

Surface Characteristics of Hobbed Gears

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Gear hobbing is one of the most productive manufacturing processes for cylindrical gears. The quality of the gears is a result of the tool quality, the precision of the workpiece, tool clamping and kinematics of the machine. The dry gear hobbing process allows machining of gears with a quality according to the DIN standard up to IT 5. To evaluate which gear quality is possible to machine with a given clamping and hob, it is useful to simulate the process in advance. This is also an opportunity to order the required quality of the hob according to its application. The objective presented in this report is to simulate the gear hobbing processes and to calculate the geometry and surface of the workpiece. By a geometric penetration calculation, the resulting gear geometry as well as process characteristic values are determined. By an evaluation of tool and clamping tolerances, these deviations can be used to modify the ideal simulation model. Afterwards a non-ideal hobbing simulation can be performed and the resulting gear geometry can be analyzed using a virtual measurement machine. A virtual measurement machine analyses the geometry according to VDI/VDE 2612/2607 and DIN 3961. The resulting measurements of the flank and lead lines can be used for a classification of the gear quality. An advantage of this non-ideal simulation is also the possibility of calculating the tool load taking tolerances into account and to use the results for further process designs to reduce the risk of tool failure. This method also can be used to design machining processes for gear finish hobbing which has economic advantages because of the shortened process chain. To evaluate the effect of different characteristic process deviations on the operational behavior of the gears, running tests are conducted.

Gear Hobbing: State of the Art

Gear hobbing is a continuous generating process which can be compared to kinematic conditions of worm and worm gear. The workpiece is represented by the worm gear whereas the hobbing tool is designed like the worm (Fig. 1, top left). By a continuous rotation ω_0 of the tool, the cutting movement is realized. An axial feed f_a of the hob across the face of the gear is superimposed upon the tool rotation. Because of the continuous cutting process, the secondary processing times are low which makes gear hobbing to be one of the most productive manufacturing processes for cylindrical gears (Ref. 1).

Due to the kinematic coupling, characteristic cutting deviations occur on the flanks and the tooth root of the workpiece. These deviations are called “feed marks” (Fig. 1, middle) and “generated cuts” (Fig. 1, bottom). The feed marks are oriented in direction of the workpiece width and the generated cuts occur in profile direction.

The height of the feed marks mostly depends on the axial feed and the outside diameter of the hob. Typically,

the height of the feed marks is greater than the height of the generated cuts. Generated cuts are mostly depending on the number of gaps and threads of the tool. For both deviations, analytical Equations 1 and 2 exist (Ref. 2). However, these equations only calculate the deviations for an ideal process.

$$\delta_x = \left(\frac{f_a}{\cos \beta_2} \right) \cdot \frac{\sin \alpha_{r0}}{4 \cdot d_{a0}} \quad (1)$$

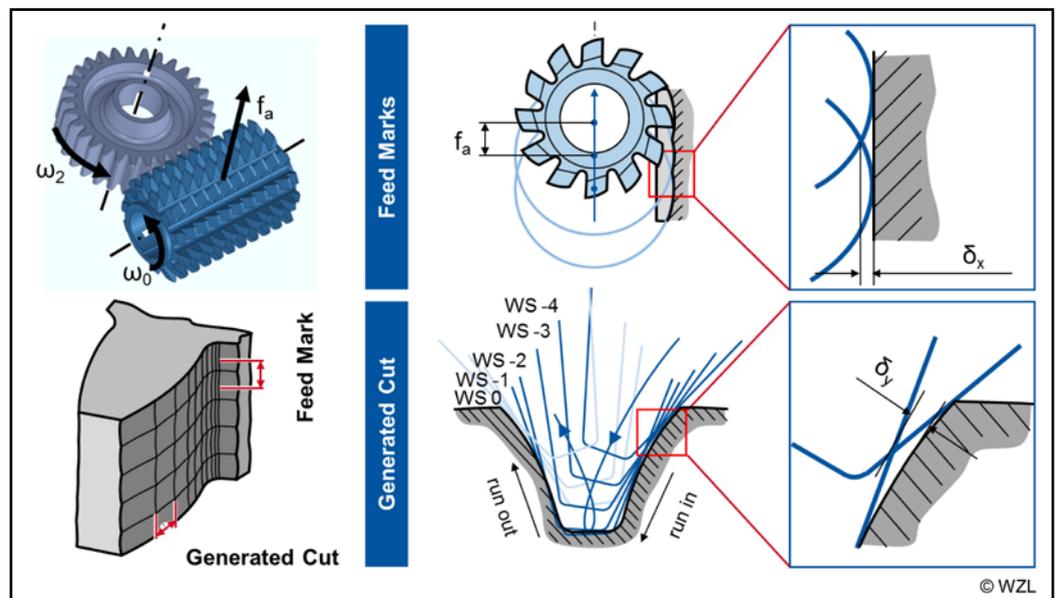


Figure 1 Characteristic deviations due to kinematics of hobbing process.

