMRC with Boeing, University of Sheffield, Wallis Way, Catcliffe, Rotherham S60 5TZ, UK

Published online: 09 October 2018

approaches [10, 11]. Each of the simulation methods has different requirements regarding modelling and computing effort, which affects the quality and detail of the final results. Applications of models in gear manufacturing processes are limited in gear hobbing [12–14] and gear shaping [15] as they are the most commonly used machining methods in industry.

This paper presents a novel approach for simulating the power skiving process using a CAD system. The model developed takes advantage of the increased capabilities of commercial CAD systems to predict the non-deformed chip geometry as well as the morphology of the produced gear. The kinematic chain of the process is accurately represented in the CAD environment based on the data provided by the end user of the model. The results of the model have been verified with the use of data from literature and the analytical equations describing the geometry of gears.

The originality of the proposed approach is based in the novel approach used in the development of the system, which allows the modelling of the cutting process and the calculation of the chip and gear geometry without discretisation of the cutting edge or gear geometries thus allowing for the best possible accuracy of the model. In literature, a series of solid modelling approaches have been introduced in the simulation of a series of manufacturing methods. The simulation model introduced in this research focuses on the simulation of the power skiving process, which has not been investigated in the context of CAD-based simulation. Since the power skiving process is still not fully established as a machining process, the model would allow engineers to select the most appropriate cutting parameters for machining gears without the need for costly trials. The code would also help in the optimisation of the process parameters and tool geometry.

The remainder of the paper is organised as follows: Section 2 presents the kinematic chain of the power skiving process. The simulative approach developed is presented in Section 3, while Section 4 details the algorithm for the calculation of the chip thickness. Section 5 describes the results obtained by the model. Finally, Section 6 contains concluding remarks.

2 Power skiving process

Power skiving is a continuous generating method that allows the creation of external and internal gears. Power skiving offers considerable benefits in machining internal gears due to the continuous nature of the process. The kinematics of power skiving is presented in Fig. 1 with the right side presenting the kinematics for internal gears and the left for external power skiving. The kinematic chain of power skiving consists of three movements the correct synchronisation of which is critical for the creation of a high precision gear. The workgear is rotated with a given angular velocity (ω_1), whereas the cutting tool is rotated with an angular velocity ω_2. The cutting feed is defined as a relative movement of the tool along the axis of the workgear (f_a).

The positioning of the tool is such that an angle between the axis of the tool and the workgear, named inclination angle (Σ), is formed. The inclination angle provides the main cutting motion of the power skiving process. The inclination angle can be chosen independently from the helix angle of the workgear and has a big impact on the cutting process and the geometry of the gear gap as well as the chip. In a gear pair, the angular velocity of a driven gear in relation to the master gear is defined by the gear ratio and described by Eq. 1. Due to the unique pairing of the cutter and the work gear, an additional term must be included to ensure a correct mesh between the two bodies [16]. When calculated in the pitch circle, the velocity due to the feed (f_a) would result in an additional rotation because of the inclination angle (Σ) as it can be seen in Eq. 2.

$$\omega_1 = \frac{z_1}{z_2} \cdot \omega_2 + d\omega_1 + d\omega_2 \tag{1}$$

$$d\omega_1 = 2 \cdot f_a \cdot \frac{\tan\Sigma}{D_g} \tag{2}$$

where z_1 and z_2 are the number of teeth of the workgear and the tool respectively, f_a is the feed speed, Σ is the shaft angle and D_g is the diameter of the pitch circle of the workgear.

In the case of helical workgears, an additional correction must be added in the angular velocity of the workgear to account for the helix angle of the workgear. This correction has the same rational as the one presented in Eq. (2) and is presented in Eq. (3).

$$d\omega_2 = 2 \cdot f_a \cdot \frac{\tan h_a}{z_2 \cdot m} \tag{3}$$

where m is the module of the gear, ha is the helix angle of the gear and f_a the cutting feed used. The complex kinematics of the process makes it very challenging to understand, model and optimise. Traditionally, cutting trials would be used for understanding and

