Practical Gear Characteristics: Process Characteristics of the Most Popular Cutting Methods

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Bevel Gear Technology

Chapter 5

The geometry of bevel gears depends more than for cylindrical gears or other machine elements on the design of the tool. A face cutter with radially oriented blades will produce spiral bevel and hypoid gears with a circular lead function in a face milling process. If the blades of the face cutter are oriented with a radius and an offset in blade groups, representing a number of spirals equal to the number of blade groups, then this cutter is designed to produce an epicyclic lead function in a continuous face hobbing process. If the blades are protruding radially out on a peripheral cutter head, then this cutter can manufacture straight bevel gears or even face gears. The same, or similar peripheral cutter heads can be used to manufacture cylindrical gears in a Power Skiving process. In this case the blade front face is rotated from its tangential orientation such that it points in the axial cutter direction.

This chapter will explain the different bevel gear machining processes sorted by the different cutter head designs and the subsequently different flank geometries produced with them. The chapter also explains the different process kinematics, using simple explanations rather than formulas. In summary, the following fundamentally different bevel gear cutting methods i.e. bevel gear geometries exist:

Face Milling Generated	pinion and gear are generated
Face Milling Formate (form-generated	pinion generated, gear plunge cut
Face Hobbing Generated	pinion and gear generated
Face Hobbing Formate (form-generated	pinion generated, gear plunge cut
Straight Bevel Gears Generated & Formate	pinion generated, gear gen. or form-gen
Face Gears	face gear always generated

This chapter concludes with the table which shows the geometrical and kinematical placement of the different bevel gear cutting methods and the produced flank geometries.

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Plunging and Generating

The cutting process consists of either a roll only (only generating motion), a plunge only or a combination of plunging and rolling. The material removal and flank forming due to a pure generating motion is demonstrated in the simplified sketch in Figure 1 in four steps. In the start roll position (step 1), the cutter profile has not yet contacted the work. A rotation of the work around its axis (indicated by the rotation arrow) is coupled with a rotation of the cutter around the axis of the generating gear (indicated by the vertical arrow) and initiates a generating motion between the not-yet-existing tooth slot of the work and the cutter head (which symbolizes one tooth of the generating gear). The "forced" generating contact eventually results in the removal of material in the developing tooth slot (step 2). This is continued in step 3 until the cutter head (generating gear tooth) comes out of engagement with the work in step 4 (cutter is rolled out). The cutter moves now without any contact with the work — from the rolled out position back to the starting point (step 1). The work now rotates counterclockwise back to the rotational position of step 1 (plus one additional tooth spacing) in order to prepare for the cutting of the next slot.

The manufacture of a tooth slot by plunging is only possible for non-generated gears (Formate gears). Figure 2 provides a schematic explanation of pure plunging. Step 1 in Figure 2 shows the cutting blade in a position where it is not yet in contact. Step 2 shows the plunging move of the cutter head while the work gear is fixed in its position. Correct tooth form and tooth depth have been achieved in step 3. The cutter head withdraws now from the work gear until the blade clears sideways. After that, the work gear rotates about one pitch (arrow in step 1) and the plunge procedure is repeated in order to cut the next tooth slot.

It is also possible to begin the cutting of a generated pinion or ring gear with a plunging cycle in order to remove the majority of the chip volume at the beginning. The following step is a generating finishing cycle to create the correct flank form. This case, often applied in completing methods, consists of a combination of the movements shown in Figures 1 and 2.

Process Characteristics of the Most Popular Cutting Methods

Five-cut method. Five-cut is a single indexing method in which the tooth slots are cut in several steps.

- **Step one**: The ring gear tooth slots are roughed out with a cutter head that carries inside, outside, and sometimes bottom blades.
- **Step two**: The ring gear tooth slots are finished with a cutter head that carries inside and outside blades.
- **Step three**: The pinion tooth slots are roughed out with a cutter head that carries inside, outside, and sometimes bottom blades.
- **Step four**: The convex flanks of the pinion are finished with a cutter head

