UNIMILL for Prototype and Small-Batch Bevel Gear Manufacturing

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Introduction

The manufacturing of spiral bevel and hypoid gears can be conducted in several ways. The following methods are commonly known:

A. Face hobbing with a circular face cutter that rotates while the work rotates in the opposite direction (continuous indexing).
B. Face hobbing with tapered hob (peripheral cutter) that rotates while the work rotates as well (continuous indexing).
C. Planing method with one or two tools that move linearly, while the work either is performing a roll rotation or a combination of roll rotations and an additional rotation for a spiral-shaped flank line (single indexing).
D. Face milling with circular face cutter that rotates while the generating gear is not rotating, the work only performs a roll, but no indexing motion (single indexing).
E. Universal 5-axis milling with pencil-shaped end mill or disk-shaped cutter (single slot manufacturing).

Methods A through D are well known and have been performed for more than 70 years. Method E became available with the possibility to enter complex free-form surfaces into the control of 5-axis universal milling machines. While the manufacturing time is between 10 and 100 times that of the processes A through D, the accuracy might generally be lower than that of the dedicated machines used to perform methods A through D. The advantage of 5-axis bevel gear machining is the flexibility; no special cutting tool is required and the bevel gear size is only limited by the size of the 5-axis machines available (Refs. 1–2).

Five-axes machining uses a spherical- or cylindrical-shaped mill to shape the flank surfaces. The data post-processing uses flank surface points and, in some cases, normal vectors to calculate the machining paths. The machining paths must be close enough to achieve enveloping paths that approximate the target surface with sufficient precision. The orientation of the enveloping paths (flats) is linked only to the machining strategy in order to minimize the machining time and the deviation from the target flank surface. It has to be considered in manufacturing of bevel gears with machining centers that a generated bevel gear tooth consists of up to 7 different areas:

1. Flank surface — first flank
2. Flank surface — second flank
3. Root fillet radius — below first flank
4. Root fillet radius — below second flank
5. Slot bottom — between both root fillet radii
6. Undercut section — below first flank and above root fillet
7. Undercut section — below second flank and above root fillet

The true profile and lead generation, according to the gearing law, only works within the flank surface and in the root fillet area, i.e. — from the flank transition down towards the root bottom, ending in the area of the 30° tangent point. Depending on the severity and character of the undercut, it is impossible to generate this area precisely with correct normal vectors. Also the slot bottom — connecting the fillet region from the 30° tangent through the deepest bottom land to the opposite side root radius at the 30° tangent — cannot be generated using the common surface-generating algorithm for bevel and hypoid gears.

In regards to face-hobbed gears with extended toe or heel ends, it is also equally difficult or impossible to generate the extension of the flank surface, which in many cases does not consist of a true flank surface according to the gearing law. One typical example is slotted nose pieces that represent flank surface extension far behind the heel of the pinion to be clamped in front of the nose piece. However, those problem areas are formed with a face cutter head that represents one tooth of the generating gear. The generating gear (Fig. 1) will form them as: an undercut section, as root bottom area, or as enveloping form cuts beyond the theoretical face width. If the undercut, root bottom area, etc. are formed by the generating gear, then it is assured that rolling without disturbances between pinion and gear can occur. Undercut, for example, is not an "evil" caused by the manufacturing process; rather, it is a geometrical necessity in order to assure correct rolling without interferences (Ref. 3).

But the solution for the problem areas is not a substitution of those sections with plane, cylindrical or parabolic surface elements, because of the risk of either weakening the teeth or causing rolling disturbances.

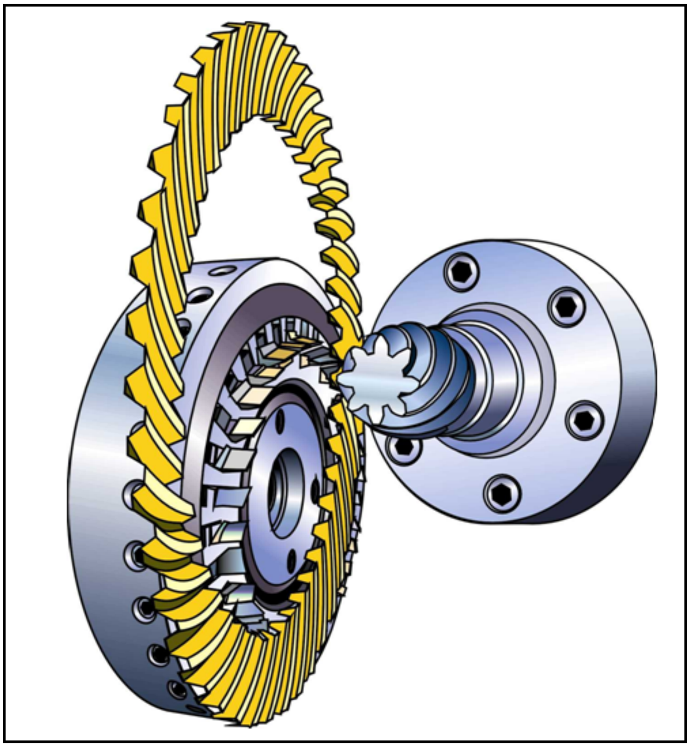


Figure 1 **Face cutter representing one tooth of a generating gear.**

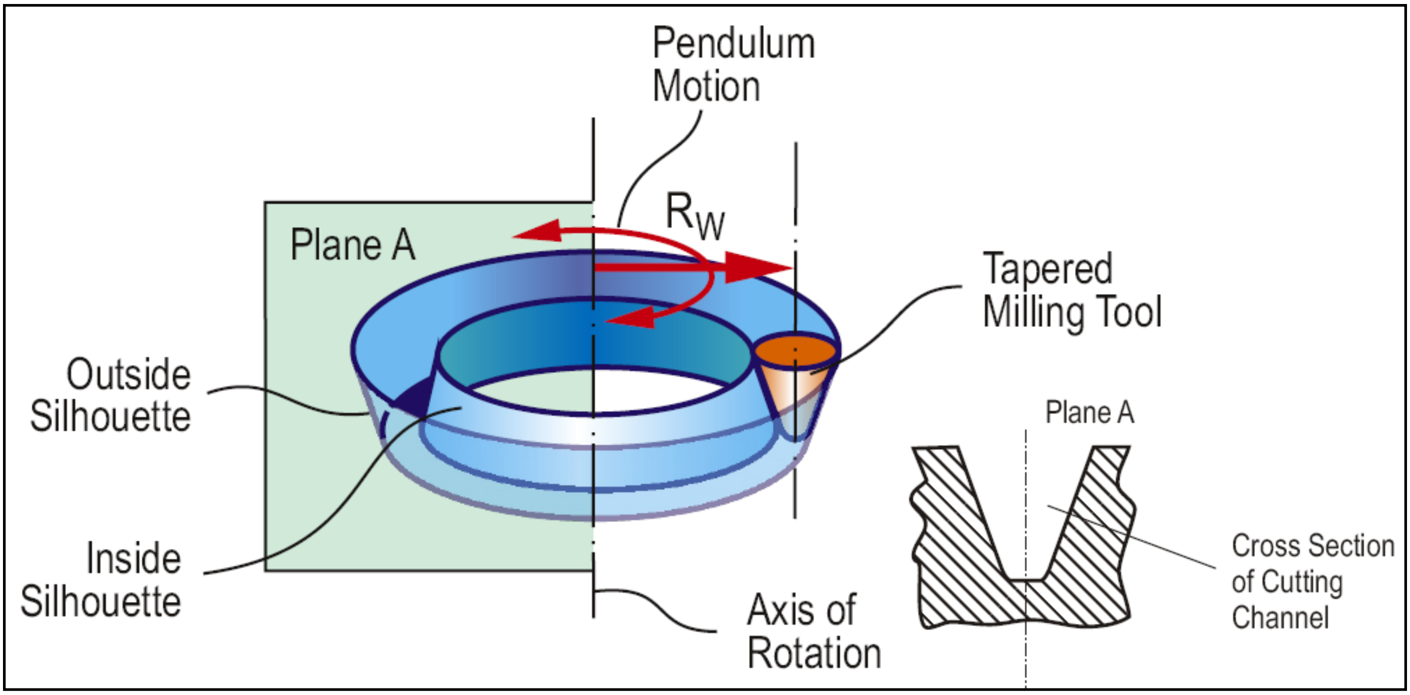


Figure 2 A typical cutting or grinding channel.

Universal Method Derived from Face Cutting Process

The face milling method defines flank surfaces dependent on basic settings that define the relative location between a face cutter head, a generating gear axis and a work axis — as well as a kinematic relationship between those three components. A spread blade face milling cutter envelopes both an outside cone and an inside cone which in turn form a circular channel. Cup-shaped grinding wheels are dimensioned to duplicate the cutting channel for one particular gear design (with stock allowance taken into account).

