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Technological and simulative analysis of power skiving

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Abstract

Power skiving is a modern and productive machining process in the manufacturing of cylindrical internal gears and external gears surrounded by interfering contours. The influence of geometric process settings on characteristic values such as the chip thickness or cutting and sliding velocities will be investigated. Therefore, a numerical simulation based on a penetration calculation of the process is performed. With a demonstration part, cutting trials are conducted and the resulting tool wear is analyzed. Because chip welding can be a problem in power skiving, the investigation covers the influence of process parameters and chip geometry on chip welding, as well. The results support design and process engineers in the optimization of the power skiving process regarding productivity as well as quality.

Keywords: Simulation driven design; Manufacturing; Process design; Power skiving; Gears; Surface defects

1. Introduction

Modern drive train designs are characterized by reduced dimensional measures at an increased power density. In order to achieve such efficient drive train designs single components need to be designed more compact, lightweight and integral. However production of such components can be challenging especially in gear manufacturing due to interfering contours and at the same time increased quality requirements. Conventional gear manufacturing strategies like hobbing, shaping or broaching hereby reach their limits. Power skiving as a continuous gear cutting technology is a possible alternative for manufacturing of such components. Power skiving enables the machining of parts with interfering contours or internal gears at an increased productivity, in soft machining, as well as in hard machining.

1.1. State of the art

Power skiving was patented in 1910 and is a continuous cutting process for machining of gears and shafts with periodic features [1]. It is a machining process with a defined cutting edge. In 1960 first skiving setups were commercially available as an addition to hobbing machines [2]. First scientific investigations regarding power skiving and its technological properties have been performed by Loomann [3] and Maros [4] in the 70s. However the lag of adequate tool life, precision of the machine tools and technological knowledge hindered an effective industrial establishment. In 1980 Jansen [5] gave a first thorough investigation of power skiving in terms of kinematics, cutting conditions, tool life and work piece quality. A first simulative approach is given by the calculation of the undeformed chip thickness and an empirical estimation of the resulting process forces. In 2002 Hühsam [6] investigated the influence of tool geometry and technological parameters onto the cutting conditions. A more recent work of Bechle [7] mostly investigates process optimization by varying micro and macro geometry of the cutting tool as well as different substrate materials, coatings and different process parameters. The latest investigation is given by Kühlewein [2] who set up an FEM-based cutting simulation that is verified by machining tests. His focus is on the resulting process force, the temperature of the work piece and the chip as a result of the process parameters: axial feed, spindle speeds, cutting velocity and the applied cutting strategy.

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Nomenclature

β	helix angle
γ	rake angle
Δ_w	tilt angle
Σ	axis crossing angle
ω_0	angular velocity of the tool
ω_2	angular velocity of the work piece
d_a	tip diameter
h_{max}	maximum chip thickness
Δh	difference in the chip thickness
m_n	normal module
s_x	axial feed
VB	amount of tool wear
v_c	cutting velocity
v_s	sliding velocity
x	addendum modification
z_0	number of teeth of the tool

1.2. Kinematics of power skiving

The machine setup and the kinematics of the power skiving process are shown in Fig. 1. With power skiving it is possible to manufacture both internal and external gears. While the manufacturing of external gears also can be conducted with gear hobbing the big advantages of power skiving are the reduced working areas and the ability to machine internal gears. However, the manufacturing of internal gears can be difficult because of problematic chip removal due to limited space and the centrifugal force. The machine setup is shown in the left graphic of Fig. 1. The work piece rotates with an angular velocity of ω_2 while the tool rotates with an angular velocity of ω_0. Both rotations are synchronized by an electronic gearbox. The actual cutting velocity v_c in the power skiving process is created by the axis crossing angle Σ between the rotational axis of tool and work piece. Because of these geometric relations v_c is much lower than the velocity of tool and work piece in the point of contact due to the spindle rotation.

