9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '14

Design of Gear Hobbing Processes Using Simulations and Empirical Data

C. Brecher*, M. Brumm*, M. Krömer*

*Laboratory for Machine Tools and Production Engineering, Steinbachstraße 19, 52074 Aachen, Germany

* Corresponding author. Tel.: +49-241-80-28295; fax: +49-241-80-22293. E-mail address: m.kroemer@wzl.rwth-aachen.de

Abstract

Gear Hobbing is one of the most productive manufacturing processes for pre-machining cylindrical gears. The process design as well as the tool selection is often based on experience or is limited to an iterative procedure. Existing methods for process and tool design are limited regarding the size of the gears and the process parameters.

The objective presented in this paper is to support the process design by suggesting process parameters. To achieve this goal, a simulation for continuous gear hobbing was developed. By calculating planar intersections of transverse sections of both gear and tool, the generated chip geometries are determined. Due to the general approach of positioning tool and workpiece in the program, all continuous processes with defined cutting edges can be simulated. The generated chip geometries are analyzed and characteristic values for each position of the tool are defined. Beside the chip geometries, other parameters such as working areas and the length of axis movements are calculated too.

Since the simulation process is time-consuming, it is not possible to calculate each hobbing process for different designs. Also, the simulation program cannot be implemented into the machine control due to the needed computing capacity. Thus, a large amount of hobbing processes with varying gear geometries as well as different tools with the corresponding profiles are calculated in advance. By the use of regression analysis, the results of these variations are transferred to approximation formulas afterwards, which are easy to calculate and to implement into other software products.

To support the tool and process design, existing hobbing processes will be simulated with the help of the developed manufacturing simulation and the results will be stored in a database. By comparing the results of the approximation formulas with the values in the database, it is possible to evaluate a given process.

1. Introduction

For designing gear hobbing processes, certain values are necessary that can be compared and determined unambiguously. An established value for hobbing is the maximum chip thickness. Determining the chip thickness can be conducted according to different methods and formulas. A common and industrially as well as scientifically established way is the approximation formula for the maximum chip thickness according to HOFFMEISTER [18]. The approximation formula represents a simplified calculation that is based on empirical studies up to the module of \( m_n = 4 \) mm. Investigations have shown that for gears of larger modules, the results according to HOFFMEISTER deviate from the actual chip thickness and underestimat them [10].

To define a reliable process design of large module gears, a dependable method for calculating the maximally occurring chip thickness in a process is necessary. For this purpose, a new formula for calculating the maximum chip thickness up to modules of \( m_n = 30 \) mm will be created. In order to achieve this objective, a variation model will be set up. This allows determining approximation functions for different characteristic values by means of results of a penetration calculation and a regression analysis. With the help of this method, subsequently a function for calculating the maximum chip thickness for gear hobbing can be developed.

2. State of the Art

For turning or milling processes with defined cutting edges, the process design and the cutting parameters are most likely specified based on empirical knowledge, structured in
form of charts. These charts contain axial feeds and cutting speeds for different workpiece and tool material combinations and are provided by the tool manufacturers. The parameters in these charts are based on the chip thicknesses. Fig. 1 shows the maximum chip thicknesses $h_{cu, max}$ occurring in the turning, milling and gear hobbing process. Because of the continuous chip formation on one single cutting edge, the calculation of the maximum chip thickness in the turning process is trivial. The chip thickness depends on axial feed $f_a$, cutting speed $v_c$ and a tool angle. For milling processes, the chip thickness $h_{cu}$ varies along the cutting length. Although the milling process has a discontinuous chip formation, it is possible to calculate the maximum chip thickness with the help of analytic formulas. In gear hobbing this is possible. As it is shown in the right column in Fig. 1, the chip formation varies with the cutting length. Because of the rolling process of gear hobbing, the chip formation takes place at different cutting edge sections. Thus, $h_{cu}$ varies with the profile and for each single blade. Also, the chip geometries are highly depending on the superposition of the single cuts. Due to these unique and complex kinematic conditions, a calculation based on analytic formulas of the maximum chip thickness is not possible.

