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Describing and evaluating deviations for bevel gear flanks

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Abstract

Designing the cutting process of bevel gears poses a considerable challenge. For understanding as well as analyzing the bevel gear cutting process and eventually predicting the effects on wear behavior, knowledge of the chip geometry, its formation and characteristic values is essential. One existing method for simulating bevel gear cutting is based on a two-dimensional penetration calculation.
The objective of this paper is to validate the simulation method by means of the derived flank geometry. As a result, a validated and verified flank geometry is obtained which can be applied to a FE-based tooth contact analysis.

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Keywords: Manufacturing simulation; Bevel gear;

1. Introduction and Motivation

Bevel gears are generally manufactured on special machine tools with the help of tool systems consisting of cutterhead and several stick blades [1], [2]. Due to the machine and process kinematics, the relations between work piece, tool and process parameters prove to be complex [3]. Consequently, the tool wear for bevel gear cutting can be described analytically only with difficulties [4].

In recent years, extensive investigations on simulative analysis of bevel gear cutting have been conducted at the WZL of the RWTH Aachen University by BEULKER [5], RÜTJES [6], HARDJOSUWITO[4] and HERZHOFF [3]. The objective was to reduce time and costs for the process design and to predict tool wear. By defining suitable characteristic values, tool wear was described and reduced. Furthermore, the understanding of the cutting process for bevel gears was extended systematically. These findings were combined in developing the manufacturing simulation BEVELCUT [7]. By optimizing the underlying algorithm of the penetration calculation, a significant decrease in calculation time could be achieved.

Fig. 1 provides an overview of the steps of the manufacturing simulation BEVELCUT. In the beginning, the input data is imported. It includes the blank and tool geometry as well as the machine and process kinematics. Subsequently, blank and tool are discretized. The blank is represented by intersecting places. The profile edge's trace through space is described by the resulting enveloping body.

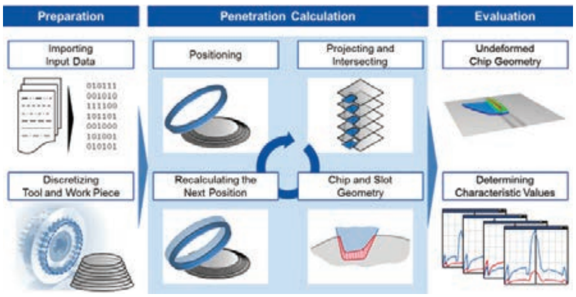

Fig. 1. Steps of the manufacturing simulation BEVELCUT

The core of the manufacturing simulation constitutes of the penetration calculation. Work piece and tool are positioned according the machine and process kinematics incrementally. By projecting the profile edge onto the individual intersecting planes, the spatial penetration is reduced to a two-dimensional problem. The points of intersection between the outline of the workpiece and the projected outline of the blade are determined. Based on these, the chip area is determined for the both outlines. The chip for every cut is composed of the chip

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areas for the individual planes. Tool and work piece are then repositioned for the next process increment until full depth is attained. [7]

After concluding the penetration calculation, the undeformed chip geometry for every cut is evaluated. Characteristic values are derived which can be attributed either to the point of chip formation for the entire process, for the single feed increments or to the creating point on the profile edge. The characteristic values of the current version of the manufacturing simulation BevelCut consist of the number of cuts, the chip thickness, the length of the cutting arc and the chip volume. Furthermore, the final geometry of the cut slot is displayed. [7]

The left half of Fig. 2 summarizes the steps taken so far for validating the manufacturing simulation BevelCut. The calculated chip geometry was evaluated by means of chips from cutting trials. The two flank chips characteristic for bevel gear cutting could be correlated regarding the shape as well as the point of origin on the profile edge. [7]

Subsequently, the tool wear of a blade taken from high volume production was compared to the characteristic values calculated by the manufacturing simulation. For this, the distribution of the chip thickness along the profile edge was analyzed. A very good correlation between the calculated chip thickness and the tool wear could be asserted. [7]