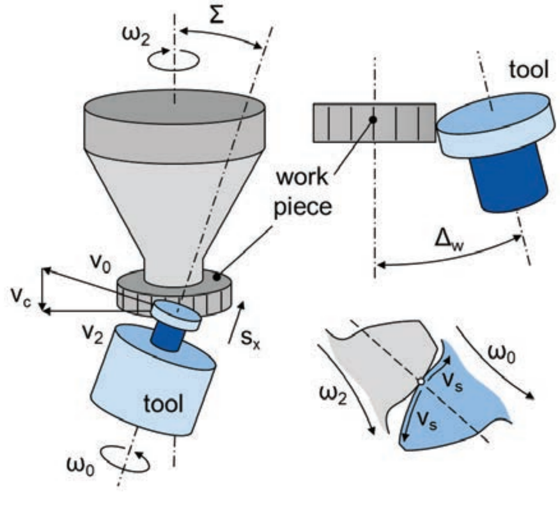

Fig. 1. Positioning of work piece and tool in power skiving

In case of a cylindrical tool a tilt angle Δ_w is additionally necessary to create the required clearance angle between the tool cutting edges and the gap of the gear. This angle can also be used to reduce or void collisions of the tool while machining an internal gearing. Besides the cylindrical tool it is also possible to use a conical tool with a designed clearance angle. In this case it is not necessary to use a tilt angle in the process setup.

2. Simulative approach

Because of the complex kinematics of the skiving process, a manufacturing simulation is needed to evaluate the cutting process and to calculate characteristic values such as chip thickness or working angles. Besides the characteristic values, the geometry of work piece, tool and chips are also a result of a simulation.

In [8] and [9] the simulation software SPARTApro for the calculation of characteristic values for the gear hobbing process was introduced. By executing a penetration calculation, values such as the chip thickness and cutting length are calculated. This software is now enhanced to be capable of simulating the power skiving process. In SPARTApro it is possible to simulate different work piece and tool designs and combine these with kinematics represented by a mathematical model. The machining process is simulated by a geometrical penetration between tool and work piece along the complete manufacturing process.

In power skiving the tool geometry depends on the gear geometry to be produced as well as the geometric setup of the skiving process. Therefore, the tool geometry can not be described by a simple reference profile. Thus, the tool profile geometry has to be calculated within the simulation software. Left of Fig. 2 the method of creating the tool geometry is shown. First, the desired target geometry of the gear is described by the basic rack profile (a) as well as the number of teeth, helix angle and diameters (b). Second, the gear geometry is used in a backwards calculation with the given machine setup including the axis crossing and tilt angle (c). By intersecting the resulting helix with a plane, according the rake angle of the tool, the final profile edge is determined. The profile afterwards is extruded to a helix which can be used in the penetration calculation.

The penetration calculation is performed in three steps. At the beginning the work piece is represented by circular planes with the outside diameter of the gear. For each of these planes the intersection with the tool helix, which is positioned according to the kinematics, is calculated. After the intersection of each plane of the work piece with the tool helix is simulated, the resulting chip geometry can be determined by a comparison of the previous and new work piece planar intersections. In the next step the chip geometry can be analyzed and characteristic values, such as chip thickness and cutting length, are calculated and displayed along the unrolled cutting edge. Furthermore, the kinematics can be analyzed and the rake and clearance angles as well as the cutting v_c and sliding velocity v_s can be calculated at any given time and for every single point of the cutting edge.

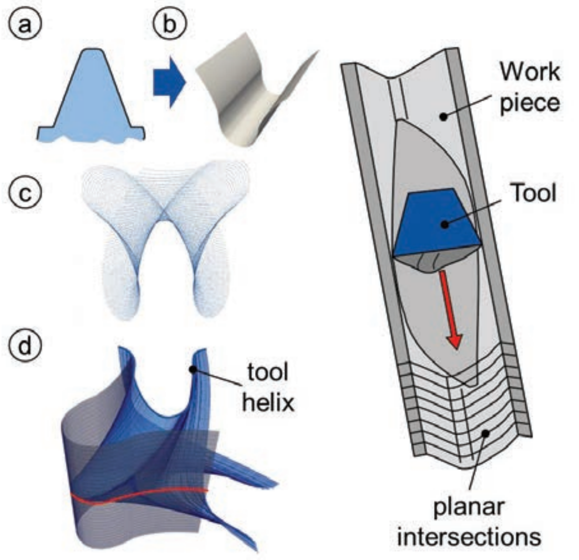

Fig. 2. (a) reference profile creates the target geometry (b); (c) backwards calculation of the target geometry with machine kinematics to get tool profile; (d) generate the tool helix for the penetration calculation; right: the tool helix cuts the planar intersections of the work piece

