

Generative Gear Milling

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Introduction

This paper outlines the basic principles of involute gear generation by using a milling cutter; the machine and cutting tool requirements; similarities and differences with other gear generative methods; the cutting strategy; and setup adjustments options. It also discusses the applications that would benefit the most: for coarse-pitch gears the generative gear milling technologies offer improved efficiency, expanded machine pitch capacity, decreased cutter cost, and a possibility for reducing the number of machining operations.

While this method for gear cutting had started gaining visibility and being offered by various machine & tool makers, probably no more than a decade ago, the Maag Gear Company had introduced this gear cutting concept and received a U.S. patent (#4565474) in 1986; see Figure 1 depicting how the disc cutter can be used for involute generation.

The generative gear milling principle is based on an incremental (or continuous) positioning of the cutting edge tangentially to the involute curve along the "line of action." The cutter can have a form of:

- Milling "disc" cutter with:
 - trapezoidal cutting edges
 - parallel cutting edges
- End mill cutter

Hypothetically, the generative gear milling has always been possible on a 5-axis milling machine that had a rotary table. However, it was impractical without a special software, as the operator would have had to perform bulky calculations to determine the cutter and gear positions for each generative cut and for every tooth.

With the advancements of software development and expanding libraries of functions and features, multiple machine and tool makers are now offering software for this technology under their respective brand names.

In this paper, "generative gear milling" refers to a general method of gear cutting by using milling cutters, while "*Generative Gear Milling*" refers to proprietary MTB software to enable such a process on hobbing or milling machine that has a rotary table.

While conceptually the generative milling method borrows a little from several established involute generative methods — such as Maag gear

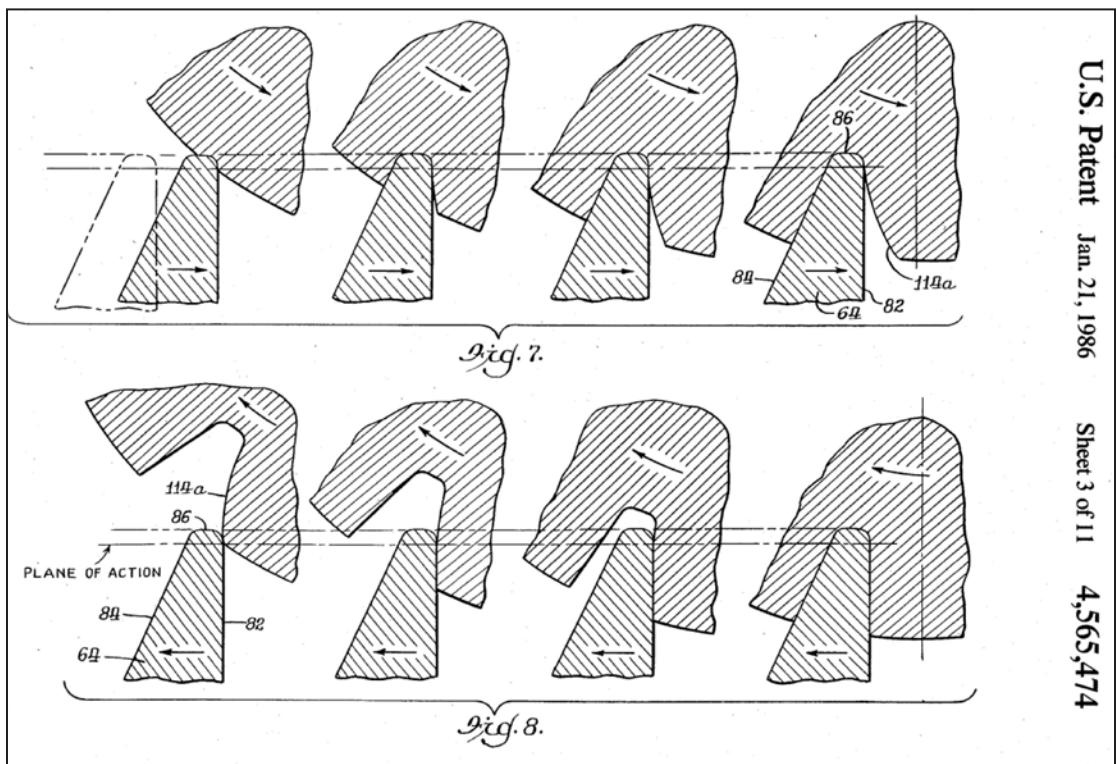


Figure 1 Maag patent 4565474 (Ref. 1).

U.S. Patent Jan. 21, 1986

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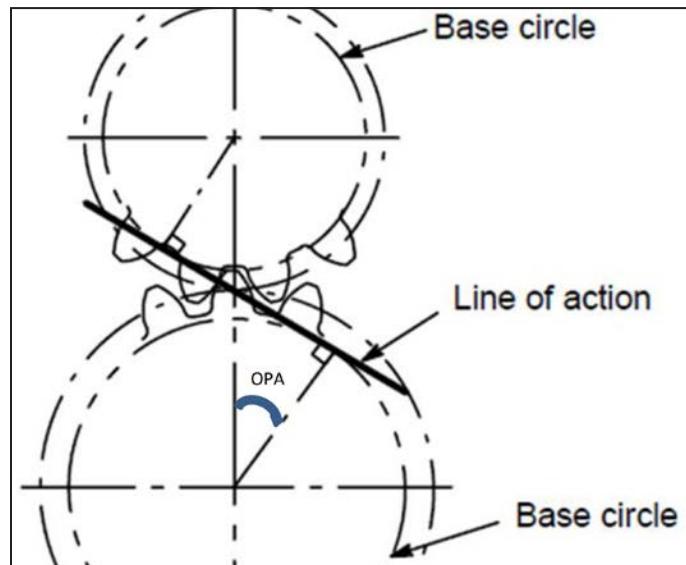


Figure 2 Line of action/gear mesh (Ref. 16).

