Characteristic Value-Based Process Design of Gear Hobbing Processes with Radial Infeed

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Introduction

In industrial practice, axial gear hobbing is generally used as common process variant of the gear hobbing process. If an interference is present near the gear teeth, the process is limited in terms of applicability as the required infeed path is no longer available. For components with interference close the gear, alternative soft machining processes, e.g., gear skiving or shaping, are often used. One way of countering the limitation due to the limited working space is to adjust the infeed direction of the tool during the infeed phase. Since only pure roughing and no profiling of the gap takes place during the infeed, a change in the feed amount and feed direction has no influence on the shape and dimensional accuracy of the gear flank. To avoid a collision with the interference, it is therefore possible to carry out the infeed not axi ally, but radially or diagonally at any infeed angle φ to the workpiece axis (Fig. 1).

In contrast to axial hobbing, there are no knowledge-based methods for designing the process for radial or diagonal infeed strategies, but only rule of thumb or empirical values. Scientific studies on the efficiency of the hobbing process under consideration of the infeed strategy are only available to a limited extent. In the research project "Design of gear hobbing processes with variable infeed," on which this report is based, an analysis of the technological interdependencies for different infeed angles is currently conducted. On the basis of the results, it will be possible to produce parameters and models for the design of the hobbing process for any infeed strategy in future.

State of the Art

The design of axial hobbing processes is generally based on various parameters, such as the maximum feed mark depth δ_x or the maximum tip chip thickness $h_{cu,max}$. Since no profiling of the final gap takes place during the infeed, a design of the infeed according to the height of the feed marks is not relevant. For the maximum tip chip thickness, a mathematical correlation according to Equation 1 was derived by Hoffmeister (Ref. 1).

$$h_{cu,max} = 4.9 \cdot m_n \cdot z_2^{(9.25 \cdot 10^{-3} \cdot \beta_2 - 0.542)} \cdot e^{-0.015 \cdot \beta_2} \cdot e^{-0.015 \cdot x} \cdot \left(\frac{r_{a0}}{m_n}\right)^{-8.25 \cdot 10^{-3} \cdot \beta_2 - 0.225} \cdot i^{-0.877} \cdot \left(\frac{f_a}{m_n}\right)^{0.511} \cdot \left(\frac{T}{m_n}\right)^{0.319} \tag{1}$$

$h_{cu,max}$	[mm]	Maximum tip chip thickness
z_2	[-]	Number of workpiece teeth
x	[-]	Profile shift coefficient
i	[-]	Effective number of gashes
T	[mm]	Cutting depth
m_n	[mm]	Module
β_2	[rad]	Helix angle
r_{a0}	[mm]	Tip radius of the hob
f_a	[mm]	Axial feed

However, this equation was developed for the full-cut in axial gear hobbing and is not permissible for a design of the infeed under consideration of any infeed angle. For the design of the radial infeed, a design according to Equation 2 is recommended in the literature (Ref. 4). According to this method, the feed ratio f_r to f_a is chosen accordingly to the ratio of the respective infeed path E to the cutting depth T. This way, a process

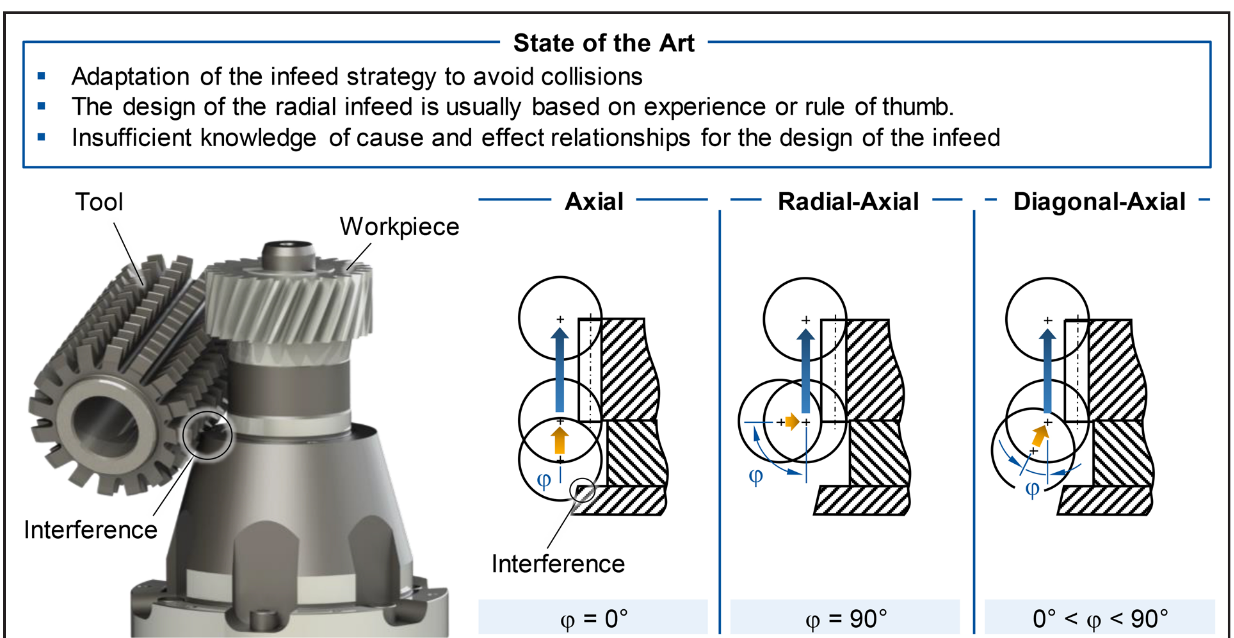


Figure 1 Motivation and challenge.

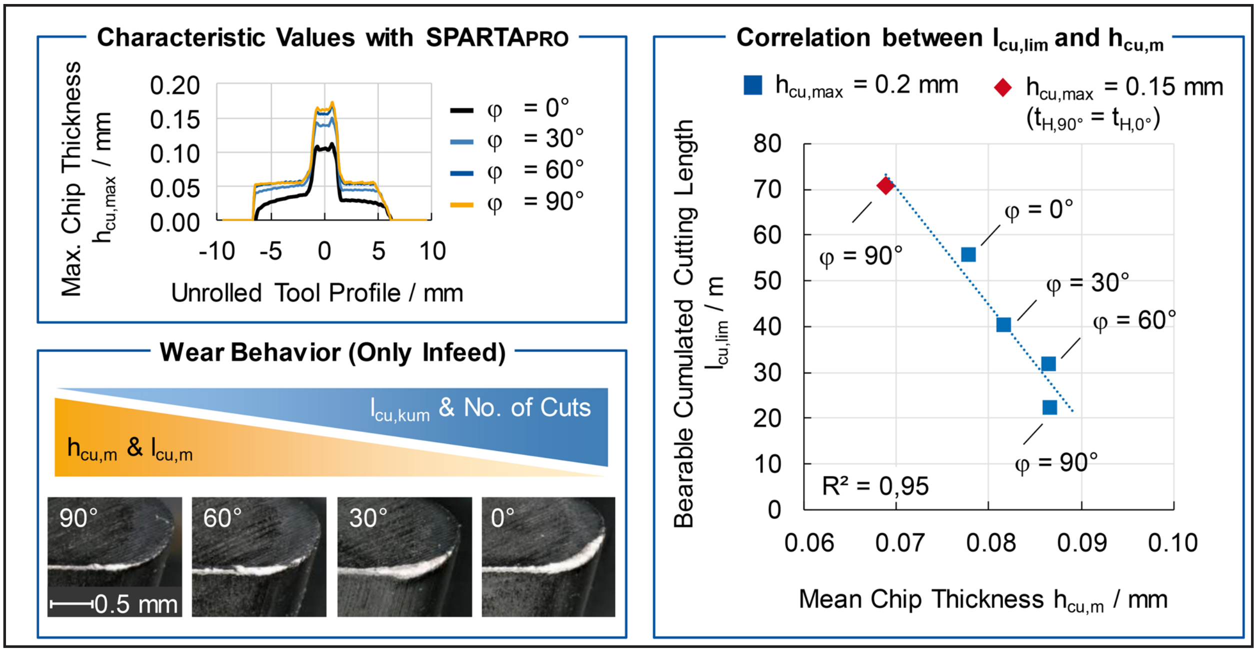


Figure 2 Influence of the infeed angle on tool wear (Ref. 5, Ref. 6).

design with a constant process time is realized. However, with this design method the technological interdependencies during machining are not taken into account and no conclusions can be drawn regarding the tool load.

$$f_r = f_a \cdot \frac{T}{E} \tag{2}$$

f_r	[mm]	Radial feed
T	[mm]	Cutting depth
f_a	[mm]	Axial feed
E	[mm]	Axial infeed path

One possibility of determining the characteristic chip values and designing the hobbing process is given by the manufacturing simulation software *SPARTApro*. The workpiece is abstracted by a defined number of parallel planes, which are penetrated by the tool profile under simulation of the machine kinematics. The intersection results in the penetration area which corresponds to the undeformed chip geometry of the respective generating position in the process. The determined chip characteristics allow an assessment of the loads acting on the hob during the cutting process (Ref. 2).