3. Results and discussion

3.1. Simulation results

To evaluate the influence of different process setups first a variation calculation is performed. The test gear in this test series is a helical internal gear with $z_2 = 105$ teeth, a module of $m_n = 1$ mm and a helix angle of $\beta = 10°$. The tip radius of this gear is $d_a = 90$ mm. The geometry of the gear is fixed, only the tool geometry and the process parameters are changed. To be able to compare the different processes with each other in terms of productivity, the axial feed of the tool as well as the angular velocity of the work piece are kept constant. Table 1 shows the variation range of tool as well as the process parameters.

Table 1. Range of variations for the different geometric influences

Parameter	Variation range
Number of teeth of tool [z_0]	52 / 68 / 84
Addendum modification factor [x]	-0.4 / 0.0 / 0.4
Axis crossing angle [Σ]	-10° / -20° / -25° / 30°
Tilt angle [Δ_w]	-10° / -15° / -20°

By using a design of experiments the number of simulation variants can be reduced to 23. These variants are simulated and the results are analyzed regarding the chip thickness, cutting and sliding velocity as well as rake angle of the tool. The chip thickness has an influence on the tool load. Higher chip thicknesses result in a higher tool load. Trials also have shown that if the mean chip thickness is less than a lower limit that depends on the material, cutting edge and tool geometry the tool wear increases as well [10]. This can be explained by the fact that no plasticity of the material is reached and only elastic deformation occurs which adds extra load to the cutting edge. The rake angle of the tool has also an effect on the tool load, because negative rake angles are causing higher cutting forces. Also a high sliding velocity can result in higher tool wear at the cutting edge as well as the tool clearance. According to [11], because of the sliding, the tool cutting edge experiences an additional wear.

Fig. 3 shows the condensed simulation results in terms of the influence of the absolute value of the axis crossing angle Σ, the tilt angle Δ_w and the number of tool teeth z_0 on the maximum chip thickness h_{max}, the effective rake angle γ, cutting and sliding velocity v_c and v_s. Because the axial feed s_x has nearly no influence on the values of γ, v_c and v_s, it is not shown in the figure. But as shown, the effect of s_x on the chip thickness is nearly linear and an increasing axial feed results in an increasing chip thickness. An increasing amount of Σ and z_0 cause a reduction in the maximum thickness.

Regarding the minimum effective rake angle γ_{min} the axis crossing angle Σ has a negative influence, means the effective rake angle decreases with an increasing crossing angle, while an increase in the tilt angle Δ_w and the number of teeth z_0 increases the rake angle. The influence of the axis crossing angle, the tilt angle and the number of tool teeth on the cutting velocity v_c is directly proportional. As described the sliding velocity v_s should be low to reduce the tool wear. In this case the higher axis crossing angles as well as number of tool teeth have a positive effect, while the tilt angle has a negative effect and therefore should be kept low. Since this also affects the clearance angle, a low tilt angle may not be possible in every process design.

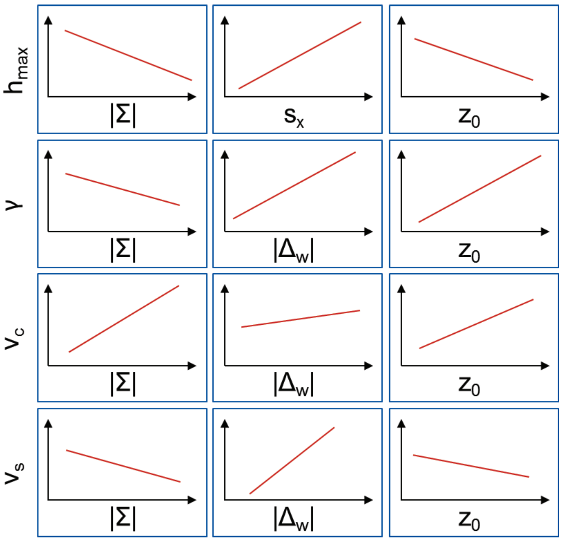

Fig. 3. Qualitative influence of geometric parameters on characteristic values in power skiving