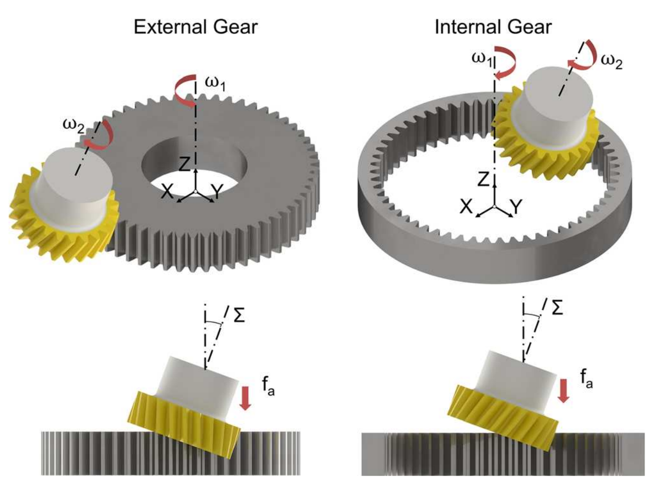

Fig. 1 Basic kinematics of power skiving

optimising the cutting process. The cutting trials in this process would require considerable funds and time. This leads to the need for an accurate model that can visualise and simulate the cutting process, thus leading to the optimal parameters for the process.

3 Simulative approach

In order to simulate the cutting process of power skiving, a novel simulation model, named Skiv3D, was developed. This model was developed using a commercial CAD environment. With the use of a CAD environment, the simulation model is able to describe the movements involved in the process with the best available precision thus ensuring the accuracy of the results. The solid modelling approach followed reduces the discretization in the description of movements to a minimum. The simulation code also allows the visualisation of the cutting process and enhances the understanding of the process by end users.

In order to model the cutting process, all the movements involved in the process are transferred on the cutting tool. This way, the tool rotates around both its own axis and the workgear axis, while it translated along the latter axis. Due to the rotational symmetry of the gear, the simulation of the cutting process in one gear gap is sufficient for characterising and simulating the manufacturing process of the full workgear. Moreover, due to the kinematics of the process, the chips created by the individual cutting edges are identical.

The data needed for the simulation include the geometrical characteristics, such as the module, pressure angle and teeth of the workgear and the cutting tool and cutting process parameters, such as the inclination angle, cutting feed and speed. Figure 2 presents the information flow of Skiv3D. The simulation code was fully embedded on the programming interface (VBA) of Autodesk Inventor. The simulation model collects all the information needed from the user through a graphical user interface. When the user starts the simulation, all the processes that are required are automatically initiated and executed. At the end of the simulation, the results are stored in the location indicated by the end user.

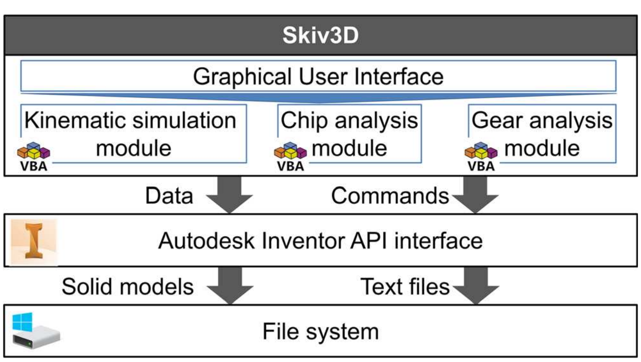

Fig. 2 Skiv3D information flow

After the data have been entered by the end user, the simulation process is initialised. The first step of the simulation is the creation of the cutting tool form, which is based on the reference profile of the workgear, the inclination angle and the helix angle of the workgear. The calculation of the reference profile of the tool is presented in Fig. 3. The profile of the cutting tool resembles the one used in gear shaping but is altered to accommodate for the inclination angle of the tool.

The profile is obtained by sectioning the reference profile of the gear geometry at an angle equal to the tool inclination angle; the reference profile can be calculated. The profile characteristics are used to calculate the geometry of the cutting tool and generate it as a spline curve. After the generation of the tool profile, any additional tooth modifications can be added at the top of the tool profile. Depending on the application and the tool design, some modifications such as corner radius and chamfer might be included in the design of the tool. The user has the option through the software to include such modifications in the tool design so that they are included in the simulation.