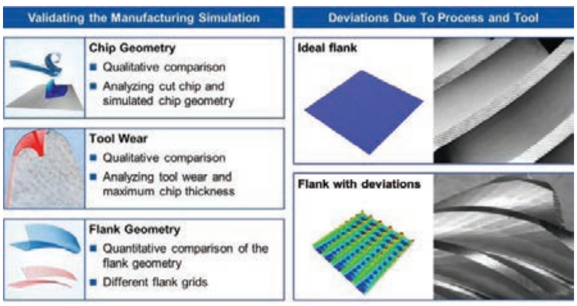

Fig. 2. Motivation for developing and evaluating the flank comparison

As a final step of the validation, the obtained final outline of the simulated work piece was compared to the target of a commercial design program. The different grids between target and simulated flank posed a considerable challenge. Using the approach of flank comparison according to Röthlingshöfer [8], maximum deviation of 77.2 µm occurred at the root of the heel. Therefore, the flank comparison could not be deemed successful. The irregular shape of the surface deviations could not be traced back to either irregularities of the target flank or of the flank simulated by BevelCut. Furthermore, the deviations do not display typical behavior related to kinematic causes. Hence, a reliable method for comparing flanks of bevel gears is necessary. [7]

For bevel gears, so far the focus of evaluating tool wear lay on manufacturing ideal flanks [3], [4], [5], [6]. Mainly, plunged ring gears were investigated [3], [4] and sample tests of generated pinions were conducted [5], [6]. Deviations due to the manufacturing process and their impact on the flank geometry have not yet been investigated systematically. However, due to deviations caused by the tool position and the manufacturing process as they have been researched for cylindrical gears [9], the actual flank of bevel gears exhibits deviations.

As the bottom photo on the right hand side of Fig. 2 shows, process related generating flats and feed marks can superimpose on the flank and lead to characteristic scales [9]. Furthermore, shape and positional tolerances of the blade profile regarding the cutterhead, of the cutterhead regarding the machine axes as well as the tool wear influence the microgeometry of the flank. In order to investigate these influences systematically, a method for comparing flanks of a targeted, ideal flanks to simulated flanks with deviations is necessary as well.

Nomenclature

a	Coefficient of the line g
b	Coefficient of the line g
d	Coefficient of the line g
g	Line between points of the work piece outline
k	Circle described by the radius r of a given point
r	Radius of a given point on the target grid
x_1, y_1	Coordinates of the neighboring point P_1
x_2, y_2	Coordinates of the neighboring point P_2
x_m	Mean deviation
x_{max}	Maximum deviation
x_{min}	Minimum deviation
x_p, y_p	Coordinate of the intersecting point
Δx	Range of the deviation

2. Objective and Approach

The manufacturing simulation BevelCut allows a versatile application for analyzing the relations between input and process parameters for bevel gear cutting. A successful comparison between simulated and targeted flank geometry is necessary to conclude the validation of the two-dimensional penetration calculation. Basis for this is a reliable method for flank comparison of bevel gears.

Due to the short calculation time of BevelCut, it is furthermore possible to investigate the influence of deviations due to the manufacturing process as well as the tool locations on the flank geometry of bevel gears. For this, a method for describing and quantifying deviations is necessary.

The objective of this paper is to develop and apply a method for evaluating deviations for simulated bevel gear flanks. The method is implemented in the manufacturing simulation BevelCut. For accomplishing this objective, the approach depicted in Fig. 3 is applied.

As a first step, the flank grid is fitted to the targeted flank grid. For this, the intersecting planes are distributed variably along the rotational axis of the work piece. Subsequent to the penetration calculation, the coordinates and normal vectors of the flank are determined. The objective is to facilitate a flank comparison between a target flank and the flanks resulting from the manufacturing simulation BevelCut.

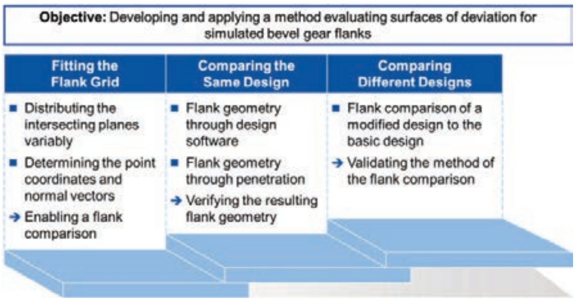

Fig. 3. Approach

The comparison of the same design aims at verifying the resulting flank geometry of the manufacturing simulation. For this, the flank geometry of a basic design is determined on one hand with the help of the penetration calculation and on the other hand by means of a commercial design program. The geometry of both flanks is compared. As both flanks represent the same design, the deviations between both flanks should amount to zero in the best case. If the flanks coincide to an acceptable degree, it can be concluded that the kinematics and tool creation of the manufacturing simulation have been implemented correctly.