3.2. Tool wear in cutting trials

After performing the simulations for the different parameter sets, the tool with $z_0 = 68$ teeth is selected for experimental investigations. This tool is a good tradeoff between productivity caused by lower working area compared to the cutting tool with $z_0 = 84$ teeth and also higher number of cutting edges which results in lower chip thickness and higher tool life then the tool with $z_0 = 52$ teeth. For this tool four different process settings are chosen and cutting trials are performed with an axial feed of $f_a = 0.3$ mm per work piece revolution. In Table 2 the simulation results for chip thickness h_{max}, rake angle γ, cutting v_c and sliding velocity v_s are displayed.

Table 2. Simulation results for the cutting trial variants

Parameter		V 1	V 2	V 3	V 4
Σ	[°]	25	30	20	20
Δ_w	[°]	15	10	10	20
h_{max}	[µm]	141	135	168	168
γ_{min}	[°]	-37.8	-32.5	-38.5	-38.5
γ_{max}	[°]	4.4	12.1	1.7	1.9
v_c	[m/min]	185.5	217.7	156.8	156.8
v_s	[m/min]	66.6	44.2	59.8	59.8

Instead of using the actual tool with $z_0 = 68$ teeth an analogy trial is used for the cutting trials. In this analogy trial the complete tool is represented by one cutting edge. Thus, the setup is similar to fly cutting in gear hobbing which was developed at the WZL and used successfully in many research projects [10] [12]. The main advantage of this single blade cutting process is the reduced number of work pieces that have to be manufactured until the tool reaches end of its lifetime. As tool material cemented carbide with a (AlCr)N coating was used. Because of the unexpectedly high tool life, the trials were ended after manufacturing 50 work pieces. This number of work pieces represents 3400 gears manufactured with a full teethed tool. Continuously, after every workpiece the tool wear was measured along the cutting edge and documented by microscopic images. Because of this high tool lifetime no repetition of the cutting trials were conducted. For a validation this should be done in future. Fig. 4 shows the maximum tool wear VB_{max} of each trial after 50 parts. The tool wear in trial V1 and V2 is around 20 to 25% lower than in the other two variants. Comparing this to the simulation results, a correlation between the maximum chip thickness and tool wear can be shown.

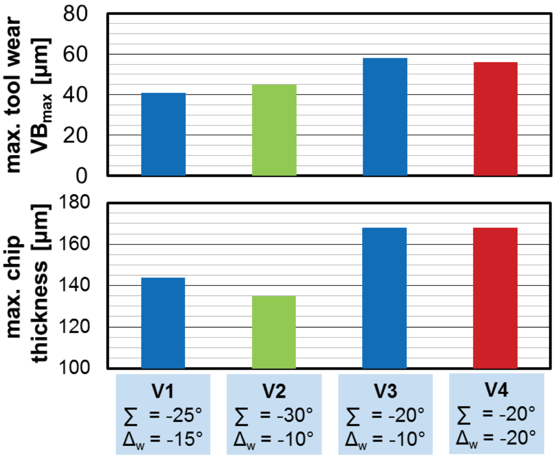

Fig. 4. (top) Tool wear after 50 work pieces and; (bottom) Maximum chip thickness

3.3. Chip clamping and chip welding in the work piece gap

A well known problem in industrial manufacturing of gears is the clamping of chips in the gap between two teeth of the work piece [13] [14]. These chips, or part of chips, are welded onto the tooth flanks and can be a problem for further machining steps, hardening and also the direct application. Chip welding is a surface defect of gears and has to be avoided, especially because an automatic detection of these defects is complicated [14]. Two different manifestations of chip welding are shown in Fig. 5. In the left image small parts of chips are shown which are spread over a relatively wide area of both flanks and the tooth root. In the right image one big chip is welded in the gap between two teeth.