Following the creation of the profile of the cutting tool, the main part of the simulation process, summarised in Fig. 4, can be initiated. The simulation process of Skiv3D is based on the creation of a surface that describes the movement of an individual cutting edge in the 3D space. In order for the motions involved in the process to be synchronised, the rotation of the cutting tool is defined as the primary motion (master), and the other two are driven by the cutting tool rotation (slave). The construction of this surface is based on instantaneous positions that the cutting tool passes through, named revolving positions (RP).

The first step of the simulation is the creation and positioning of the cutting tool profile in the 3D space. The positioning of profiles is calculated so that the cutting edges describe successive positions of the cutting tool in the machining process. For every revolving position, the geometry of the tool as calculated in Fig. 3 is inserted. This ensures that the form of the tool at each revolving position is accurate and decreases the overall amount of revolving positions required to accurately describe the toolpath. The collection of profiles created in the first step is used to build a 3D surface that incorporates all the movements involved in the kinematic chain of the process. After the calculation of the trajectory, the workgear blank is modelled base on the inputs of the user as a solid body.

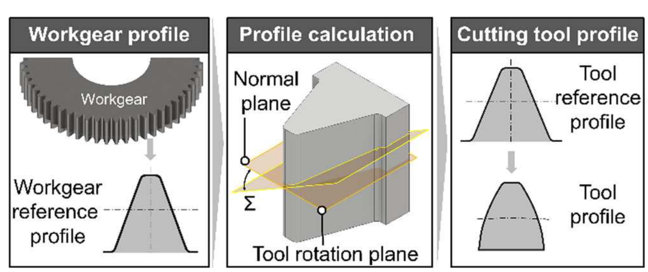

Fig. 3 Calculation of the tool profile

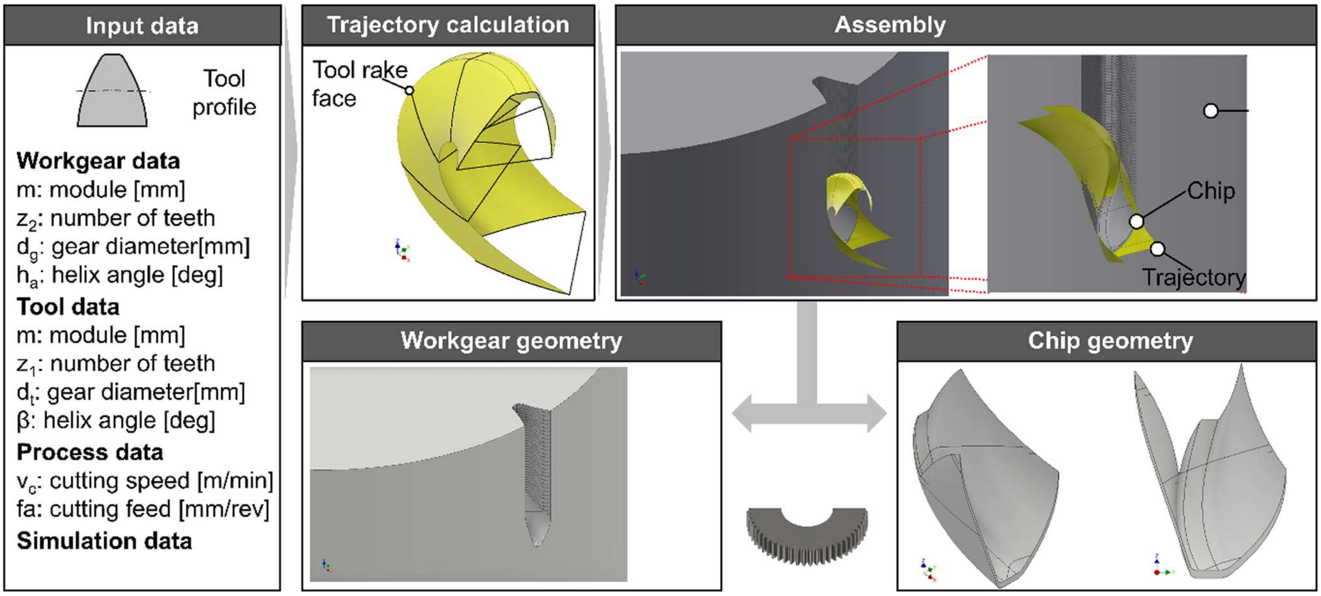

Fig. 4 Skiv3D simulation process

The angular step between the successive revolving positions is the only simulation parameter introduced in the simulation approach. The larger the value of the angle between successive revolving positions the faster but less accurate the simulation results are. The approach used in the model, using successive profiles to describe the movement of the tool throughout the 3D space, allows for a better control of the accuracy of the created solid body. This is due to the fact that the profile shape and orientation are defined in each of the RP. In simulations performed, it was found that for an angular step of 10°, the maximum measured error, in terms of misalignment, was under 1 μm, while it was decreasing rapidly forming an exponential curve. In the simulations presented, an angular step of 2° was used.

The gear blank and the tool trajectory are assembled, with constraints used to define the correct positioning of the trajectory in relation to the gear blank. The trajectory is then used to split the volume of the workgear material in two solid bodies, with the large volume being the workgear after the pass and the smaller volume being the chip of the cutting process. The workgear after the pass is used as the blank geometry for the next step of the process. The process described above is repeated, with the workgear of the *i*th pass being the blank for pass $i+1$ until the desired number of passes is reached.