With the help of *SPARTApro*, Weber analyzed the cutting conditions during gear hobbing for different infeed angles for the first time. For a design according to a constant main time t_H, chip characteristics for different infeed angles were determined individually by means of the geometric penetration calculation. In fly-cutting trials the number of machined workpieces N, from hereafter expressed as tool life N, was determined for this design with increasing infeed angle. By interpolating the previously determined chip thicknesses, a design with constant maximum chip thickness $h_{cu,max}$ was realized in a subsequent test series. With this method, a reduction of the main time t_H with increasing infeed angle φ was achieved, but there was a significant decrease in the tool life N. Furthermore, the investigations showed a linear relationship between the mean chip thickness $h_{cu,m}$ and the tool life N. Based on this correlation, the process could be designed according to the tool life and a good approximation of the tool life for the radial infeed to the tool life of the axial infeed was be achieved. However, the design methods described require a laborious iteration of the characteristic values, which makes a practicable design of the infeed more difficult. (Ref. 7).

Troβ extended the manufacturing simulation software *SPARTApro* by a calculation method, which enables an automated penetration calculation for any infeed angle φ. This method was used to analyze the influence of the infeed angle φ on the chip parameters and the associated tool load (Fig. 2, top left). For the investigated gear case, a regression analysis was conducted on the basis of the results and a mathematical relationship was derived to describe the maximum chip thickness $h_{cu,max}$ as a function of the infeed angle φ and the path feed f_b. This equation allowed a characteristic value-based design of the infeed on the basis of the maximum chip thickness $h_{cu,max}$. (Ref. 5).

Based on the theoretical considerations, fly-cutting trials were carried out to investigate the influence of the infeed angle φ on tool wear. In the tests, only the infeed was machined in order to determine the influence of the infeed angle φ on tool wear detached from the workpiece width. In a design based on the maximum chip thickness hcu,max, a decrease in the tool life N was observed with increasing infeed angle φ. In the case of infeed angles with a large axial component, the tool is worn due to crater and flank wear as a result of the high number of load cycles and cumulative cutting arc length (Fig. 2, bottom left). With an increasing infeed angle φ the mean chip thickness $h_{cu,m}$ and the mean chip length $l_{cu,m}$ increase, which results in an increase of the tool load and a faster wear of the tool on the flank. In an additional test, the radial infeed was designed so that the machining time was identical to that of the axial infeed. This showed a slight increase of the tool life N and thus, potential for saving tool costs (Ref 6. TROß19b).

In contrast to the investigations carried out by Weber, a linear relationship between the mean chip thickness $h_{cu,m}$ and the tool life N could only be determined to a limited extent. The regression line has a coefficient of determination of $R^2 = 0.79$ if all determined data points, including the additional test, are taken into account. If, on the other hand, the bearable cumulated cutting length $l_{cu,lim}$ is plotted over the mean chip thickness, the linear correlation becomes more concise and the coefficient of determination is $R^2 = 0.95$ (Fig. 2, right). The mean chip thickness $h_{cu,m}$ and the bearable cumulated cutting length $l_{cu,lim}$ have a high potential for designing the infeed according to the tool life (Ref. 7).

The previous investigations on the influence of the infeed angle on tool wear only consider machining in the infeed phase and not the subsequent axial machining with final profiling of the workpiece. Furthermore, the knowledge gained from the fly-cutting trial in the hobbing process must be validated in order to make a design recommendation.

Objective and Approach

The objectives and approach of the research project IGF 18517 are shown in Figure 3. As can be seen from the state of the art, the required calculation method for the automated determination of the chip characteristics, taking into account any infeed angle, has already been developed. The method allows the characteristic value-based design of the hobbing process under consideration of any infeed angle. In theoretical investigations, the influence of the infeed angle on the chip characteristics and on the associated tool load was analyzed with the help of the extended calculation method. In subsequent fly-cutting trials, the influence of the infeed angle on tool wear shall be empirically determined on the basis of theoretical considerations. For this purpose, an isolated analysis of the cutting conditions during the infeed phase has already been carried out.

The present report focuses on the combined consideration of the infeed and the subsequent axial machining with additional variation of the workpiece width in order to evaluate the influence of the infeed with increasing or decreasing full cut area. The findings from the fly-cutting trials and the theoretical considerations will then be validated in gear hobbing tests. For this purpose, the process will be designed on the basis of characteristic values using the calculation method developed within the research project. The knowledge gained will be combined in a design method, which enables a knowledge-based design of the infeed during gear hobbing.

Fly-Cutting Trials

In order to evaluate the combined influence of the infeed and the subsequent axial machining, analogy tests were carried out in fly-cutting trials. In addition to the variation of the infeed angle, the workpiece width and the machining direction (climb and conventional cutting) were also varied in order to determine any differences in wear behavior.

Experimental Setup and Tool Life Prognosis.

The combination of tool and workpiece used for the investigations was chosen in analogy to the investigations for the isolated consideration of the infeed in (Ref. 6) (Fig. 4). The workpiece material corresponds to case-hardened steel typical for gears with the abbreviation 20MnCr5 and has a fine-grained, uniform, ferritic-pearlitic structure. The Brinell hardness of the workpiece was measured with 187 HB on the workpiece surface and converted to a tensile strength of $R_m \approx 630$ MPa according to DIN EN ISO 18265 (Ref. 3). The analogy test imitates a 3-start, right-hand hob with a tip diameter of $d_{a0} = 110$ mm and a number of gashes of $n_{i0} = 20$. The tool was manufactured from powder metallurgical high-speed steel (PM-HSS) and coated with a commercially available (Al,Cr)N. The layer thickness was $s = 2.5\,\mu m$ on the rake face and flank. The initial micro-geometric condition of the fly-cutter is documented in the upper section of Figure 4. The roughness of the rake face and flank as well as the cutting edge radius, the K-factor and the chipping are displayed.

The trials were carried out in dry cutting condition on a Gleason-Pfauter P400 gear hobbing machine. A maximum width of flank wear VBmax = 120 µm and a maximum depth of crater KTmax = 100 µm were defined as wear criteria. The

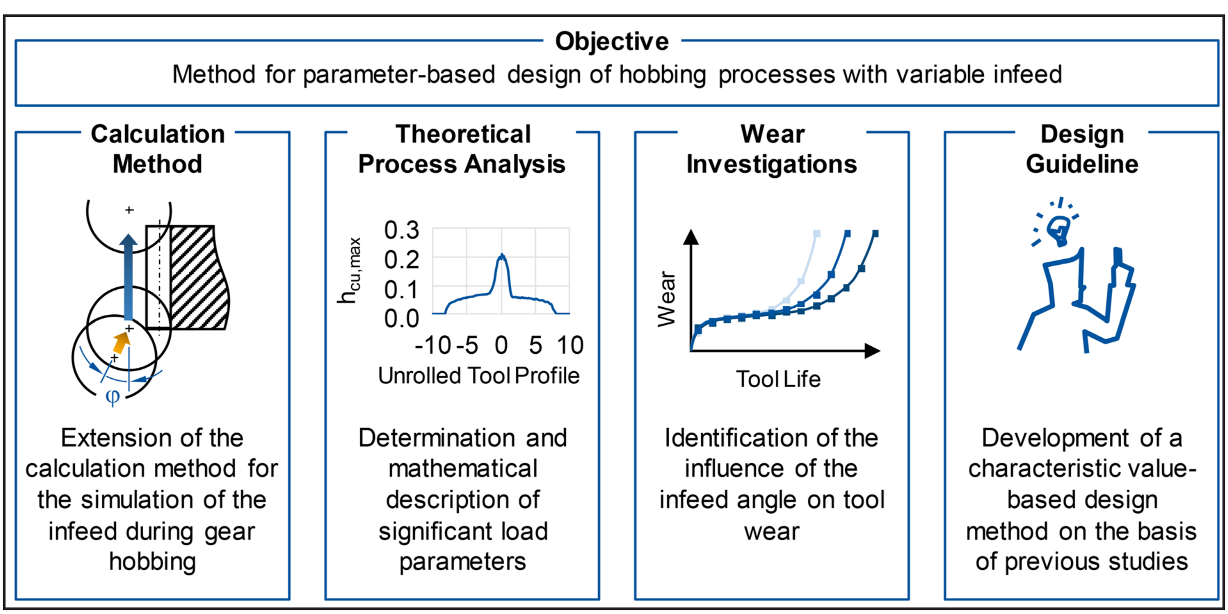


Figure 3 Objective and approach of the research project IGF 18517.