Fig. 1. Comparison of chip formation in various cutting processes

### 2.1. Characteristic Values in Gear Hobbing

Gear hobbing is the main process for manufacturing cylindrical gears [3]. However, designing a productive and stable process poses still a challenge. In the past, there were many studies analyzing the influence of different characteristic values according the tool life and wear behavior. Research was done with carbide tools [22, 18, 23, 13, 14, 11,24] as well as high speed steel hobs (PM-HSS) [19, 1, 7, 16, 15, 17, 21]. HOFFMEISTER [18] developed an approximation formula for the maximum cutting length $l_{max}$ and total cutting length $l$ of the process. He also developed formulas for calculating the maximum chip thickness at the profile tip $h_{cu, max}$ and an average chip thickness $h_{av}$. Especially the approximation formula for the maximum chip load is still widely established in industrial and scientific environment.

BOUZAKIS [1] conducted extensive research regarding the chip formation and the effects to tool wear. For this, BOUZAKIS classified the three flank chips and developed a mathematical model for calculating the corresponding tool wear. MUNDT [MUND92] also developed a formula for calculating the average chip thickness. His approximation formula is based on the results of a geometrical penetration calculation. In recent past, HIPKE [17] developed a method for calculating process parameters for HSS hobs. The method is based on the average chip thickness and cutting length. Altogether, the module range in these mentioned studies is $m_n < 10$ mm. While HOFFMEISTER and HIPKE used gears up to $m_n = 4$ mm, the formulas of MUNDT include gears with $m_n = 10$ mm.

Because none of these studies provide a comprehensive method for the full module range of currently used gears, the alternative is to design a process by the maximum chip thickness as well as experience. On this basis, an objective process design is nearly impossible.

#### 2.2. Calculation Methods for the Chip Load in Gear Hobbing

To calculate the chip thickness in gear hobbing, different methods can be used. A simple and effective option is the maximum chip thickness according to HOFFMEISTER, (1).

$$h_{cu, max} = f(…, 2\pi r, \beta, z_2, N)$$

HOFFMEISTER approximates the real maximum chipthickness by exponential and potential functions with influence factors of tool, workpiece and process. These factors are the module $m_n$, the number of workpiece teeth $z_2$, the helix angle $\beta$, addendum modification factor $x_p$, the axial feed $f_a$, the cutting depth $T$ as well as the number of gaps $n_0$ and the number of threads $z_0$. The tool profile with pressure angle and the tool tip radius had been neglected in the investigations.

Another method for calculating the chip thicknesses is using a process simulation software such as SPARTA PRO. The software was developed at the WZL of the RWTH Aachen University, Fig. 2 [8].

Fig. 2. Features of SPARTA PRO

Input parameters are the geometrical information of the workpiece like 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 undeformed chip geometries occurring in the hobbing process are determined. Afterwards, these geometries are analyzed and characteristic values such as the maximum and average chip thickness $h_{cuv,\text{max}}$ and $h_{cuv,\text{av}}$, the specific chip volume $V_c$ and the maximum and average cutting length $l_{cuv,\text{max}}$ and $l_{cuv,\text{av}}$ are calculated. The values are then displayed along the unrolled cutting edge as well 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 profitability.

Because HOFFMEISTER only used gears with a module $mn < 4$ mm, it is questionable to use the approximation formula and transferring it to large gears up to module $mn = 30$ mm. Thus, a comparison of the maximum chip thickness according to HOFFMEISTER and SPARTAPRO was conducted [8]. As it is shown in Fig. 3, the results of these two methods differ widely with increasing modules. The simulation results are constantly higher than the results by HOFFMEISTER and at some parts the difference of the calculated and simulated chip thickness is 55%. This shows that the approximation formula according to HOFFMEISTER underestimates the tool load for large module gears and therefore is not the best option to use in a process design.

### 4. Designing a Variant Calculation

The chip formation in gear hobbing processes depends on a large amount of influencing factors. Fig. 4 shows these influences categorized into workpiece, the tool and the process. The highlighted geometrical influences can be considered in the described penetration calculation SPARTAPRO. The bold factors in Fig. 4 influence the chip thicknesses in the hobbing process directly and are subsequently discussed in detail.

![Fig. 4. Factors influencing the chip formation](image)

For analyzing the maxima for different characteristic values, the gear width is often of little interest. This is because in the run-in and the overrun of the tool chip thicknesses, cutting lengths and other values increase respectively decrease. In the full-cut section of the workpiece, the characteristic values are nearly constant and have the highest values.