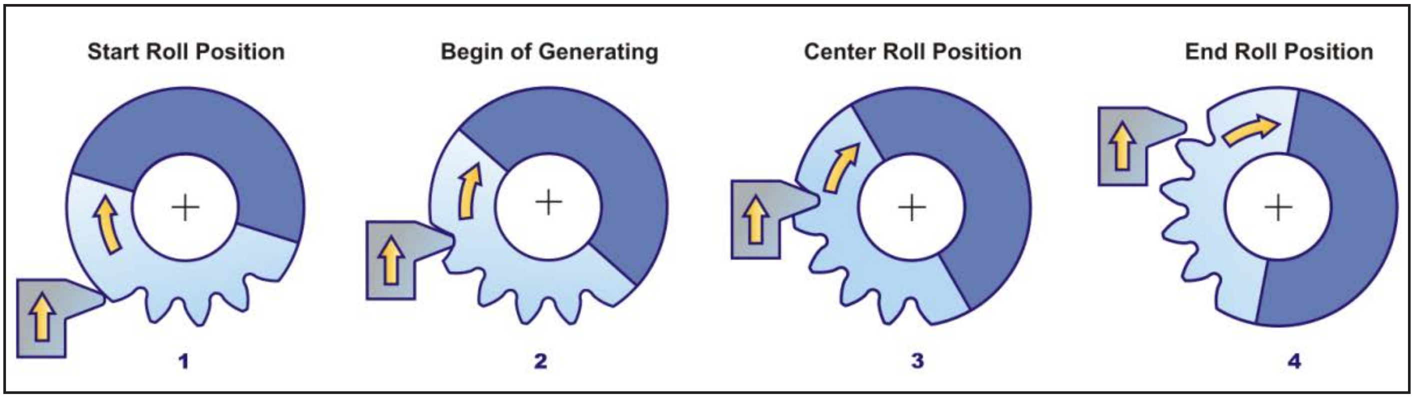

Figure 1 **Cutting of a tooth slot by generating.**

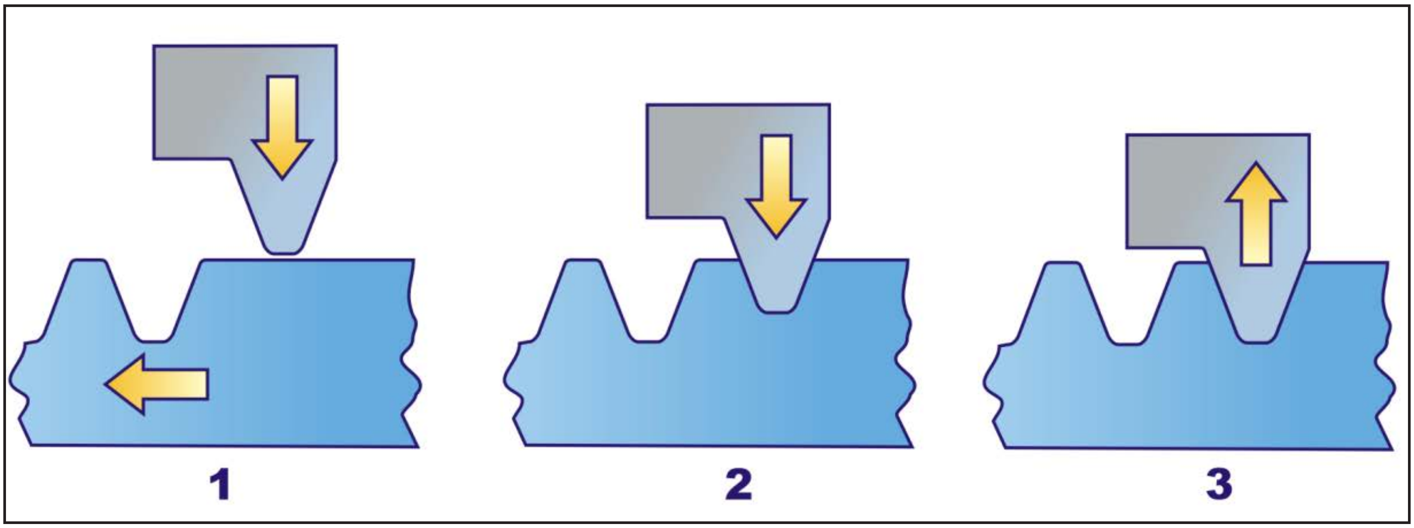

Figure 2 **Manufacture of a tooth slot by plunging.**

that carries only inside blades.

- **Step five**: The concave flanks for the pinion are finished with a cutter head that carries only outside blades.

The five cutting steps generally require five different machines, each of which performs one of the cutting steps. Parts have to be moved from one machine to the next, and the second and third cuts require a precise stock division in order to synchronize the 5-step slot cutting effort.

A typical cutter head used in five-cut is the Hardac cutter (Fig. 3, left). The blades have curved ground side relief surfaces (spiral relief) and are bolted to the circumference of the cutter body. Spiral relief ground blades are only ground on their front face for sharpening. This cutter head type is available for roughing and finishing of pinions and ring gears. A version with a circular blade stepping for the finish cutting of ring gears (Helixform method) is shown (Fig. 3, right). Similar cutter heads for the broaching of Formate ring gears in one cutter revolution (single-cycle method) are available under the name Cyclex; Cyclex cutters also feature stepped blades (analogous to a broach). Parallel shims and a variety of standard blade pressure angles make this kind of cutter head, with a minimum of required blade inventory, universally applicable (Ref. 1).

Due to the separate cutting of convex and concave pinion flanks, the highest possible number of freedoms exists for an independent optimization of coast and drive side. A process version with a generated pinion and a generated ring gear, and a version with a Formate ring gear and a generated pinion are available.

Length crowning is achieved with different cutter radii, while profile crowning — because of the standard blades (with mostly straight cutting edges) — is generated by modified machine settings.

Today, five-cut methods are outdated.

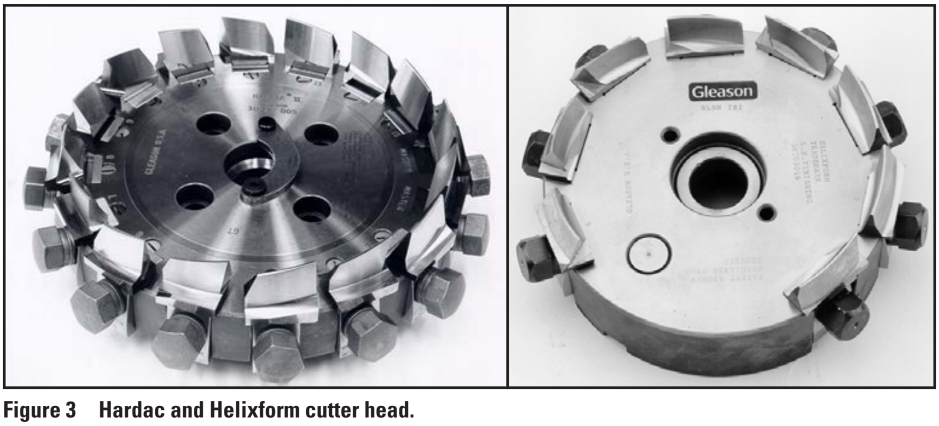

Figure 3 **Hardac and Helixform cutter head.**

All of them require wet cutting conditions with high volumes of cutting oil. They have been applied across all industries for the manufacturing of angular gear boxes. The five-cut methods were particularly well suited for the mass production of hypoid gears in the automotive and truck industry because the set-up changes of five machines between different jobs was not often required.