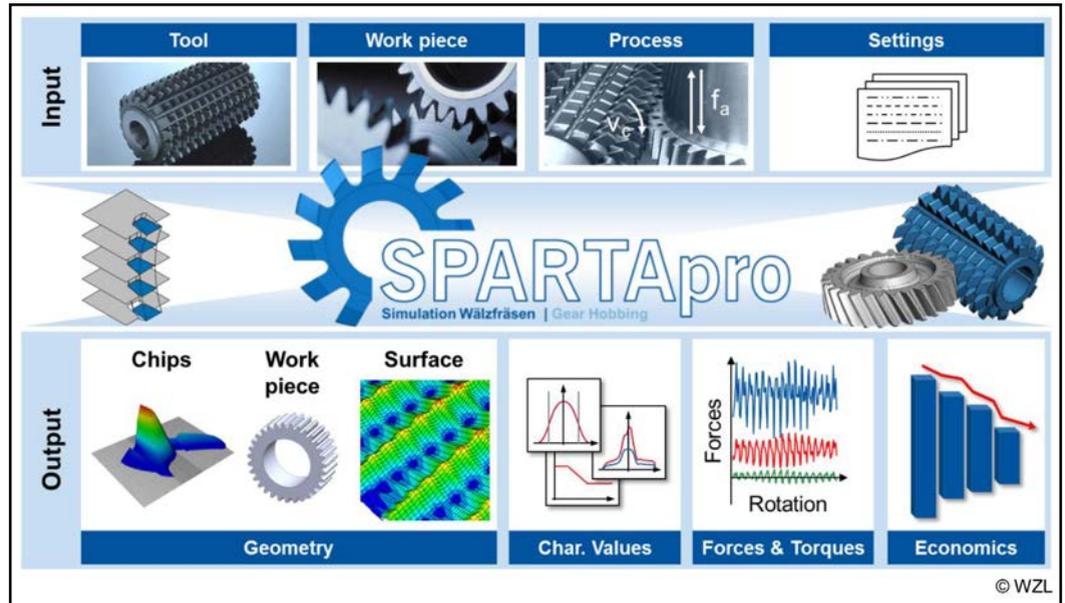


Figure 2 Process simulation for soft gear machining *SPARTApro*.

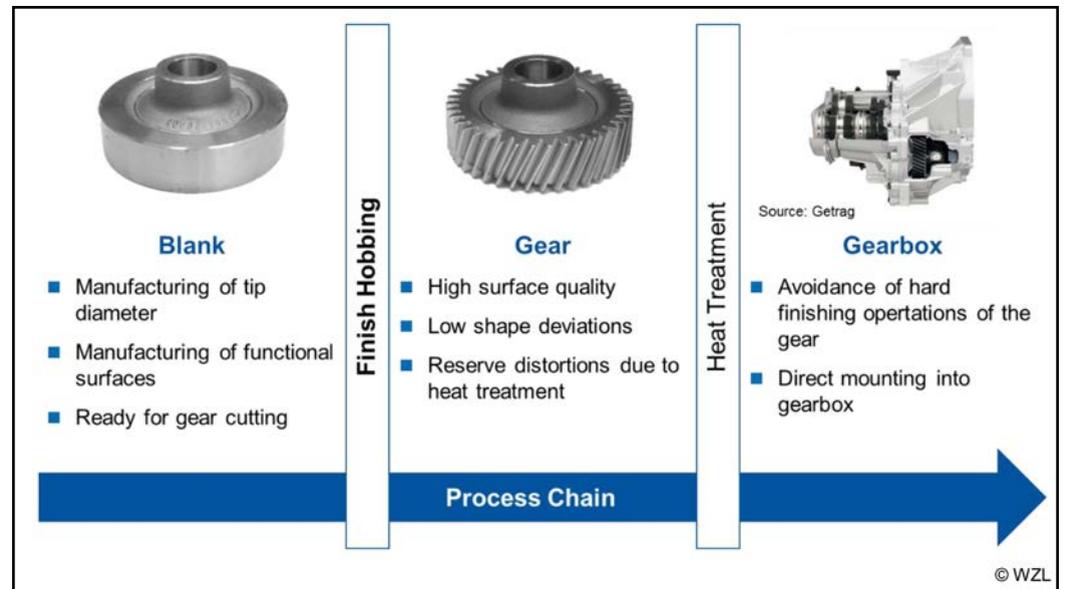


Figure 3 Process chain of gear finish hobbing (Ref. 9).

		$\delta_y = \frac{\pi^2 \cdot m_n \cdot z_0^2 \cdot \sin \alpha_{n0}}{4 \cdot n_0 \cdot z_2}$	(2)
δ_x	(μm)	Generated cuts	
f_a	(mm)	Axial feed	
α_{n0}	($^\circ$)	Normal pressure angle of the tool	
m_n	(mm)	Normal module	
n_0	(-)	Number of gaps of the tool	
δ_y	(μm)	Feed marks	
β_2	($^\circ$)	Helix angle of the workpiece	
d_{a0}	(mm)	Outside diameter of the tool	
z_0	(-)	Number of starts of the tool	
z_2	(-)	Number of teeth of the workpiece	

In general, the deviations of the final hobbed gear are greater because of the characteristic process deviations are superposed by tolerances of tool, clamping and machine kinematics. The total deviation is a combination of the described characteris-

tic deviations as well as the deviations caused by tolerances of tool, clamping and kinematics (Ref. 3). With the knowledge of the total deviation in the process, the resulting gear quality can be determined. The method of gear measuring is defined in different standards. Common standards in Europe are VDI/VDE 2612 (Ref. 4) or DIN 3961 (Ref. 5). Both standards describe the measurement of gears in direction of profile and lead of the workpiece. In addition, the deviations of pitch and radial-run out are measured. As stated in DIN 3962-1 (Ref. 6) the resulting gear quality is calculated for various module sizes and is divided into twelve different quality groups. Gears with a high quality have a low quality group (e.g., IT 1) and low-quality gears have a high quality group (IT 12).

If a certain quality of the workpiece is requested by the design department, the production planner has to select a sufficient tool and clamping for manufacturing process. Because the price of tool and clamping depends on the precision, it is desirable to

select only the required combination.

Simulation of the gear hobbing process. In (Refs. 7 and Ref. 8), the simulation software *SPARTApro* for calculating characteristic values for the gear hobbing process was presented. Input parameters are the geometrical information of the workpiece such as module, number of teeth and outside diameter as well as the tool data and its profile geometry. With the given axial feed, a penetration calculation is executed and the non-deformed chip geometries occurring in the hobbing process are determined. Afterwards, these chip volumes are analyzed and characteristic values such as the maximum and average chip thickness $h_{cu,max}$ and $h_{cu,av}$, the specific chip volume V' and the maximum and average cutting length l_{max} and l_{av} are calculated. The values are displayed along the unrolled cutting edge and as maximum and average values for the whole process. Besides these values, *SPARTApro* is capable of calculating the cutting forces of the hobbing process and the economical profitability of the process.