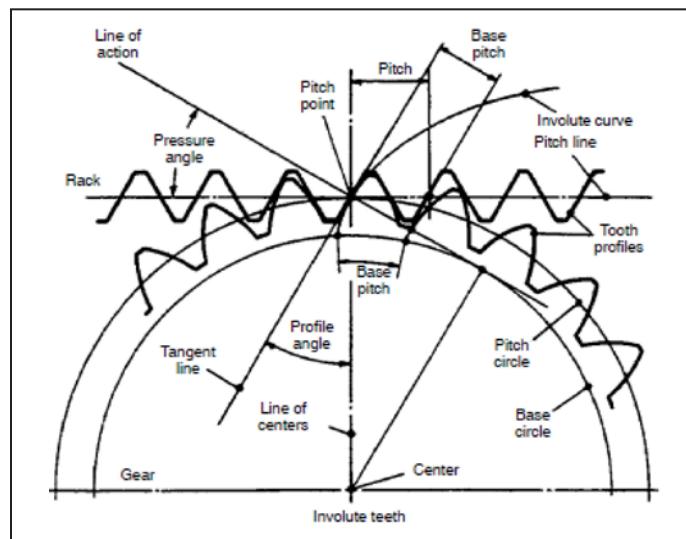


Figure 3 Line of action/cutting by rack (Ref. 15).

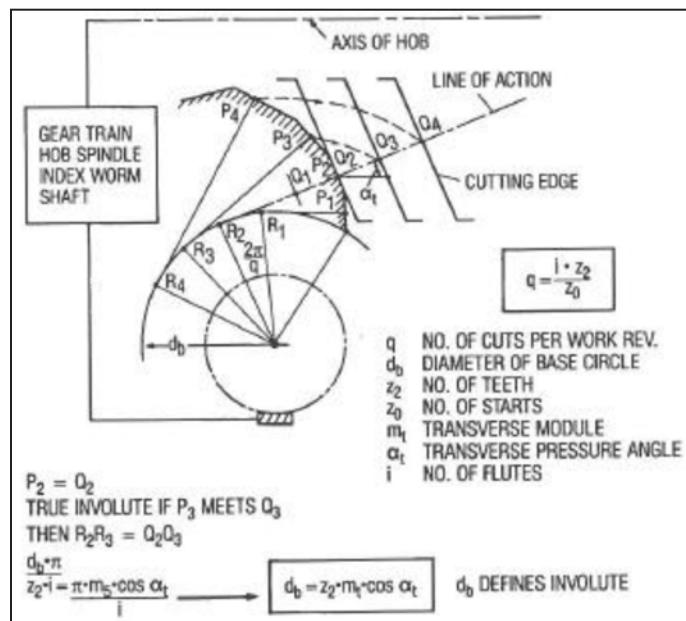


Figure 4 Tooth generation by hobbing (Ref. 13).

cutting with rack cutters, Maag gear rolling grinding, Hobbing, and Index Milling — the recent innovation is in the computerized math model that combines discrete (or continuous) cuts into a system that generates involute profile and completes the entire gear cutting.

Another innovation is how this technology can be acquired and implemented - via a software “app” that does not necessarily require a new machine.

The minimum hardware requirement for this feature is a 5-axes (4 axes for spur gears) CNC milling machine with a rotary table, or a CNC hobbing machine that has a precision tangential (hob shifting) axis. The reason for a 5-axes requirement is that all axes—X, Y, Z, C-table, and A-swivel—are mathematically interrelated for every generative cut.

Similarities with Other Gear Generation and Form Cutting Methods

There are several established methods for involute generation of parallel axes gears such as hobbing, cylindrical shaping, Maag rack shaping, zero and non-zero Maag line grinding, generative grinding as well as form milling/gashing with straight-sided cutter, or form milling/grinding with an inverse involute cutter profile.

All generative gear cutting/grinding methods take some advantage of involute properties to position the cutting edges (or the grinding wheel) tangentially to the involute curve. In the case of hobbing and shaping, the points of tangency (generative points or cuts) line up along the line of cutting action. When the operating pressure angle (OPA) defined by a line tangent to the base circles of both mating gears (Fig. 2) and the cutter pressure angles are the same, the line of gear mesh action and the line of gear cutting action coincide (Figs. 2 and 3).

Similarities with hobbing. Figure 4 depicts the hob cutting edges lining up along the line of action. Similarly, the generative gear milling is based on the incremental (or continuous) positioning of the cutter edges tangentially to the involute curve along the line of action and making successive cuts. Combined together, these successive cuts will approximate the involute curve.

Similarly, the generative milling process combines individual cuts to generate an involute curve. During the hobbing process, the precise positioning of the involute generating cuts is achieved by synchronizing the rotations of the hob and the gear.

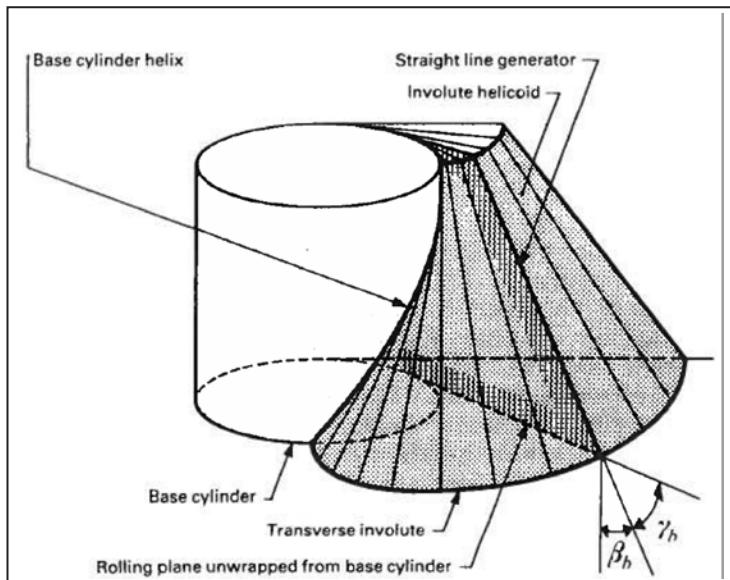


Figure 5 Base helix angle (Ref. 11).