Single-indexing two-flank cutting method; face milling-RSR-completing; Pentac FM-completing. Roughing and finishing of both flanks in one slot is performed in one step (by generating, form-cutting or a combination) (Ref. 2). The cutter heads feature an alternate arrangement of inside and outside blades. The process parameters at the beginning of the chip removal cause roughing conditions, while towards the end, when the flank forming is performed, the process parameters change in order to establish finishing conditions.

With a Formate ring gear, the process parameter change from roughing to finishing is realized rather easily. With pure rolling of pinion tooth slots, it is, for example, required to start with a rough rolling from toe to heel in conventional cutting (with reduced slot depth), followed by a finish roll in full depth position in climb cutting. Another possibility is to plunge at the heel roll position (roughing), followed by a finish roll from heel to toe. Typical cutter heads as they are used in completing cutting are shown (Fig. 4).

The RSR cutter head (Fig. 4, left) is equipped with HSS stick blades that have a rectangular cross-section. The front face of the blades is pre-formed and coated. The pre-form provides a side rake angle of 20° on the entire usable length of the sticks. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The individual control of the geometry of cutting edge and clearance edge (including the blade top width) allows the realization of a two-flank completing cutting. The Pentac cutter head (Fig. 4, right) uses stick blades with optimized, pentagon-shaped cross-section. Pentac blades are manufactured mostly from carbide and can be re-sharpened either on the two sides like the RSR blades, or on the sides and on the front face, which requires a re-coating after sharpening. In contrast to the five-cut process, length crowning in completing gears can be generated by tilting the cutter head with an appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). It is simple to produce any desired blade pressure angle, since the side relief surfaces are individually ground for every unique gear design. Profile crowning can be created simply by introducing curved cutting edges (*see also text chapter 2.6.3*). Because of the individual grinding of each set of blades, cutting edge modifications like curved blades and protuberance are accomplished without any additional complications or cost.

Single indexing completing methods replaced five-cut methods in those industries that use grinding as a hard finishing process (*see also text chapter 9*). RSR cutters and similar stick blade cutters with rectangular blade cross-section are well suited for applications with HSS blades and are therefore often linked to wet cutting processes. The later development of the Pentac FM cutter head system has replaced the RSR cutter system almost entirely; 80 percent of today's bevel gear production is performed as a high-speed dry cutting process, where Pentac tools show particularly good suitability (*see also text chapter 7*).

Figure 4 RSR and Pentac-FM cutter head.

Continuous two-flank cutting method; face hobbing-TRI-AC; Pentac-FH. For face hobbing methods, blades with curved ground relief surfaces have been replaced today by stick blades (Ref. 3). Stick blades helped to initiate a breakthrough for the face hobbing methods — especially for the manufacturing of axle drive units that are used in heavy trucks.

Roughing and finishing of both flanks are performed in face hobbing in one chucking (by rolling only; i.e. — plunging only with Formate gear members or a combination of plunging and rolling). The continuous cutting method is always based on a completing process kinematic (*see also text chapter 2.3*). The cutter heads consist of a number of blade groups — each of which generally has an outside blade first — which is then followed by an inside blade. The process parameters at the beginning of the chip removal are defined for a roughing operation where, towards the end of the machining operation, when the final flank form is created, the process parameter changes to finish cutting. This is easily done if plunging a Formate ring gear. With generated pinions the roughing portion begins with plunging at the center roll position, followed by a rough rolling (conventional cutting direction) from center to heel with reduced tooth depth, followed by a finish roll at full depth from heel to toe (climb cutting) (Ref. 4).

Typical cutter heads used in continuous completing methods are shown (Fig. 5). Face hobbing cutters generate flank lines that are epicycloids and have blade groups with one outside and one inside blade in an orientation showing the same distance between the outside blades to both the preceding and following inside blades (equal blade spacing). The face hobbing process kinematic — using equally spaced blades — generates an equal split of the pitch spacing angle into the tooth thickness taper and the slot width taper. The TRI-AC cutter head (Fig. 5, left) uses stick blades with rectangular shank cross-sections. The front surface of the blades is pre-formed and coated. There is a side rake angle of 12° on the re-sharpening length of the blade shank. The cutting edge and clearance side relief surfaces are the only sides ground or re-sharpened. The Pentac-FH cutter head (Fig. 5, right) uses stick blades with an optimized pentagon-shaped cross-section. As mentioned, Pentac blades are generally manufactured from carbide and can be re-sharpened either on the sides like RSR blades or on the sides and on the front face (three-face grinding). If three-face grinding, the blades must be completely re-coated after each sharpening; this generates higher cost but also leads to a significant increase in tool life.

Length crowning in face hobbing gears can be generated in similar fashion to the face milling completing method by tilting the cutter head with an appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). It is simple to realize any desired blade pressure angle since the side relief surfaces are individually ground for each different gear design. Profile crowning can be created by introducing curved cutting edges (*see also text chapter 2.6.3*). Because each set of blades can be individually ground, cutting edge modifications like curved blades and protuberance can be accomplished without complications or added cost.

Gearsets manufactured by a continuous cutting method can only be hard finished by lapping or skiving because of their epicyclical flank lines. This is the reason why, even today, no ground face hobbed bevel gearsets exist. Face hobbing methods replaced the five-cut methods in industries that continue to use lapping as their final flank surface finishing process (*see also text chapter 9*). TRI-AC and similar stick blade cutter systems with rectangular blade cross-section are well suited for the application of HSS blades, and therefore are bound to wet cutting processes that use cutting oils. The successive development of the Pentac FH cutter head system has replaced the TRI-AC cutter system almost entirely because 80 percent of today's bevel gear production is performed as a high-speed dry cutting process, where Pentac tools show particularly good suitability (*see also text chapter 7*).