A typical cutting or grinding channel is shown (Fig. 2). Particularly for large spiral bevel gear sets, it is common to use pressure angles of 20° for concave and convex flanks. In such cases, outside and inside silhouettes of the cutting channel are cones with angles of +20° and –20° relative to the axis of rotation. A tapered milling tool with a cone angle of 20° and a tip diameter with the value of the point width compared to the face mill cutter head (Fig. 3) would fit into the cutting channel.

If the milling tool has an edge radius and a straight or curved profile with additional features, then the cross- sectional view of the milling tool can exactly duplicate the cross-section of the cutting channel. Such a milling tool can be positioned in the cutting spindle of a free-form bevel gear cutting machine. If the cutting machine axis would perform the regular cycle of movements as it is applied to generate a bevel gear in the conventional face cutter head process, then the pencil-shaped milling tool would not form the correct tooth geometry.

However, the milling tool would in this case be located in the center of the face milling cutter. In order to duplicate the flank surface forming action (cutting and generating), two additions to the standard setup and cutting cycle are necessary to accommodate the pencil milling tool. First, the milling tool is required to be moved from the face mill cutter center to an offset location (“a” in Fig. 4). The offset vector is identical to the average

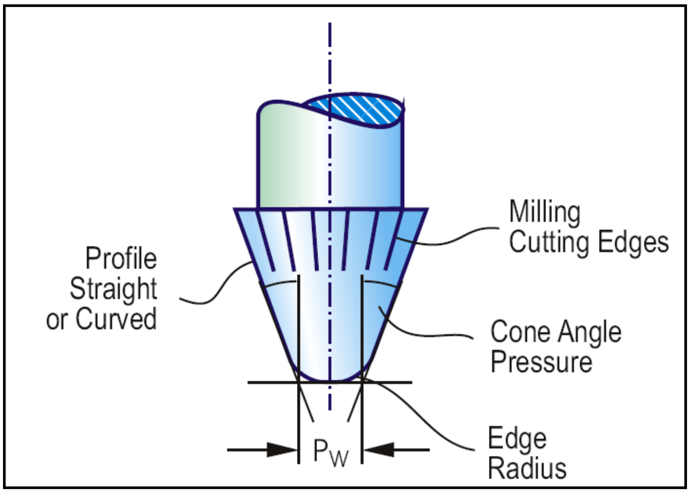


Figure 3 Conical milling tool.

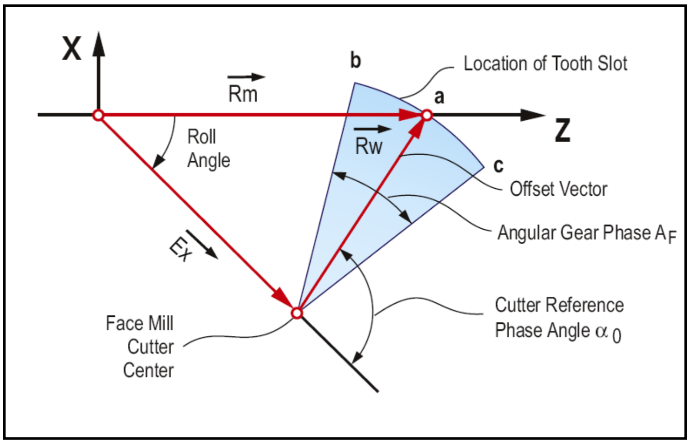


Figure 4 Pencil milling tool moved to offset location.

cutter point radius vector and can be located in the center of the tooth face width (point "a" in Fig. 4). Second, the milling tool has to follow a circular arc in the plane of the face milling cutter. Figure 4 shows the case where the face milling cutter rotational plane is identical to the plane X-Z.

The conventional cutting machine setup positions the cutter center at the tip of the vector Ex (Fig. 4). To enable use of a tapered milling cutter, the center of the cutter spindle must be positioned along the path of the arc b-a-c (Fig. 4) and also move between the positions b-a-c (and reverse), while the cutting machine is in one roll position. In the next roll position the movement along b-a-c must repeat. It is also possible to use a continuous slow roll motion, while the machine axes perform a fast pendulum motion of the tool center between b-a-c.

The cycle described can utilize a standard free-form bevel cutting machine with a modified cutting cycle. The only change vs. the conventional part program is the additional term shown in the formulas below:

Milling Cutter Location	Conventional Face Cutter Center		Additional Term
b:	$\vec{E}_X$	+	$R_W \times \begin{Bmatrix} \sin\left(-q_0+\alpha_0+\frac{A_F}{2}\right) \\ 0 \\ \cos\left(-q_0+\alpha_0+\frac{A_F}{2}\right) \end{Bmatrix}$
a:	$\vec{E}_X$	+	$R_W \times \begin{Bmatrix} \sin(-q_0+\alpha_0) \\ 0 \\ \cos(-q_0+\alpha_0) \end{Bmatrix}$
c:	$\vec{E}_X$	+	$R_W \times \begin{Bmatrix} \sin\left(-q_0+\alpha_0-\frac{A_F}{2}\right) \\ 0 \\ \cos\left(-q_0+\alpha_0-\frac{A_F}{2}\right) \end{Bmatrix}$

In order to generate the profile of a tooth, the generating gear must rotate. This rotation is equal to a rotation of the vector Ex (Fig. 4) about the axis Y (perpendicular to the drawing plane).

The introduced, proprietary new process is called *UNIMILL*. The infrastructure and accuracy level of the free-form bevel gear machine are a desirable platform for bevel gear cutting with the *UNIMILL* process.

One advantage of the *UNIMILL* method is the fact that it produces identical bevel gear geometries as produced with face milling cutters. Even the generating flats have the same characteristics and angular orientation between the presented method and the face milling cutter method. Figure 5 (left) shows a three-dimensional representation of the conical milling tool as it simulates the face cutter in one instantaneous roll position. Since the face cutter would produce in this roll position one generating flat-per-flank (indicated on the outside silhouette, Fig. 5), the tapered milling tool will produce the identical flat. As the rolling motion progresses, further flats will be produced. Figure 5 (right) shows how the generating flat sections of the tool silhouette relate to the real generating flats on a flank surface.

The generating flat orientation of the 5-axis methods E differ from the face milling or face hobbing cutting methods, which will introduce in many cases different roll conditions. A surface structure identical to the original face cutter process is a significant advantage of the *UNIMILL* process. A second advantage of this method is the fact that standard cycles can be applied (super-imposed by said pendulum motion); e.g. — for soft cutting that leads to manufacturing times of 10-to-50 times that of the processes A and D — and is, in most cases, only 50% of the manufacturing time of a 5-axis machine using an end mill according to process E. At the same time, the gear accuracy of the *UNIMILL* method is comparable to the A and D process, due to the use of a gear machine tool concept.

A third advantage of *UNIMILL* is the unlimited compatibility to the cutting and grinding with face cutters; all existing design and optimization computer programs can be used. Also the nominal data calculations and correction matrixes that are well established and proven in correction software tools such as *G-AGE* can be applied without limitation. Yet another advantage of *UNIMILL* is the fact that undercut conditions and root fillet geometry are identical to the original geometry, generated by the face cutter process. As already noted, the elimination of undercut in an existing design is not an option because of the roll disturbances this will cause.

Even with unequal inside and outside blade angles of the analogue face cutter process, a tapered milling cutter with half the included blade angles $(\alpha_{IB}+\alpha_{OB})/2$ as cone angle can be used if the milling tool will be inclined by $\kappa_{\text{mill-tool}} = -(\alpha_{IB}-\alpha_{OB})/2$.

The calculation of the position of a tapered milling tool in the general case can be achieved based on the geometric

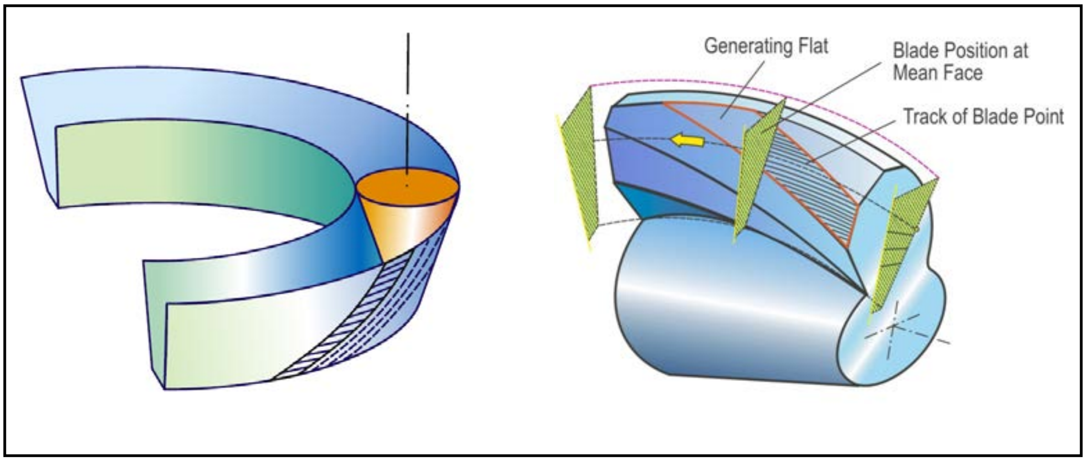


Figure 5 Cutter blade silhouette and generating flats.

