1 Introduction

In gear hobbing, as in every cutting process, the predictability of such machining parameters as tool wear, cutting forces, etc., considering workpiece tool and production data is of immense research and industrial concern [1–12]. The generating-rolling principle governing the hobbing kinematics makes difficult the analytical approach of the tool wear. On the other hand, owing to their complex geometry, hobbing cutters are quite expensive and their extended exploitation becomes dominant. The variant chip formation on each cutting tooth during hobbing provokes different wear laws and usually leads to an unequal wear distribution on the hob teeth [6,12–15]. Hereby, through an appropriate tangential tool shifting a uniform wear on the hob teeth, before the sharpening or the replacement of the tool can be reached. For this purpose, optimum values for the hob shift displacement and amount of gears per shift position have to be determined.

The restricted cutting performance of HSS tools does not fulfill the high cutting speed requirements of modern CNC hobbing machine tools. This led among others to the application of Physically Vapor Deposited (PVD) coatings on such tools, which improved the performance of HSS tools at higher cutting speeds, and increased considerably the productivity of gear manufacturing [8,16–24].

In the present paper models to predict the wear development in gear hobbing are introduced, whereas the chip generation in full cut and in the transient workpiece cutting regions is considered. The wear laws in the individual generating positions investigated in [6,13–15] are exhibited with the aid of the developed algorithm FRSWEAR and procedures to determine the optimum tangential shift amount are proposed. In order to enable the monitoring of the wear progress in the individual generating positions and the determination of the included in the wear describing equations constants, the fly hobbing with continuous axial feed was applied.

Application examples of these procedures as well as of the FR-SWEAR software will be demonstrated in manufacturing cases, with uncoated as well as coated HSS tools.

2 Chip Formation in Gear Hobbing

The gear hobbing cutting procedure is schematically presented in the upper part of Fig. 1. Due to its complicated kinematics, modeling problems are caused, since each gear gap is produced through successive penetrations of the tool teeth into the workpiece in the individual Generating Positions (GP). Considering the tool rotation during each hob tooth penetration into a gear gap, a number of revolving positions has been introduced to describe the chip cross sections, as it is further explained. Significant parameters affecting the tool wear are the chip formation and flow [6,13–15]. In the left part of Fig. 1, chip photos and the workpiece surfaces formed at the indicated generating positions, are illustrated. The undeformed chip geometries are calculated in various revolving and generating positions during the formation of a gear gap, by means of the computer program introduced in [1]. The principle of this program is based on the mathematical description of the tool penetrations into the gear gaps. The undeformed chip cross sections on the development of the cutting edge are presented in successive tool revolving positions at every generating position as illustrated in the right part of Fig. 1.

If the tool cuts in a transient, entry or exit workpiece region the chip formation is modified in comparison the full cut region (see Fig. 2) [12]. The undeformed chip geometry, considering the cutting direction, is a front or a back part of the full cut chip geometry. In the 11th and 12th cutting positions of the observed generating position in the present hobbing case, chips of the same geometry per tool rotation and with maximum overall dimensions occur (full cut chips), whereas in the rest cutting positions only parts of the full cut chips are formed. The length of the chips in the successive tool entry cutting positions is increasing, whereas in the exit region cutting positions the corresponding chip length is continuously diminishing. The relation between the gear width $b$ and the length $q$ in the workpiece axial direction (see Fig. 3) is

---

Contributed by the Manufacturing Engineering Division for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received December 1998; Revised March 2001. Associate Editor: K. Ehmann.
a magnitude affecting the occurring chip geometry and thus the corresponding hob wear. In manufacturing cases with \( b > q \) or \( b = q \), the entry, the full cut and the exit regions I, II and III respectively can be distinguished, according to the position of the cutting tool concerning the gear width. On the other hand if the gear width \( b \) is less than the length \( q \), a transient region IV between the entry and the exit regions is detected, in which the chip is always a part of the full cut one. These interactions are presented in the lower part of Fig. 3, where the previous mentioned relations between \( b \) and \( q \), in the same generating position, are considered.