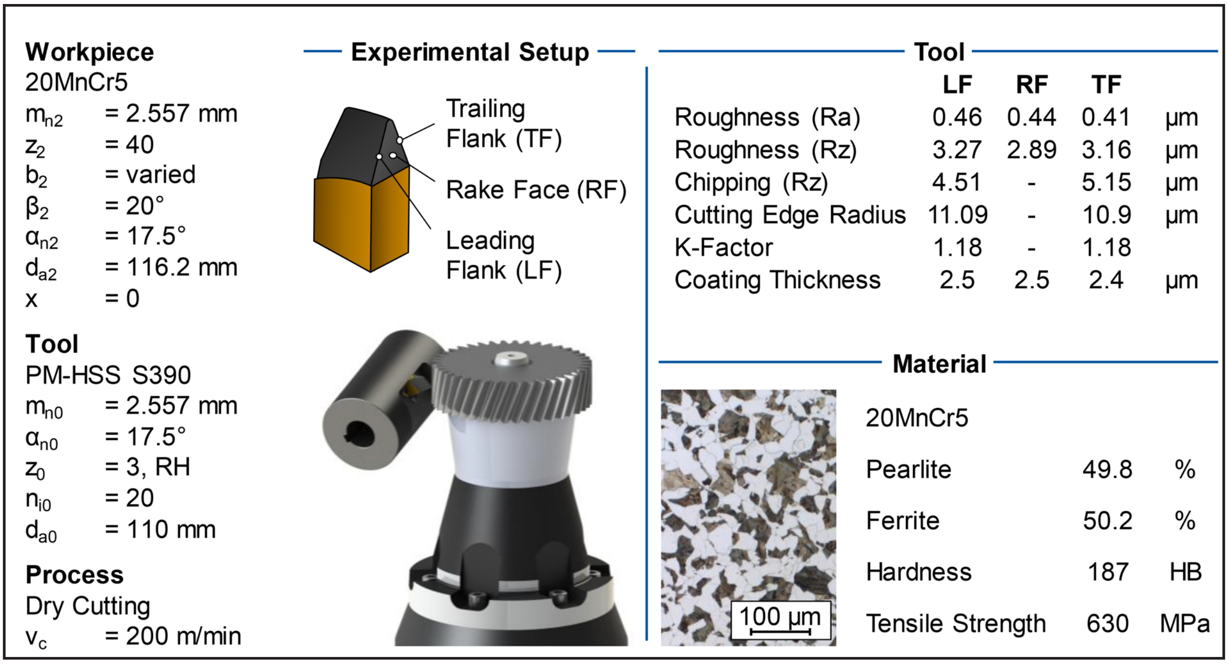


Figure 4 Experimental setup, tool and workpiece characterization.

width of flank wear VB was documented on the trailing (TF) and leading (LF) flank and on the tip clearance surface. The depth of crater was measured on the rake face (RF). For the test, a cutting speed of $v_c = 200$ m/min and a maximum tip chip thickness according to Hoffmeister of $h_{cu,max,Hoff} = 0.2$ mm were selected. In order to achieve the defined maximum chip thickness $h_{cu,max,Hoff} = 0.2$ mm, the required axial feed f_a in full-cut is $f_a = 1.95$ mm. For the climb cut trials, the workpiece width ($b_2 = 10$ mm, $b_2 = 30$ mm and $b_2 = 50$ mm) and the infeed angle ($\varphi = 0°$ and $\varphi = 90°$) were varied (Fig. 5). For workpieces with $b_2 = 30$ mm, the infeed was also investigated at $\varphi = 45°$.

The path feed f_b in the infeed phase was designed with consideration of the infeed angle φ in such a way, that maximum chip thickness $h_{cu,max}$ is the same in the infeed and in the subsequent axial machining. The extended calculation method from *SPARTApro* was used to determine the corresponding path feeds. In this case, the feed rates are $f_{b,0} = 1.95$ mm for the axial infeed, $f_{b,90} = 0.75$ mm for the radial infeed and $f_{b,45} = 0.9$ mm for the infeed at an angle of $\varphi = 45°$. Corresponding to the investigations in climb cut, trials were conducted on workpieces with $b_2 = 30$ mm in conventional cutting with otherwise identical process parameters.

In addition to the experimental design, the main time of the different variations is shown in Figure 5. The machining time of the variants with $\varphi = 90°$ and $\varphi = 45°$ for the respective workpiece width refers to the variant with $\varphi = 0°$. With a design according to the maximum chip thickness, the required machining time in the infeed and thus, also the total machining

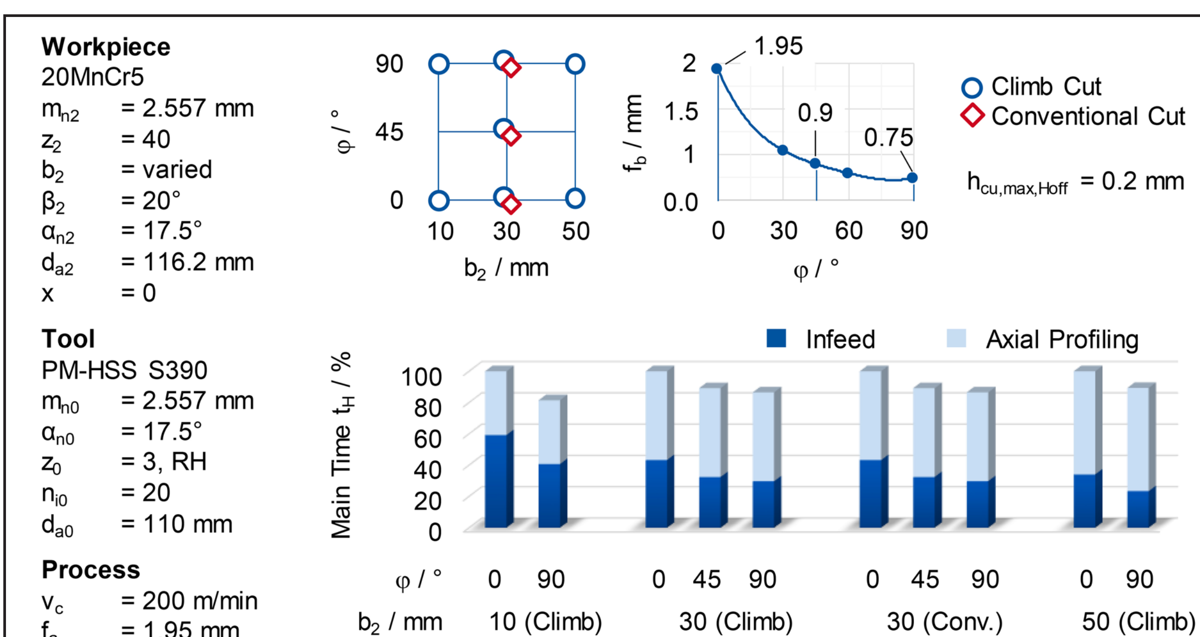
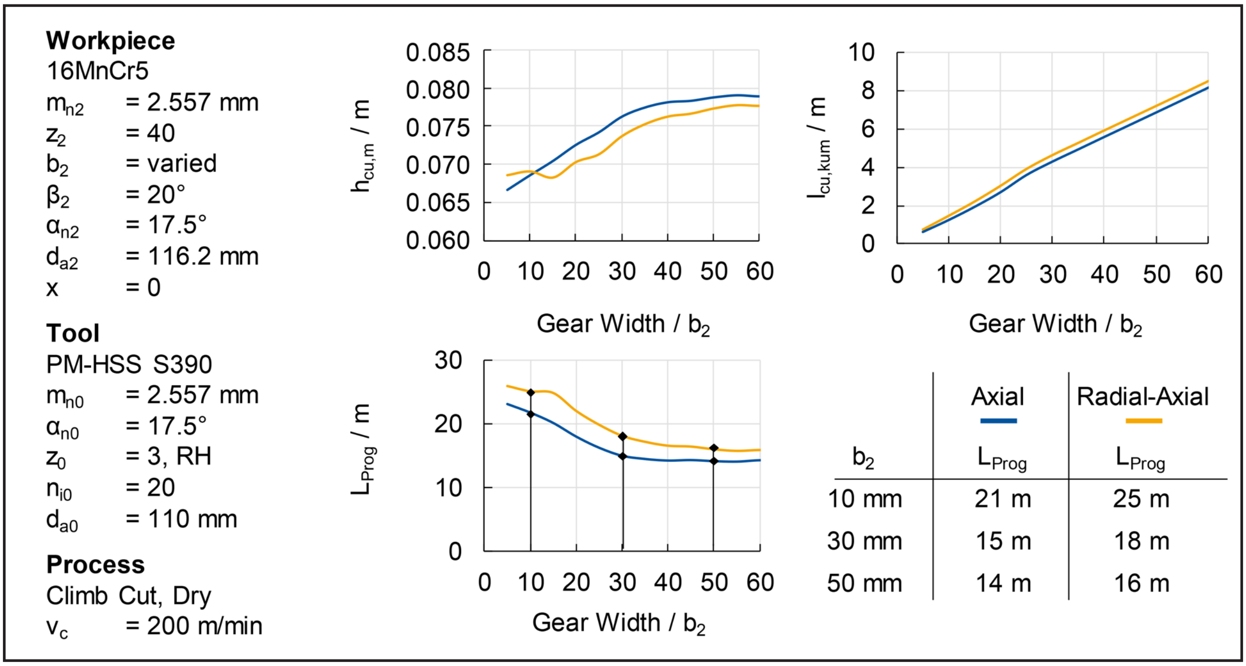


Figure 5 Design of experiments and resulting main times.

time decreases continuously with increasing infeed angle. The machining time for radial-axial process control corresponds to between 80% and 90% of the machining time for axial process strategy at the test points under consideration. This indicates a potential for increasing the process productivity.