The Cyclocut method. Cyclocut is a continuous cutting method similar to the one discussed in the previous section. What is different in Cyclocut is the low number of blade groups (generally five blade groups) and the unique generation and distribution of length crowning between pinion and gear.

In the Cyclocut process, roughing and finishing of both flanks is performed in one chucking (by rolling only). Cyclocut is based on a continuous kinematic and is always a completing method (*see also text chapter 2.3*). The cutter head consists of a number of blade groups, each of which generally have an outside blade first, followed by an inside blade. The process parameters at the beginning of the chip removal are chosen for a roughing operation. Towards the end of the machining operation, when the final flank form is created, the process parameters change to finish cutting. Cyclocut is always a generating method, where the roughing portion begins with a plunge at the center roll position, followed by a rough rolling (conventional cutting direction) from center to heel with reduced tooth depth, followed by a finish roll at full depth from heel to toe in climb cutting (*analog to regular face hobbing explained in text section 5.3.3*) (Ref. 5).

Typical cutter heads used in the Cyclocut method are shown (Fig. 6). Face hobbing cutters generate flank lines that are epicycloids and have blade groups with one outside and one inside blade in an orientation showing the same distance between the outside blades to the preceding, and the following inside blades (equal blade spacing). The cutter head in (*text Fig. 5.6, left*) is a sub-form of the TRI-AC cutter head that also uses stick blades with a rectangular shank cross-section. The front surface of the blades is pre-formed and coated. Formed is a side rake angle of 12° on the re-sharpening length of the blade shank. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The Cyclocut-Pentac cutter head, (Fig. 6, right) uses stick blades with an optimized, pentagon-shaped cross-section. The carbide Pentac blades can be re-sharpened — either on the sides like TRI-AC blades, or on the sides and front face (three-face grinding).

The length crowning in Cyclocut is split between pinion and gear and generated by tilting the cutter head with the appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). Any desired blade pressure angle can be easily realized since the side relief surfaces are individually ground for every

Figure 5 TRI-AC and Pentac-FH cutter head.

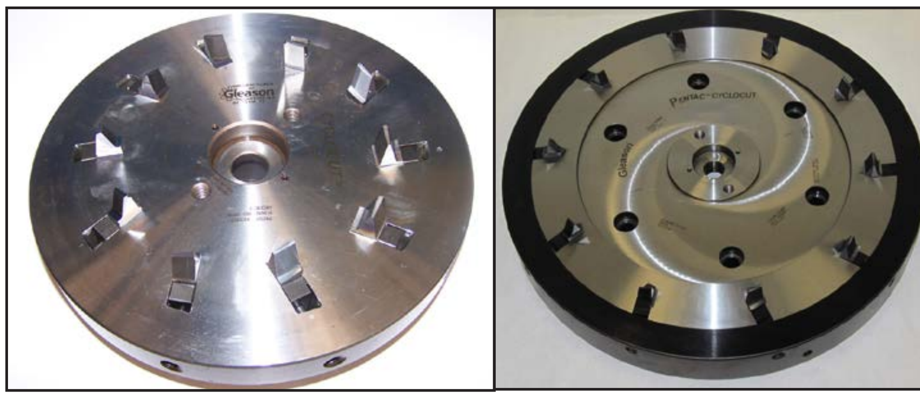

Figure 6 Cyclocut and Cyclocut Pentac cutter head.

different gear design. The desired profile crowning is also split between pinion and gear and can be created simply by introducing curved cutting edges (*see also text chapter 2.6.3*). With the individual grinding of each set of blades, cutting edge modifications like curved blades and protuberance can be realized without complication or added cost.

Cyclocut bevel gearsets are hard finished after heat treatment by skiving. Soft and hard machining is therefore possible with the same cutter heads; only the blades have to be exchanged between the soft and hard manufacturing steps. Skiving is performed with three-face ground and all around coated carbide blades which require a highly negative side rake angle. The low number of required stick blades for the manufacture of a certain gear design, as well as the fact that the same machine and cutter heads can be used for soft and hard machining, makes Cyclocut the ideal method for the manufacture of a high variety of different bevel gear designs with very small batch sizes. Cyclocut is also well suited for large bevel gearsets with ring gear diameters up to 1.5m. Simple basic settings for the cutting machine summaries — together with the easy building and trueing of Cyclocut cutter heads and even split of the crowning between pinion and gear — make this bevel gear type easy to handle — even for bevel gearsets of gigantic dimensions.

The Spiroform method. Spiroform is a face hobbing method that duplicates the flank geometries of the older Oerlikon Spiroflex-Spirac methods, and like the Oerlikon methods, features a special tooth thickness and slot width taper, which alternates between pinion and gear. Because of the tooth proportions, it is possible to generate pinions with a low number of teeth and without a high potential for crossover between the inside and outside blades, thus avoiding mutilations in the pinion toe region.