3 Tool Wear Development Description in the Individual Generating Positions in Gear Hobbing

The most wear endangered positions on a hob tooth are its tip corner regions to the flanks. The flank wear VB near the tooth head will be considered in the following analysis, as the criterion of the tool wear status. Mathematical models predicting the wear progress in the individual generating positions are introduced in former publications [6,13–15]. These models take into account the complicated chip formation, as well as the chip flow, exhibiting a remarkable influence on the tool wear. In order to describe such effects quantitatively, five different chip groups were introduced [6,13–15]. The criterion hereby was the intensity of chip flow obstruction phenomena, due to reciprocal collision of chip distinct sections. The group classification is mainly based on the shape of the undeformed chip considering its flow direction. Each of these groups (I, II, III, IV and 0) has a characteristic influence on the tool wear development. Figure 4 illustrates experimentally derived typical wear laws for each chip group, as a function of the number of successive cuts \( AS \). The figure includes equivalent chip dimensions that are further explained in the followings. It is evi-

![Fig. 1 Chip formation and typical chips at various tool generating positions in gear hobbing, as well as the corresponding analytically determined chip cross sections](image)

![Fig. 2 Undeformed chip cross sections in entry, full cut and exit or transient cutting positions in gear hobbing](image)

![Fig. 3 Undeformed chip length \( l \) in various regions during hobbing versus the gear width, in a generating position](image)
dent, that the flank wear VB progress is at most intense in the chip group case I, whereas in the case of group 0 (chip flow without obstruction), the wear slope is significantly lower.

The simulation of gear hobbing, with the aid of the program FRSWEAR, yields the chip dimensions in the successive revolving positions of every cutting position in individual generating positions, taking into account all tool, workpiece and cutting kinematics data. In a second stage, the chips are classified in the previously described five different groups, regarding their formation and flow. The reasons for this task, as already mentioned, is that the tool wear strongly depends on the chip flow obstruction described through the introduced chip groups and the constants of the applied mathematical equations to predict the tool wear in each chip group case are different. In a further calculation step, the representative magnitudes, equivalent chip length and thickness are analytically determined. Figure 5, illustrates this task for the trailing flank of a hob tooth, in a generating position during climb hobbing of a helix gear. For the presented generating position, the corresponding magnitudes and parameters related to the leading flank are calculated and demonstrated in the figure. The equivalent chip dimensions are required in wear prediction equations, derived as described in [6,13-15]. These equations correlate significant gear hobbing parameter, such as the accumulated number of successive cuts, the equivalent dimensions of the undeformed chip, the chip group and the cutting speed to the expected wear development.

The constants of such equations are usually determined as described in the following section. The mentioned equations are implemented in the FRSWEAR program to predict the wear development in gear hobbing.

The developed code selects automatically the proper wear law according to the chip group and considering the equivalent chip dimensions and the cutting speed starts counting the wear, as indicated in the upper part of Fig. 6. A cutting tooth, as for example an unworn one, develops a specific wear status after a certain number of successive cuts in the same cutting and generating positions during hobbing of a gear, predicted as previously described, considering the chip geometry and the manufacturing data. If the same tooth has to cut in a further cutting position, which obeys to a different wear law, the wear starts to be accumulated on the already existing wear, occurred due to the cut in the previous cutting position. The further wear prediction is conducted according to the current wear law due to the actual chip geometry.

The influence of the chip formation and flow in the entry, the exit and in the full cut and the transient workpiece regions on the wear development is considered in the FRSWEAR program as shown in the bottom part of Fig. 6. A tooth, with an already existing wear VBstart, on it, cuts in the generating position k for
example in the entry workpiece region. The flank wear of this hob tooth after cutting in all \( z \) gear teeth gaps in the same cutting position 1 of the generating position \( k \), continuous to increase according to the wear law of the next cutting position 2 of the same generating position \( k \). After working in all cutting positions, i.e. in every possible, entry, exit, full cut or transient workpiece region of the same generating position \( k \), the resulting flank wear \( VB_{\text{finish},k} \) is the starting flank wear \( VB_{\text{start},k} \) in the first cutting position of the same generating position in hobbing of the next gear.