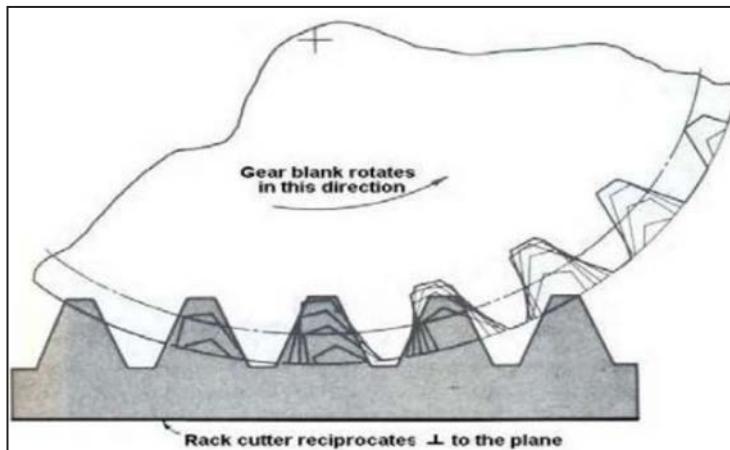
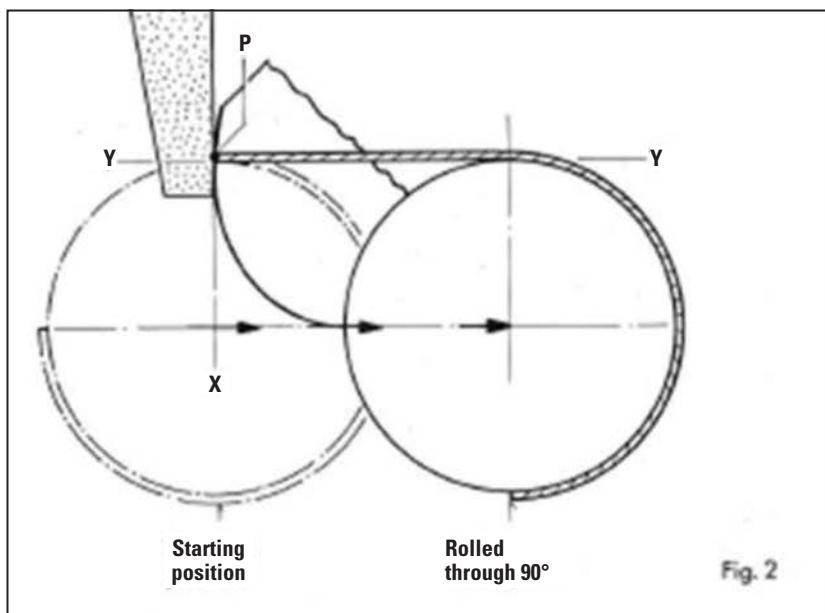


Figure 6 Maag gear cutting (Ref. 17).



Similar to the hobbing process, a greater number of generative milling cuts will lead to a closer involute approximation—a smoother curve. Unlike the hob cutter, however, the generative milling cutter has to be moved to precise X&Y positions relative to the gear rotation for every discrete cut along the line of action.

Another difference with the hobbing process is that the hob is swiveled to the angle equals to the algebraic sum of gear helix angle and hob lead angle, while the *Generative Milling* disc cutter is swiveled to the angle calculated as

$$A = \sin^{-1}(\sin(\beta_b)/\cos(CA)) \quad (1)$$

where:

- A is cutter swivel angle
- β_b is gear base helix angle (Fig. 5)
- CA is cutter side angle (Fig. 9)

When the cutter side angles equal zero (parallel sides), the cutter is swiveled to the base helix angle, as $\cos(0) = 1$ (Fig. 5)

When cutting a helical gear, the milling cutter axial travel needs to be synchronized with the gear rotation:

$$\Delta C = \Delta Z \cdot 360/\text{Lead} \quad (2)$$

where:

- ΔC is gear rotation angle corresponding to the cutter axial travel
- ΔZ is cutter axial travel
- Lead is gear lead equals to the axial advance of the helix over one gear rotation

Similarities with Maag shaping with rack cutters. There are also some similarities between the generative milling and the legacy Maag shaping process using rack cutters. This type of cutting is based on rolling the gear around the rack cutter (Fig. 6). The kinematics of the generative milling

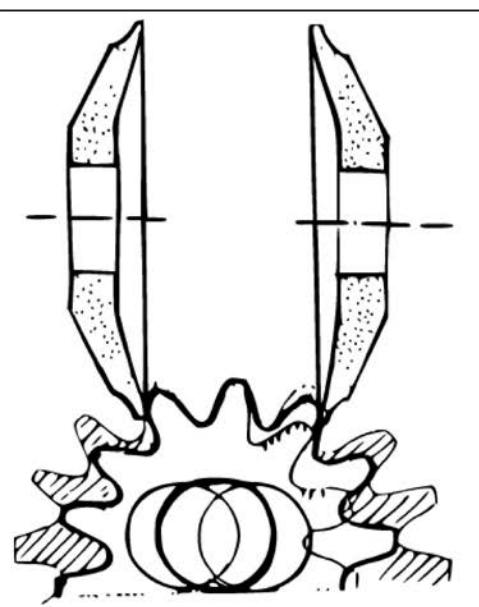


Figure 7 Maag 0° grinding method (Ref. 18).