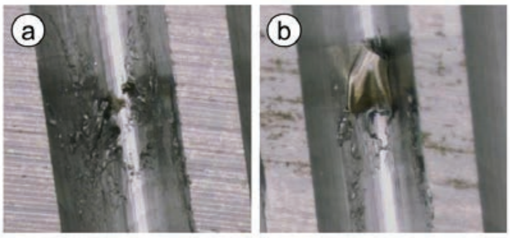

Fig. 5. (a) Small chip welding; (b) Massive chips welded on the surface

These chip weldings were detected during cutting trials and are statistically evaluated afterwards. Fig. 6 shows the total number of chips welded in the work piece gap. While in V4 77 chips are counted after the manufacturing of 50 gears, V2 shows only the occurrence of four chips welded on the flank surface. Further investigations of the simulation results show that V2 has the largest maximum rake angle (γ_{max}) and also smallest minimum (γ_{min}) rake angle, see lower half of Fig. 6. A possible explanation for this effect is that high negative rake angles lead to higher cutting forces, bad chip flow, increased friction between tool and chip and therefore higher temperatures and last higher chip compression [15]. All these effects can increase the process affinity of chip welding.

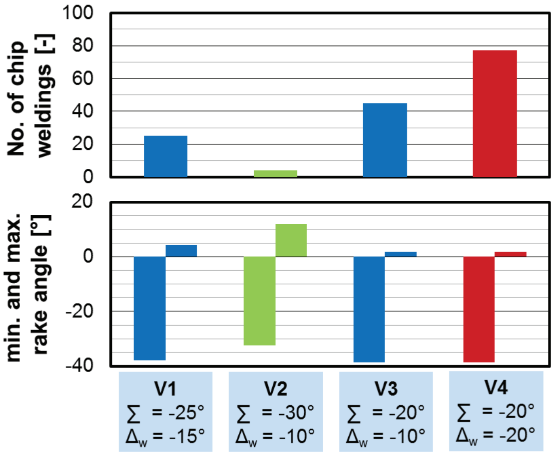

Fig. 6. (top) Total number of chips welded in the work piece gap after machining 50 work pieces; (bottom) min. and max. rake angle

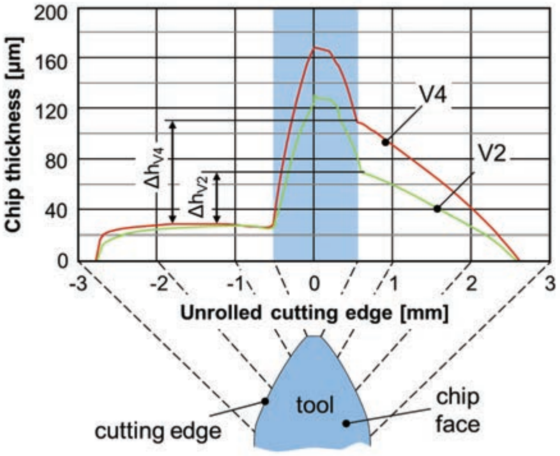

Fig. 7. Comparison of the chip thickness of the best and worst variant

Another reason for surface defects like smearings and scratches, which can properly be transferred to chip welding, is described in the work of Stuckenberg [14] for the gear hobbing process. According to his work surface defects are caused by asymmetrical chipping geometries. In the process of machining these asymmetrical chips, the material cannot be removed from the gap of the gear and the chips curl to one side, get stuck between tool clearance flank and work piece flank and are welded on the flank. While in gear hobbing different chips are machined by the blades in the different rolling positions of the tool, in power skiving only one chip geometry is produced. Because of this every chip in the power skiving process is a potential risk for surface defects and not only a certain rolling position. Thus, it is not possible to directly transfer the method of Stuckenberg developed for gear hobbing. However certain modifications and expands in the method enable the description of asymmetrical chips for power skiving as well. In Fig. 7 the maximum chip thickness of the trials V2 and V4 is displayed over the unrolled cutting edge of the tool. The tip of the tool is in the middle of the diagram. Highlighted is the tip area of the tool where the maximum chip thickness occurs. On the left side of the diagram, represented by negative values, the trialing flank of the cutting tooth is displayed. On the right side the chip thickness along the leading flank is shown.