Based on the investigations of the isolated influence of the infeed and the determined linear correlation between the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$, a tool life prognosis was performed for the following experiments. Depending on the workpiece width b_2, the geometric parameters $h_{cu,m}$ and $l_{cu,kum}$ were determined using *SPARTApro* (Fig. 6). Depending on the mean chip thickness $h_{cu,m}$, the bearable cumulated cutting length $l_{cu,lim}$ can either be taken graphically from the diagram in Figure 2 or, if the regression parameters a and b are known, calculated according to Equation 3. By inserting the determined parameters in Equation 4, the tool life N and, based on this, the machined length L, hereafter expressed as tool life L, can be determined according to Equation 5.



b_2	Axial L_{Prog}	Radial-Axial L_{Prog}
10 mm	21 m	25 m
30 mm	15 m	18 m
50 mm	14 m	16 m

Figure 6 **Tool life prognosis.**

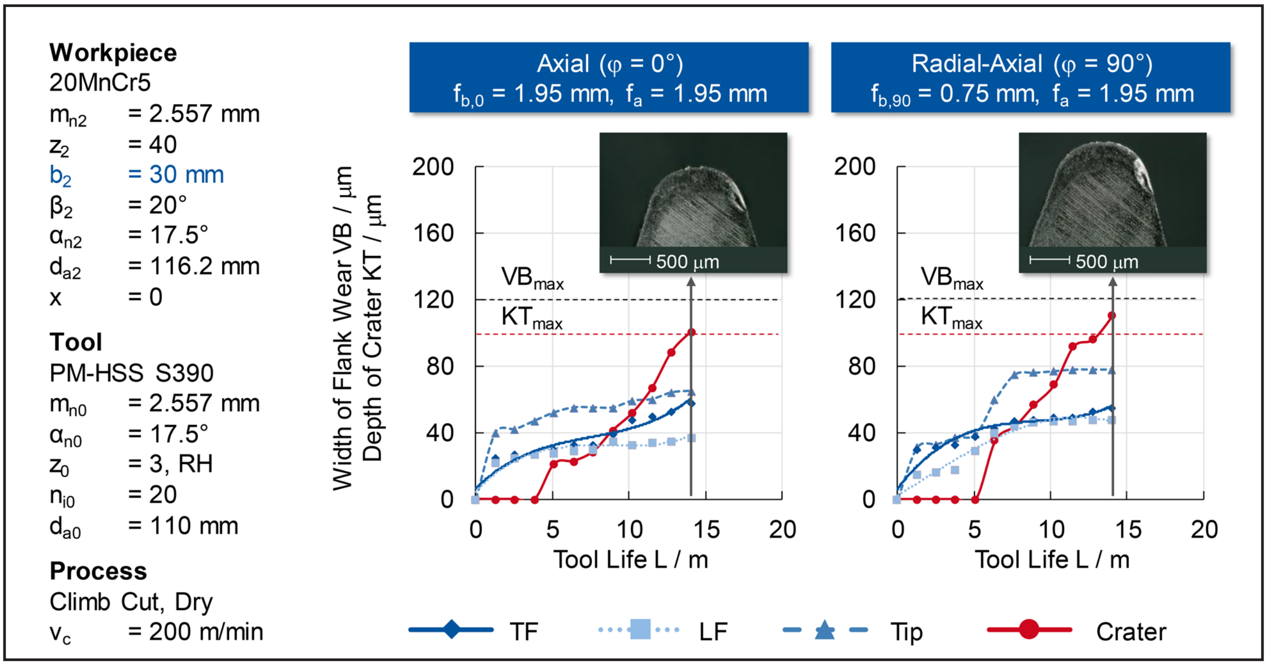


Figure 7 **Wear behavior for axial and radial-axial process control (b_2 = 30 mm) for a design of the infeed according to the maximum chip thickness $h_{cu,max}$ = 0.2 mm.**

$$l_{cu,lim} = a \cdot h_{cu,m} + b \quad (3)$$

$$N = \frac{l_{cu,lim}}{l_{cu,kum} \cdot z_2} \quad (4)$$

$$L = N \cdot \frac{b_2 \cdot z_2}{\cos(\beta)} \quad (5)$$

$l_{cu,lim}$	[mm]	Bearable cumulated cutting length
$h_{cu,m}$	[mm]	Mean chip thickness
$l_{cu,kum}$	[mm]	Cumulative cutting arc length
L	[m]	Tool Life (machined length)
β	[°]	Workpiece helix angle
a, b	[mm]	Empirical regression parameters
N	[-]	Tool Life (machined workpieces)
z_2	[-]	Number of teeth
b_2	[mm]	Workpiece width

For the trials with axial and radial-axial process control in climb cut, the predicted tool life L_{Prog} is plotted over the workpiece width. With a workpiece width of $b_2 = 10$ mm, the largest tool life is expected with $L_{Prog} = 21$ m for the axial and $L_{Prog} = 25$ m for the radial-axial variant. With increasing workpiece width, the predicted tool life decreases degressively to $L_{Prog} = 15$ m or $L_{Prog} = 18$ m for $b_2 = 30$ mm and $L_{Prog} = 14$ m or $L_{Prog} = 16$ m for $b_2 = 50$ mm. For all cases, the predicted tool life of the radial-axial variant is higher than of the axial variant due to a lower mean chip thickness $h_{cu,m}$.

Discussion of the Fly-Cutting Trials

The wear curves of the climb cutting trials with $b_2 = 30$ mm are shown for $\varphi = 0°$ and $\varphi = 90°$ in Figure 7. With a design of the infeed according to the maximum chip thickness $h_{cu,max}$, reaching the permissible depth of crater $KT_{max} = 0.1$ mm led to the end of the test in both cases. The documented wear curves at the leading and trailing flank as well as at the tool tip show a qualitatively and quantitatively similar curve in comparison of the radial to the axial variants. An exception to this is the course of the width of flank wear at the tip clearance surface. In the tool life range from L = 5 m to L = 7.7 m, the width of flank wear at the tip of the radial variant was doubled from VB = 40 mm to VB = 80 mm, which was due to a stochastic breakout of the cutting edge. As the tests were continued, a linear wear development without further, sudden damage occurred. In contrast to the investigations on the isolated influence of the infeed area, no significant influence of the infeed strategy on the tool wear could be determined. This can be explained by the fact, that with increasing workpiece width the proportion of the full cut area increases continuously and the influence of the infeed decreases accordingly.

The phenomenon, that the influence of the infeed decreases with increasing workpiece width and that the difference between the wear characteristics of an axial and a radial-axial process control decreases is also supported by the test results for the gear with $b_2 = 50$ mm. The wear development of the tools for the climb cutting trials with $b_2 = 50$ mm for $\varphi = 0°$ and $\varphi = 90°$ are displayed in Figure 8. Qualitatively, the wear behavior of the variants hardly differ from each other. Quantitatively, there is a difference between the curves due to a deviating initial wear on the tip clearance surface and on the flanks.

The difference in the wear behavior should be more significant when machining narrower workpieces. So far, this could not be verified, since in the investigations on the workpieces with $b_2 = 10$ mm the tools reached an end of life due to unsystematic breakouts at the tip cutting edge. These tests must be repeated in the future in order to verify or falsify the hypothesis.