As a final step, two different designs are compared. The objective is to validate the method of the flank comparison. For this, the basic design is compared to a modified design. A flank comparison has to display significant deviations between both flanks. The flank comparison is conducted with the flank comparison described in this paper and with a flank comparison included in a commercial design program. If both surfaces of deviation coincide, it can be concluded that the methodology of the developed flank comparison is valid.

3. Creating an Evenly Spaced Grid

Due to the work piece discretization and the penetration calculation described in section 1, the original final geometry of the simulated flank displays an irregular flank grid. The distribution of the points depends on the position of the intersecting plane and the outline of the projected profile edge. In order to compare flanks, the flank grid has to be fitted to the target flank first.

The approach of obtaining an evenly spaced grid is depicted in Fig. 4. The basis for the regular grid are Sollmess data calculated by the commercial design program. They contain the coordinates of every point as well as the normal vector of the ideal flank surface in the work piece coordinate system [1]. By means of the information of the Sollmess files, a grid is generated with the radial component r and axial component z. This grid forms the basis of the flank generation with help of the manufacturing simulation BEVELCUT.

As described in section 1, the blank is divided into intersecting planes. The intersecting planes are perpendicular to the work piece's rotational axis and hence represent the circular sections of a plane and a cone. Originally, the intersecting planes have been positioned equidistantly. Now, they are situated according to the z component of every flank coordinate of the Sollmess data. Thus, the number of intersecting planes depends on the resolution of the target flank.

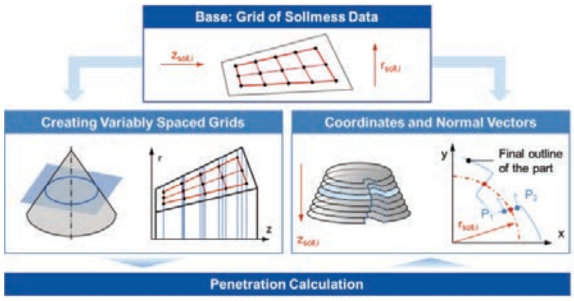

Fig. 4. Approach for obtaining an evenly spaced grid

Subsequent to the discretization of the work piece, the penetration calculation is conducted. High resolutions of more than 100 flank and profile lines can lead to a large number of intersecting planes and thus, to a high calculation time. However, the number of points in a Sollmess file is limited to 4,000 points, the calculation time for the highest possible resolution remains within maintainable 20 minutes. The result of the penetration calculation are flank points and normal vectors situated on the described intersecting planes.

In order to determine the coordinates and normal vectors of the flank, every point on the Sollmess flank has to be attributed to an intersecting plane. The radius of a point on the Sollmess flank describes a circle, as it is shown on the right of Fig. 4. This circle k(x,y) intersects with the outline of the simulated work piece which can be described between two points as the line g(x,y). The intersecting points represent the coordinate of the BEVELCUT flank on the grid of the Sollmess flank and can be determined according to the formulas (1) to (5).

$$x_{p1/2} = \frac{a \cdot d \pm b \cdot \sqrt{r^2 \cdot (a^2 + b^2) - d^2}}{a^2 + b^2} \quad (1)$$

$$y_{p1/2} = \frac{b \cdot d \mp b \cdot \sqrt{r^2 \cdot (a^2 + b^2) - d^2}}{a^2 + b^2} \quad (2)$$

where

$$k(x, y): x^2 + y^2 = r^2 \quad (3)$$

$$g(x, y): ax + by = d \quad (4)$$

As a line and a circle can maximally possess two intersecting points, it has to be tested whether the determined intersecting points lie between the two points on the work piece outline P_1 and P_2. Subsequently, the normal vector of the intersecting point can be determined with the help of the neighboring points P_1 and P_2 according to formula (5).