Gear finish hobbing. With the knowledge of characteristic deviations of the machining process, it is possible to design a hobbing process with very low deviations. Figure 3 shows the process chain of gear finish hobbing. First, the blank of the workpiece is machined. The machining includes turning of the blank as well as grinding of functional surfaces. Afterwards the blank is ready for gear hobbing. For gear finish hobbing, characteristic deviations have to be about one μm and lower. These low deviations are achieved using multi cut strategies. The simplest type of multi-cut strategy are two separate cuts. First the roughing cut in which most of the workpiece material is machined. In the following finishing cut only a stock of around $T=100\mu\text{m}$ is removed. Because of the low volume which is machined in the second cut, high cutting speeds can be used. This gives the process designer the possibility to reduce the axial feed, feed marks and still get economical process designs.

Due to the advantage of low deviations and a low surface roughness, gear finish hobbing offers the possibility to shorten the process chain for gear manufacturing, by eliminating the gear grinding process. However, for gear finish hobbing the

deviations coming out of the heat treatment have to be known. These deviations have to be considered and eliminated by flank modifications in the hobbing process. After heat treatment, modifications in the hobbing process and deviations of the heat treatment should eliminate each other and the final workpiece results. After heat treatment, the gear is ready for assembling (Ref. 9).

Special advantages of gear finish hobbing are high cutting speed and low amount of stock. These points were investigated in several research projects at WZL. First, the influence of several cutting materials on tool life was investigated in an analogy trial (Ref. 10). Afterwards, the results of the analogy trial have been transferred on the load collective in gear hobbing (Ref. 11). The potential of several cutting materials for gear finish hobbing was not the only focus of the investigations. Additionally, the possible workpiece quality was a topic. For these, the fly-cutter trial was used. The influence of different process parameters on the possible profile and surface quality was investigated. The deviation from the ideal involute depends on the number of generating cuts. By using more generating cuts (higher number of gashes or reduced number of threads), the straight tool profiles can approximate the ideal involute more accurate (Eq. 2) (Ref. 9).

Simulation of Characteristic Deviations in Gear Hobbing

The presented manufacturing simulation *SPARTApro* was enhanced to be capable of simulating the surface topography of the gear. Therefore, a penetration calculation with the designed process parameters is executed and afterwards the resulting gap geometry is compared with an ideal gear geometry (Fig. 4). The ideal workpiece can be calculated within *SPARTApro* or can be calculated and imported from other software such as *GEARGENERATOR* (Ref. 12), which has been developed at the WZL. *GEARGENERATOR* uses the basic requirements of a gear tooth system (Ref. 13) to calculate the ideal gap geometry. The simulated surface can be measured and analyzed in any direction with a virtual measurement machine based on the VDI/VDE 2612 (Ref. 4) standard.

Figure 5 shows an example of the surface topography of a hobbled workpiece. The data of the workpiece, tool as well as process is depicted at the bottom. At the top the surface topographies are shown as a mountain map. The lines plotted on the mountain map represent the lines of measurement in direction of profile and lead. The simulated measurement lines are shown at the right side of Figure 5. The axial feed used in this process is set to $f_a=2.4\text{ mm}$. This value also can be found in the measurement of the lead line as the distance of

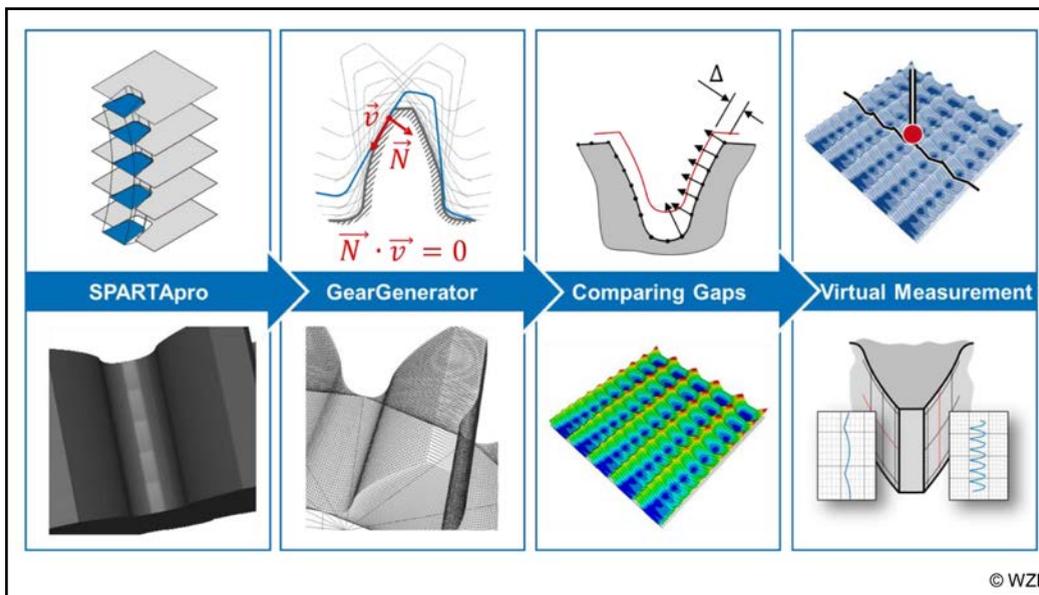


Figure 4 Approach for calculating gear surface topography.

two peaks. Both, the measurement of the profile as well as of the lead line show a deviation of five μm to the ideal flank. According to DIN 3962 6 this is a gear quality of IT 5 which is close to the best quality which can be achieved economically in the conventional hobbing process.

In the graphical interface of SPARTApro, the WZL GEAR TOOLBOX, the output of profile and lead lines is based on the design of measurement sheets of gear measurement machines. An example of a simulated measurement is given in Figure 6. At the top of the output three measurements of the profile for left and right flank are shown.