In the Spiroform process, roughing and finishing of both flanks are performed in one chucking (by rolling only, plunging only in case of Formate gear members or a combination of plunging and rolling). Spiroform is based on a continuous kinematic that is always a completing method

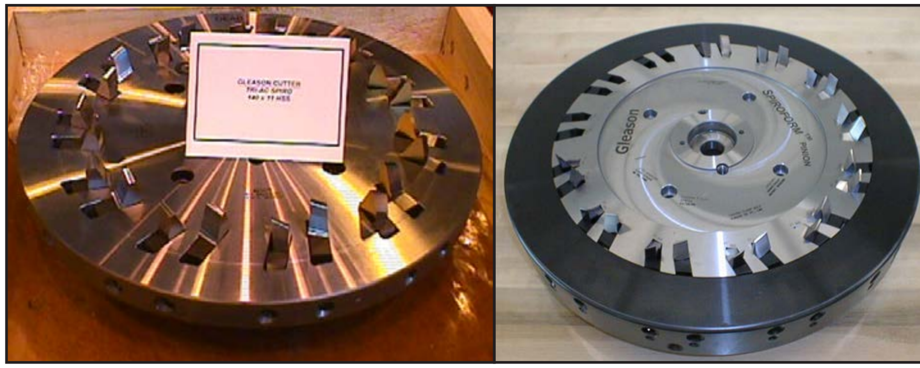

Figure 7 Spiroform ring gear cutter head (left), and Spiroform-Pentac pinion cutter head (right).

(*see also text chapter 2.3*). The cutter heads consist of a number of blade groups, each of which first has an outside blade that is followed by an inside blade. The process parameters at the beginning of the chip removal are chosen for a roughing operation; towards the end of the machining process, when the final flank form is created, the process parameters are changed to a finish operation (Ref. 6).

Typical cutter heads used in the Spiroform method are shown (Fig. 7). These cutter heads generate flank lines that are epicycloids and have blade groups — with one outside and one inside blade — in a spacing orientation that is specifically adjusted to achieve a small slot width taper and a high tooth thickness taper in the pinion member, and the opposite tapers in the gear member. The cutter head (Fig. 7, left) is a subform of the TRI-AC cutter head and also uses stick blades with a rectangular shank cross-section. The front surface of the blades is pre-formed and coated. Formed is a side rake angle of 12° on the re-sharpening length of the blade shank. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The Spiroform-Pentac cutter head (Fig. 7, right) uses stick blades with an optimized, pentagon-shaped cross-section. The Pentac blades are usually manufactured from carbide and can be re-sharpened — either on the sides like TRI-AC blades or on the sides and on the front face (three-face grinding). The special blade arrangement requires, for each spiral angle direction, one pinion and one gear cutter, i.e. — four cutter heads for each cutter head size.

As previously mentioned, the modified slot width and tooth thickness taper are realized by unequal distances between the outside blade and preceding inside blade, and the inside blade in the next blade group. Spiroform cutter heads for ring gear cutting therefore have a large distance between the outside blade that enters the slot first and the following inside blade. The next outside blade that belongs to the next blade group follows with a small distance inside said blade from the previous blade group. A combined "large" and "small" distance amounts to one blade group spacing (360°/number of blade groups). The relationships of the blade spacing in a ring gear cutter head are visible (Fig. 7, left). The two blades with the large distance between them form one blade group. For the pinion cutting, the blade distance relationships between outside and inside blades have to be the opposite of the ring gear cutting. Only in this case is it guaranteed that the pinion teeth have a tooth thickness taper that fits perfectly with the slot width taper of the ring gear. The sample photograph (Fig. 7, right) shows a Spiroform pinion cutter. The blades with the smaller distance always belong to the same blade group.

Length crowning is created by cutter head tilt, with the blade angles adjusted accordingly — just as with TRI-AC. Any blade pressure angle can be realized because the side relief surfaces (that form the cutting edges) are individually ground for each gear design. Profile crowning is realized with cutting edges that have a circular curvature. Cutting edge modifications like curvature and protuberance can be realized rather easily due to individual grinding of each set of blades.

Bevel gearsets manufactured with the continuous indexing Spiroform method

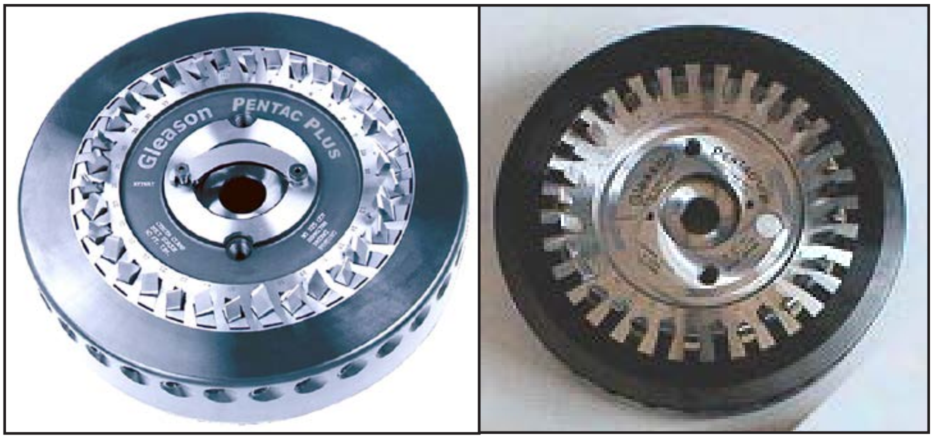

Figure 8 Pentac FH cutter head (left), and Pentac FM cutter head (right).

Figure 9 Fine-pitch Pentac face milling cutter head with large diameter.

have to be lapped or skived; grinding is not possible because of the epicyclic flank lines. The cutting methods Spiroflex-Spirac® and Spiroform have replaced the five-cut method for the manufacture of axle drive units for light, medium and heavy trucks.

The super reduction hypoid – SRH method. The SRH method is used for the manufacture of high-reduction bevel-worm gear drives from ratios 1×5 up to 1×100 (*see text chapter 4.7*). The lowest number of pinion teeth of a SRH pair is "one." SRH pinions are generated pinion worms, while the ring gears are cut and ground in Formate. The cutting process is always completing, where both versions — single indexing (face milling) as well as continuous indexing (face hobbing) — are available.