$$\vec{n}_p = \frac{\vec{n}_1 + (\vec{n}_2 - \vec{n}_1) \cdot \sqrt{\frac{(x_p - x_1)^2 + (y_p - y_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2}}}{\left\| \vec{n}_1 + (\vec{n}_2 - \vec{n}_1) \cdot \sqrt{\frac{(x_p - x_1)^2 + (y_p - y_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \right\|} \quad (5)$$

Instead of an initially irregular grid in consequence of the penetration calculation, now the final geometry of the manufacturing simulation BEVELCUT can be described by any given target grid. The deviation of the target grid and the obtained grid with the new method are in the range of the machine accuracy of the computer [10]. Therefore, any deviation between the simulated flank and the targeted flank now have to be due to flank geometry and cannot be explained by the deviating grid structures.

The steps of the flank comparison are described in Fig. 5. The flank simulated by means of bevel gears is described in the work piece coordinate system. The coordinates included in the Sollmess files are rotated so the mean point of the convex and concave flank coincide in a common point on the x-axis. Therefore, a rotation of the BEVELCUT flank is necessary in order to compare both flanks.

Subsequently, the simulated flank is triangulated. Condensing three points to a triangle is necessary for determining the distance between a point and the flank in normal direction. For every point on the Sollmess flank, a ray is emitted in the direction of its normal vector. The ray intersects any of the previously determined triangles. The length of the ray between the coordinate and the intersecting point represents the distance between both flanks in normal direction for the examined point. It has to be taken into consideration that for a low resolution, the interpolation error increases. For highly contorted surfaces, as the case with flanks of bevel gear pinions, the resolution of the target flank has to be chosen accordingly.

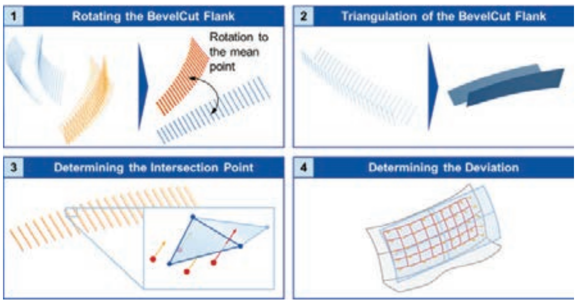

Fig. 5. Steps of the flank comparison in detail

In order to determine the distance between both flanks, the distance to the triangle is determined for every coordinate included in the Sollmess files. Thus, every point of the grid can be attributed to a distance value. The resulting surface of deviation is evaluated in the following section.

4. Determining and Evaluating the Surface of Deviation

Due to obtaining regular flank grid for the manufacturing simulation BEVELCUT, applying a flank comparison for bevel gears is made possible. In the following section, the results of the flank comparison for two variants are evaluated. On one hand, the flanks of the same design are compared. On the other hand, a comparison of two different designs is conducted.

4.1. Flank Comparison of Identical Designs

The objective of comparing the identical designs is to verify the flank geometry obtained with the manufacturing simulation BEVELCUT. The approach is described in Fig. 6. The basic design of an automotive gear set, represented by its ease off, is used as an example. By means of the blank and tool data as well as the machine kinematics, the design software can calculate Sollmess files that describe the flank of pinion and ring gear for design A.

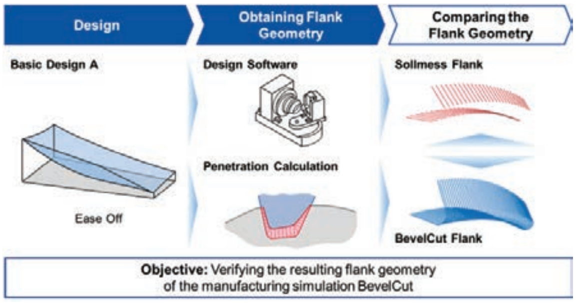

Fig. 6. Objective of comparing flanks of the identical design

Since the ring gear is produced by discontinuous plunging and the manufacturer supplied process data, the geometry of the ring gear flanks can be obtained by means of BEVELCUT. For plunging process, the flank geometry represents the shape of the blade for full depth. For this reason, no deviations due to the manufacturing process should occur on the simulated flank. Subsequently, the flanks of the targeted flank and the flank simulated with BEVELCUT are compared according to the flank comparison developed in section 3.