relationships of Figures 6 and 7, as follows:

Input:

- Cutter tilt = W_x
- Cutter swivel = W_y
- Mean cutter radius = R_w
- Cutter phase angle reference value = α_o
- Cutter phase angle = α_x = Swing Angle
- Roll position = q
- Blade reference height = H_R
- Sliding base position = X_B
- Additional milling tool inclination = κ_{Mill_Tool}
- Radial Setting = S
- Cutter Radius vector at reference position = R_w (α_0)

After performing the transformations from conventional basic settings to the settings of a tapered mill cutting tool, the following steps can be applied in order to prepare all data for the *UMIMILL* process:

- Choose a number of roll positions that split q_{start} and q_{end} in 50 increments:

$$\rightarrow \qquad q_1, q_2, q_3 \ldots q_{51}$$

where:

$$q_1 = q_{start};\ q_2 = q_{start} + \Delta q;\ q_3 = q_{start} + 2\Delta q;$$
$$q_{51} = q_{start} + 50\Delta q$$
$$\Delta q => \Delta q = (q_{end} - q_{start})/50$$

- Apply for each roll position the formulas for the tool position, e.g. — for 200 increments:

$$\rightarrow \qquad \alpha_1, \alpha_2, \alpha_3 \ldots \alpha_{201}$$

where:

$$\alpha_1 = \alpha_0 - A_F/2; \alpha_2 = \alpha_1 + \Delta\alpha;\ \alpha_3 = \alpha_1 + 2\Delta\alpha;$$
$$\alpha_{201} = \alpha_1 + 200\Delta\alpha$$
$$\Delta\alpha = A_F/200$$

Data Processing for Generation and Swing Motion

While the described method was shown and explained for the single indexing process, it can also be applied to the continuous indexing process. The cutter rotation ω is in a timed relationship with the work rotation, superimposed to the roll motion on the work (in a continuous mode) or applied in discrete roll positions. This is similar to the previous explanations, where either roll and/or cutter rotation angle (equal tapered mill position) have been observed in discrete increments:

$$\omega_{work} = \Omega_{Cradle}/RA + \omega\ Z_{Tool}/Z_{Work}$$

or

$$\delta_{work,i,j} = \delta_{work,start} + q_i/R_A + \alpha_j Z_{tool}/Z_{work}$$

However, the discrete observation and the processing of the roll positions lead to a looped data and position processing:

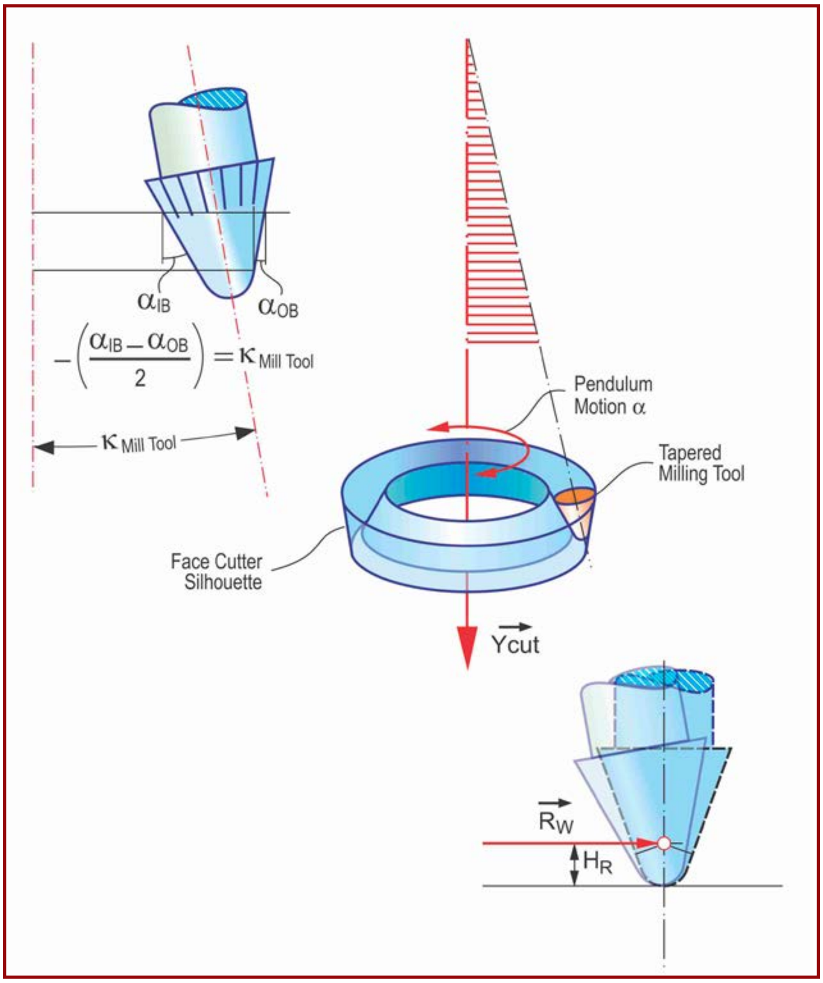


Figure 6 Inclination of tapered milling tool.

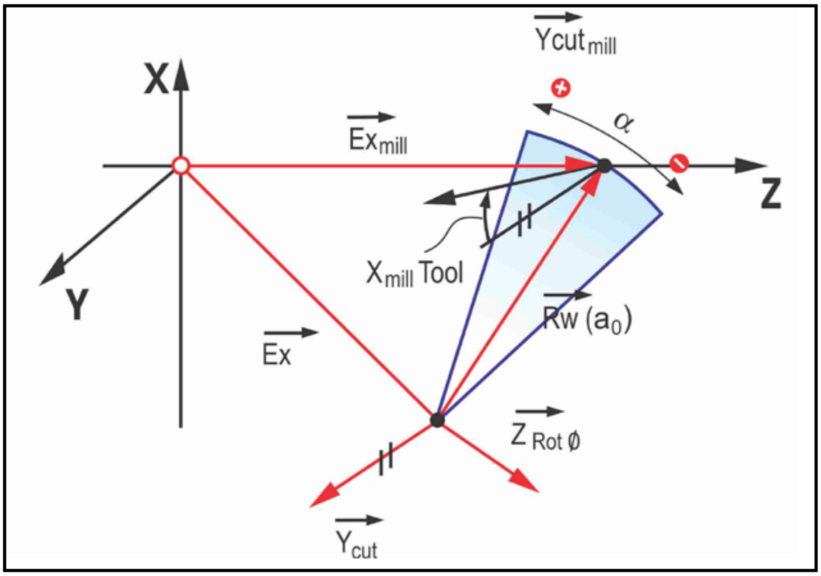
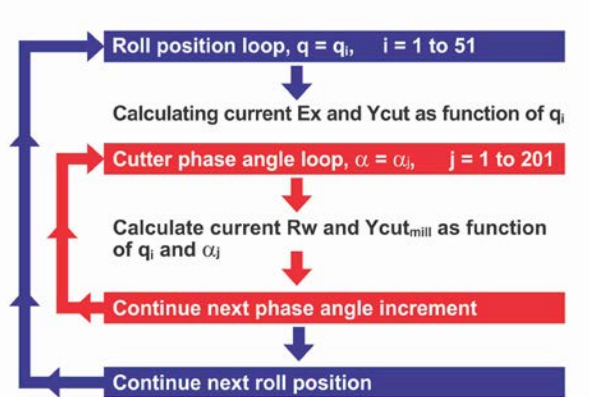


Figure 7 Triangular vector for generating bevel gears with tilted end-mill.



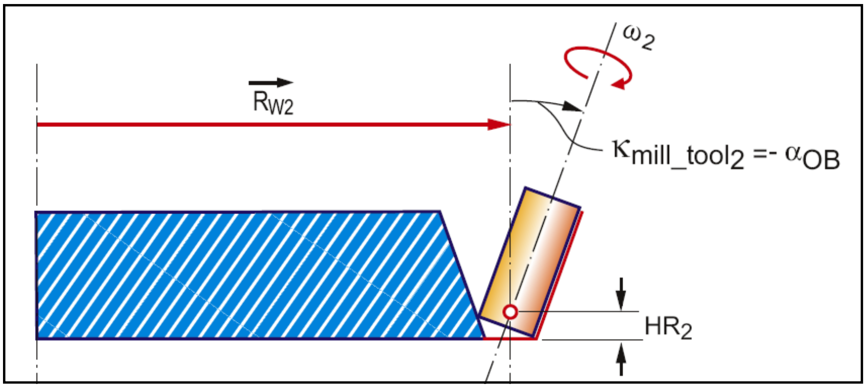


Figure 8 Cylindrical tool, machining outside profile only.