To examine the influence of the pressure angle, preliminary investigations on the profile addendum and the generating addendum modification were performed in advance. While the cutting depth was kept constant, in each simulation the profile angle was varied between $\alpha_p = 10^\circ$, $\alpha_p = 20^\circ$ and $\alpha_p = 30^\circ$. It shows that this modification has no effect on the resulting maximum chip thickness. Furthermore, the addendum of the tool profile was also changed in three steps. This change leads to a varying tooth width of the gear, but also has no effect on the maximum chip thickness. Because the generating addendum modification factor also changes by varying the addendum height, this factor has no effect on the maximum chip thickness as well.

### 5. Developing of Functions describing Characteristic Values

After gear width, pressure angle and the addendum modification could be excluded, as they have no effect on the chip thickness, the parameters listed in Table 1 are varied throughout the specified range. For each parameter up to seven incremental steps are used. Furthermore, the process is simulated for climb as well as conventional cutting. A design of experiments (DOE) method is used to reduce the number of

---

**Table 1: Parameter values for the design of experiments (DOE)**

| Parameter          | Values                      |
|--------------------|-----------------------------|
| Module $mn$        | 1 - 30 mm                   |
| Pressure angle $\alpha$ | 10°, 20°, 30°               |
| Helix angle $\beta$ | 2.0°, 2.5°, 3.0°            |
| Number of threads $z_2$ | 2, 3, 4                    |
| Number of gaps $g_2$ | 1, 2, 3                     |
| Addendum height $h_a$ | 2.0 mm, 2.5 mm, 3.0 mm     |

---

Fig. 3. Comparison of approximate formula and simulation according to different modules [8]
necessary simulations. Because of the multifactorial influences, a D-optimal design is used. This reduces the number of simulations to 77 for each cutting strategy (climb and conventional cutting).

Table 1. Variation Range of the influence factors

| Parameter                  | Symbol | Range   | Unit |
|----------------------------|--------|---------|------|
| Module                     | m_n   | 1 – 30  | mm   |
| Number of teeth            | Z      | 10 – 120|      |
| Helix angle                | Β      | -40 – 40| °     |
| Outside diameter of tool   | d_a   | 50 - 380| mm   |
| Number of gaps             | n_o   | 8 – 23  |      |
| Number of threads          | z_o   | 1 – 5   |      |
| Profile edge radius factor | σ_a0  | 0.1 – 0.5|      |
| Cutting depth factor       | T*    | 0.1 – 1 |      |
| Axial feed                 | f_a   | 0.5 – 6 | mm   |
| Climb / conventional cutting| -     | A or B  |      |

For evaluating the resulting characteristic values, it is possible to use several regression functions. The evaluating software used in this paper provides a quadratic, cubic and biquadratic regression model. To compare the different approaches, the coefficient of determination R² is used [6]. The coefficient R² can vary between 0 < R² <100%. It indicates the fitting of the statistical model to the original data points. In general a R² > 90% is deemed to be good [12]. In this study a quadratic model is used because it fits the transfer functions best. The coefficient of determination for this approximation function is R² = 94%.

In Fig. 5, the function for each parameter is shown. It is striking that the function curve for the module is decreasing with higher modules. Because this is not plausible, the function is manually adjusted and reintegrated into the approximation model. Furthermore, an analysis of the curves also shows that the profile edge radius σ_a0 and the helix angle Β of the gear do not have a significant effect on the resulting maximum chip thicknesses and therefore both can be neglected in the model. In addition, the influence of the number of gaps n_o and threads z_o can be condensed to one parameter, the effective number of gaps i_0. Because the regression functions of the tool diameter d_a0, effective number of gaps i_0 and cutting depth T are nearly linear, these functions are linearized. Due to these changes in the regression model, the approximation formula is now less complex but the coefficient of determination only deteriorates by ΔR² = 0.4%.