Fig. 7 shows the result of the flank comparison of the basic design. For the concave flank, the maximum deviation of 0.75 µm occurs at the toe. The minimum of -1.36 µm occurs at the heel. Therefore, the range of the deviation amounts to 2.11 µm and is lower than the deviation obtained with the method described in section 1 [7]. The mean deviation x_m of 0.17 µm is below 1 µm. Therefore, the flank comparison for the concave flank can be regarded successful.

For the convex flank (Fig. 7, right), the flank comparison shows a waviness. The maximum deviation of 1.18 µm and the minimum deviation of -2.66 µm occur at the peaks and valleys of this waviness. The range spans 3.84 µm and is larger than the range of the concave flank. The direction of the waviness is in opposite direction of the contacting lines between cutting edge and flank. As the investigated process is discontinuous plunging, the origin of the waviness cannot originate in the machine or process kinematics. As the outlines of the profile edges are generated with the same routines, waviness caused by a faulty tool geometry must occur on both flanks. As this is not the case, the waviness cannot be attributed to an incorrect description of the tool or the machine and process kinematics. As the deviations are in the range of single digit microns and the average deviation x_m of -0.36 µm also is below 1 µm, the flank comparison for the convex flank can be regarded successful.

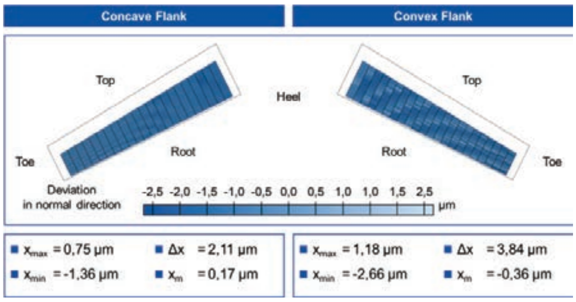

Fig. 7. Result of comparing flanks for the basic design

In conclusion, the flank comparison shows deviations which range is below 5 µm for both flanks. The average deviation of both flanks is below 1 µm. Respectively, the verification of the flank geometry can be regarded successful. As the verification of the flank geometry remained unsettled, the two-dimensional penetration and therefore, the manufacturing simulation BEVELCUT are now validated. In order to use the simulated flanks for further analysis, such as a tooth contact analysis, the slot width or the tooth thickness at the mean point can be investigated further. As there is no information on the tooth root geometry in the Sollmess file, the root geometry cannot be validated in this paper. In order to calculate the correct tooth root bending stresses in a tooth contact analysis, the root geometry also has to be verified.

4.2. Flank Comparison of Different Designs

Objective of the flank comparison of different designs is to validate the methodology of the flank comparison based on the results of the commercial design software. The approach for this comparison is depicted in Fig. 8.

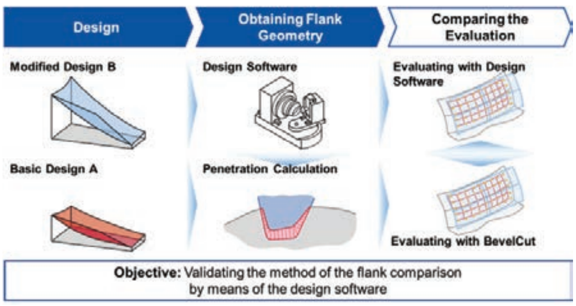

Fig. 8. Objective for the flank comparison of different designs

The basic design A, which has been investigated in the previous section 4.1, is modified. The machine settings are changed in a way that the resulting modified design B exhibits an additional spiral angle deviation. By means of the design software, a flank comparison between design A and B is conducted.

Additionally, the basic design A is simulated by the manufacturing simulation BEVELCUT. Instead of the original Sollmess files of the basic design, the modified design B is basis for the flank comparison. Subsequently, the surfaces of deviation of the flank comparison are compared for the design software and for BEVELCUT.