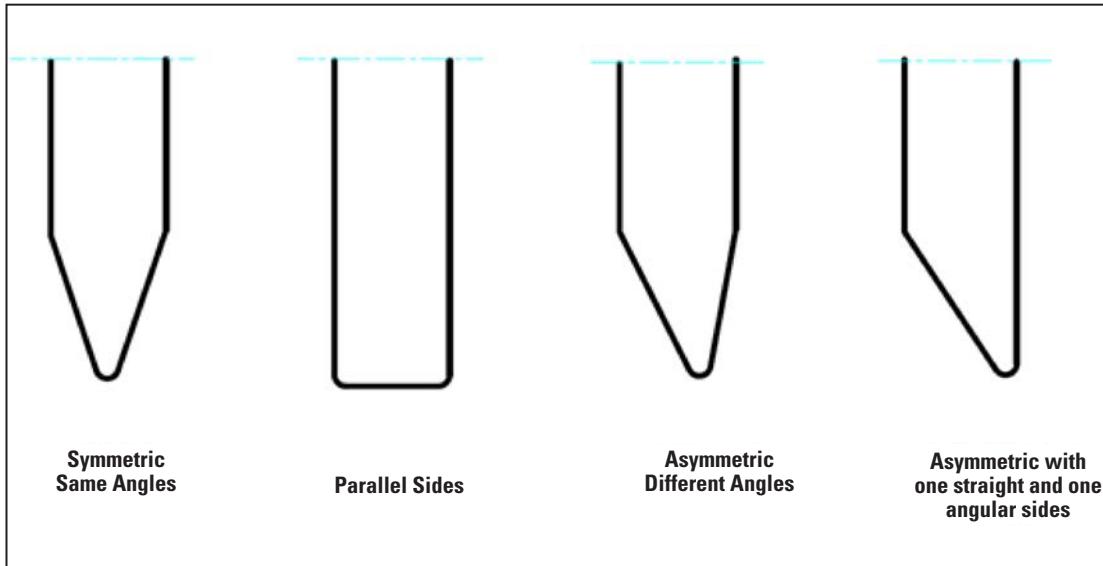


Figure 8 Milling cutter profiles.

are also based on gear rolling around the disc cutter. While Maag rack-type cutting method employs a single cutting edge for each generative point as the rack cutter traverses the gear face width, the generative milling cutter has the benefit of many cutting edges around the cutter periphery, thus facilitating an increased productivity.

Similarities with Maag 0° grinding method. The legacy line grinding method (Fig. 7), employed by Maag, Hoefler, and others, has probably the most similar kinematics to the generative milling. While kinematics of machine movements is similar, the generative milling is different than line grinding in many ways, including:

- The entire tooth gap is milled out, while line grinding required a prior roughing operation
- CNC controls align the milling cutter with gear teeth, while the legacy grinding machines relied on mechanical linkages between the grinding wheel and the gear
- Milling material removal rate is several magnitudes greater as compared to grinding

Similarities with index milling/gashing. Lastly, the kinematics of generative milling has some similarity with the index milling (gashing). Moreover, the gashing cutters can be employed for generative milling as is, thus making it possible to combine gashing and involute form generation within one set up, or even eliminate the gashing operation. Both the index milling/gashing and the generative milling require that the cutter traverses the face width to complete the cut. The kinematics of gashing machines, as well as hobbing machines that have precision tangential slides, make them capable (software would have to be added) of the generative gear milling process.

Milling Cutters

The disc cutter's simplicity and universality are the major advantages of the generative gear milling. The geometry of the inserts can be very flexible. The cutting inserts can have parallel sides (Fig. 8), or trapezoidal sides, symmetrical or asymmetrical when the right and left side angles are different. Angles of the left and right side are specified independently (Fig. 9).

Unlike the hob cutter, the milling cutter tooth depth does not have to match the gear tooth depth. Compared to the gear, the cutter can have a

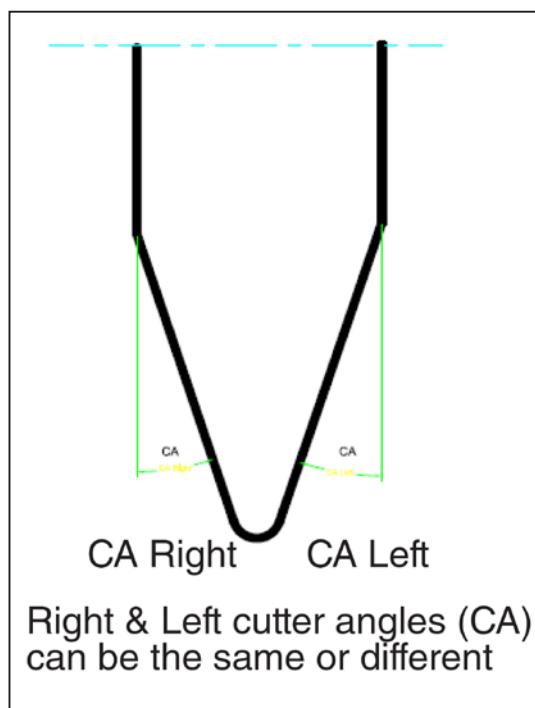


Figure 9 Cutter left- and right-side angles.

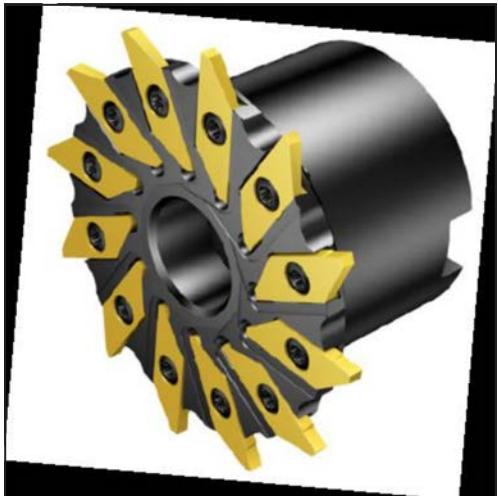


Figure 10 Milling cutter with parallel sides (Ref. 9).



Figure 11 Milling cutter with non-parallel sides (Ref. 9).



Figure 12 Cutters with carbide inserts (Ref. 7).

smaller or larger tooth depth. The cutter can have carbide inserts (Figs. 10, 11, 12, and 13; or be a solid HSS (Fig. 14)). Generally, the larger the cutter diameter, the more cutting edges could fit around the cutter's periphery, prolonging the cutter life.

In addition to the disc cutter, the end mill cutter type (Fig. 15) can be employed in the situations where the disc cutter would interfere with a part's shoulder, for example, when cutting a double-helical gear with an insufficient gap for a larger diameter cutter. However, the end mill cutters may necessitate an additional milling axis. A hobbing machine would certainly require a special attachment in order to drive an end mill cutter.

While there is a lot of flexibility with respect to cutter form and size, there are a few limitations.