### 4 Wear Development Description Considering the Tool Tangential Shifting in Gear Hobbing

If the tool cuts only at a certain relative position to the workpiece, each hob tooth cuts always in the same generating position, and thus the occurring wear distribution on the cutting teeth is highly dissimilar. To achieve a uniform wear at the majority of the cutting teeth, a tool tangential shifting is required. The corresponding shift amount, i.e., the number of hobbed gears per shift position, depends on the geometrical and the technological tool and workpiece data and can be determined by means of the FR-SWEAR algorithm, as presented in Fig. 7.

To elucidate this computational procedure, it is assumed that the manufacturing of a tooth gap contour is conducted in four distinct generating positions \( 1 \) to \( IV \). The produced workpiece surfaces and typical chips are illustrated in the left part of this figure. During the formation of one gap, four of the seven teeth of the specific assumed tool take part to the cutting process for the first time. The corresponding wear regularities in those generating positions are determined as described in the previous paragraph. Due to these regularities each hob tooth exhibits a different wear development after cutting a certain number of gears in the individual generating positions, which corresponds to a number of cuts \( AS \). The course of the maximum width of flank wear \( VB \), is illustrated in the bottom part of the same figure for each generating position. To achieve a uniform distribution of the wear over the contest of the cutting teeth, the hob must be shifted tangentially.

Assuming a tangential shift equal to the tool axial pitch \( \text{SHD} = \varepsilon \) the cutting tooth \( i \) takes the generating position of the tooth \( i + 1 \). Hereby, the tooth 1 quits cutting, whereas the tooth 5 cuts for the first time in the generating position \( IV \). The wear behavior of each tooth is now obeying the wear law that governs the generating position, where they cut after shifting. The wear progress on a hob tooth starts from the status developed by the end of the former cut of the observed tooth in the previous generating position.

In this way the wear on the hob teeth becomes uniform, the tool exploitation is enhanced and the manufacturing cost reduced. Tool wear calculations to determine optimum shifting conditions in specific cutting cases, will be presented in a later paragraph dealing with uncoated and coated HSS tools.

The wear prediction in gear hobbing with uncoated or coated tools and the optimization of the tool shifting can be conducted by means of the FR-SWEAR program (see Fig. 8). This software enables the hobbing process simulation and incorporates a database of experimentally-analytically derived wear equation constants, for a variety of tool coatings and workpiece materials. The code is built in an open and modular structure and offers a graphical interface with interactive communication for the data input and results output. The tool wear prediction can be carried out by taking into account the process kinematics and all technological parameters of an examined manufacturing case. This is conducted after determined the group and the equivalent dimensions of every chip in all generating positions, either in transient or in full cut workpiece regions. Optimized shift conditions to achieve a prescribed and almost uniform wear distribution on the hob teeth can also be provided by means of the FR-SWEAR program.

### 5 Development of an Experimental Procedure to Investigate the Wear Development in the Individual Hobbing Generating Positions

During gear hobbing, as already described, each cutting tooth cuts in a certain generating position in a gear gap and after a hob revolution, in the case of a hob with one helix, penetrates into the same generating position of the next gear gap. To investigate the wear development in the individual generating positions, gear hobbing wear experiments have to be conducted. Since the enhanced wear on hob teeth, working in generating positions with
large chips, imposes the termination of the experiments, the wear development on hob teeth cutting in less endangered generating positions cannot be investigated.

To cope with this problem an experimental procedure with one cutting tooth, the so-called fly hobbing, is applied. In this technique, the cutting tool is replaced with a cylindrical holder, in which in the case of simulating a hob with one helix, one cutting tooth has to be fixed. The tooth geometry corresponds to the DIN 3972 regulations. The tool workpiece system in this approach of the hobbing process is illustrated in the upper part of Fig. 9. The holder is constructed in such a way as to enable easy mounting and release of the cutting tooth, as well as increased stiffness, to ensure cutting stability at high speeds or feedrates.

The fly hobbing kinematics with discontinuous axial feedrate (DAF) are illustrated in the middle of Fig. 9. In this hobbing procedure, the cutting tooth cuts with continuous tangential feed and without axial feed one generating position in all gear gaps, during one workpiece revolution and moreover all generating positions in further workpiece revolutions. After completing these tasks, the tool is moved axially for the amount of the axial feed, to manufacture in this way discontinuously the entire gear width. This experimental procedure is applied in many research works as for example in [1–8,11,13–15]. The main disadvantages of this experimental approach is that the cutting tooth penetrates continuously in all successive generating positions of the gear gaps, and it is not possible to mount efficiently into the tool holder an individual tooth per generating position, or for a batch of generating positions in which chips with approximately similar equivalent geometries are formed.