While the chip thickness on the left flank is almost the same in both trials, the chip thickness on the right flank differs widely. The trial V2 has a maximum chip thickness of $h_{max} = 75$ µm on the right flank, while the chip thickness of V4 is $h_{max} = 110$ µm in maximum. Consequently, the chips have a much higher stiffness on the right flank than on the left. This difference in chip thickness might cause problems in the process of chip formation.

4. Conclusion

By using a new manufacturing simulation for power skiving different variants of process setups can be simulated and characteristic process values, like the chip thickness, the rake angle or the velocities, were calculated. Based on this simulation four different process designs were used in cutting trials in order to determine the resulting tool wear. A correlation between the simulated maximum chip thickness and the tool wear can be observed. During the cutting trials the effect of chip welding occurred which has to be avoided to get a stable and productive process. To investigate the reasons for the chip welding the simulated characteristic values as well as the geometry of the chips were analyzed and a possible explanation for the chip welding was given. Finally the process design with the lowest number of chip weldings during the machining also showed a low tool wear, thus this is a stable as well as economical process design.

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References

[1] Pittler von W.: Verfahren zum Schneiden von Zahnrädern mittels eines zahnradartigen, an den Stirnflächen der Zähne mit Schneidkanten versehenen Schneidwerkzeugs. Patent Application, 1910

[2] Kühlewein C.: Untersuchung und Optimierung des Wälzschälverfahrens mit Hilfe von 3D-FEM-Simulation. 3D-FEM Kinematik- und Spanbildungssimulation. In: Forschungsberichte aus dem Wbk, Institut für Produktionstechnik, Universität Karlsruhe (TH), 2013

[3] Looman J.: Wälzschälen von innenverzahnten Stirnrädern. VDI-Zeitung, 1971

[4] Maros D.: Beitrag zur Kinematik der Erzeugung von Zahnflanken nach

dem Wälzschälverfahren.Industrie-Anzeiger, 1971

[5] Jansen W.: Leistungssteigerung und Verbesserung der Fertigungsgenauigkeit beim Wälzschälen von Innenverzahnungen, Dissertation RWTH Aachen, 1980

[6] Hühsam A.: Modellbildung und experimentelle Untersuchung des Wälzschälprozesses. Institut für Werzeugmaschinen und Betriebstechnik, Universität Karlsruhe. 2002

[7] Bechle A.: Beitrag zur prozesssicheren Bearbeitung beim Hochleistungsfertigungsverfahren Wälzschälen. Aachen, Shaker, 2006

[8] Brecher, C., Brumm, M., Krömer, M.: Design of Gear Hobbing Processes Using Simulations and Empirical Data. 9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME ‘14; 2014; Naples Italy

[9] Klocke, F.; Brecher, C.; Löpenhaus, C.; Krömer, M.: Influence of Tolerances on Characteristic Manufacturing Deviations in Soft Gear Machining. International Conference on Gears 2015, Garching

[10] Klocke, F.; Löpenhaus, C.; Sari, D.: Process concepts for gear finish hobbing. 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015, 2015; Naples Italy

[11] Stadtfeld, H.J.: Power Skiving of Cylindrical Gears on Different Machine Platforms. Gear Technology, January/Februray 2014

[12] Winkel, O.: Steigerung der Leistungsfähigkeit von Hartmetallwälzfräsern durch eine optimierte Werkzeuggestaltung. Dissertation RWTH Aachen, 2005

[13] Klocke, F.; Gorgels, C.; Stuckenberg, A.: Investigations on Surface Defects in Gear Hobbing. 1st CIRP Conference on Surface Integrity, 2012

[14] Stuckenberg, A.: Vermeidung von Oberflächendefekten beim Wälzfräsen. Dissertation RWTH Aachen 2014

[15] Heisel, U.; Klocke, F.; Uhlmann, E., Spur, G.: Handbuch Spanen. Hanser Verlag, 2014