- The cutter tip radius should be smaller or equal to the gear fillet radius
- The cutter tip width should be smaller than the tooth gap in its narrowest location
- The width of the parallel side's cutter should be smaller than the chord of tooth gap at its narrowest location (typically at the form gear diameter)

When a tooth undercut/protuberance is required, the cutter may have some additional limitations in order to generate the required undercut.

The smaller the cutter tip radius, the more flexibility there is to generate undercut/protuberance

To minimize a chance of cutter interference with the root diameter, the insert's tip should be a semi-circle without a flat area

The Involute Generation

Since the involute profile curve exists only in the transverse plane (plane perpendicular to the axis of gear rotation), it's advantageous to determine the profile generative points and their respective cutter positions in the transverse plane. The same set of formulas could be used for both helical and spur gears because the transverse and normal planes coincide in the case of spur gears. While formulas may vary depending on machine's kinematics, for a traditional hobbing machine the Cartesian profile coordinates and their respective gear rotation angles for each generative point can be determined (see Fig. 19 for visual depiction of coordinates):

$$X_i = R_i * \cos(TPA_i - CA_i) \quad (3)$$

$$Y_i = R_i * \sin(TPA_i - CA_i) \quad (4)$$

$$C_i = C_o + \theta_i \quad (5)$$

where:

X_i, Y_i are coordinates of one generated point on the involute curve, considering the Cartesian coordinates origin is in the gear center

C_i is the gear's angular position for the generated point

R_i, TPA_i is the radius and the transverse pressure angle of the generated point, respectively

CA_t is cutter side angle in transverse plane:

$$CA_t = \tan^{-1}(\tan(CA)/\cos(A)) \quad (6)$$

where:

CA is cutter side angle (Fig. 9)

C_o is the involute origin angle

θ_i is roll angle of the generated point

The corresponding cutter coordinates will need to be determined as functions of generative points, the cutter swivel angle, and the cutter geometry. An example of a coordinate system of a hobbing machine is represented (Fig. 16).

Gear roughing cutters

with indexable carbide inserts

20° pressure angle
basic profile IV to DIN 3972
with keyway to DIN 138
optionally with drive slot

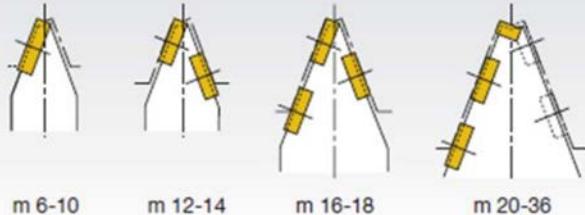


Figure 13 Roughing cutters (Ref. 7).



Figure 14 Solid cutters (Ref. 8).



Figure 15 End mill cutter (Ref. 9).

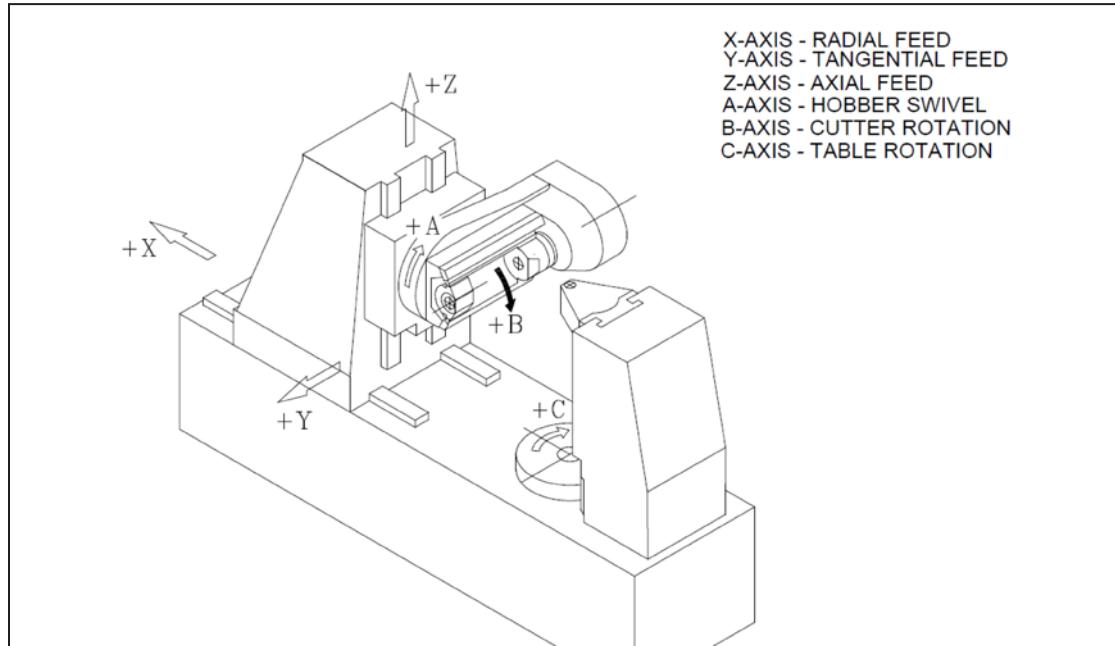


Figure 16 Gear hobbing machine.

Parallel sides disc cutter. The tooth generation with parallel sides cutter is similar to the Maag 0-grinding method (Fig. 17). The cutter width should be less than the tooth gap at the minimum gear diameter. This method will require the longest cutter travel in the tangential direction. The tangential machine slide should allow for a minimum \pm travel to be equal to the length of roll plus one-half of the cutter width (Eq. 7).