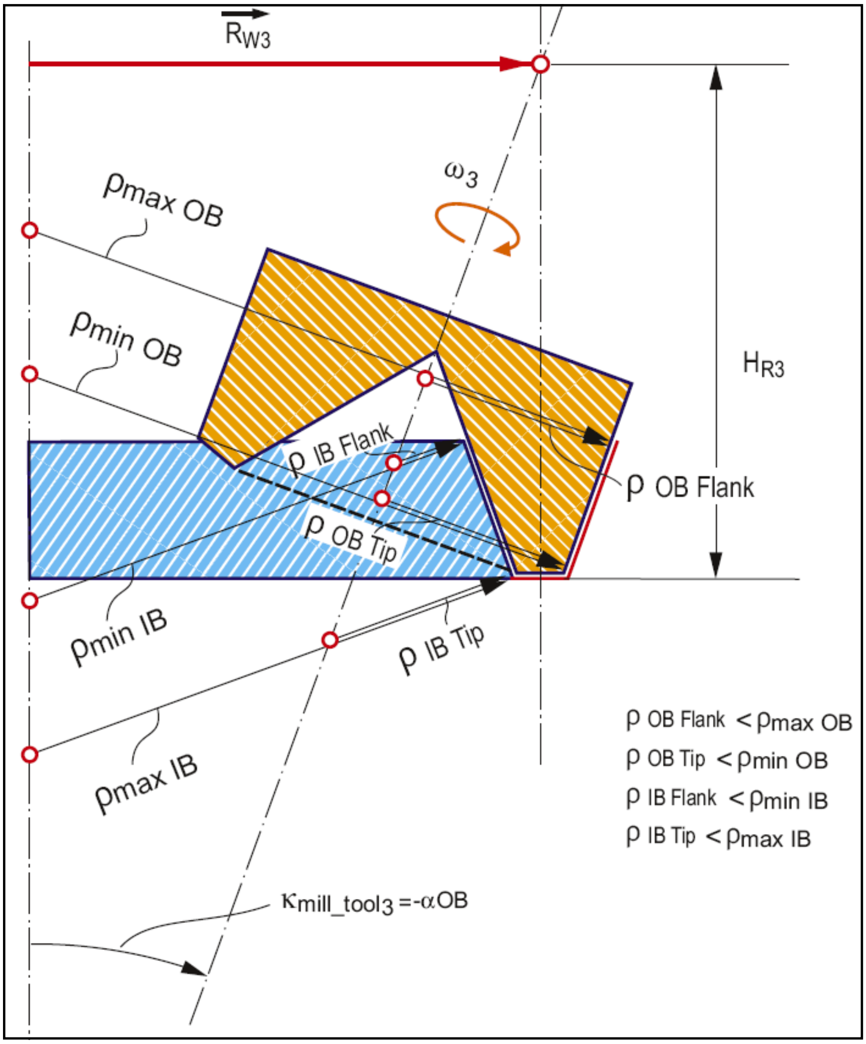


Figure 9 Cylindrical tool with conical inside profile.

In both cases — continuous or single index — machining, the last presented formulas are valid and can be applied. Those formulas can be applied for an asymmetrical cutting channel (Fig. 6), as well as for a symmetrical cutting channel (Fig. 2). The symmetrical cutting channel only presents a special case of the more general asymmetrical cutting channel ($\kappa_{mill\_tool} = 0$).

There are a multitude of possibilities to derive the formulas in order to position and move the tapered milling tool. However, trigonometric calculations would in their solution show intrinsic function depending on roll, tool rotation, and work rotation angles, as well as linear constants. The derivations shown here use the basic machine settings that relate to the generating gear. The resulting vectors Ex_{mill} and $Ycut_{mill}$ can be converted to basic settings:

$S_i = \sqrt{Ex^2_{mill,x} + Ex^2_{mill,y}}$ ⟶ Radial Distance
$q_i = \arctan(Ex_{mill,x}/Ex_{mill,y})$ ⟶ Roll Position
$X_{B,i} = Ex_{mill,y}$ ⟶ Sliding Base
$Wx_{,i} = \arccos(Ycut_{mill,y})$ ⟶ Tilt
$Wy_{,i} = \arctan(Ycut_{mill,x}/Ycut_{mill,z}) - q_i$ ⟶ Swivel

Additional basic settings, such as:

X_P… Head Setting
E_M… Machine Offset
γ_M… Machine Root Angle
R_A… Ratio of Roll

do not change during the conversion from conventional tool to tapered mill. The basic settings, as shown above, can be converted into a 6-axes Phoenix coordinate system.

Expanding to a Variety of Highly Efficient Tools

The *UNIMILL* machining method can be expanded to use a milling tool which is, for example, cylindrical and only machines one flank surface at a time (like outside flank shown in Fig. 8). The tool inclination angle in this case is $-\alpha_{OB}$. The maximal diameter of such a tool is limited (Fig. 8). A diameter larger than shown in Figure 8 causes mutilation of the opposite flank (inside flank). It is possible with such a cylindrical tool to machine the opposite flank in a second set of machining passes, if the sign of the tool inclination angle is changed ($+\alpha_{OB}$). For correct definition, it should be stated that the vector R_{W2} points to the centerline of the reference profile. Its preferred location is in the center of the face width; in cases of asymmetric pressure angles it is located radially in order to split the point width of the reference profile in two equal parts. The point width is the width of the bottom of the reference channel — in an axial plane in case of face milling cutters, and in the offset plane in case of face hobbing cutters.

If the tool diameter is increased to a certain extent, it then becomes possible to machine the second flank (IB) simultaneously to the first (OB-flank; Fig 9).

However, in order to machine a flank without mutilation, the requirement regarding the curvature radius is as follows:

$\rho_{OB\ Tip} \leq \rho_{minOB}$ (given in Fig. 9)
$\rho_{OB\ Flank} \leq \rho_{maxOB}$ (given in Fig. 9)
$\rho_{IB\ Tip} \geq \rho_{maxIB}$ (not given in Fig. 9)
$\rho_{IB\ Flank} \geq \rho_{minIB}$ (not given in Fig. 9)

The diameter of the cutting tool in Figure 9 must be increased until the axis of rotation crosses the origin of ρ_{minOB} (intersection with original cutting tool axis). In such a case, $\rho_{IB\ Tip} = \rho_{maxIB}$ and $\rho_{IB\ Flank} > \rho_{minIB}$ applies (Fig. 10). κ_{mill_tool} in Figure 10 is still $-\alpha_{OB}$, as with Figure 8. Different angles of κ_{mill_tool} can be realized if the axis of rotation intersects with the original tool axis in point $P\rho$. $P\rho$ is determined as the origin of ρ_{minOB}. $\rho_{IB} > \rho_{maxIB}$ is always given in such a case. Figure 11 shows machining tool geometries based on $\kappa_{mill\_tool} = -60°$, $-70°$ and $-90°$. $\kappa_{mill\_tool} = -90°$ is an interesting, special case of a peripheral tool.

In every case in Figure 11 (vector designations 5, 6, and 7) the vector ρ_{minOB} was constructed first. It has an intersection with the face cutter tool axis in point $P\rho$. The chosen milling tool inclination angle κ_{mill_tool} leads in Figure 11 to a tool axis, which crosses the face cutter tool axis in point $P\rho$. This leads to the smallest possible milling tool diameter which fulfills the requirements:

$\rho_{OB\ Tip} \leq \rho_{minOB}$ (Figure 11 — $\rho_{OB\ Tip} = \rho_{minOB}$)
$\rho_{OB\ Flank} \leq \rho_{maxOB}$ (given in Figure 11)
$\rho_{IB\ Tip} \geq \rho_{maxIB}$ (given in Figure 11)
$\rho_{IB\ Flank} \geq \rho_{minIB}$ (given in Figure 11)