Typical cutter heads used for completing cutting of SRH gearsets are shown (Fig. 8). For the face hobbing version, Pentac FH cutter heads (Fig. 8, left) are used. For the face milling version, Pentac FM cutter heads (Fig. 8, right) are used. Standard, free-form Phoenix bevel gear cutting machines are well suited for cutting SRH gears (Ref. 7).

Length crowning of face hobbed SRH gearsets is created by cutter head tilt in the pinion cutting. With face milled SRH gearsets the naturally existing length crowning is reduced to the desired level by an evenly split, reversed cutter head tilt in both pinion and gear. Profile crowning is completed in both cases (face hobbing and face milling) with circularly curved cutting edges.

SRH gears with low requirements for noise emission and efficiency are preferably manufactured by face hobbing; the hard finishing operation is lapping in this case. The lapping time has to be limited to a few seconds (or eliminated) because of the very high number of pinion rotations during one ring gear rotation. SRH transmissions with a high requirement for quiet operation and efficiency have to be manufactured by face milling in order to allow for flank grinding after heat treatment. The major application of SRH gearsets is industrial gear boxes. With SRH it is possible to realize high ratios in a single stage reduction, enabling the design of cost-effective and efficient angular gear boxes.

The Hypoloid method. Hypoloid gears are slightly conical and look very similar to cylindrical gears (*see also text chapter 4.8*). The teeth wind under a certain spiral angle around a slightly conical base element. The face width of Hypoloid gears is significantly larger than that of comparable bevel gears. Small cutter radii lead to a borderline mesh condition in the toe region since the spiral angle increases from heel to toe continuously. Thus practical cutter diameters are about twice as large as the cutter diameters used for equal size bevel pinions. This led to the design of special, large cutter heads using fine pitch blades.

The driving pinion of the Hypoloid pair is generated while the driven gear is machined in Formate. Hypoloid gears are manufactured in single indexing completing since grinding is the only recommended hard finishing method. The gears are manufactured simply by plunging. Because of the large "rollout angle" (Fig. 1), the pinions are plunged at the toe (roughing) and then finished by rolling to the heel. A typical cutter head for the soft cutting of Hypoloid gears is shown (Fig. 9). For cutting and grinding

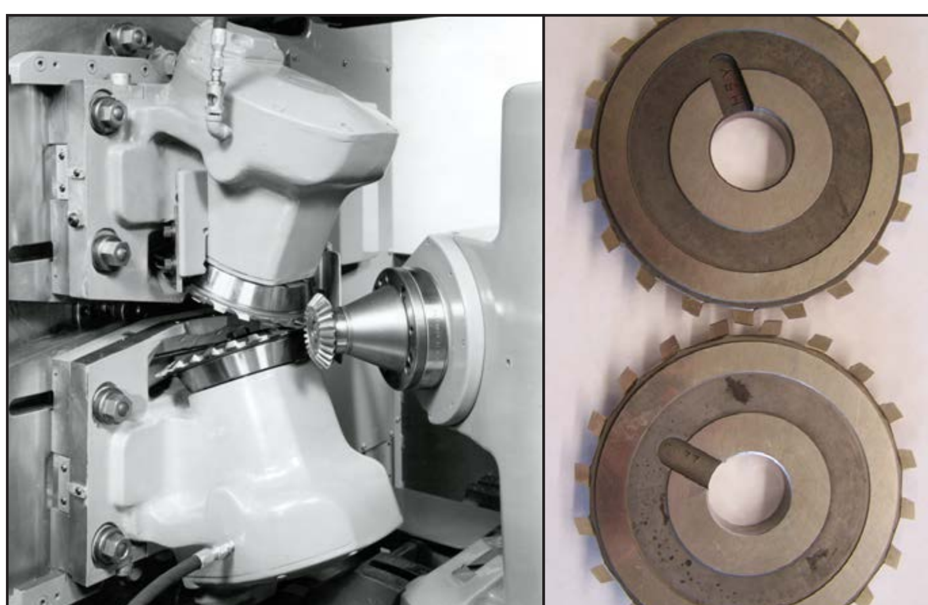

Figure 10 Mechanical Coniflex cutting machine (left) und HSS cutter disks.

machines, standard Phoenix free-form machines are utilized (Ref. 8).

The desired length crowning is created by cutter head tilt and re-adjusted blade angles. Profile crowning is realized with circular curved cutting edges. Hypoloid gearing is applied in transfer cases of all-wheel-driven passenger cars and SUVs. All of the existing applications are ground. The major advantage of Hypoloids vs. Beveloids is their very forgiving displacement behavior under high load in aluminum gearbox housings.

The Coniflex method. Coniflex is a single-indexing method used for the manufacture of straight bevel gears. The classical method uses two interlocking disk cutters from solid HSS on a special machine that applies, in most cases, a combined plunge and roll cycle.

A typical Coniflex cutting machine (No. 104) that features a cradle with two cutter spindle units is shown (Fig. 10, left). The machines are difficult to set up, and perform pre-determined cycles that are controlled with cams. Figure 10 (right) shows a pair of interlocking HSS disks with diameters of 4.25inches. These cutters are mounted in the machine under an angle that relates to the pressure angle of the part and includes certain corrections (Ref. 9).

Today's more modern method uses peripheral cutters with carbide Pentac stick blades that are applied on the same standard Phoenix machines used for spiral bevel gear cutting (*see text chapter 4.2*). The high-speed power cutting is either performed as a pure rolling process or as a combination of plunging and rolling. Figure 11 (left) shows a view of the work area of a Phoenix free-form machine with a Coniflex carbide cutter. To the right is shown the top view of a peripheral Coniflex Plus cutter head with carbide stick blades.