The tool lives determined in the wear investigations for the combined influence of infeed and axial machining until reaching the tool life criterion are displayed in Figure 9. Machining the workpieces with a width of $b_2 = 10$ mm resulted in a tool failure due to breakouts at the tool tip after a comparatively low tool life of $7.4\,\text{m} < L < 8.8\,\text{m}$ in both axial and radial-axial process control. When machining the workpieces with $b_2 = 30$ mm,

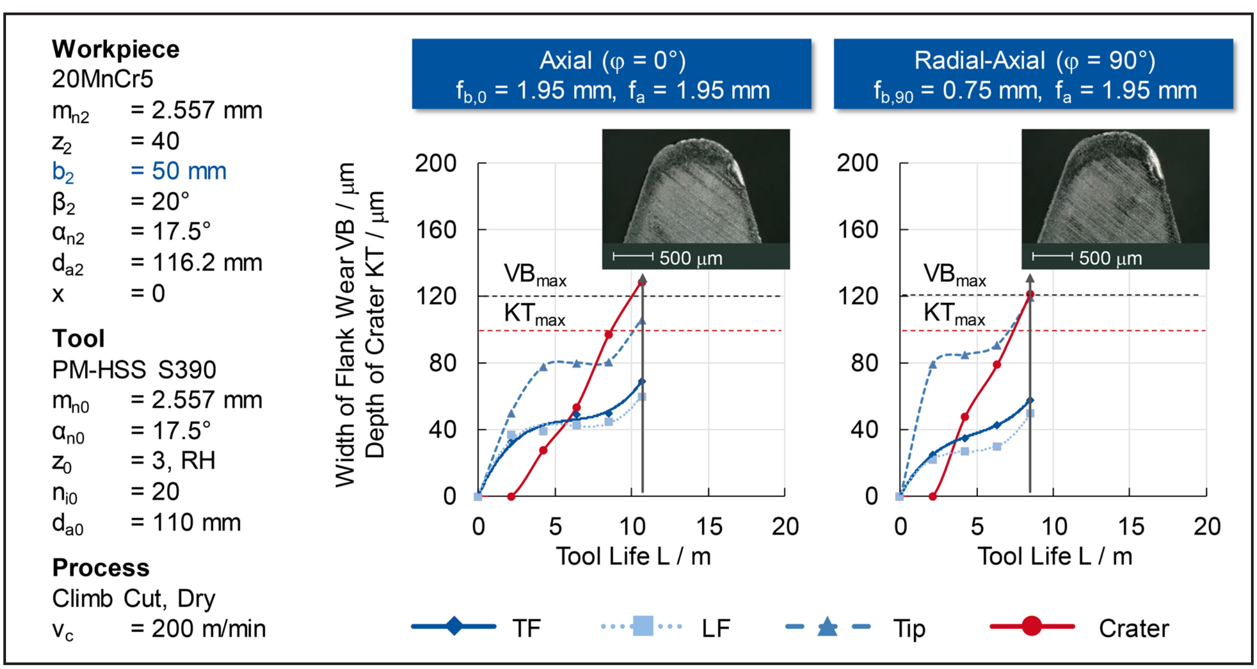


Figure 8 **Wear behavior for axial and radial-axial process control ($b_2 = 50$ mm) for a design of the infeed according to the maximum chip thickness $h_{cu,max} = 0.2$ mm.**

a radial-axial strategy achieved an identical tool life with $L = 14.4$ m as the axial process control while simultaneously increasing productivity. Compared to the predicted tool life $L_{prog} = 15$ m or $L_{prog} = 18$ m, a lower tool life was achieved in the experiment. Furthermore, no difference in tool life could be determined between the radial and radial-axial variants. A design with $\varphi = 45°$ infeed angle resulted in a lower tool life with $L = 11.8$ m in direct comparison. The tool life could be further increased by machining in conventional cut. While for the variant with axial infeed the tool life was $L = 17$ m, the largest tool life of all variants with $L = 19.6$ m could be achieved with radial-axial process control. However, a diagonal-axial machining strategy resulted in an abortion of the experiment as a result of premature tool failure due to cutting edge breakouts. With an increase in the workpiece width from $b_2 = 30$ mm to $b_2 = 50$ mm, a decrease in the tool life was recorded. This result is also in accordance with the previously carried out tool life prognosis. In contrast to the prognosis, the tool lives determined in the test are lower than those prognosticated and the tool life of the axial variants was higher than the tool life of the radial-axial variants.

To verify the linear correlation of the bearable cumulated cutting length $l_{cu,lim}$ with the mean chip thickness $h_{cu,m}$, the individual tool lives L of the variants were converted into the bearable cumulated cutting length $l_{cu,lim}$ according to Equation 4 and Equation 5 and plotted over the corresponding mean chip thickness $h_{cu,m}$. In this case, too, the bearable cumulated cutting length $l_{cu,lim}$ correlates with the mean chip thickness h (Fig. 10). The tools which failed due to breakouts were excluded from the evaluation.

In comparison to the investigations on the isolated influence of the infeed angle, the regression line shows a different slope

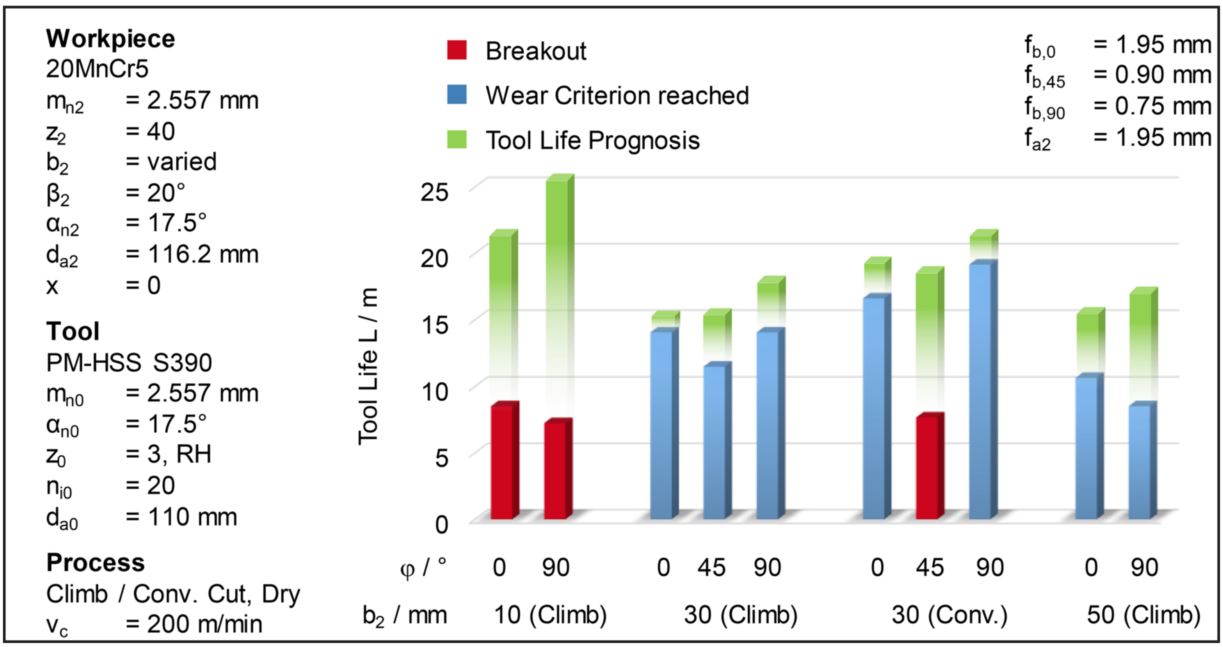


Figure 9 Comparison of the tool life of the investigated variants.

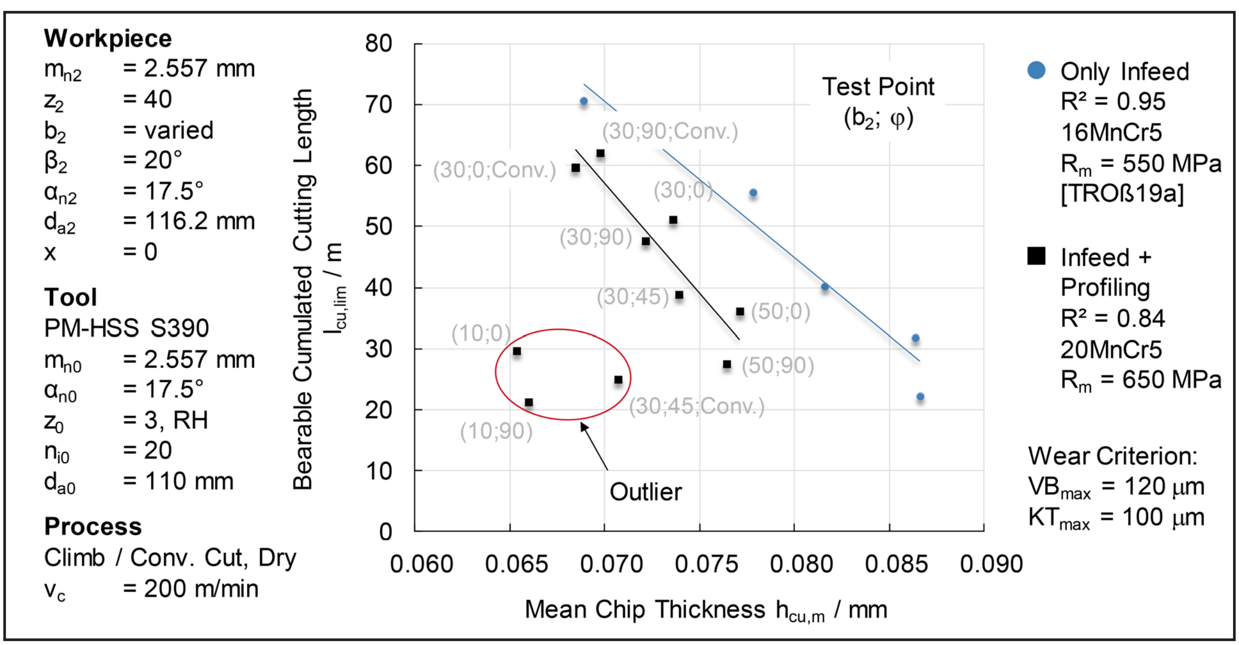


Figure 10 Correlation of the total arc length with the mean chip thickness.