While the gear measurement machines measure a specific number of teeth of the gear, the software measures only one tooth on different heights, see left bottom of Figure 6. By analyzing one tooth it is not possible to measure radial run-outs or pitch errors but it is possible to analyze modifications of profile and lead such as crowning or the natural twist. In future versions it will also be possible to analyze a various number of teeth of the workpiece. In the lower half of the graphical output, the measurements of the lead lines are displayed. For each flank, the measurement results are depicted for three diameters of the gear. Below each measurement plot, the numerical values of the profile and lead modifications are plotted.

Simulation of tool and process errors. Deviations in the hobbing process can occur as tolerances of the tool and gear or due to displacements in the clamping of tool and workpiece (Ref. 3). The tolerances of the tool are defined in DIN 8000 (Ref. 14). The top half of Figure 7 shows the devia-

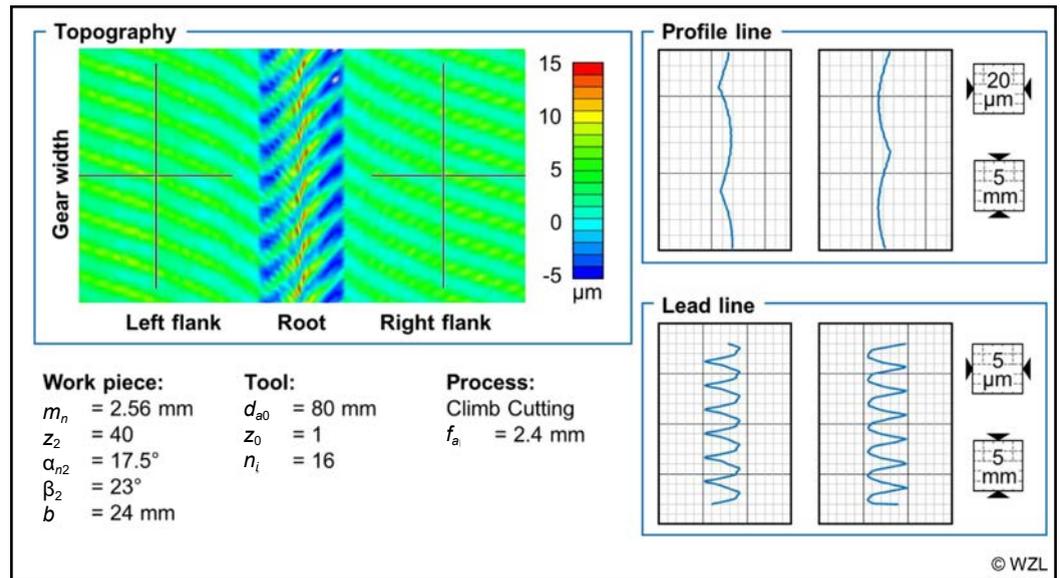


Figure 5 Topography and measurements of ideal gear.

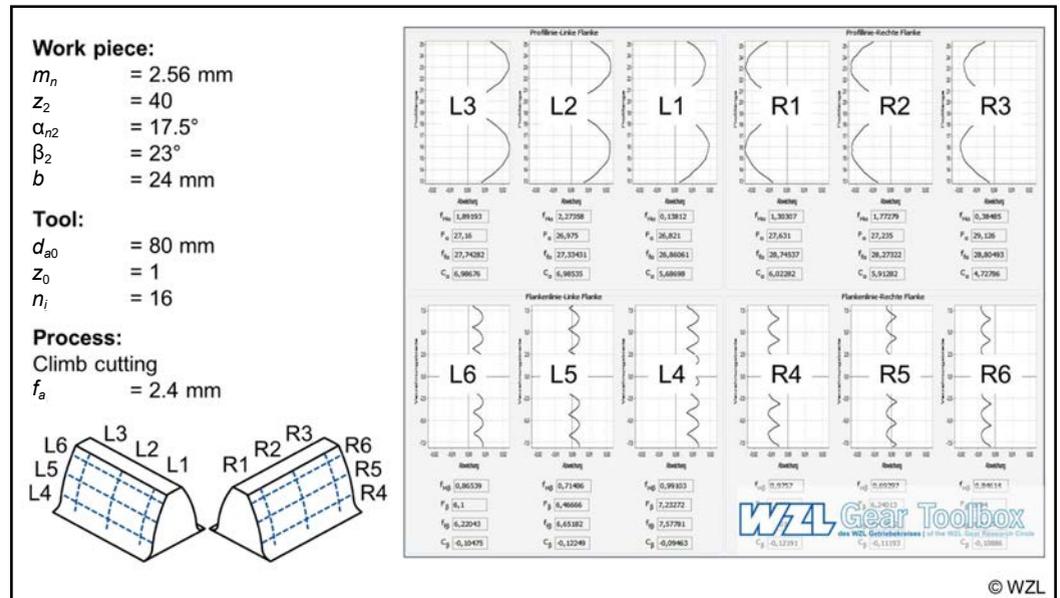


Figure 6 Graphical output of virtual measurement machine.