Trapezoidal disc cutter. Cutters that have trapezoidal form (Fig. 18) provide greater flexibility, as there are fewer restrictions for the cutter width—only the cutter tip width has to be less than the tooth gap at the minimum gear diameter. This type of cutter can cut a much larger range of gear pitches and sizes. Another benefit of such a cutter is that the machine tangential travel can be much smaller. To simplify the illustration of the tangential cutter travel TT, Figure 19 depicts an example for a spur gear when $CA_t = CA$. Note that Equation 7 below is universal for cutters with

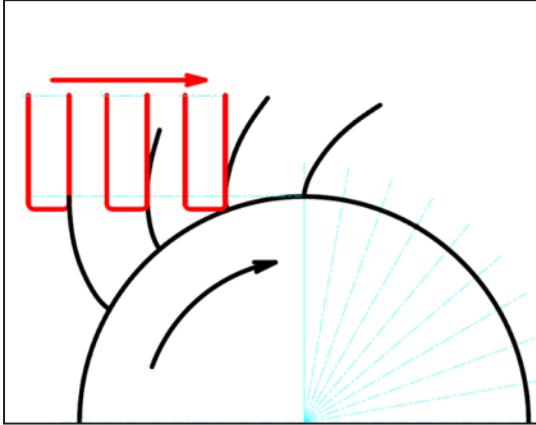


Figure 17 Gear generation with parallel sides cutter.

parallel or trapezoidal sides.

$$TT = R * \sin(TPA - CA_t) / \cos(A) + W \quad (7)$$

where:

TT is tangential travel required for cutting one side of the gear tooth; note that for parallel sides cutter $\frac{1}{2}$ of the cutter width needs to be added to determine required machine tangential travel for a specific gear application.

R is largest gear radius ($OD/2$)

TPA is involute transverse pressure angle at the largest radius ($OD/2$)

CA_t is cutter side angle in transverse plane (Eq. 6)

W is the tangential distance from the generating point to the middle of the cutter (W is one-half cutter width for parallel sides cutter)

A is cutter swivel angle (for spur gears, the cutter swivel angle is zero)

Since the right and left flanks are generated independently, the cutter does not have to have a symmetrical profile. One gear can be generated by a cutter that has different left- and right-side angles.

Regardless of the cutter form (parallel or

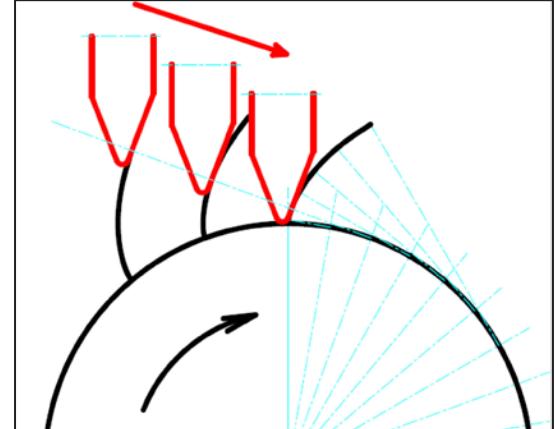


Figure 18 Gear generation with trapezoidal form cutter.

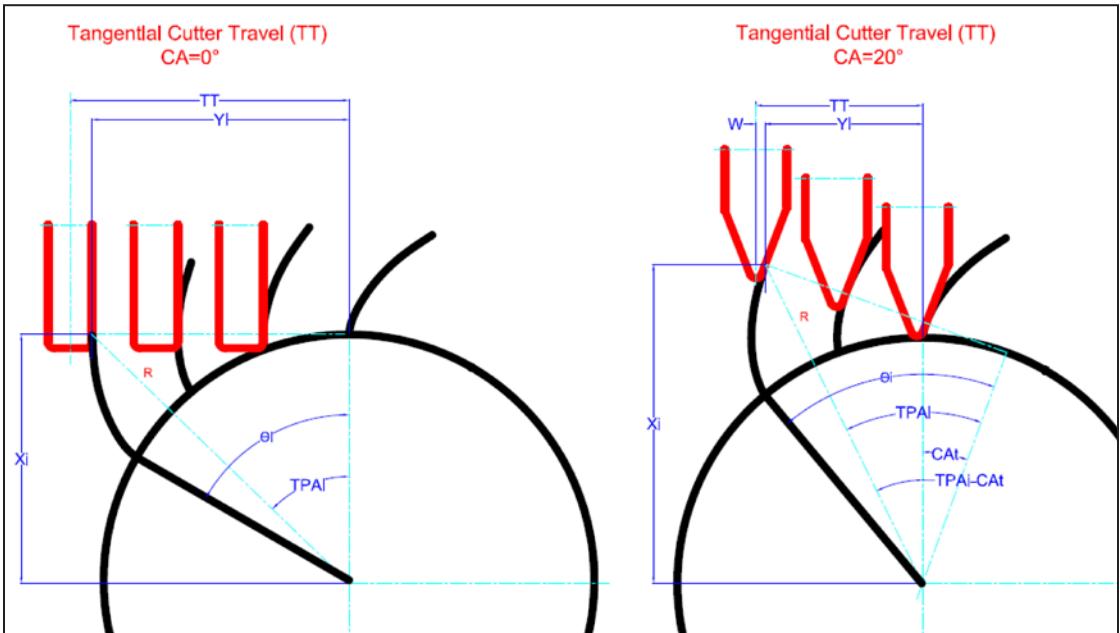


Figure 19 Cutter tangential travel.

non-parallel sides), the radial distance between the point of tangency and the cutter tip can migrate throughout the tooth generation. At the beginning of the cut, when the involute points are generated closer to the gear OD, it may be prudent to take a deeper cut. As the cutter gets closer to the root area, the radial distance between the generated point and the cutter tip may have to be shortened to avoid undercutting the root diameter.

Generative cuts. During the hobbing process, the number (density) of generative cuts is predetermined by the number of hob gashes and starts, and the number of gear teeth (Fig. 20). The cuts are incremented by a pre-determined angle of gear rotation (degrees of roll) per every successive generative cut.

The pattern of generative milling cuts (thus profile surface pattern) can be the same as hobbing when the angular increment of generative cuts is applied (Fig. 21). Or, the pattern can be slightly different when a radial increment for generative cuts is applied (Fig. 22). The operator has a choice of applying angular or radial increment.

Unlike hobbing, however, the number of milling

cuts for either mode (radial or angular increment) is infinitely variable—programmable. It is a part of the process data entry in that the operator can provide the number of cuts or accept recommendations based on a built-in algorithm for an optimum material removal.