Fig. 9 shows the results of the flank comparison between the basic design A and the modified design B. The design software's output of the maximum deviations are whole-number microns. It cannot be traced whether the values have been rounded up, down or the information after the decimal points has been disregarded. The flank comparison of the design program shows the expected spiral angle deviation on the left side of the figure. For the convex flank, the deviation amounts to -26 µm at the root of the toe and to -25 µm at the top of the toe. At the heel, the deviation between the basic design A and the modified design B is 28 µm at the root and 26 µm at the top.

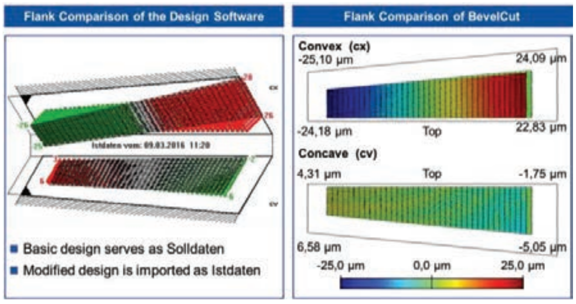

Fig. 9. Result of comparing different designs

For the convex flank, the flank comparison integrated in BEVELCUT also displays a clear spiral angle deviation. At the toe, the deviation amounts to -25.1 µm at the root and to -24.18 µm at the top. Therefore, the deviations at the toe are within 1 µm as for the targeted flank comparison. For the heel, the last profile line could not be evaluated as the gradient of the normal vector was too high and no intersecting point between the ray and the triangulated flank could be determined (compare section 3). For this reason, only the second to last profile line is evaluated with deviations of 24.09 µm at the root and 22.83 µm at the top.

The concave flank displays smaller deviations. At the toe, the flank comparison of the design software shows deviations of 6 µm at the root and 3 µm at the top. For the heel, the deviations amount to -2 µm at the root and -6 µm at the top.

With the help of the flank comparison described in this paper, the deviations at the root of the toe are 6.58 µm and 4.31 µm at the top of the toe. For the heel, no deviations could be determined for the last profile line for the aforementioned reasons. Here, also the second to last profile line has been evaluated. There, the deviations amount to -5.05 µm at the top and -1.75 µm at the root.

The accuracy of the flank comparison integrated in BevelCut accord to the specifications of the commercial design software. The deviations between both methods are generally within the error due to rounding of 1 µm for both small and large deviations. The origin of missing deviations for the last profile line of the heel is investigated further. For high deviations as between the basic design A and the modified design B, the normal vectors of the flank do not intersect the triangles at the edge of the flank. By enlarging the triangulated area and thereby, the provided flank gird, this error can be avoided in the future. The deviations for these special cases are still within an acceptable range of less than 5 µm. Therefore, the results for the developed method of comparing flanks can be regarded verified.

5. Summary

Due to the complex relation of mechanisms for bevel gear cutting a manufacturing simulation is necessary. For the manufacturing simulation BevelCut which is based on a two-dimensional penetration, the comparison between simulated and target flank has posed a challenge so far. Basis for the validation is a reliable methodology for comparing flanks of bevel gears. Furthermore, the low calculation time allows high resolution simulations for investigating the influence of deviations due to the process and tool. For this as well, describing and quantifying flank deviation is necessary.

Objective of this report is to develop and apply a method for evaluating surfaces of deviation for simulated bevel gear flanks. For this, the methodology for obtaining a regular flank grid for the manufacturing simulation BevelCut is presented. Basis for the grid are Sollmess files that are provided by the design software. The position of the intersecting planes is determined by the target values. Subsequent to the penetration calculation, the coordinates of the points on the grids as well as their normal vectors are calculated. Prior investigations showed that the obtained grid matches the target grid .

With the help of the developed flank comparison, as a next step the flank geometry of the same design can be compared. The flank geometry is determined by means of a commercial design software as well as by means of the manufacturing simulation BevelCut. With an average deviation below 1 µm and a deviation range below 5 µm, the flank comparison for both methods of obtaining flanks is successful.

As a last step, two different designs are compared. Objective is to validate the methodology of the developed flank comparison by means of verified results. The developed flank comparison shows consistent results for low and high deviations compared to the results of the design software. Therefore, the validation of the methodology is also successful.

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