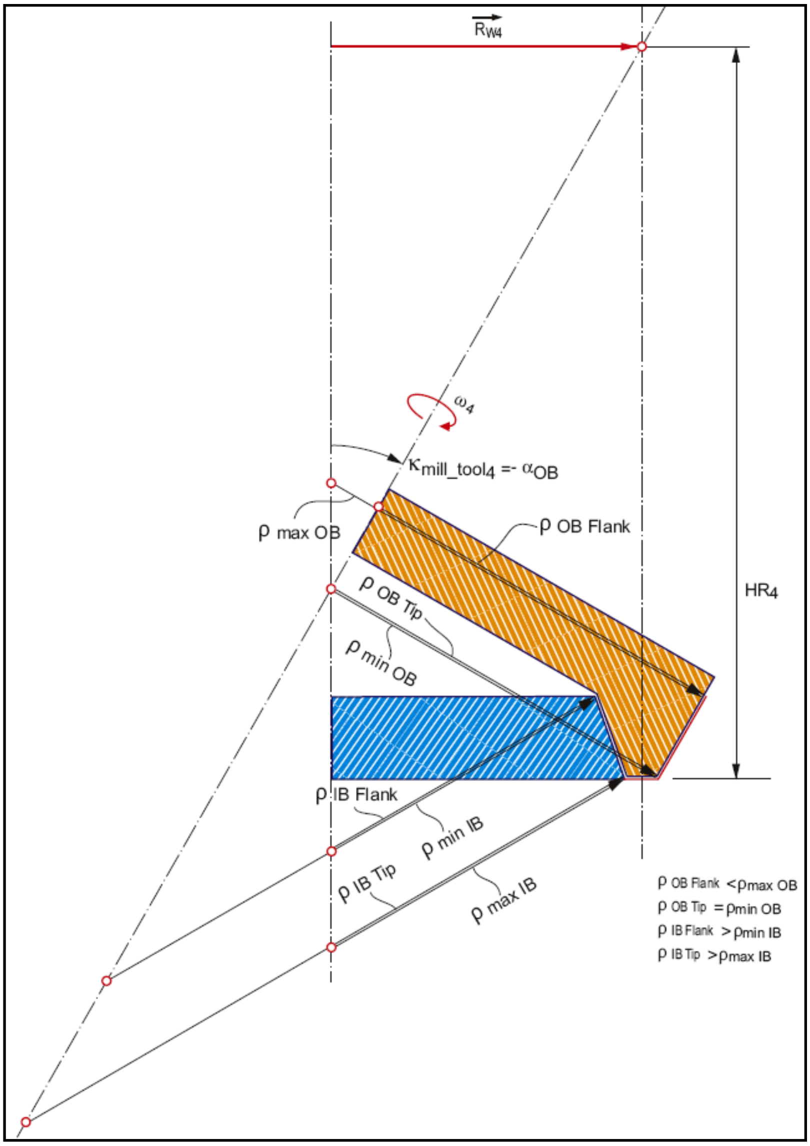


Figure 10 Cylindrical tool with conical inside profile and larger diameter in order to avoid mutilation.

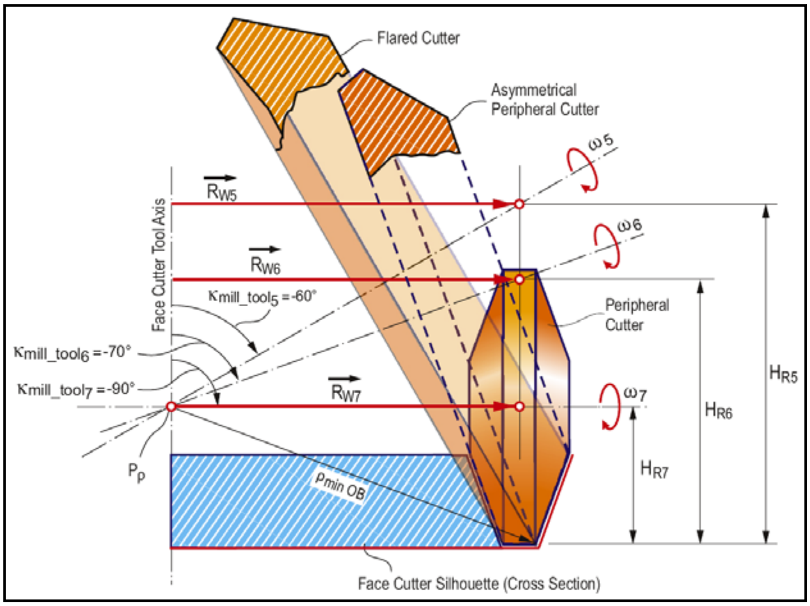


Figure 11 Variety of tools by increasing tool inclination angle, leading to a pure peripheral cutting tool.

Tools and Examples

If *UNIMILL* is utilized as a prototyping method, the use of disk cutters is most productive; but the use of tapered end mills requires the lowest tool investment (Fig. 12, right and middle). Due to the use of standard inserts (Fig. 12, left), multi-start fly cutters similar to bevel gear chamfer cutters present certain restrictions regarding blade point width and edge radius. Flared disc cutters that use stick blades (PentacSlimLine) are also available (Ref. 4). The advantage of tapered end mills is that most gear manufacturers can find nearby local tool shops that can manufacture a new milling tool from carbide material — including coating — in less than two weeks. The basic dimensions of a tapered end mill are point width, edge radius, and the included angle of the taper.

The cutting scenario of a face-hobbed hypoid pinion is shown (Fig. 13, left). The end mill moves from heel to toe while it is milling one generating flat at the convex pinion flank. After the end mill exits the slot at the toe, the machine axes set over to the concave side in order to machine the corresponding drive side generating flat.

The movement along the face width is called "swing motion." Changing the swing motion between start and end roll position is possible in three sections, depending on the different chip load in the different areas. After a part is finished, a coordinate measurement is conducted and, in case of significant deviations between nominal and actual flank, *G-AGE* corrections are calculated and sent via network to the Phoenix machine control. Similar to the procedure in conventional bevel gear manufacturing, the corrections are applied in a menu to the basic settings and the *UNIMILL* software converts the basic settings to a part program with axes motion commands.

In Figure 14 the scenario of a nose piece milling with a disk-shaped HSS cutter is shown. In the case of nose pieces, disk cutters are very beneficial; the slots are normally very wide and the root fillet radius can be standardized, because root bending strength is not a criterion for those parts.

Today, all the *UNIMILL* software is implemented in the machine control. The control computer receives a download file that includes basic settings with gear blank data — very similar to regular bevel gear machining. The operator screen allows the entering of speeds and feeds, as well as the number of generating flats and over travel amounts, etc. In order to utilize existing experiences in bevel gear manufacturing, the basic settings are calculated by the machine control and displayed to the operator. The basic settings can be changed not only with *G-AGE* corrections, but also by adding or subtracting delta values. The "*Master Summary*" feature allows return from the developed summary to the original summary at any time.

Figure 12 Variety of *UNIMILL* tools.

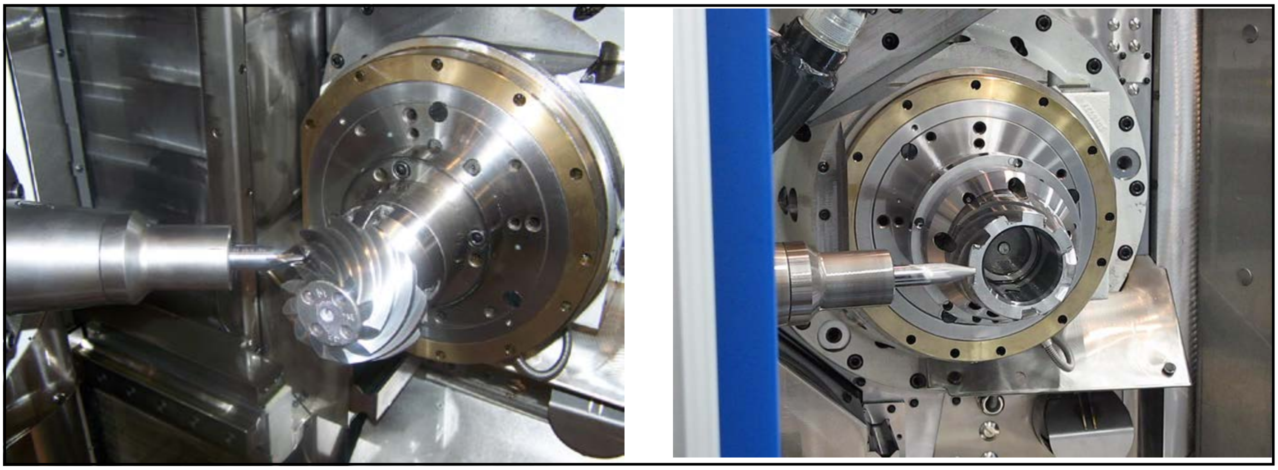


Figure 13 Milling of a face hobbed hypoid pinion (left) and a slotted nose piece (right).

A variety of different parts manufactured with *UNIMILL* is shown (Fig. 15). In addition to spiral bevel and hypoid gears, the milling of straight bevel gears has also been developed. Figure 15 (right) shows a large spiral bevel gearset that was soft cut with *UNIMILL* and then hard skived after heat treatment. The *UNIMILL* process has shown to be suitable for a hard skiving process, which replaces either grinding or skiving with a dedicated face cutter. Just like in soft cutting, the *UNIMILL* hard skiving process also applies to small quantities as, for example, prototypes, in order to minimize the cost of required equipment and tooling.