The ability to control the density of generative cuts can be beneficial for:

Adjusting the material removal rate depending on cutter and gear materials, number of cutting edges, cutter width, and gear's number of teeth

Reconciling a need for increased productivity versus a need for a smoother profile surface

The Cutting Strategy

With respect to the cutter selection, the generative gear milling process provides a lot of flexibility. On the other hand, a smaller cutter (when “t” cutter height (Fig. 13)), is significantly smaller than gear's tooth whole depth) requires a different strategy for sequencing the gear cutting steps.

Gashing. A small cutter may require additional center cuts—gashing—to remove most material in the middle prior generating cuts.

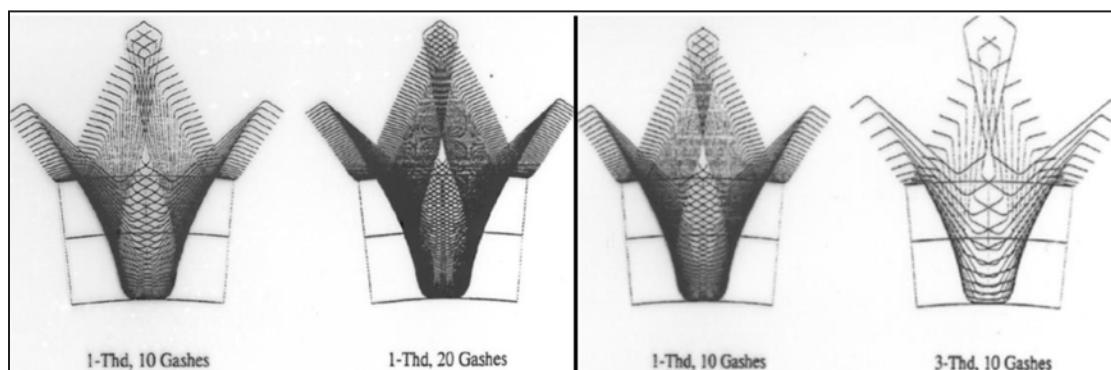


Figure 20 Generative cuts density (Ref. 12).

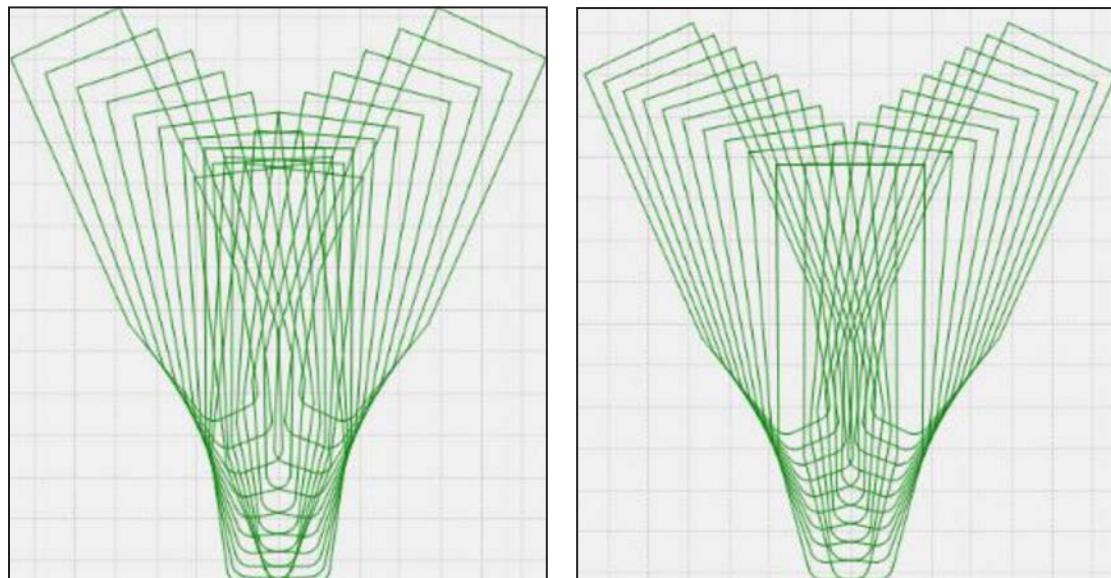


Figure 21 Generative cuts indexed by roll angle.

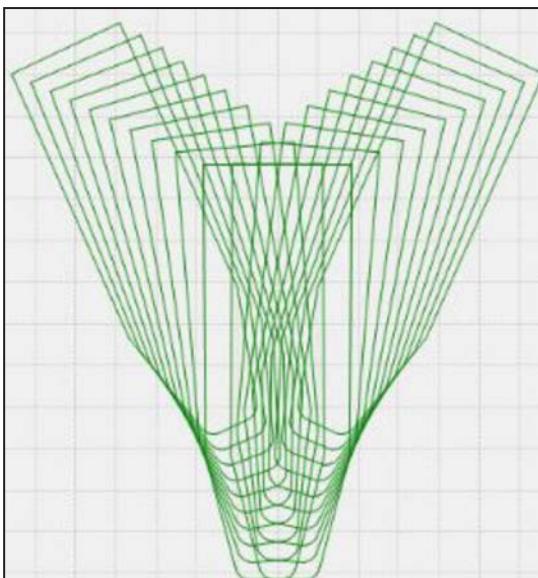


Figure 22 Generative cuts indexed by radial change.

Such initial material removal reduces a chance of unwanted interference of the cutter body with the opposite gear flank.

Regardless of the cutter size, a safe approach to avoid unwanted side interference would be to center cut/gash out most of material before initiating the involute generation cutting. However, when the cutter whole depth is larger than the gear tooth depth, an initial center cut (gashing) may not be necessary. The simulation may provide visual clues whether the center cut could be skipped.

Involute profile generation:

Discrete generative cuts with traversing the cutter along the gear face. One strategy for the involute generation is to make discrete generating cuts by traversing the cutter along the gear face for each generation increment along the line of action. This will create a tooth surface pattern that is similar to the legacy Maag or Hoefer line grinding pattern.

The other strategy is a continuous profile generation for each discreet cutter "Z" position along the gear face.

Tooth undercut, root radius, and special modifications. Additional generative cuts are to be applied for generating a tooth undercut, a tooth root radius when it is greater than the cutter tip radius, or for a profile modification. Unlike during hobbing or generative grinding, the twist or bias phenomenon is not present because a) each flank is generated independently, and b) the cutter swivel angle is related to the base helix angle that is a constant for each gear.