The process described above is fully automated and can support internal as well as external gear geometries. After the end of the simulation, the results include the chip and workgear solid geometries for all the individual passes. Since all results are stored as solid geometries in the native CAD format, they can be subsequently used for further analysis. The workgear geometry can be analysed for extracting the morphology of the flanks, the root form as well as finite element analysis regarding the strength of the machined gear. The chip geometry can be further analysed to extract information with regard to the instantaneous chip thickness, which can in turn lead in the calculation of the cutting forces as well as the chip formation, heat load and dynamic characteristics of the cutting process.

4 Chip thickness calculation

After the end of the simulation, the analysis of the chip geometry is automatically initiated. The analysis algorithm extracts the chip thickness during the cutting process, calculates the volume of the chip as well as the evolution of the chip cross-section area. The chip thickness is based on the cross-section of the non-deformed chip geometry on the successive rake face positions of the cutting tool. To increase the accuracy of the results, the cross-sections analysed are extracted on the planes used for the construction of the trajectory surface. The process of extracting the information from the non-deformed chip geometry is summarised in Fig. 5.

The first step of the analysis process is the generation of the planes where the sectioning of the chip is going to be performed. These planes are matched with the ones generated during the trajectory creation process. The planes are created and generated based on the cutting process direction. For every one of the planes that interacts with the chip geometry, the cross-section is retrieved from the solid and its cross-section area is measured. For measuring the chip thickness, the tool profile is used as a reference curve. Measurements are taken perpendicular to the cutting edge on the plane of the section at regular intervals, defined by the user, starting from the leading edge of the tool and finishing at the trailing edge. After the end of the trailing edge is reached, the process gets repeated in the next section plane until all the planes that interact with the non-deformed chip geometry are analysed. After the end of the analysis, the data are stored in text files for further processing and if needed.