The desired length crowning is created by using a cutter head tilt and cutting edges that describe a cone element while the cutter rotates. For the generation of profile crowning, a machine root angle modification, or a second order ratio of roll modification, is applied. The modified ratio of roll (modified roll) can be easily realized on free-form machines and is well suited to make profile crowning corrections during the practical development of a gearset.

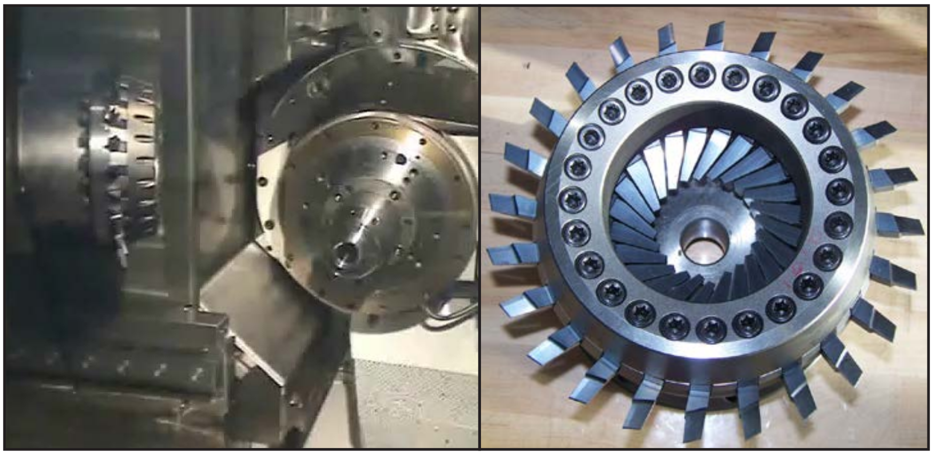

Figure 11 Coniflex Plus cutting (left), Coniflex Plus cutter head (right).

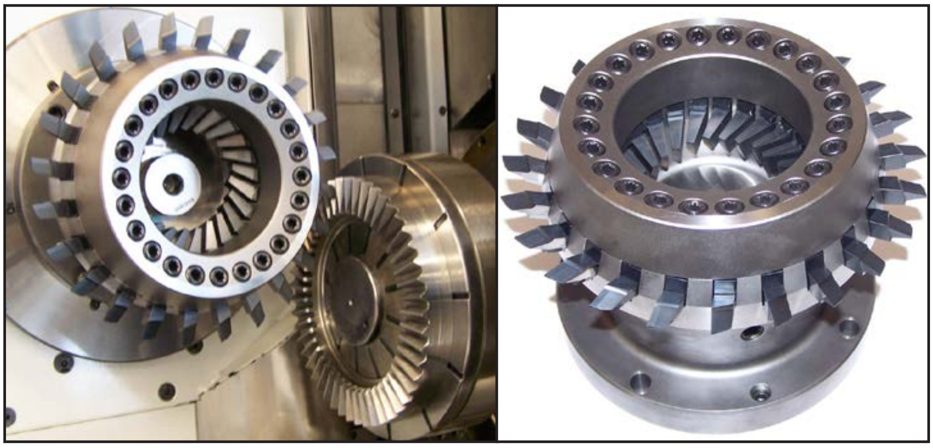

Figure 12 Coniface cutting (left), carbide stick blade cutter (right).

Coniflex gears are applied as differential bevel gears in trucks, construction equipment, rail road transmissions and marine applications. They are also used as axle drives in farm tractors, construction machines, auxiliary transmissions for agriculture as well as industrial applications and power tools. Straight bevel gears usually do not undergo any hard finishing operations after the heat treatment process.

The Coniface method. Face gears can be manufactured on the same standard Phoenix free-form machines that are used for the manufacture of spiral bevel gears. The cutting edges of the stick blades in the peripheral cutter head (Fig. 12, right) have an involute shape that represents one side of the generating tooth. A view into the work area of a Phoenix free-form machine during the cutting of the face gear is shown (Fig. 12, left). Face gears are manufactured similar to Coniflex straight bevel gears by rolling or a combination of plunging and rolling.

The machine motions required to form face gear teeth are quite different from the motions used in the Coniflex method. The cutting tools are Coniflex Plus peripheral stick blade cutters, as the one shown (Fig. 12, left). Only the form of the cutting edges is not like, in the case of Coniflex, straight lines, but involutes that represent a flank of the mating pinion (Ref. 11).

The desired length crowning is achieved by cutter head tilt and cutting edges that generate an internal cone element while the cutter rotates. Profile crowning is realized by circular modifications of the involute blade profile. Machine freedoms like modified roll and a second order tilt-swivel motion can be applied during face gear development. However, it must be realized that all modifications that are known from spiral bevel and straight bevel gears will deliver exotic Ease-Off shapes that are difficult to convert to a decent looking Ease-Off (*see also text chapter 18.4.5 — Not optimized "butterfly Ease-Off"*). A special correction software has been developed and is offered as an option with the Gleason *GAGE* software.