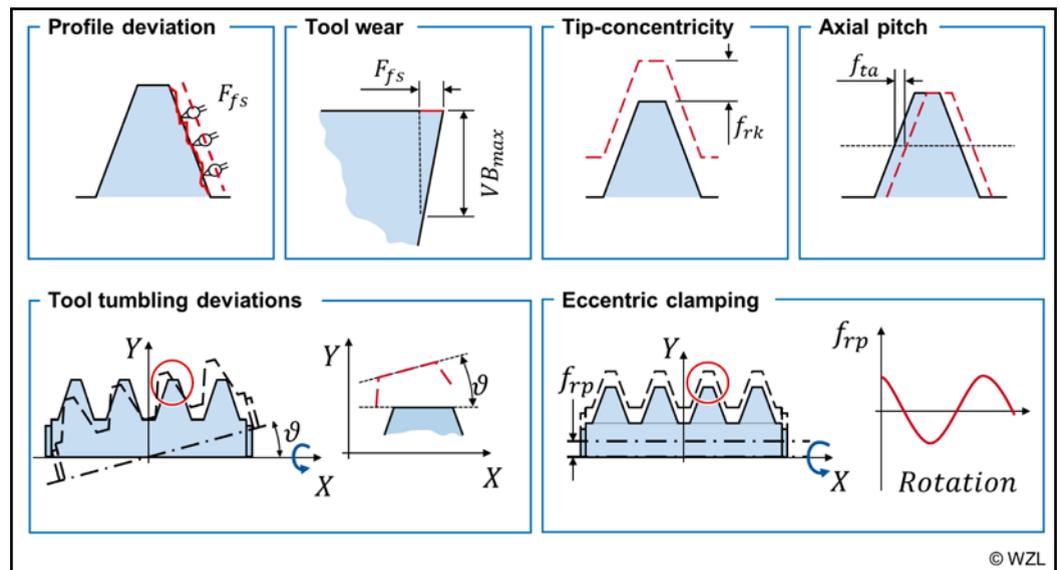


Figure 7 Profile deviations of tool and clamping errors.

tions which can occur at the tool. These are deviations of the pitch, concentricity or flank profile. These three tolerances will be investigated. The flank profile can differ from the ideal profile because of tolerances in manufacturing of the hob or due to tool wear. Besides the height of the tool profile can deviate which leads to a tip-concentricity of a single blade. This is typical if an indexable insert hob is used and a chip is stuck between the mounting and the insert. The third mentioned deviation is a variation of the pitch, which can be consolidated to the axial pitch deviation between two teeth of the hob. On the tool clamping two different types of deviations have to be taken into account. These are tumbling and eccentricity deviations, as shown in the bottom half of Figure 7. While tumbling leads to a tilt of the tool profile and to an eccentricity, which depends on the distance of the hob tooth to the axial hob center, the eccentricity causes an evenly changing radial run out of the tool profile. The described tolerances of the tool clamping also can occur as deviations of the workpiece clamping. However,

Tolerance	A	AA
Axial pitch [f_{ta}]	19 μm	11 μm
Profile deviation (tolerance) [F_p]	14 μm	8 μm
Profile deviation (tool wear) [F_{ps}]	18 μm	18 μm
Tumbling [ϑ]	5 μm	3 μm
Eccentric [f_{rp}]	25 μm	16 μm

because only one tooth is simulated in SPARTApro, these deviations cannot be evaluated in the latest version of the software and therefore are neglected.

After identifying possible tolerances and deviations of tool and clamping of the tool, the maximum of each tolerance within the tolerance field has to be determined. Tolerances of the tool are defined in DIN 3968 (Ref. 15) and depend on module and quality category of the hob. There are five grades for the quality but only the two best are relevant in practice nowadays. These quality grades are saved in the software and can be selected. In the following a gear with a module of $m_n = 2.56 \text{ mm}$ is selected.

Table 1 shows the maximum of each tolerance class for a hob with this module. For this example, the profile deviation and the eccentricity have the highest maximum values.

First, the effect of an eccentricity will be shown. In Figure 8 the results of a hobbing simulation with an eccentric clamping of $f_{rp} = 60 \mu\text{m}$ are given. This high eccentricity is greater than the allowable tolerance of the tool which is, according to DIN 3968 15 and Table 1, only $f_{rp} = 25 \mu\text{m}$. However, because of this high eccentricity the effect of the tolerance to the topography as well as the profile and lead lines can be seen directly. As it is shown the surface topography differs from the ideal surface in Figure 5. Again, lines in the mountain map represent the measurement path of profile and lead lines. Analyzing the measurements show nearly the same deviations in direction of the workpiece width as in the ideal simulation but much higher deviations of the profile. These profile deviations have a maximum value of $F_p = 32 \mu\text{m}$, which is the maximum distance to the ideal flank. A deviation such as the presented results in a gear quality of IT 10. In

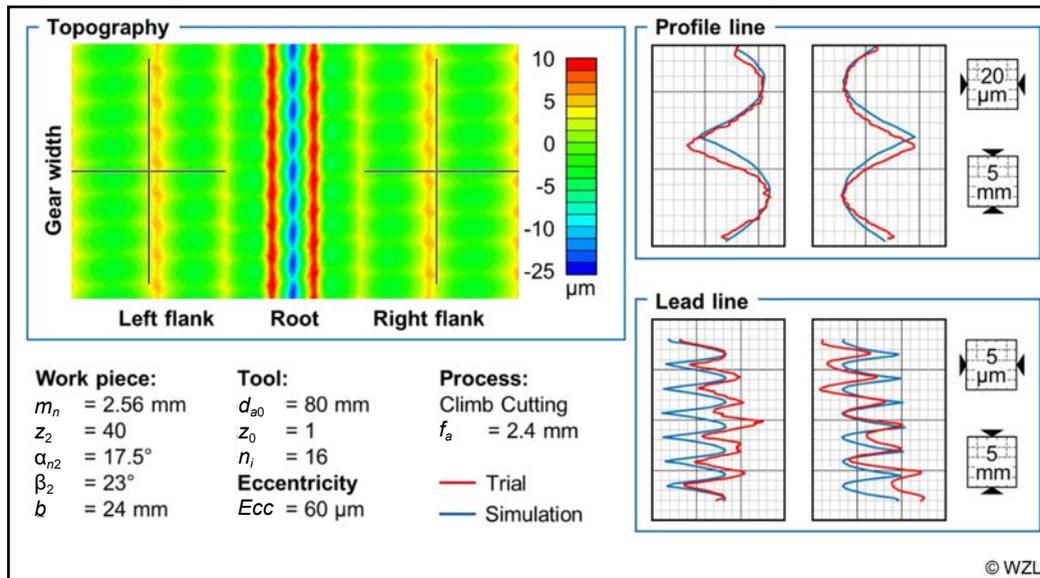


Figure 8 Resultant gear quality of hobbing with deviations.