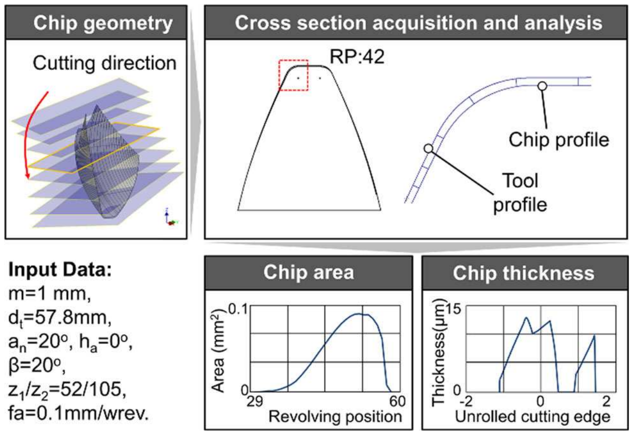

Fig. 5 Chip thickness calculation process

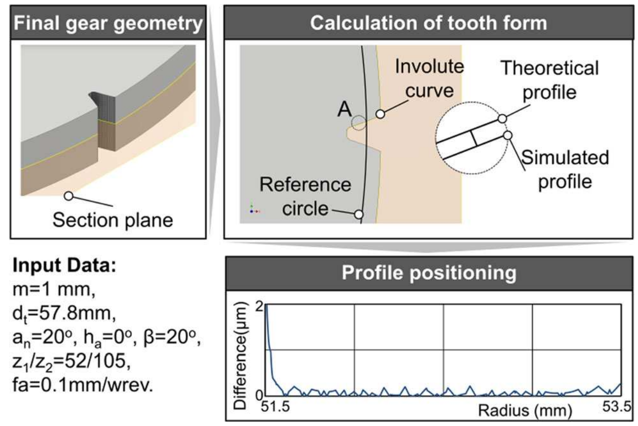

Fig. 6 Validation of gear morphology

5 Results

In order to investigate the power skiving process, a series of simulations were carried out. Initially, simulations focused on validating the accuracy of the model by comparing the resulting gear geometry, after the end of the simulation, with the analytic equations of the involute curve for a given set of parameters. Moreover, simulations were executed in order to measure the influence of process and cutting tool parameters in the resulting chip geometry.

5.1 Simulation model validation

In order to verify the results of the simulation model, the gear gap produced through simulations was compared against the analytical form of the involute curve. The initial form of an involute curve is given by Eq. 4–6. In order for the involute curve to be positioned correctly, the thickness of the gear on the pitch circle has to be taken into consideration. Therefore, the profile needs to be rotated with an angle that is described in Eq. 7. By rotating the points acquired in Eq. 4–5 with x_1, y_1 being the final points of the involute curve can be described in Eq. 8–9.

$$x = r\cdot\cos(\mathrm{inv}\, a) \tag{4}$$

$$y = r\cdot\sin(\mathrm{inv}\, a) \tag{5}$$

$$a = \cos^{-1}\frac{r_b}{r} \tag{6}$$

$$b = \mathrm{inv}(a) + \frac{\pi}{z} \tag{7}$$

$$x_1 = x\cdot\cos(b) + y\cdot\sin(b) \tag{8}$$

$$y_1 = x\cdot\sin(b) + y\cdot\cos(b) \tag{9}$$

With the points describing the involute curve calculated, the curve is designed on the normal plane of the gear as a spline curve. By comparing the cross-section of the workgear with the involute curve, the deviation of the leading and trailing flank of the workgear can be measured. The deviation is measured perpendicular to the involute curve at regular intervals. The process of comparing the curves as well as results of the validation are summarised in Fig. 6. As it can be observed, the gear profiles show good agreement with the theoretical profile of the workgear. The small deviations observed are a result of the kinematics of the process.

In order to validate the geometry of the produced chips, a series of simulations were performed, the results of whom were compared with chip geometries acquired from experiments in the literature [7]. The production of the gear in this case was performed in five depths of cut, thus producing equivalent unique chip geometries. The results of the simulations using Skiv3D are presented in Fig. 7. The results show good agreement with the results of the literature.

5.2 Simulation results

The simulation code was executed for internal and external gear configuration. The tool inclination angle and cutting feed were varied, in order to study the effect of cutting parameters on the resulting chip geometry. The results for the external gear cases are summarised in Fig. 8. At the top of the figure, the solid chip geometries for the studied cases are presented. The charts at the bottom of Fig. 8 present the evolution on the maximum chip thickness and chip cross-section area when the inclination angle and the cutting feed are altered. As it can be observed, the cutting process in all cases starts from the leading edge, followed by the head of the cutting tool on the trailing edge side. After the first few revolving positions, the tool is fully engaged in the cut.