The resulting approximation formula is shown in (2). To improve the coefficient of determination, a logarithmic transformation of the target value, the maximum chip thickness, was done. This transformation is a common method to improve the R². Because of the described modifications to the original approximation model, the resulting equation is not more complex than the equation to HOFFMEISTER.

\[
\begin{align*}
\hat{h}_{cu,max} &= e^x \\
    x &= -1.446 - 2.78 \times 10^{-3} \cdot d_{a0} \\
    &- 0.065 \cdot n_o \cdot z_o \\
    &+ 0.0186 \cdot T \\
    &+ 0.122 \cdot m_n - 2.24 \times 10^{-3} \cdot m_n^2 \\
    &- 0.02621 \cdot z_2 + 0.123 \times 10^{-3} \cdot z_2^2 \\
    &+ 0.6447 \cdot f_a - 0.07486 \cdot f_a^2
\end{align*}
\]

The validation of the approximation formula for the characteristic value can be done with the help of the process simulation SPARTAPRO. During the experimental design, three points of stability were defined by the DOE. Furthermore, the data of two very different, real cylindrical gears are available for validation. Fig. 6 shows the gear, tool and process parameters of these five gears. At the bottom of Fig. 6, the resulting maximum chip thicknesses according to the simulation SPARTAPRO, HOFFMEISTER and the new approximation formula are given. This shows that the chip thickness calculated with SPARTAPRO and the developed formula are in four of these five cases nearly the same. Especially the large gear with a module of m_n = 16 mm shows the advantage of the new formula compared to HOFFMEISTER. While the calculated chip thickness by HOFFMEISTER is 25% lower than the simulated one, the value calculated by the new approximation formula is only 3% higher than the simulation and therefore nearly the same.
A similar pattern emerges by comparing the results of the second and third points of stability. Also, in these cases the deviations of the developed formula and SPARTAPRO are minimal (1.5% and 4%) while the chip thickness according to HOFFMEISTER differs to the simulation by 20% and 28%. This improvement of the results of calculating the maximum chip thickness is mainly attributable to the fact that the module range of the new formula is wider than HOFFMEISTER. Only the first point of stability does not match to the good results of the other cases. While the calculated chip thickness by HOFFMEISTER and the new formula are nearly the same, the thickness by simulation is 20% higher.

Beside these five gear sets, also the known module variation of Fig. 3 was done. The curves of the maximum chip thickness can now be used to calculate existing hobbing processes. By setting up a database with the calculated chip thicknesses, the workpiece and tool material as well as the used processes. By setting up a database with the calculated chip thicknesses, the workpiece and tool material as well as the used processes. By setting up a database with the calculated chip thicknesses, the workpiece and tool material as well as the used processes. By setting up a database with the calculated chip thicknesses, the workpiece and tool material as well as the used processes. By setting up a database with the calculated chip thicknesses, the workpiece and tool material as well as the used processes.

For future investigations, it is possible to develop approximation formulas for further characteristic values like the average chip thickness with the help of the presented method. Also, calculating the axial feed with the help of the presented approximation at a given geometry and maximal tolerable chip thicknesses is possible. For this, however, the knowledge of the maximally possible chip thickness of a hobbing process is necessary.
Acknowledgements

\[ \alpha_n \] Pressure angle
\[ \alpha_0 \] Profile angle of the tool
\[ \beta_0 \] Helix angle of the workpiece
\[ d_{ao} \] Outside diameter of the tool
\[ \sigma_{ao} \] Profile edge radius
\[ f_a \] Axial feed
\[ h_{av} \] Average chip thickness
\[ h_{cu,max} \] Maximum chip thickness
\[ l_{av} \] Average cutting length
\[ l_{max} \] Maximum cutting length
\[ m_n \] Module
\[ n_{o0} \] Number of threads (tool)
\[ R^2 \] Coefficient of determination
\[ T \] Cutting depth
\[ x_p \] Generating addendum modification
\[ z_0 \] Number of threads (tool)
\[ z_2 \] Number of teeth