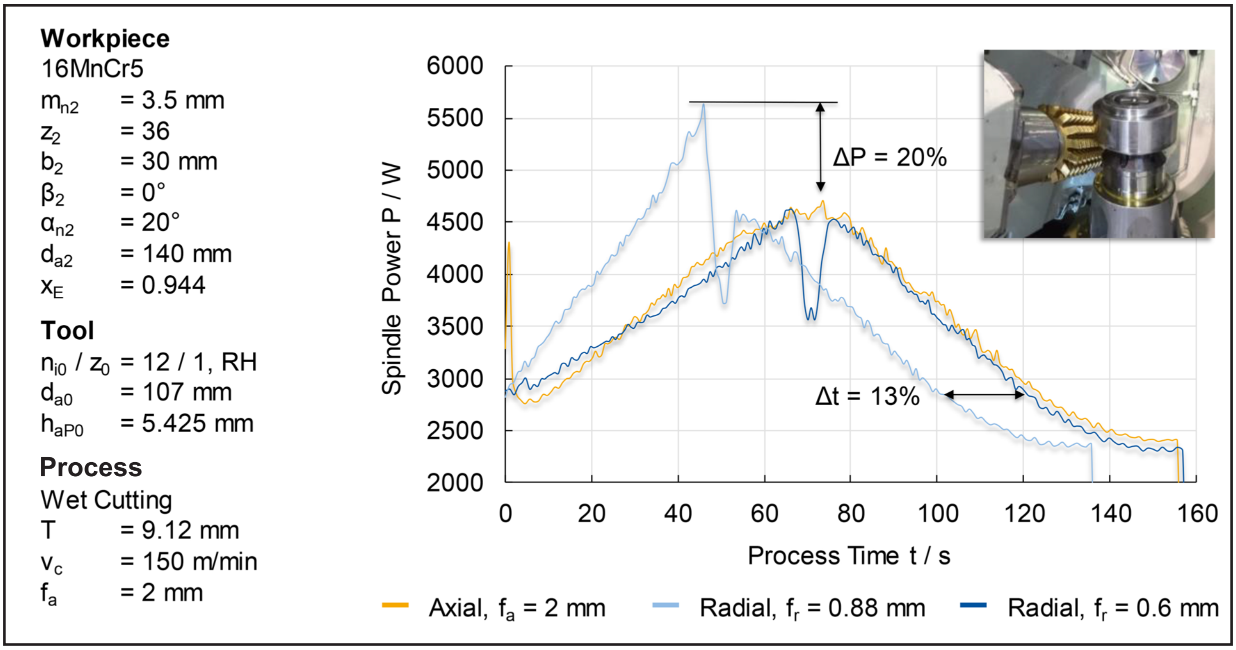


Figure 11 **Comparison of the spindle power curves of the process strategies investigated.**

and ordinate segment. This explains the lower tool lives in the experiment compared to the prognosis. The lower bearable cumulated cutting length $l_{cu,lim}$ determined in the investigations can be explained by the higher strength of the workpiece material 20MnCr5 with a tensile strength of $R_m \approx 630$ MPa. In the previous tests, a case hardening steel 16MnCr5 with a tensile strength of $R_m \approx 550$ MPa was machined.

Based on the characteristic values, the tool lives determined in the fly-cutting trial can be analyzed more precisely. An increase of the workpiece width leads to an approximation of the chip thickness and the chip length to the respective maximum value, which is present in the full-cut (see also Fig. 6). This means that the load on wider workpieces is higher than on workpieces which have no or hardly any full cut area. This explains the shorter tool life of the wide workpieces ($b_2 = 50$ mm) compared to the narrow workpieces ($b_2 = 30$ mm).

By adjusting the infeed angle or the machining direction, the penetration geometry changes during machining with otherwise identical parameters. This results in a change of the chip geometries, the resulting tool load and thus, the tool life. The results show that the process variables examined here, i.e. infeed angle, machining direction and workpiece width, influence the tool life only indirectly. A variation of the machining strategy and the workpiece width results in a change of the geometric penetration ratios and thus, of the tool load. Which process strategy led to the formation of these conditions is of secondary importance.

Knowledge of the linear relationship between the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$ can be used to design the hobbing process on the basis of tool life. The bearable cumulated cutting length $l_{cu,lim}$ can either be determined graphically from the diagram or calculated according to Equation 3. The coefficients a and b are to be determined empirically in wear investigations, e.g. in the fly-cutting trial. The mean chip thickness $h_{cu,m}$ can be derived numerically using the *SPARTApro* manufacturing simulation software. Equation 4 and Equation 5 can be used to transfer the bearable cumulated cutting length $l_{cu,lim}$ to the number of machined workpieces N or the tool life L. For this purpose, the cumulative chip length per gap must be known, which can be determined simulatively with *SPARTApro*.

Hobbing Trials

In order to validate the knowledge gained in the fly-cutting trials and to identify a suitable design method, tests were carried out in the hobbing process based on the previous investiga tions. For this purpose, trials were performed at the research facility and in an industrial environment.

Hobbing Trials at the Research Facility

The path feed f_b for the fly-cutting trials was designed based on the maximum chip thickness $h_{cu,max}$. In order to confirm or reject the suitability of this design method for the actual hobbing process, various process strategies and their effect on the spindle power P were tested at the research facility.

Climb cut axial gear hobbing at a cutting velocity of $v_c = 150$ m/min and an axial feed of $f_a = 2$ mm was used as a reference process. Radial-axial gear hobbing in climb cut was used as a further process strategy. The cutting velocity v_c and feed rate f_a during axial machining were selected in analogy to the reference process. The path feed f_b for the infeed was initially designed so that a maximum chip thickness $h_{cu,max}$ comparable to that of the subsequent axial machining is available when the tool is immersed. In this case, the radial feed rate is $f_r = 0.88$ mm.

During the infeed phase of the axial reference process, the power signal continuously increased until the maximum value $P_{max} = 4{,}500$ W was reached (Fig. 11). Due to the small workpiece width in relation to the tip diameter of the tool, there is hardly any full-cut for the tool/workpiece combination under consideration. Thus, the infeed phase went directly into the emersion phase, which is expressed by a continuous decrease of the effective power signal due to decreasing chip sizes.

For the radial-axial process, a continuous increase in spindle power was also be observed at the beginning. Compared to the reference process, the signal increased faster and reached a by $\Delta P = 19.5\%$ higher peak value. In the transition from radial plunging to axial machining, the power dropped briefly and then proceeded analogously to the reference process. With regard to the spindle power, the difference between the two process strategies in a design based on the maximum chip thickness was only present in the infeed phase. With regard to the machining time, the use of the radial-axial process strategy resulted in a productivity gain of $\Delta t = 13\%$.

In order to avoid the power difference between the infeed and the full-cut and to perform the radial-axial process under comparable conditions to the reference process, the radial feed was further reduced from $f_r = 0.88$ mm to $f_r = 0.60$ mm. The reduced radial feed results from adapting the machining time to the reference process. With the same process time, the same volume per time is machined, whereby the performance curves converge. A design based on the machining time allowed a comparable spindle power progression and thus, a robust, radial-axial process control was achieved. Due to the significantly higher spindle power in the infeed phase, a design of the infeed solely according to the maximum chip thickness $h_{cu,max}$ can only be evaluated as conditionally suitable.

Hobbing Trials in Industrial Environments

Since the batch size of the test gear production at the research facility is not sufficient to make a meaningful assessment of the tool life, a series production was accompanied in the industrial environment. Figure 12 shows the production of a double sun gear at ZF Friedrichshafen AG in Saarbrücken, Germany. Sun gear 2 is currently produced with a two-cut strategy due to an interference resulting from the front face of sun gear 1. By

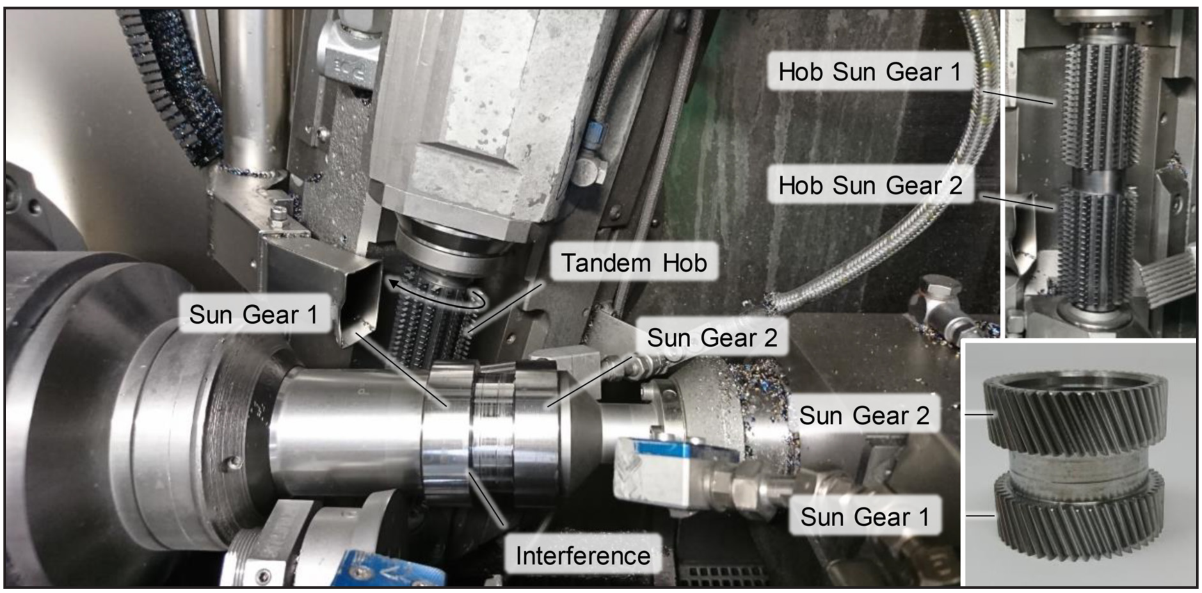


Figure 12 Manufacturing of a double sun gear at ZF in Saarbrücken, Germany.