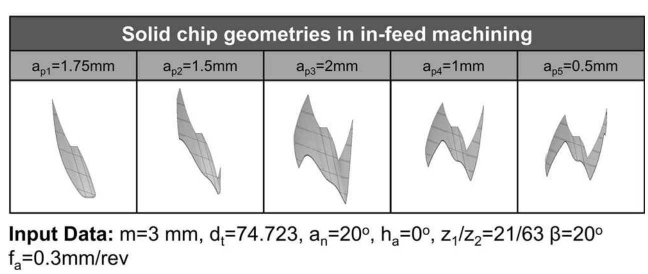

Fig. 7 Simulation results for the chip form validation

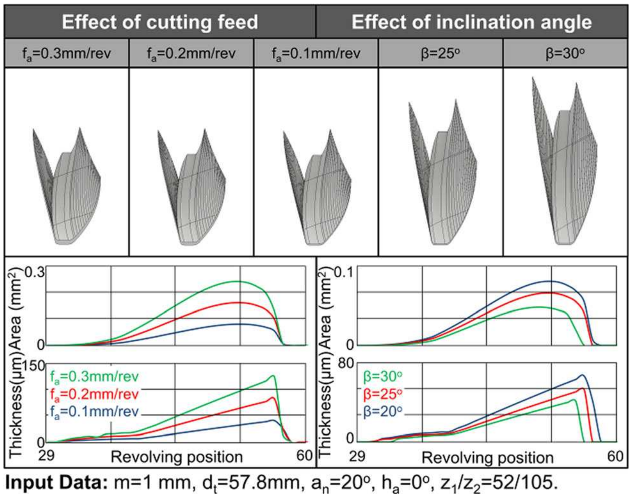

Fig. 8 Effect of machining conditions in the resulting chip geometry for external gears

Towards the end of the cutting process, the leading and trailing flanks exit the cut followed by the head of the cutter. With regard to the effect of the inclination angle of the tool in the chip geometry, it can be observed that an increase in inclination angle leads in the decrease in chip thickness and cross-section area of the chip. Higher values of the inclination angle lead to longer chips, effect that is attributed to the higher engagement between the tool and the workgear. Increasing cutting feed leads in an increase of both chip thickness and chip cross-section area. In all cases, the maximum chip thickness and area was observed during the latter stages of the cut. During the main part of the cutting process, the maximum chip load was located in the head portion of the cutter.

Simulation results regarding internal gears are summarised in Fig. 9. As it can be seen, the chip geometry resembles the one produced by the external power skiving process, but the chips are longer and larger in size than the ones produced by the external process. The difference is attributed to the longer contact time between the gear and the cutting tool. The chip geometry shows that the cutting process started also from the leading edge of the cutter and then progressed towards the head of the cutter and the trailing edge. The chip thickness graphs indicate that the maximum chip thickness was observed near the later stages of the cut. This also aligns with the results of the external gear case. The maximum chip thickness is reduced with the increase of the inclination angle of the tool trend that is also observed in the chip cross-section area. With regard to the effect of cutting feed on chip geometry characteristics, it can be observed that an increase in the axial feed leads in an increase in both the chip thickness and the chip cross-section area.

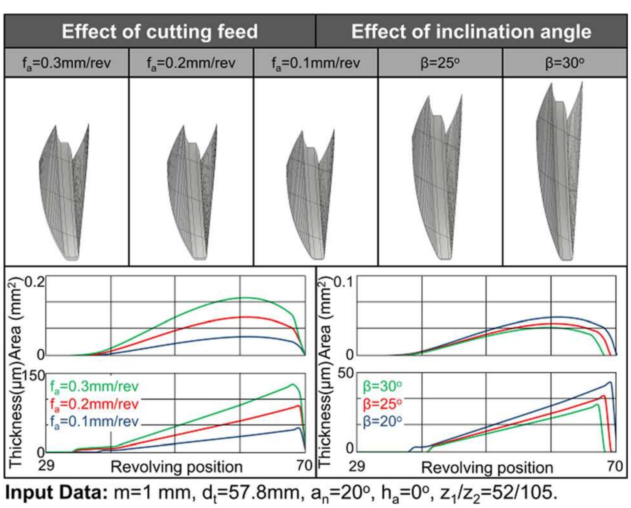

Fig. 9 Effect of machining conditions in the resulting chip geometry for internal gears

In all the simulations executed, the chip thickness and chip area were most influenced by the cutting feed showing a direct link between the feedrate and the chip form. Since in many cases the area surrounding the gear is limited, large values of inclination angle are not always achievable.