In order to enable wear investigations in the individual generating positions, the kinematics of fly hobbing were modified and the continuous axial feed (CAF) fly hobbing was introduced, as illustrated in the bottom part of Fig. 9 [23,24]. The aim of this procedure is to investigate the wear behavior separate in each generating position. According to this experimental technique a cutting tool works along the entire width of all gear gaps in the same generating position. After the formation of the entire width of all gear gaps, in a generating position, through an appropriate rotation and shifting of the tool holder, the cutting tooth is relocated to work in the next generating position, and keeps on manufacturing in this new generating position for the whole gear width of all workpiece gaps. In this way the wear progress during gear hobbing of a chip corresponding to a certain chip group concerning its geometry can be monitored, by replacing the hob tooth before moving it, to a next generating position. Hence, the related wear equations constants may be easily determined, as it will be further described. The experiments and the evaluation of the corresponding results will be demonstrated as a case study for one coated tool, workpiece material combination. On the other hand, reference experiments with uncoated HSS tools in hobbing of the same gear material have been carried out and are also presented in this paper.

To reduce the experiments duration, the generating positions of the observed gear hobbing case are classified in batches of almost similar chips belonging to the same chip group and having approximately the same dimensions and contribution to the tool wear. Figure 10 illustrates an example of how the observed gear hobbing case, with nominally 35 generating positions, can be investigated using only 4 different cutting teeth. Hereby at least in 6 generating positions small chips are formed, which do not have any contribution to the wear progress on the endangered transient
cutting edge regions from the tooth head to the flanks. The occurring chips in the present manufacturing case are classified to the group 1 or 0. Their equivalent chip dimensions, as well as the corresponding group for each of the four generating position batches are inserted in Fig. 10. The equivalent chip dimensions are mean values of the corresponding chip dimensions of each batch. The analytically derived equivalent chip dimensions as well as the experimentally derived flank wear versus the number of cuts were used, as described in the next paragraph, in order to determine the wear prediction equation constants in the case of chip groups 0 and 1, included in the database of the developed FRSWEAR code.

The flank wear progress was monitored by means of optical microscopy. The coating wear was investigated through Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray (EDX) microanalyses. The wear development for one generating positions batch is presented in Fig. 11. According to these results in the present hobbing case the most endangered cutting edge position is on the trailing flank. The micrograph of the same figure illustrates an oblique view of the transient position from the tooth head to the trailing flank. In this micrograph can be observed that the coating has been removed mainly on the flank. EDX analyses also proved this optical observation. The flank wear, was measured by means of optical microscopy, whereas in random cases the corresponding values were successfully crosschecked with the aid of more accurate SEM measurements.

6 Evaluation of Experimental Results in Order to Determine the Hob Wear Prediction Equation Constants

The basic equation used in the algorithms of the FRSWEAR program is the following [6,13–15]:

\[
\log \frac{AS_i}{C_{AS}} + \log (h_{si})/C_{hs} + \log (l_i)/C_{l} = -\frac{1}{C_v} + \frac{1}{C_{AS}}(VB_i/(C_{AS}C_{VB}) + 1 - VB/(C_{VB}C_{AS})) + \frac{1}{C_{VB}}(VB_i/(C_{VB}C_{AS}))
\]

whereas the parameters \(AS_i\), \(h_{si}\), \(l_i\) and \(v_i\) are the number of cuts, the equivalent chip thickness, the cutting length and the cutting speed respectively. VB describes the flank wear progress between a predefined minimum and a maximum value VB as a reference one. The flank wear between the zero and the predefined minimum VB values is determined through a linear interpolation.

The constants \(C_{AS}\), \(C_{hs}\), \(C_{l}\), \(C_{VB}\) and \(C_v\) in the previous equation are different for every combination of cutting tool and workpiece material and have to be experimentally derived. The measured values of the flank wear VB, versus the number of successive cuts, in combination with the calculated equivalent chip dimensions, allow the calculation of these constants. Since the constant values depend on the chip group, to enable their determination, experimental data are necessary.