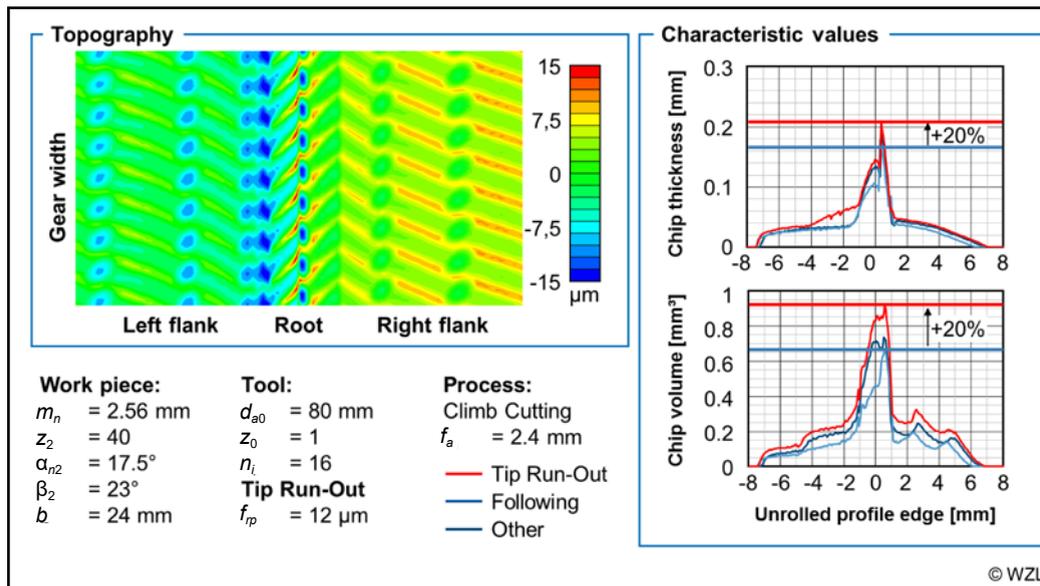


Figure 9 Gear geometry due to tip run-out of tool profile.

comparison to the simulation results (blue line), the measured profile and lead lines of a hobbing trial machined with the same eccentricity are plotted in the same graph (red line). For the profile, simulation and trial are nearly identical and, besides the non-simulated lead error, also the lead lines coincide. This comparison shows that the simulation, as well as the virtual measurement machine, are capable of simulating and analyzing deviations.

Influence of tolerances on characteristic values. After calculating the gear geometry and analyzing the resulting gear quality, the influence of tool deviations to the characteristic values in the hobbing process will be discussed. The focus in this report is the maximum chip thickness and the chip volume. The chip thickness is one of the most important characteristic values for process design in machining with defined cutting edges (Refs. 1 and 16). The chip volume is a combination of cutting length and chip thickness and correlates with cutting forces and tool load.

In the top-left picture of Figure 9, the surface topography of a simulated gear is shown. The characteristic line of contact of hob and gear is visible but the structure of the surface is intermittent by small 'buckles'. These buckles are a result of a tip concentricity at one hob tooth of $f_{rK} = 12 \mu\text{m}$.

In the diagrams in the right section of Figure 9, the characteristic values chip thickness and chip volume are plotted alongside the unrolled cutting edge. In each diagram, three graphs are shown. The solid, dark-red graph has the highest values for the hobbing tooth with a defined deviation of $f_{rK} = 12 \mu\text{m}$. Besides, a second solid-light graph displays the following profile in contact after the first one. The last graph represents all other tool profiles, which have all nearly the same values. As it is shown the values of the tooth with a radial run-out are the highest for both values, while the following tooth has the lowest. The chip thickness as well as the chip volume of the profile with a run-out deviation, is around 20% higher than of all other profiles. As expected, the values of the following profile are in both cases the same amount lower as the values of the deviation profile are

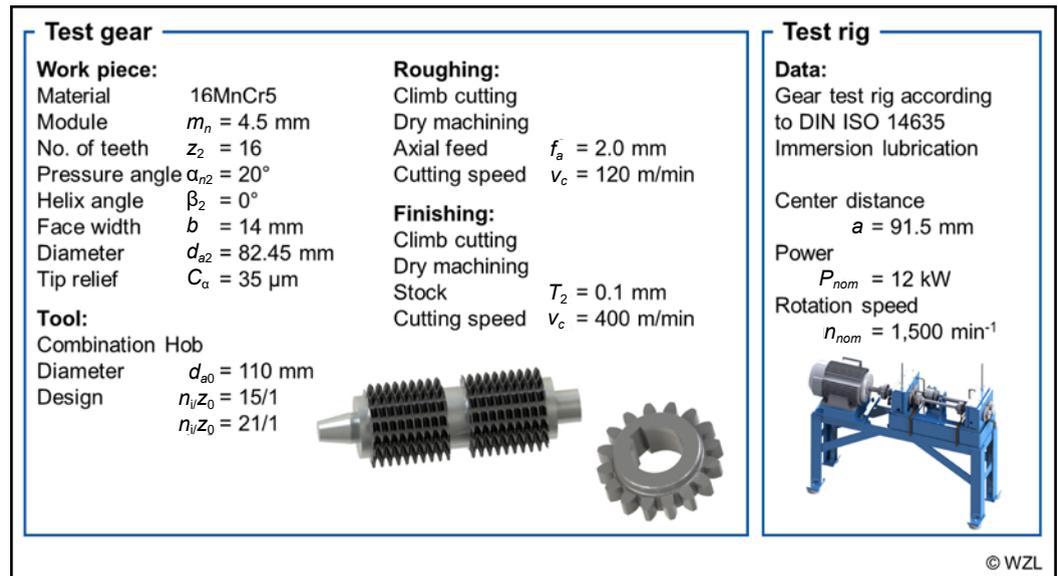


Figure 10 Test gear and test rig for pitting load carrying capacity investigation (Ref. 20).