Results of the simulation code highlight the ability of the model to simulate the cutting process of power skiving in a robust and accurate way. The information derived from the model can improve the understanding of the cutting process and drive towards its optimisation.

6 Conclusions

This paper introduces a novel simulation method for the power skiving machining process. The simulation code was developed to work in tandem with a commercial CAD environment, thus taking advantage of the increase accuracy such platforms. The simulation code, named Skiv3D models the cutting process using a solid modelling approach and calculates the non-deformed chip geometry as well as the gear geometry. Based on post simulation analysis of the results, information such as the non-deformed chip thickness can be extracted from the results. The results of the model were compared against the analytical defining the form of gear teeth results indicated good agreement between the two.

The proposed simulation code excels against existing models in several aspects:

- It simulates the power skiving process using a solid modelling approach that ensures the best available accuracy of the results.
- Keeps the number of tuning parameters and discretization of the process to a minimum.
- The simulation is able to simulate the cutting process of helical, spur, internal and external gears. This is achieved by manipulating the user inputs without any interference in the simulation code.

References

1. Karpuschewski B, Knoche H-J, Hipke M (2008) Gear finishing by abrasive processes. CIRP Ann Manuf Technol 57(2):621–640
2. Radzevich SP (2012) Dudley's handbook of practical gear design and manufacture, second edition, CRC Press
3. Bouzakis KD, Lili E, Michailidis N, Friderikos O (2008) Manufacturing of cylindrical gears by generating cutting processes: a critical synthesis of analysis methods. CIRP Ann Manuf Technol 57(2):676–696
4. Pittler von W (1910) Verfahren zum Schneiden von Zahnrädern mittels eines zahnradartigen, an den Stirnflächen der Zähne mit Schneidkanten versehenen Schneidwerkzeugs, Patent Application, Germany
5. Spath D, Huehsam A (2002) Skiving for high-performance machining of periodic structures. CIRP Ann 51(1):91–94
6. Klocke F, Brecher C, Löpenhaus C, Ganser P, Staudt J, Krömer M (2016) Technological and simulative analysis of power skiving. Procedia CIRP 50:773–778
7. Guo E, Hong R, Huang X, Fang C (2015) Research on the cutting mechanism of cylindrical gear power skiving. Int J Adv Manuf Technol 79:541–550
8. Guo E, Hong R, Huang X, Fang C (2016) A novel power skiving method using the common shaper cutter. Int J Adv Manuf Technol 83(1):157–165
9. Guo E, Hong R, Huang X, Fang C (2014) Research on the design of skiving tool for machining involute gears. J Mech Sci Technol 28(12):5107–5115
10. Altintas Y, Kersting P, Biermann D, Budak E, Denkena B, Lazoglu I (2014) Virtual process systems for part machining operations. CIRP Ann Manuf Technol 63(2):585–605
11. Chang Z, Chen Z, Mo R, Zhang D, Deng Q (2017) An accurate and efficient approach to geometric modeling of undeformed chips in five-axis CNC milling. Comput Aided Des 88:42–59
12. Tapoglou N, Antoniadis A (2012) CAD-based calculation of cutting force components in gear hobbing. J Manuf Sci Eng 134(3):031009 1-8
13. Antoniadis A (2012) Gear skiving-CAD simulation approach. Comput Aided Des 44(7):611–616
14. Sabkhi N, Nouari M, Moufki A (2017) Mechanistic approach applied to the gear hobbing process. Advances in Materials and Processing Technologies 3(1):45–51
15. Erkorkmaz K, Katz A, Hosseinkhani Y, Plakhotnik D, Stautner M, Ismail F (2016) Chip geometry and cutting forces in gear shaping. CIRP Ann Manuf Technol 65(2):133–136
16. Stadtfeld HJ (2014) Power skiving of cylindrical gears on different machine platforms. Gear Technology