Figure 12 illustrates the hereby applied procedure. In a first stage, the coefficient of the wear zone width \(C_{VB}\) is determined.
For this purpose, the diagrams of the flank wear VB versus the achieved number of cuts are transformed into semi logarithmic ones, regarding their abscissa. In the considered hobbing case with coated tools, the flank wear values between 0.1 and 0.3 mm form an inclined line. The tangent of the inclination $\varphi$ of this line is the coefficient $C_{VB}$. Considering these results flank wear calculations using Eq. (1) can be conducted, between 0.1 and 0.3 mm.

In a further stage, the determination of the coefficients $C_l$, $C_{HS}$ and $C_{AS}$ necessitate hobbing experimental flank wear data of at least three chips, belonging to the same chip group, having different equivalent dimensions. The intermediate diagram of Fig. 12, illustrates measured flank wear values for three different generating position batches, which belong to the same chip group. Each chip corresponds to a point of the three dimensional diagram in the bottom figure part, the Cartesian coordinates of which are their equivalent width, length and number of achieved cuts, at a reference flank wear of VB = 0.3 mm. With the aid of at least three points the indicated plane is defined. If more than three points are considered to determine the previous mentioned plane, its location is defined by means of the least square optimization method. This plane intersects the axes $\log(hs)$, $\log(l)$ and $\log(AS)$ at points corresponding to the coefficients $C_l$, $C_{HS}$ and $C_{AS}$ respectively (see the bottom diagram of Fig. 12) [6,13–15]. If another reference VB value is set as tool life criterion a further plane is defined and consequently different $C_i$ ($i: l, hs, AS$) coefficient values are determined. By means of this procedure, the coefficients of the mathematical model are defined and implemented in the database of the FRSWEAR program.

With the aid of this program the determination of the number of successive cuts, until a set VB criterion, as for example of VB = 0.3 mm is fulfilled, in gear hobbing of various chip groups and different dimensions can be conducted. The diagrams of Fig. 13 illustrate such results, in hobbing with uncoated and with SUPERTIN® coated HSS tools. The workpiece material in all these cases is the steel 42 CrMo4 V. The superior behavior of the coated tools relatively to the uncoated ones is evident. The number of successive cuts can easily be transformed to an overall width of gears to be manufactured, until the tool re-sharpening or replacement is necessary.

The reliability of the determined wear prediction constants can be judged considering the results illustrated in Fig. 14. In this figure the convergence between the measured and the predicted VB wear values, in three different generating positions is obvious. Further comparisons between measured and calculated results are presented in [6,12–15].

7 Applications of the Tool Wear Prediction Models to Determine Optimum Shifting Conditions in Gear Hobbing

With the aid of the introduced analytical-experimental procedures, optimum tangential shifting parameters can be determined, in order to achieve a uniform wear distribution on the majority of the tool cutting teeth.

These calculations are carried out as demonstrated in the upper part of Fig. 15, where the accumulated wear, occurring on the individual hob teeth after the manufacturing of ten gears in each shift position is illustrated. In this case the test gear has of a width of 25 mm. After the sixth tangential shifting, the maximum flank wear amounts approximately 0.3 mm on the most endangered 9th hob tooth.

The expected wear development on the used hob teeth during the previous described tool shifting procedure is shown in the lower figure part. As it can be observed the cutting teeth 4 and 5 after the 4th and the 5th tool shifting respectively, don’t participate to the hobbing process, due to the fact that through the tool shift they exit from the contact area between the hob and the workpiece.
By means of the introduced hob wear calculations the appropriate shift amount i.e. the number of gears per shift position for various shift displacements, can be determined (see Fig. 16). Hereby two manufacturing cases are considered. In the first case a gear with a relatively small width of 25 mm is examined, whereas in the second one a gear with ten times bigger width. In both cases, the number of gears are illustrated, after which, for various tangential displacements a tool shift is necessary, in order to obtain concrete flank wear values. The appropriate numbers of gears per shift position to achieve a prescribed maximum flank wear depends as expected on the gear width.