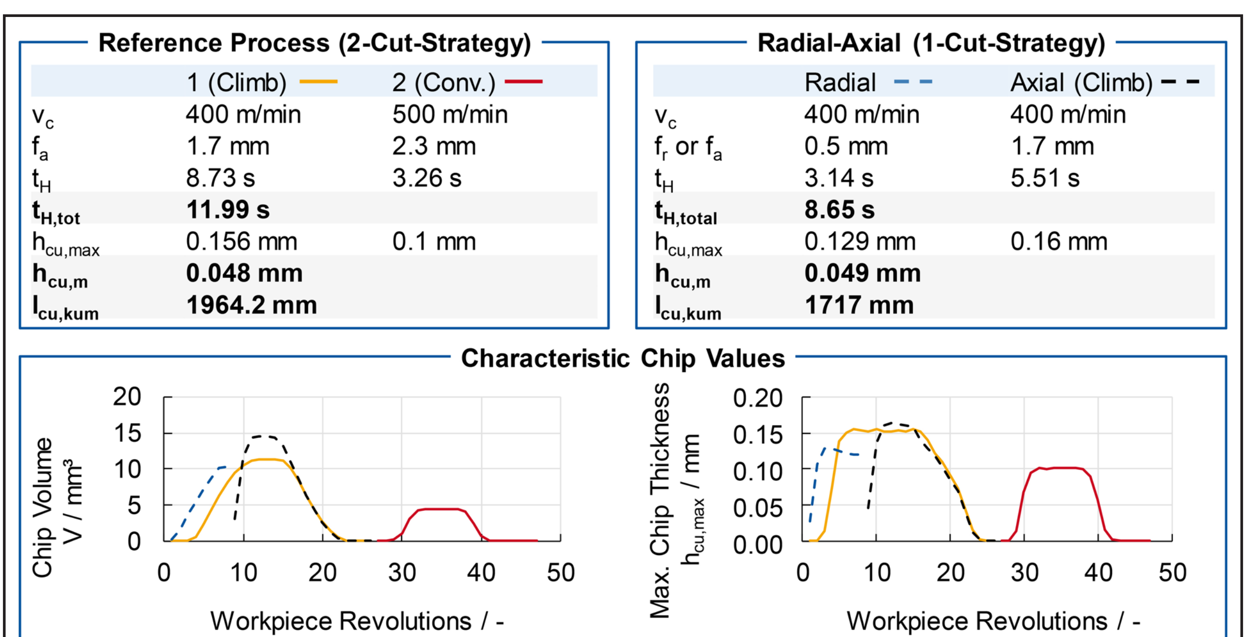


Figure 13 Design of a radial-axial machining strategy for the production of the sun gear 2.

reducing the number of cuts and thus, increasing productivity, the methods developed in this project were used to design a radial-axial process strategy for manufacturing sun gear 2. The gear was then produced in series with the developed strategy until a defined tool life was reached.

The process parameters of the developed radial-axial process strategy as well as those of the reference design are shown in Figure 13. The use of radial-axial hobbing for the process parameters shown is expected to increase productivity by around $\Delta t \approx 3$ s. A comparison of the characteristics $l_{cu,kum}$ and $h_{cu,m}$ indicates a slightly higher load ($\Delta h_{cu,m} = 0.001$ mm) with a simultaneously shorter cutting length compared to the reference process. If these parameters are considered solely based on the linear correlation between $l_{cu,lim}$ and $h_{cu,m}$ determined in the fly-cutting trial, no deterioration of the tool life is expected. Furthermore, for the second cut, the cutting speed was reduced to $v_c = 400$ m/min, which can also indicate a lower tool life due to lower temperature development during machining. The maximum chip thicknesses are smaller or equal to the maximum chip thickness for the first cut of the reference process for both the radial infeed and the subsequent axial machining. Therefore, no tool life losses are expected. The curves of the chip volume and the maximum chip thickness are shown in the lower part of the figure. Due to the shorter machining time, the course of the machined volume has a higher maximum value than for the reference process. For this reason, a slight increase in the spindle power signal is expected.

The objective of the radial-axial process strategy is to achieve a tool life that is in a similar range as the average tool life of the reference process as well as to meet all quality criteria. A comparison of the profile and helix deviation of the reference process and the radial-axial process strategy is shown in Figure 14. Despite a change of the infeed strategy, it was possible to achieve a comparable gear quality to the reference process. Due to the lower axial feed in the radial-axial variant, feed marks were also reduced. Compared to the reference process, the right flanks show a lower helix crowning. This could result from the higher forces due to the higher chip volume during axial machining.

The tool life, expressed as number of machined workpieces N, documented for the reference process is plotted for the period from November 2018 to March 2019 in the form of a frequency distribution (Fig. 15). The normal distribution was used as the distribution function. At the time of the evaluation, the mean value of the tool life achieved in the reference process was $N_\mu = 2{,}570$ workpieces and the standard deviation $N_\sigma = 750$ workpieces.

The tool life achieved with the radial-axial process strategy is illustrated in the bell curve. After reaching a tool life of $N = 3{,}000$ workpieces, the hob was removed and analyzed with a reflected-light microscope at the research facility. The achieved tool life lies within the interval $N_\mu + N_\sigma$ and is higher than the average tool life of $N_\mu = 2{,}570$ workpieces. The degree of wear on the tool is shown representatively in Figure 15 on the right. The left flank with $VB_{max} = 40$ mm has a larger maximum width of flank wear than the right flank with $VB_{max} = 20$ mm. Crater wear was not observed on the rake faces of the tool and is not to be expected as carbide cutting material was used. Despite the high number of machined workpieces, only a comparatively low degree of wear was observed. Thus, a potential for increasing the tool life by means of a radial-axial process strategy could be identified.

Conclusion and Design Recommendation

A radial-axial process strategy offers an effective alternative to conventional axial hobbing to avoid collisions with interference. Since no profiling of the final gap geometry takes place during the infeed, the infeed strategy has no influence on the gear quality. This could also be verified by trials in industrial environment. A significant advantage of a diagonal infeed strategy over a radial or axial infeed strategy could not be identified in the investigations and is therefore not recommended. Figure 16 compares a conventional axial machining strategy to two design approaches for a radial-axial strategy, on the one

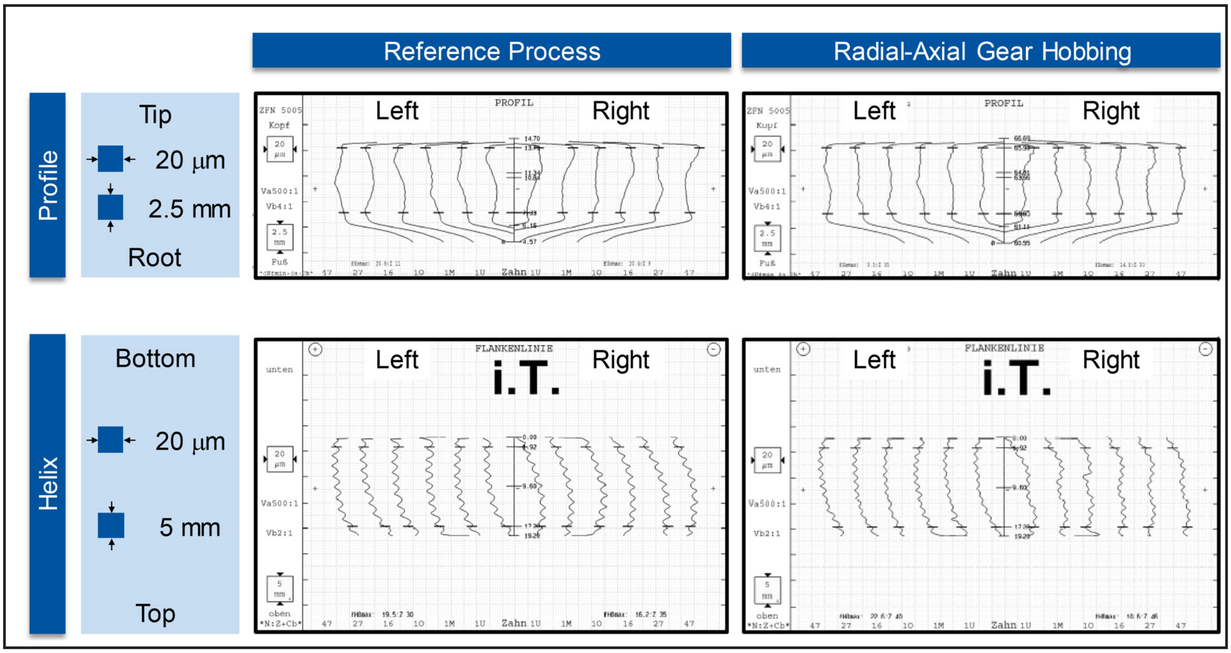


Figure 14 Comparison of gear quality.

hand according to the maximum chip thickness $h_{cu,max}$ and on the other hand according to a constant main time t_H.