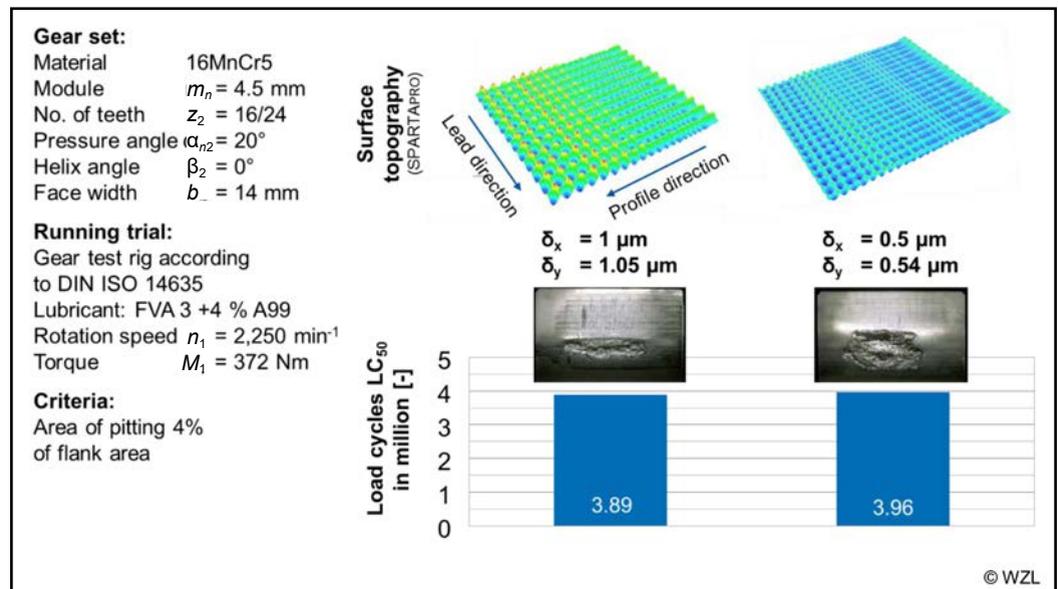


Figure 11 Influence of machining process on pitting strength (Ref. 20).

higher than the other teeth of the hob. This observation shows that there is a significant influence of tool deviations on characteristic values.

Operational Behavior of Finished Hobbed Gears

The presented method of calculation of the surface structure can be used in the design of gear finish hobbing processes. By knowing the height of the characteristic deviations for a process and tool design, each parameter can be set to an economical or technical optimum.

In the following, the operational behavior of finished hobbed gears will be discussed. Therefore, two sets of gears with different surface structures are manufactured and afterwards the load carrying capacity regarding pitting is investigated on test rigs according to DIN 14635 (Ref. 17). The geometrical data of the gear is given (Fig. 10). The rough machining of both gear sets is done with an axial feed of $f_a = 2.0 \text{ mm}$ and a cutting velocity of $v_c = 120 \text{ m/min}$. Afterwards, the stock of $T_2 = 0.1 \text{ mm}$ on the

flanks of the gear is removed in a finishing cut. Because of a modified tool profile, the tooth root is not machined in the finishing cut. In both gear sets the cutting velocity during finishing is set to $v_c = 400$ m/min, which is state of the art in gear finish hobbing (Ref. 18).

To investigate the effect of different surface structures, in the first finishing process a one start hob with 15 gashes is used. This tool design, in combination with an axial feed of $f_a = 1.16$ mm, results

in a maximum deviation due to feed marks of $\delta_x = 1.0 \mu\text{m}$. The deviation due to generating cuts is nearly the same ($\delta_y = 1.05 \mu\text{m}$). As second, process and tool design an axial feed of $f_a = 0.8$ mm and a hob with 21 gashes is used. This leads to a maximal deviation of $\delta_x = \delta_y = 0.5 \mu\text{m}$. The heat treatment after hobbing of both gear sets is low-pressure carburizing and afterwards high-pressure gas quenching. By using this method of heat treatment, a totally dry manufacturing chain of the gears can be realized (Ref. 18).

The investigations regarding the tooth contact fatigue are realized on a gear test rig according to DIN 14635 (Fig. 10, right). The test rig has an axial distance of the gears of $a = 91.5$ mm. By a mechanical load clutch, a defined torque can be applied to the gear set. The friction losses are compensated by a motor with a constant rotation speed of $n = 1,500 \text{ min}^{-1}$ and a torque of $T = 480$ Nm. All investigations are performed with the FVA 3 +4% A99 reference oil at a temperature of $T = 90^\circ\text{C}$. The end of each load carrying test is reached if the pitting has a surface of more than $V_{EZ} = 4\%$ (Refs. 19 and 18).

The simulated characteristic deviations of both gear sets as well as the lifetime of the gear are shown in Figure 11. The end of lifetime is defined by means of the reached number of load cycles at which 50% LC_{50} of the gears failed. To determine the surface structure of the gears the presented simulation method implemented in SPARTApro is used (Ref. 18).

The evaluation of LC_{50} is done with the help of a Weibull distribution grid and the probability calculation according to Weibull and Gabner. After conducting three load cycle tests for each variant, the number of load cycles LC_{50} is nearly the same for both gear sets. The lifetime of the variant with the higher characteristic deviations of around one μm was $LC_{50} = 3.89$ million load cycles and the lifetime of the other variant $LC_{50} = 3.96$ million. In all trials, the size of the flank defects for both variants are nearly the same. In Figure 11 representative pictures of the flanks are shown. These results show that an increase of the process characteristic deviations from $\delta_x = \delta_y = 0.5 \mu\text{m}$ to $\delta_x = \delta_y = 1.0 \mu\text{m}$ nearly have no effect on the resulting pitting strength of the finished hobbled gear (Ref. 18).