The overall gear width per hob tooth, as well as the number of cuts per hob tooth, up to a flank wear of 0.3 mm in the previous considered manufacturing cases are demonstrated in Fig. 17. The required number of gears to be hobbled per shift position in order to get the previous mentioned maximum flank wear is also shown. By increasing the tangential displacement amount, a slight growing of the overall gear width per hob tooth as well as of the number of cuts per hob tooth can be observed. This increasing is explained through the better exploitation of the cutting teeth in the hob external regions (hob teeth 1−8 and 15−22). For example on the 6th hob tooth in the cases of 1e, 2e, and 3e displacement per shift, in hobbing of a gear width of 25 mm, the flank wear amounts 0.18, 0.20 and 0.22 mm respectively (see Fig. 16).

On the other hand, in the case of a larger gear width as for example the examined case with \( b = 250 \text{ mm} \), the overall hobbled width is lower in comparison to the corresponding one when gears with a width of 25 mm are manufactured.

This can be explained through the diminishing in the case of a gear width of 250 mm, of the number of cuts in transient work-piece cutting regions, where chips with small dimensions are formed, in relation to the overall number of cuts.

The better cutting performance of the coated tools in comparison to uncoated ones, can be observed in Fig. 18. In all applied shifting conditions the SUPERTIN® coated tool leads to a significant higher cutting performance. Further corresponding results with TINALOX® coatings [16–18, 21] ascertain this tendency.

8 Conclusions

The aim of this paper is to exhibit methods to predict the tool wear development in gear hobbing. The introduced procedures are based on the analytical determined chip geometry and its correlation to experimental results in order to establish wear laws, covering every possible hobbing case. In this way, mathematical models to determine the wear progress on hob teeth in individual cutting and generating positions as well as to describe the wear development considering the hob tangential shifting are available. With the aid of the described experimental results evaluation and applying fly hobbing with continuous axial feed, the tool wear equations constants of the used algorithms in the FRSWEAR program can be efficiently determined.

The results of the presented investigations show that the proposed numerical experimental approach can be applied successfully to predict the tool wear behavior in gear hobbing and to optimize cutting and hob tangential shifting conditions in order to achieve a uniformly distributed wear on the tool teeth. The coated hob teeth showed in the conducted investigations a significantly increased cutting performance in comparison to uncoated ones.
Fig. 17 Achieved overall gear width and number of cuts per hob tooth at various shift conditions and gears widths

Fig. 18 Achieved overall gear width per hob tooth with coated and uncoated tools

Acknowledgments

This research was financially supported by the General Secretariat for Research and Technology of the Greek Ministry for Development in the frame of the BE411 PA VE project for the development of industrial research entitled “Determination of tool life time in gear hobbing, to increase the productivity and to reduce the manufacturing costs.” Besides the Laboratory for Machine Tools and Manufacturing Engineering of the Aristotle University, an industrial partner to this project was Northern Greek Workshops ORFANIDES SA. The authors would like to thank CemeCon GmbH (Aachen, Germany) for the coating service required by the experimental project needs.

Nomenclature

\[
\begin{align*}
\text{AS} & = \text{number of cuts} \\
\text{b} & = \text{gear width (mm)} \\
\text{CAF} & = \text{continuous axial feed} \\
\text{CP} & = \text{cutting position} \\
\text{DAF} & = \text{discontinuous axial feed} \\
\text{f}_a & = \text{axial feed (mm/rev)} \\
\text{G} & = \text{chip group} \\
\text{LF} & = \text{leading flank} \\
\text{n}_1 & = \text{number of hob columns} \\
\text{SHD} & = \text{tangential displacement} \\
\text{SHN} & = \text{number of gears per tangential displacement} \\
\text{TF} & = \text{trailing flank} \\
\text{v} & = \text{cutting speed (m/min)} \\
\text{VB} & = \text{wear flank} \\
\text{z}_1 & = \text{number of hob helices} \\
\text{z}_2 & = \text{number of gear teeth} \\
\text{e} & = \text{tool helix axial pitch (mm)}
\end{align*}
\]

References

Hobbing,” 1st International Conference THE Coatings, October, Ziti Ed., Thessaloniki pp. 139–158.