Due to a design of the radial-axial hobbing process based on characteristic values, a robust process control can be realized and a potential for increasing tool life and productivity is given. In this project, different procedures for an appropriate design were shown. A design based on a constant machining time was identified as a practicable and quick to implement method, which enables a robust process control. The manufacturing simulation *SPARTApro* was extended by the consideration of the infeed angle in the context of this research project for characteristic value-based design. This allows the determination of common chip parameters, which can be used as further parameters for process design. For the empirical investigations, a design based on the maximum chip thickness resulted in an increase of productivity on the one hand and a decrease on tool life on the other. Taking the correlation of the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$ into account for process design, an increase of process efficiency was achieved for the industrial series test.

Summary and Outlook

Based on the theoretical considerations and fly-cutting trials on the isolated influence of the infeed angle, the combined influence of infeed and subsequent axial machining was further investigated in wear investigations. In addition to the infeed angle, the workpiece width and the machining direction (climb and conventional cut) were varied as well. The investigations indicated that the influence of the infeed decreases with increasing workpiece width and that the difference between the wear

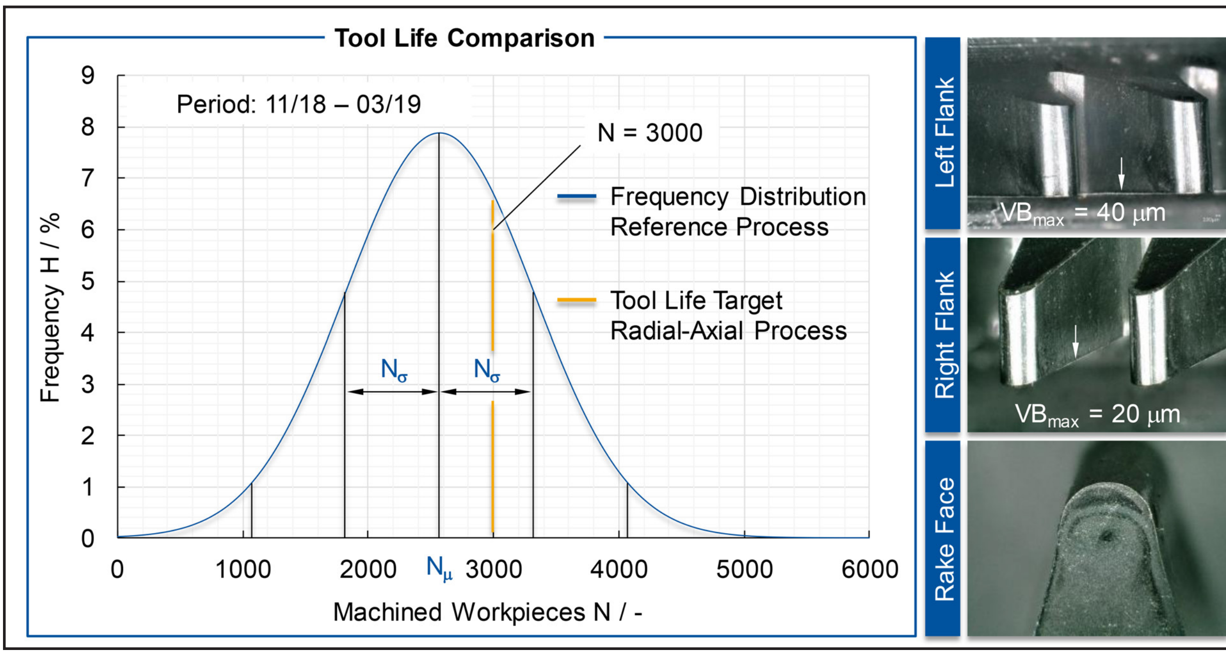


Figure 15 Assessment of the achieved tool life by radial-axial hobbing.

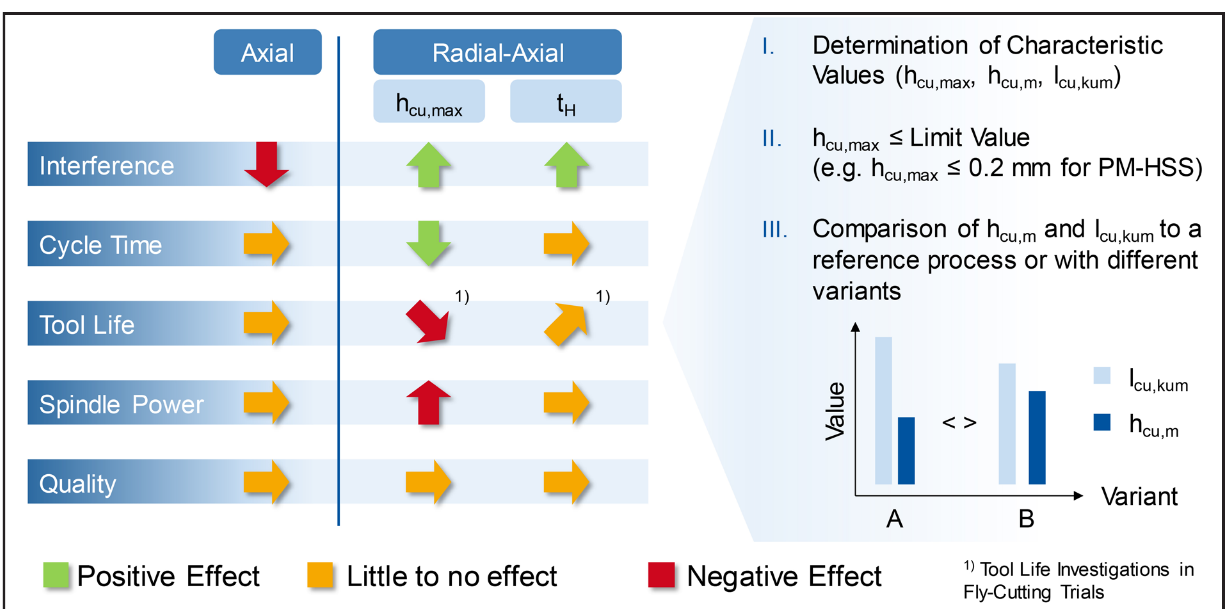


Figure 16 Comparison of a radial-axial to an axial process strategy.

characteristics of an axial and a radial-axial process control decreases. This can be explained by the fact that with increasing workpiece width, the proportion of the full-cut increases continuously and the influence of the infeed decreases accordingly. Further wear trials are necessary to verify this phenomenon.

In order to validate the findings gained by the fly-cutting trials, the research institute produced test gears by conventional axial gear hobbing and, with otherwise identical process parameters, by radial-axial gear hobbing. The latter strategy was designed in such a way that the maximum chip thickness in the infeed is comparable to that of the subsequent axial machining. A design of the radial-axial hobbing process according to the maximum chip thickness achieved a shorter process time on the one hand, but on the other hand resulted in higher spindle power for the infeed phase. The radial feed rate was further reduced in order to avoid the high power difference between the infeed phase and the full cut phase as well as to carry out the radial-axial process under comparable conditions as the reference process. The reduced radial feed resulted from an adaptation of the machining time to the reference process. This method enabled a comparable spindle power curve and thus, a robust radial-axial process control.

For the industrial series test, an increase of process efficiency could be achieved by means of radial-axial hobbing through a characteristic value-based design. The results confirm that there is no deterioration in gear quality due to an adjustment of the infeed strategy and an increase in productivity can be achieved with a comparable tool life. The main parameters for the design were the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$. Despite the high number of machined workpieces, only a small width of flank wear was measured on the hob. In further investigations, the tool is to be reinstalled and used up to the point where regrinding is necessary in order to determine the maximum tool life. For a statistical verification of the result, additional tools based on the radial-axial strategy for series produc tion are to be used.

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