Setup adjustments for profile correction can be achieved by two methods. Since all generative milling positions are functions of the base circle diameter and the cutter side angle, either of them could be mathematically adjusted to counterbalance machining dynamics, axes alignments, cutter quality, and other system errors affecting the

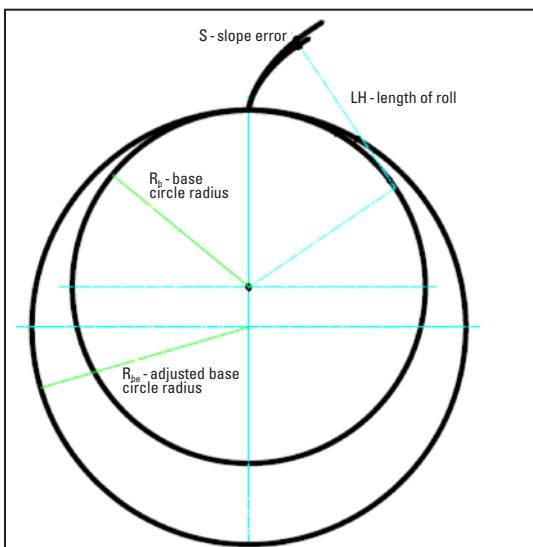


Figure 23 Involute profile adjustment.

profile slope quality. A similar methodology is used for profile adjustment on CNC-controlled gear grinding machines. It is also possible to make profile and lead modifications such as crown, taper, heat treat compensation, etc.

Base circle adjustment (Fig. 23). If the cut gear has an excessive slope error, the generative cuts can be re-calculated using the adjusted base circle instead of the theoretical base circle indicated on the gear drawing.

$$R_{be} = R_b(1 - S/LR) \quad (8)$$

where:

R_b is base circle radius specified on the drawing

R_{be} is adjusted base circle radius to be used for calculating generative cuts

S is profile slope error with its sign (\pm according to the material condition at the tooth tip)

LR is length of roll over which the slope error was determined

A is cutter swivel angle

Cutter angle adjustment. The other alternative for eliminating the profile slope errors is re-calculating the generative cuts based on adjusted cutter profile angle CA_e instead of CA .

$$CA_e = \tan^{-1}(\tan((CA_i - \tan^{-1}(S/LR))) \cdot \cos(A)) \quad (9)$$

where:

CA_e is adjusted cutter side angle

CA_i is cutter side angle in transverse plane, see Eq. 6

S is profile slope error (\pm according to the material condition at the tooth tip)

LR is length of roll related to the slope error

A is cutter swivel angle

Applications and Benefits

Applications of generative gear milling process. While in principle the generative milling method is capable of cutting gears of any pitch size, this method is most economical for cutting or re-cutting coarse-pitch gears (typically coarser than 3-2.5 DP). Generally, the coarser the pitch, the less economical is the hobbing process, the more economical is the generative gear milling process. Examples of applications that offer most benefits:

- Cutting coarse pitch gears that are beyond hobbing process capability
- Cutting gears that exceed the maximum pitch rating of an existing hobbing machine
- Small lot size gears when a hob or a form cutters are not available, too expensive, or require a long lead time
- Gear re-cutting/thinning/repairing when a hob or form cutter are not available
- Decommissioning of legacy Maag gear cutting machines for course pitch gears
- Replacement of a two- or three-step operation, e.g. — gashing (roughing) followed by a secondary hobbing or other finishing process

Benefits:

Reduced number of process steps/cost.

Sometimes, a coarse-pitch gear is machined in two or more steps. First, the gear is roughed by a single index cut on a hobbing machine. After that, the gear is moved to a Maag rack shaper for a finish cut. The generative gear milling will enable roughing and finishing of the gear on the same machine using one cutter with much greater efficiency while maintaining accuracy similar to the Maag method.

Reduced cutter cost and delivery time. Off-the-shelf standard disc cutters with rectangular or trapezoidal carbide inserts (typically less inexpensive than hobs for coarse-pitch gears) would be used to produce precision-quality gears. Side cutter angles do not matter; as the only requirement for the cutter is that it fits inside the tooth space (cutter tip should be smaller than tooth space at its narrowest location).

Expanded pitch range capability. The *Generative Milling* software feature can expand the pitch range of a hobbing machine. As long as a gear and cutter fit within the machine working range (do not exceed center distance and swing diameter limitations), the gear could be coarser pitch than the original hobbing machine rating allowed.

Improved efficiency. Compared to a legacy Maag gear cutting machine with rack cutters, the cutting efficiency is improved as multiple (instead of one) cutting edges remove material with every stroke.

Summary

- **Technology.** Generative gear milling is an innovative, software-centered gear cutting technology that offers new cost reduction opportunities for machining coarse-pitch gears.
- **Software app.** A hobbing machine or a milling machine with a rotary table can be equipped with a generative gear milling software app that would expand the machine capabilities to include generative milling, increase pitch capacity, and improve efficiency for cutting coarse-pitch gears.
- **Flexibility.** Since generative gear milling allows for an infinitely variable density of generative cuts, a hobbing machine or a milling machine equipped with software can cut much coarser gears as compared to the hob cutting process.
- **ROI.** The implementation of the generative gear milling technology does not necessarily require a new hobbing or milling machine. An existing CNC hobbing or milling machine with a rotary table could be upgraded with a software app to enable the generative gear milling process, providing an appealing ROI.
- **Opportunity.** Confluence of machine computerization, legacy mechanical gear cutting concepts, and a possibility of a relatively inexpensive way of technology acquisition and implementation, e.g.—adding a software app and a PC if

necessary—makes the generative gear milling technology accessible to a wider range of coarse-pitch gear manufacturers.

Computer simulation

(www.machinetoolbuilders.com/115):

- Unequal sides
- Equal sides
- Parallel Sides

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For more information. Questions or comments regarding this paper? Contact Yefim Kotlyar—YKotlyar@machinetoolbuilders.com.

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