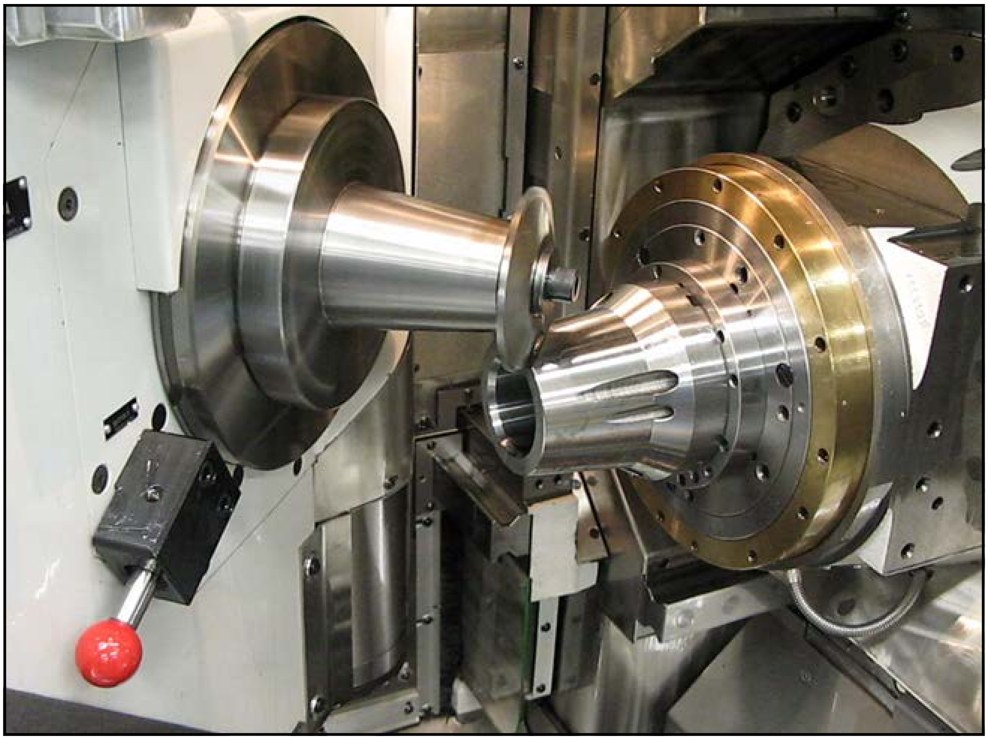


Figure 14 Milling of slotted nose piece with HSS disk cutter.

Figure 15 Different gear types machined with the *UNIMILL* process.

Practical Experience with Straight Bevel Gears

With straight bevel gears — in addition to prototype manufacturing — the possibility of machining parts with a front bearing hub is an attractive application for *UNIMILL*. These parts have been manufactured in the past with two-tool generators, which only deliver medium quality in a rather slow process. Often, the material of solid parts with an integrated front hub was difficult to machine because of a high strength requirement. The possibility to use coated carbide tools in *UNIMILL* gives manufacturers an incentive to replace their aged two-tool generators with modern CNC equipment, allowing for state-of-the-art closed-loop manufacturing. The straight bevel gear (Fig. 16) requires a manufacturing time of 2 hours, with a tool life of 4 parts. The tools can be re-sharpened up to 10 times before requiring replacement.

Experience in the cutting of straight bevel gears with *UNIMILL* has been gained over the past few years. A variety of tool holder and coated-carbide cutting tools was applied. In some cases the manufacturers of these gears prefer using pre-slotted parts in order to reduce the amount of chip removal and, subsequently, reduce the *UNIMILL* cutting time. The software was also expanded for stock division capability, vector feed and a Coniflex quick cycle.

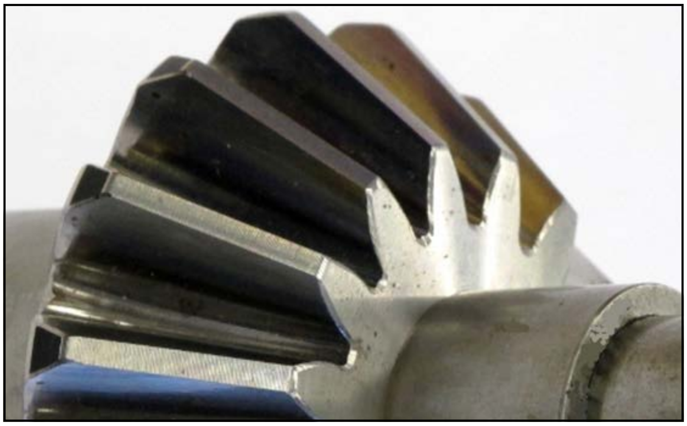
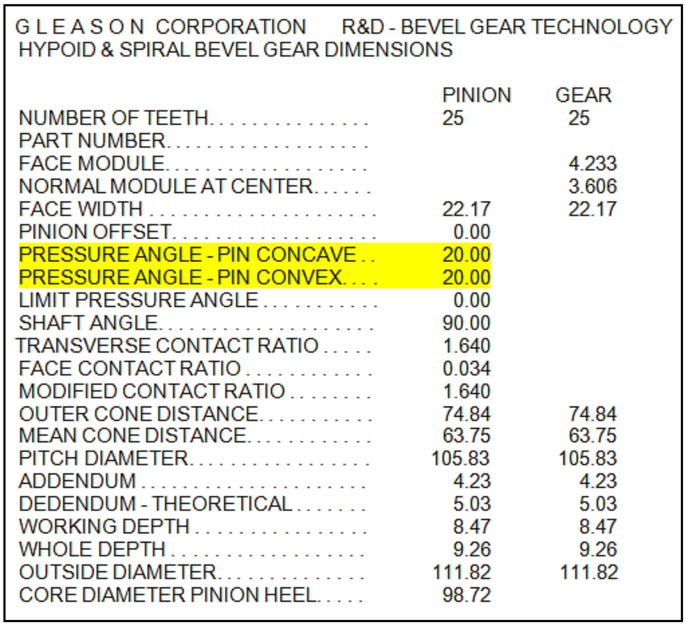


Figure 16 Straight bevel gear with front hub.



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G L E A S O N  CORPORATION       R&D - BEVEL GEAR TECHNOLOGY
HYPOID & SPIRAL BEVEL GEAR DIMENSIONS

                                    PINION     GEAR
NUMBER OF TEETH. . . . . . . . . . . . . . .   25          25
PART NUMBER. . . . . . . . . . . . . . . . . .
FACE MODULE. . . . . . . . . . . . . . . . . .              4.233
NORMAL MODULE AT CENTER. . . . . .                          3.606
FACE WIDTH . . . . . . . . . . . . . . . . . . .  22.17      22.17
PINION OFFSET. . . . . . . . . . . . . . . . .   0.00
PRESSURE ANGLE - PIN CONCAVE . .     20.00
PRESSURE ANGLE - PIN CONVEX. . . .   20.00
LIMIT PRESSURE ANGLE . . . . . . . . . .   0.00
SHAFT ANGLE. . . . . . . . . . . . . . . . . .  90.00
TRANSVERSE CONTACT RATIO . . . . .   1.640
FACE CONTACT RATIO . . . . . . . . . . .   0.034
MODIFIED CONTACT RATIO . . . . . . . .   1.640
OUTER CONE DISTANCE. . . . . . . . . .  74.84      74.84
MEAN CONE DISTANCE. . . . . . . . . . .  63.75      63.75
PITCH DIAMETER. . . . . . . . . . . . . . . 105.83     105.83
ADDENDUM . . . . . . . . . . . . . . . . . . .   4.23       4.23
DEDENDUM - THEORETICAL. . . . . . .   5.03       5.03
WORKING DEPTH . . . . . . . . . . . . . . .   8.47       8.47
WHOLE DEPTH . . . . . . . . . . . . . . . . .   9.26       9.26
OUTSIDE DIAMETER. . . . . . . . . . . . . 111.82     111.82
CORE DIAMETER PINION HEEL. . . . .  98.72
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Figure 17 Section of dimension sheet.

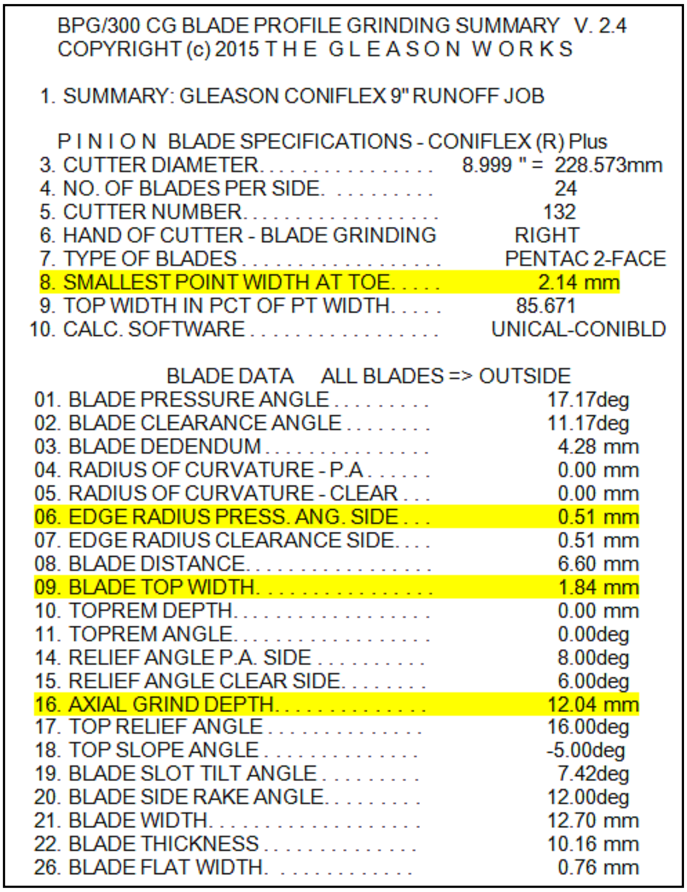
Basic Milling Tool Data

The basic information is retrieved from the dimension sheet and from the blade profile grinding summary of the particular job. Figure 17 shows a section of the dimension sheet with the convex and concave pressure angles (highlighted yellow). Both added together (in the present case 20° + 20°) results in the included pressure angle (here equals to 40°). The end-mill cone angle must be less than half of the included pressure angle. In the present case, a cone angle of 15° is optimal.