Because the characteristic deviations of the flank surface up to $\sigma_x = 1 \mu\text{m}$ have no effect on the achievable load cycles the increase in the axial feed can be used to get a faster and possi-

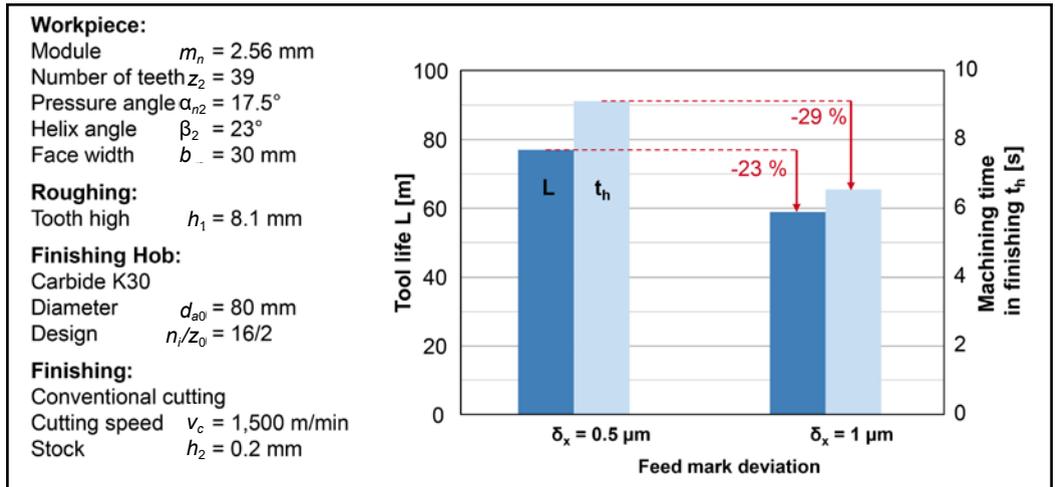


Figure 12 Comparison of tool life and machining time in finishing (Ref. 18).

bly more economical process. Figure 12 shows the effect of the increased axial feed on the tool life and the machining time. During the machining with the lower axial feed of $f_a = 0.67$ mm the maximum chip thickness which can be calculated with the help of SPARTApro is $h_{cu} = 13 \mu\text{m}$. Comparing this to the higher maximum chip thickness of $h_{cu} = 20 \mu\text{m}$ in the machining with an axial feed of $f_a = 1.0$ mm explains why there is a decrease of the tool life by 23%. But at the same time also the machining time decreases by nearly 30% which is a significant gain in productivity. Finally, the process designer has to choose between low machining times and higher tool life. A change of the pitting strength due to the increased axial feed could not be shown.

Summary and Outlook

Until now, calculating characteristic values for the gear hobbing process has neglected the possibility of inaccuracies and tolerances of the tool as well as of the clamping. To consider these tolerances in early stages of the process design, a simulation has been developed and presented. The model simulates the hobbing process and calculates established characteristic values such as the chip thickness h_{cu} and the cutting length l_c . Furthermore, the topography of the gear flanks and the root geometry is analyzed and depicted. The software can calculate profile and lead lines of the gear. Furthermore, the roughness of the tooth root geometry can be measured. Besides calculating characteristic values, this information can be used to design machining processes, like the gear finish hobbing. Gear finish hobbing enables the implementation of a resource saving and cost effective process chain for gear manufacturing industry. Production-related product properties are resulting from the gear finish hobbing process and can have an influence on the gear's application characteristics. Some of these properties like the characteristic deviations can be predicted with the presented simulation model. But the effect of these on the application characteristics are unknown. Therefore, there is no basis of decision-making in the industrial environment. This knowledge is required for implementing this technology. To gain first knowledge on the operational characteristics of finished hobbled gears, the pitting load carrying capacity of finish hobbled gears, depending on the process-related geometrical deviations, was

investigated. The final evaluation states that a high optimizing potential of can be used through an adapted process design of gear finish hobbing.

In conclusion, it remains unclear which impact the increasing tool wear has on the application characteristic of finish hobbled gears. In previous studies, a new tool has always been used for the manufacturing of experimental gearings. Furthermore, an analysis of the maximum permissible process-related deviation of gear finish hobbled gears on the pitting load carrying capacity is useful. Provided that a maximal permissible limit of the process-related deviations is known, the productivity of this process can be increased by a further axial feed.

Acknowledgement. *The investigations described in the present report were conducted as a part of the project sponsored by the Gear Research Circle. The investigations described in the present report were conducted as a part of the projects (IGF 17007 N and 17262 N) sponsored by VDW, FVA and the German Federation of Industrial Research Associations (AiF).* 

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Dr.-Ing. Deniz Sari in 2012 received his degree in mechanical engineering from the RWTH Aachen University. He began his career as a research engineer and a group leader of the Gear Manufacturing Group of Laboratory of Machine Tools and Production Engineering (WZL) of RWTH Aachen University. In 2016 he earned his Doctorate—with a core emphasis on gear finish hobbing—in Mechanical Engineering (Dr.-Ing./Phd) from the RWTH Aachen University. Also in 2016 Sari began work as gear technology manager for Samputensili (Bentivoglio Italy) and its joint venture, Star SU.



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Prof. Dr.-Ing. Christian Brecher has since January 2004 been Ordinary Professor for Machine Tools at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen, as well as Director of the Department for Production Machines at the Fraunhofer Institute for Production Technology IPT. Upon finishing his academic studies in mechanical engineering, Brecher started his professional career first as a research assistant and later as team leader in the department for machine investigation and evaluation at the WZL. From 1999 to April 2001, he was responsible for the department of machine tools in his capacity as a Senior Engineer. After a short spell as a consultant in the aviation industry, Professor Brecher was appointed in August 2001 as the Director for Development at the DS Technologie Werkzeugmaschinenbau GmbH, Mönchengladbach, where he was responsible for construction and development until December 2003. Brecher has received numerous honors and awards, including the Springorum Commemorative Coin; the Borchers Medal of the RWTH Aachen; the Scholarship Award of the Association of German Tool Manufacturers (Verein Deutscher Werkzeugmaschinenfabriken VDW); and the Otto Kienzle Memorial Coin of the Scientific Society for Production Technology (Wissenschaftliche Gesellschaft für Produktionstechnik WGP).



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