References

[1] Bouzakis, K.-D.; et al.: Effect of the Cutting Edge Radius and its Manufacturing Procedure on the Milling Performance of PVD Coated Cemented Carbide Inserts. In: Annals of the CIRP 51, 2002, p. 61-64
[2] Bouzakis, K.-D.; Lili, E.; Michailidis, N.; Friderikos, O.: Manufacturing of Cylindrical Gears by Generating Cutting Processes: A Critical Synthesis of Analysis Methods. CIRP Annals - Manufacturing Technology 57 (2008) No. 2, pp. 676-696
[3] Bouzakis, K.-D.: Konzept und technologische Grundlagen zur automatisierten Erstellung optimaler Bearbeitungsdaten beim Wälzfräsen. Habilitation, RWTH Aachen, 1980
[4] CRGraph: Versuchsverfahren. DoF: und Datenanalyse. www.crgraph.de [Stand: 18.03.2014]
[5] DIN 3972: Bezugsprofile von Verzahnwerkzeugen für Evelventen-Verzahnungen nach DIN 867 Berlin, 1952
[6] Fahrmeir, L.; Kneib, T.; Lang, S.: Regression: Modelle, Methoden und Anwendungen. Springer Verlag, Berlin, 2009
[7] Kauven, R.: Wälzfräsen mit Titan nitrid-beschichteten HSS-Werkzeugen. Diss. RWTH Aachen, 1987
[8] Steger, M.; Winter W.; Klocke F.; Winkel O: Analysis of Gear Hobbing Processes by Manufacturing Simulation. In: Wissenschaftliche Gesellschaft für Produktionstechnik (WGP). Production Engineering: Research and Development. Volume X, Issue 1. WGP Annals, WGP Eigendruck, Berlin, 2003.
[9] Klocke, F.; König, W.: Fertigungsverfahren – Drehen, Fräsen, Bohren, Band 1. 8. Aufl. Springer: Berlin, 2008
[10] Klocke, F.; Brümmer, M.; Weber, G.: Prozesssimulation für Wendeschneidplatten-Wälzfräser. In: Seminar Aktuelle Entwicklungen beim Vorverzahnen, WZL, RWTH Aachen, 2012
[11] Kleinjans, M.: Einfluss der Randschräugegenen auf den Verschleiß von beschichteten Hartmetallwälzfräsern. Diss. RWTH Aachen, 2003
[12] Klocke F; Winter W.; Klocke F.; Winkel O: Analysis of Gear Hobbing Processes by Manufacturing Simulation. In: Wissenschaftliche Gesellschaft für Produktionstechnik (WGP). Production Engineering: Research and Development. Volume X, Issue 1. WGP Annals, WGP Eigendruck, Berlin, 2003.
[13] Knöpf, D.: Trockenbearbeitung beim Hochgeschwindigkeitswälzfräsen mit beschichteten Hartmetall-Werkzeugen. Diss. RWTH Aachen, 1996
[14] Koblalka, K.: Prozessanalyse für das Trockenwälzfräsen mit Hartmetallwerkzeugen. Diss. RWTH Aachen, 2002
[15] Lux, S.: Einfluß von Oberflächenstrukturen auf den Verschleiß von Verzahnwerkzeugen aus Schnellarbeitsstahl. Diss. RWTH Aachen, 1997
[16] Mundt, A.: Modell zur rechnerischen Standzeitbestimmung beim Wälzfräsen. Diss. RWTH Aachen, 1992
[17] Hipke M: Wälzfräser mit pulvermetallurgisch hergestelltem Schnellarbeitsstahl. Dissertation Otto-von-Guericke-Universität Magdeburg, 2012
[18] Hoffmeister, B.: Über den Verschleiß am Wälzfräser. Diss. RWTH Aachen, 1970
[19] Joppa, K.: Leitungsteuerung beim Wälzfräsen mit Schnellarbeitsstahl durch Analyse, Beurteilung und Beeinflussung des Zerspanprozesses. Diss. RWTH Aachen, 1977
[20] Scheffler, E.: Statistische Versuchsplanung und –auswertung. Deutscher Verlag für Grundstoffindustrie Stuttgart, 1997
[21] Schallast, R.: Optimierung des FertigwälzfräSENS von Verzahnungen. Diss. RWTH Aachen 2012
[22] Sulzer, G.: Leistungssteigerung bei der Zylinderadherstellung durch genaue Erfassung der Zerspankinematik. Diss. RWTH Aachen, 1973
[23] Venohr, G.: Beitrag zum Einsatz von Hartmetallwerkzeugen zum Wälzfräsen. Diss. RWTH Aachen, 1985
[24] Winkel, O.: Steigerung der Leistungsfähigkeit von Hartmetallwälzfräsern durch eine optimierte Werkzeuggestaltung. Diss. RWTH Aachen, 2005
[25] Ziegler, K.: Untersuchung der Hauptschnittkraft beim Wälzfräsen von Stirnrädern. Diss. RWTH Aachen, 1967