The axial height of the end-mill can be retrieved from the Blade Profile Grinding Summary in Figure 18, item 16 "Axial Grind Depth."

For the correct dimensioning of the edge radius R_E, it is advisable to calculate first the maximum possible edge radius for the given dimensions. In addition to the cone angle α_T, the end-mill point width P_W is required. The end-mill point width should match the blade top width (item 09 in Fig. 18). A larger P_W can be used within limits, but P_W cannot be larger than the smallest point width of the gear slot (item 8 in Fig. 18, top). The formula (Fig. 19) is used to calculate the largest possible edge radius for the end-mill R_E. In the present case, using $P_W = 1.84$ mm, the largest possible edge radius is $R_E = 0.65 \times P_W = 1.2$ mm. After R_E is calculated, it has to be compared to the Edge Radius Pressure Angle Side (item 06 in Figure 18). If the result of R_E is smaller than item 06 in Figure 18, then the calculated number of R_E must be used for the end-mill.

In the present case, the summary item 06 in Figure 18 is 0.51 mm, which is smaller than the calculated maximum



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BPG/300 CG BLADE PROFILE GRINDING SUMMARY   V. 2.4
COPYRIGHT (c) 2015 T H E   G L E A S O N   W O R K S

 1. SUMMARY: GLEASON CONIFLEX 9" RUNOFF JOB

  P I N I O N  BLADE SPECIFICATIONS - CONIFLEX (R) Plus
 3. CUTTER DIAMETER. . . . . . . . . . . . . . . .    8.999 " =  228.573mm
 4. NO. OF BLADES PER SIDE.  . . . . . . . . .              24
 5. CUTTER NUMBER. . . . . . . . . . . . . . . . . .             132
 6. HAND OF CUTTER - BLADE GRINDING               RIGHT
 7. TYPE OF BLADES . . . . . . . . . . . . . . . . . .        PENTAC 2-FACE
 8. SMALLEST POINT WIDTH AT TOE. . . . .              2.14 mm
 9. TOP WIDTH IN PCT OF PT WIDTH. . . . .            85.671
10. CALC. SOFTWARE . . . . . . . . . . . . . . . . .       UNICAL-CONIBLD