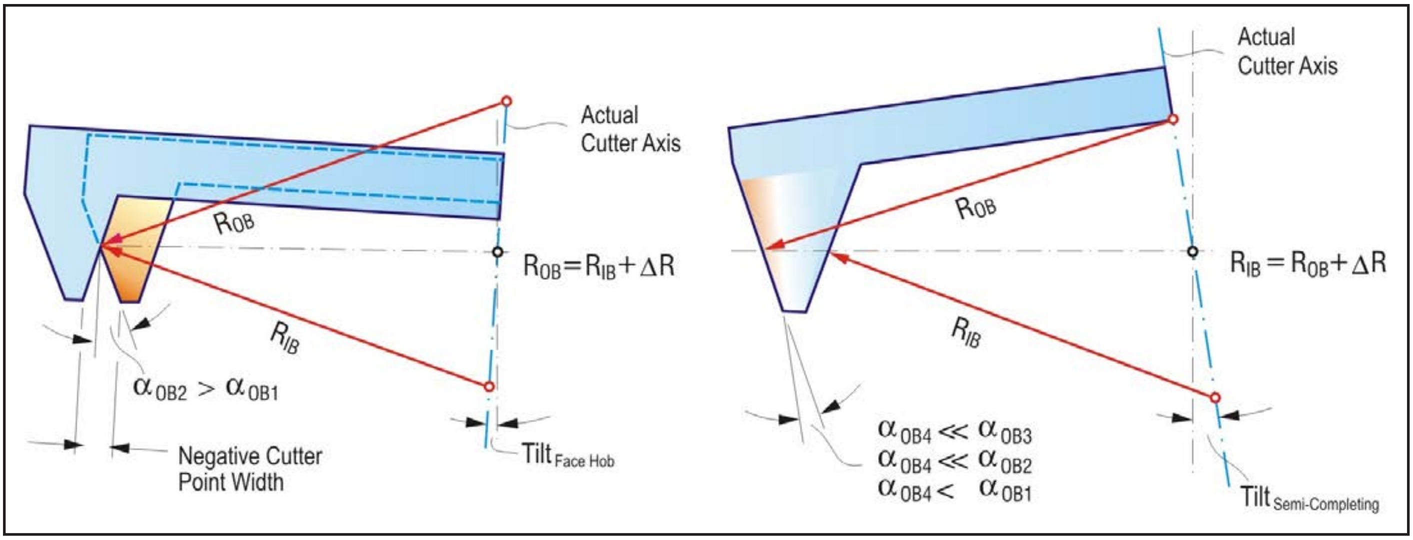

Figure 13 Continuous working cutter head (left) and semi-completing grinding wheel profile (right).

Table 1 Geometrical and kinematical classification of Gleason bevel gear cutting methods.

Method	Indexing Kinematic	Flank Line	Tooth Depth	Number of Cuts	Gear Formate	Length Crowning	Profile Crowning	Inventor
Five-Cut	single indexing	circular Arc	tapered	5	possible	cutter radii	machine	Böttcher, Wildhaber
Completing	single indexing	circular Arc	tapered	2	possible	cutter tilt	in blades	Wildhaber, Baxter
TRI-AC	continuous	epicycloid	parallel	2	possible	cutter tilt	in blades	Krenzer
Cyclocut	continuous	epicycloid	parallel	2	N/A	cutter tilt	in blades	Stadtfeld
Spiroform	continuous	epicycloid	parallel	2	possible	cutter tilt	in blades	Stadtfeld
HRH SRH	single/continuous	circlular arc/ epicycloid	parallel/ tapered	2	always	cutter tilt	in blades	Baxter, Stadtfeld
Hypoloid	single indexing	circlular arc	tapered	2	always	cutter tilt	in blades	Stadtfeld
Coniflex	single indexing	straight	tapered	4	possible	in the tool	machine	Carlsen
Coniflex Plus	single indexing	straight	tapered	4	possible	in the tool	machine	Carlsen, Stadtfeld
Coniface	single indexing	?	parallel	4	N/A	in the tool	in blades	Stadtfeld
Semi-Completing	single indexing	circlular arc	parallel	4	possible	cutter tilt	in blades	Brandner

Face gears are applied in special transmissions, e.g. — for actuation in aircraft, in transfer cases of four-wheel-drive vehicles, in special industrial applications and power tools. Depending on the field of application, face gears are either ground after heat treatment or used without any hard finishing.

The semi-completing method. Semi-completing is a single indexing method that machines both flanks of one slot in one chucking, yet applies two passes each with different machine basic settings. In case of the classical five-cut method (and continuous cutting methods), the problem is the fact that the radius of curvature of the inside blades must be larger than that of the outside radius. The curvature radius is the length of a line that is perpendicular to the blade enveloping cone and connects the blade reference point and the tool axis. This is shown (Fig. 13, left) for a continuous working Cyclocut cutter head (see R_{OB} and R_{IB}). The inside and outside cutting edges of a continuous working cutter head cross each other at the blade reference point with the slot width the result of the spacing between those blades and the continuous cutting motion.

It is also possible to achieve the resulting curvature relations between inside and outside blades in a single indexing cutter head by drawing the cutting edges of inside and outside blade with the a reduced point width (Fig. 13, right). Then the curvature radii from the left part of Figure 13 are drawn perpendicular to the respective cutting edges, beginning at the blade reference points. The connecting line of the two radii end points is the position of the new cutter axis. With knowledge of the cutter axis position, all cutter head and profile parameters of the newly designed tool can be determined (Ref. 12).

Semi-completing is applied for the grinding of bevel gears that are semi-finished in the soft with the continuous Cyclocut method. The epicyclic flank lines are replaced by circles that require a highly uneven stock removal between toe and heel. Semi-completing is used in certain applications, mostly for ring gear diameters between 400 mm and 800 mm, like industrial gear boxes as well as ship and railroad transmissions.

Geometrical and Kinematical Placement of the Different Methods

The eleven common Gleason bevel gear cutting methods are listed in Table 1 with regards to their geometrical and kinematical characteristics. The table provides an overview regarding indexing method; mathematical flank line function; tooth depth taper; number of manufacturing steps; kind of crowning generation; and the originator of the particular method. The table also mentions whether the ring gears can be manufactured in Formate, i.e. — if they are always manufactured in Formate.

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Figure 14 **Wooden model of large cutting machine—Gleason No. 675.**

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