               BLADE DATA     ALL BLADES => OUTSIDE
01. BLADE PRESSURE ANGLE . . . . . . . . .                 17.17deg
02. BLADE CLEARANCE ANGLE . . . . . . . .                 11.17deg
03. BLADE DEDENDUM . . . . . . . . . . . . . . .                  4.28 mm
04. RADIUS OF CURVATURE - P.A . . . . . .                  0.00 mm
05. RADIUS OF CURVATURE - CLEAR . . .                  0.00 mm
06. EDGE RADIUS PRESS. ANG. SIDE . . .                  0.51 mm
07. EDGE RADIUS CLEARANCE SIDE. . . .                  0.51 mm
08. BLADE DISTANCE. . . . . . . . . . . . . . . .                  6.60 mm
09. BLADE TOP WIDTH. . . . . . . . . . . . . . .                  1.84 mm
10. TOPREM DEPTH. . . . . . . . . . . . . . . . .                  0.00 mm
11. TOPREM ANGLE. . . . . . . . . . . . . . . . .                  0.00deg
14. RELIEF ANGLE P.A. SIDE . . . . . . . . . .                  8.00deg
15. RELIEF ANGLE CLEAR SIDE. . . . . . . .                  6.00deg
16. AXIAL GRIND DEPTH. . . . . . . . . . . . .                 12.04 mm
17. TOP RELIEF ANGLE . . . . . . . . . . . . . .                 16.00deg
18. TOP SLOPE ANGLE . . . . . . . . . . . . . .                 -5.00deg
19. BLADE SLOT TILT ANGLE . . . . . . . . .                  7.42deg
20. BLADE SIDE RAKE ANGLE. . . . . . . . .                 12.00deg
21. BLADE WIDTH. . . . . . . . . . . . . . . . . . .                 12.70 mm
22. BLADE THICKNESS . . . . . . . . . . . . . .                 10.16 mm
26. BLADE FLAT WIDTH.  . . . . . . . . . . . .                  0.76 mm
```

Figure 18 Blade profile grinding summary.

possible radius for R_E. In this case, $R_E = 0.51$ is the correct edge radius for the end-mill. In the present case, the end-mill design, according to the graphic (Fig. 20), will have a flat spot at the tip, connecting the two edge radii in the cross-sectional drawing (which of course is) only one edge radius of the rotationally symmetric end-mill.)

Measurement of the stock division probe reference height is shown (Fig. 21, left). The probe is placed in the milling tool holder and an electronic height measurement caliper on a granite plate, or any other precisely flat surface, is used to determine the overall height (stock division probe reference height) of the assembly. The same procedure (Fig. 21, right) is applied to determine the cutter reference height. Both reference heights are entered into the machine summary. For the initial stock division teaching, the probe is inserted into the tool holder on the machine instead of the tool. The next step is performed manually by jogging the probe along a predetermined feed vector while the unclamped work is rotated back and forth until the probe sphere begins to contact both flanks (Fig. 22). Now the part is clamped and the automatic stock divider teaching is done by simply running the teaching routine via menu. To begin the milling, the probe is now exchanged with the milling tool.

Coniflex cutting with *UNIMILL* uses basic settings from a AAA data file. Because the original Coniflex process is not a completing, but a single side cutting method, it is recommended to use the standard *UNIMILL* cycle if the parts are not pre-slotted. The standard cycle mills a surface flat in one roll position on the lower flank (from heel to toe), and then a surface flat in the same roll position on the upper flank in the return swing, as schematically explained (Fig. 23, left). This cycle, which constantly alternates between lower and upper flank, avoids double flank contact of the fast rotating tool — thus assuring a

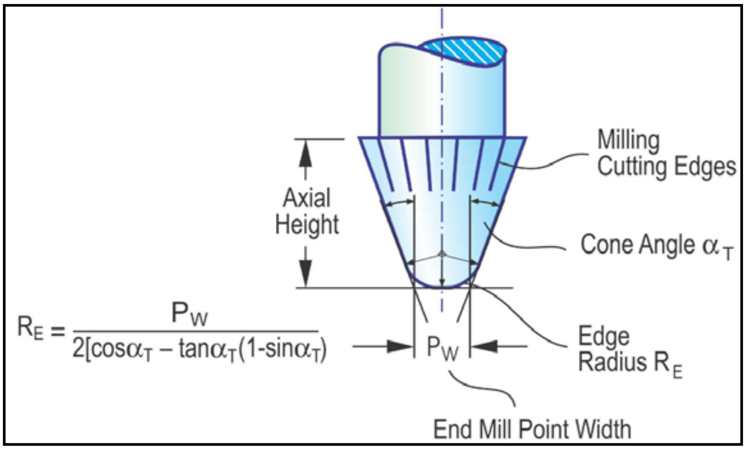

Figure 19 Fully rounded end-mill tip.

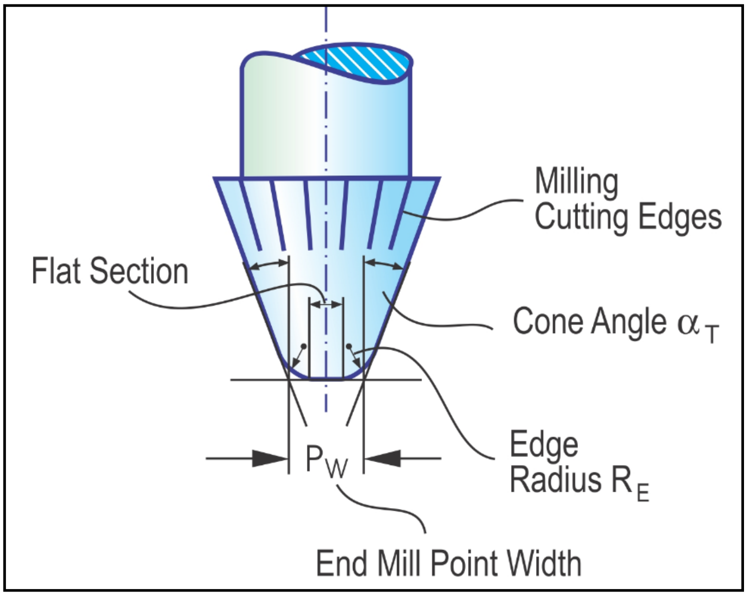

Figure 20 Conical end-mill with edge radius smaller than the fully rounded radius.

Figure 21 Reference height measurement of stock division probe and milling cutter.

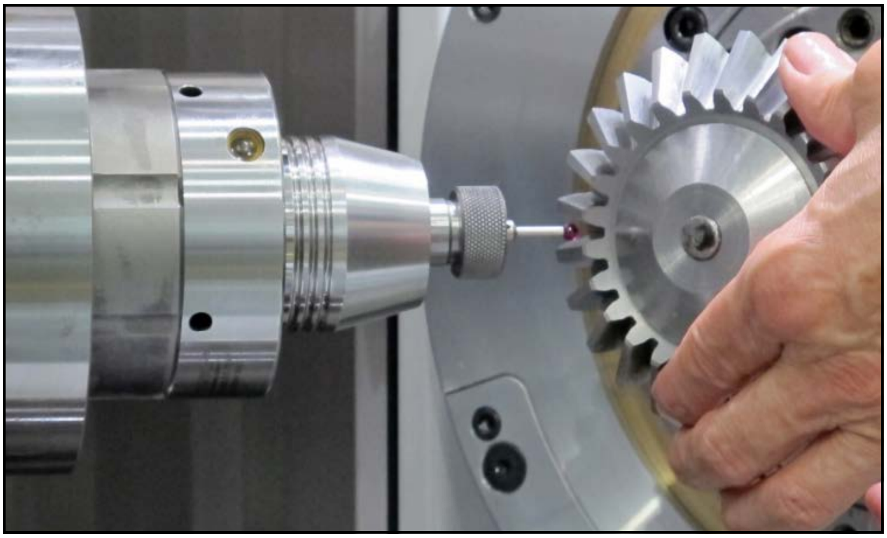

Figure 22 Manual stock division of pre-slotted part.

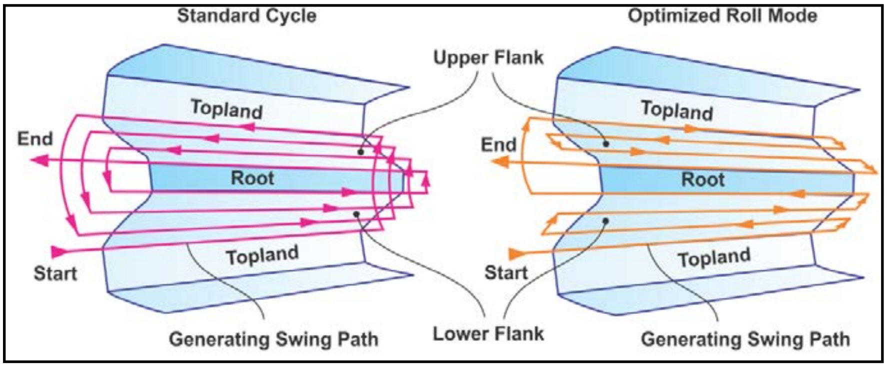

Figure 23 Standard and optimized roll mode for straight bevel gears.

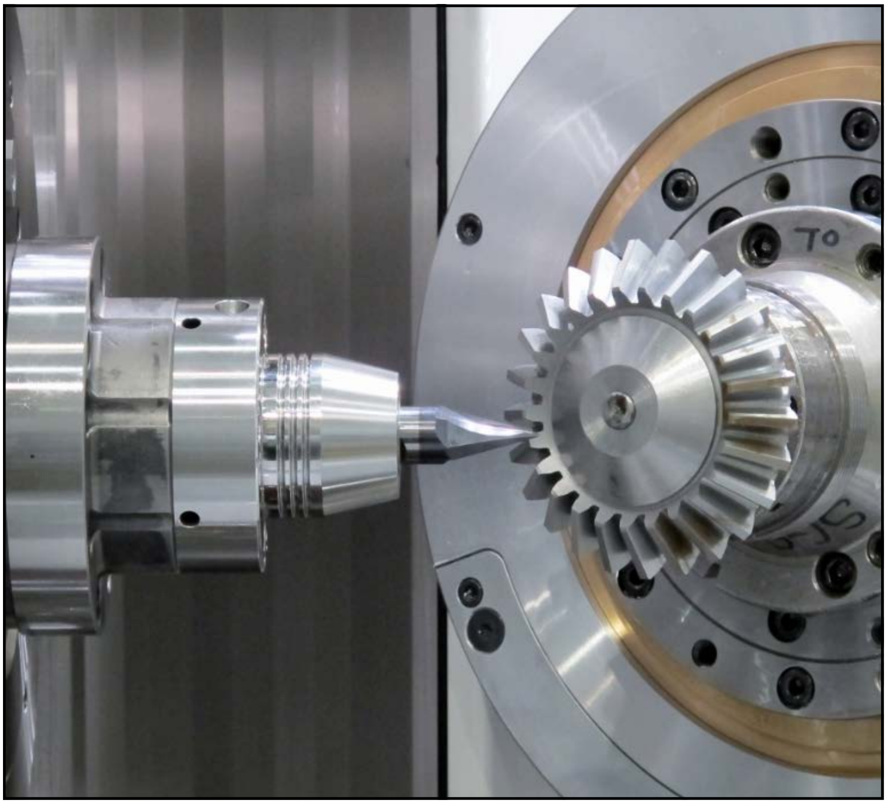

Figure 24 *UNIMILL* straight bevel gear milling.

smooth milling action.

If straight bevel gears are pre-slotted, the slotting can be done on a two-tool generator or on planers with an indexing head. For the case of pre-slotted parts, the "Optimized Roll Mode" is recommended. In the optimized roll mode the tool swings from heel to toe in one roll position (cutting the lower flank), and then returns from toe to heel in the next roll position, still milling the lower flank, as indicated in the right-side graphic in Figure 23. The heel to toe swing is, for example, conventional cutting, while the return swing is climb cutting. After finishing the complete lower flank, the milling tool changes to the upper flank and repeats the same cycle. With the described optimized cycle the constant change between lower and upper flank is avoided, which saves about 15% cycle time. The pre-slotting allows faster milling with a lower number of roll positions, which saves 25% of the original cutting time. Both cycle time reduction elements together will reduce the cycle time for cutting pre-slotted parts down to about 40% of the original cycle time of cutting un-slotted parts.

An interesting observation is the fact that the optimized roll mode mills consecutive surface flats alternating between conventional and climb cutting; this results in a very good average surface finish and two completely equal flank surface structures. In the standard cycle that alternates after each swing between upper and lower flank, the lower flank is milled in conventional cutting, while the upper flank is milled in climb cutting. This leads to slightly different surface textures between the two flanks.

In order to allow for easy contact pattern development via roll tester, the *UNIMILL MMC* software was expanded to accept and process standard proportional changes. In addition, independent depth and slot width changes can be entered into the *UNIMILL* summary.

After setup and summary entry, the outer swing position on toe and heel can be tested for sufficient clearance in the start and end roll positions. If the clearance values appear too small or too large, corrections of the input items for swing over-travel as well as roll positions can be independently entered into the *UNIMILL* summary.

Before starting the cutting cycle, a hold-back value can be entered for cutting of a first slot with some stock allowance. If cutting surface finish, over-travel on toe and heel and correct flank form have been verified, the hold-back can be cleared via soft key.

The cutting engagement of a tapered *UNIMILL* end-mill in the end-roll position of the lower flank is shown (Fig. 24). The surface speed of 250m/min is calculated in the middle of the whole depth of the tooth, which is at the blade dedendum point of the end-mill. The end-mill material is Alcona Pro coated tungsten carbide with a 10% cobalt content.

Summary

UNIMILL is a milling method for the manufacture of prototype bevel gears using end mills or disk cutters. The *UNIMILL* software requires basic settings in form of SPA of AAA files as an input. Additional input items — like speeds and feeds, number of generating flats, over travel amounts, etc. — are entered into the process parameter input screen directly on the Phoenix cutting machine. If high RPMs are required, as in the case of tapered end mills, it is possible to use Phoenix grinding machines or cutting machines with high-speed spindles.

In contrast to general multi-axes machining that utilizes surface coordinates and normal vectors, *UNIMILL* does not depend on certain grid specifications and definitions regarding undercut and root fillet (which are difficult to obtain). *UNIMILL* tools follow the path of a face cutter head silhouette, while the face cutter is performing a generating (or form cutting) motion. The result is a faster process with surface finish characteristics very similar to the traditional cutting process. *UNIMILL* is available on all Phoenix II cutting and grinding machines, as well as on all later models. ✪

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Dr. Hermann J. Stadtfeld received in 1978 his B.S. and in 1982 his M.S. in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994 — joining The Gleason Works — also in Rochester — first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002–2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to *Gear Technology*), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents on gear design, gear process, tools and machinery.