Power Skiving of Cylindrical Gears on Different Machine Platforms

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It has long been known that the skiving process for machining internal gears is multiple times faster than shaping, and more flexible than broaching, due to skiving's continuous chip removal capability. However, skiving has always presented a challenge to machines and tools. With the relatively low dynamic stiffness in the gear trains of mechanical machines, as well as the fast wear of uncoated cutters, skiving of cylindrical gears never achieved acceptance in shaping or hobbing — until recently. Indeed, the latest machine tools — with direct drive train and stiff electronic gearboxes, complex tool geometry and the latest coating technology — now present an optimal opportunity for the skiving process, including the soft-skiving of cylindrical gears.

The Power Skiving Machine Setup Definitions

The geometric setup of a skiving cutter relative to an internal ring gear is shown (Fig. 1). The front view of the generating gear system is shown in the upper left graphic. The ring gear is oriented in the main coordinate system with its axis of rotation collinear to the Y_4 axis. The cutter center (origin of R_w) is positioned out of the center of Y_4 in the X_4 -Z_4 plane by a radial distance vector Ex. The pitch circles of the cutter and the ring gear contact tangentially at the lowest point of the pitch circle. The top view, which shows the tool inclination angle or shaft angle Σ, is drawn below the front view. In case of a spur gear the stroke motion is directed in line with the Y axis. The relative velocity required as cutting motion is generated with a shaft angle Σ around the X_4 axis of the coordinate system shown in Figure 1. In case of a helical gear, the cutter inclination can be chosen independently from the helix angle. However, a helix angle of 20° or greater offers the possibility to be matched with the shaft angle Σ and to use a simplified spur gear-style shaper cutter for the skiving operation. Also in this case, the stroke motion is oriented in Y direction but an incremental rotation ω_2, which depends on the stroke feed, has to be added to ω_1. The shaft angle Σ can also be defined differently than the helix angle and it will still require the same incremental ω_2, but the tool front face orientation and side relief angles have to be calculated from the difference between helix angle and the shaft angle Σ. The side view to the right (Fig. 1) shows a second possible tool inclination which is called the "tilt angle." This tool tilt angle can be used to increase the effective relief angles between the blades and the slots; it can also be used to eliminate interferences between the back-side of a long spur gear-style shaper cutter with minimum relief angles (*see section* Skiving Tools). Within limits, it is also possible to utilize the tilt angle for pressure angle corrections.

The three-dimensional side view (Fig. 2) shows an internal helical gear with a shaft angle Σ between work and tool. The graphic shows the base angular velocities of the work ω_1 and the formula for its calculation. Figure 2 also includes the incremental angular velocity ω_2 and

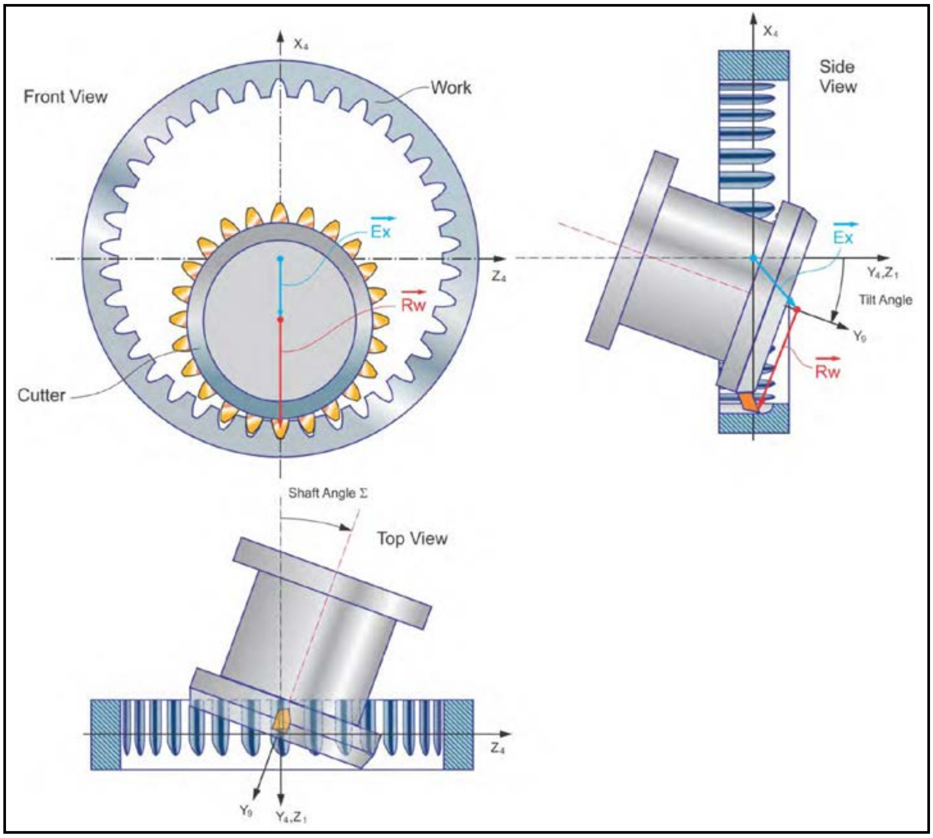


Figure 1 Basic geometry and kinematics of power skiving.

the formula to calculate it from the helix angle and the axial feed motion (stroke motion). The cutting velocity is calculated as the difference vector between the circumferential velocity vectors of work and tool in the cutting zone. Figure 3 shows a top view of the configuration between tool and work with the velocity vectors.

The reference profile of the tool is determined from the reference profile of the work applying the procedure (Fig. 4). The reference profile of the work with pressure angles α_1 and α_2 and point width W_p is drawn as a trapezoidal channel, and it is cut with a plane under the shaft angle Σ (Fig. 4, top, right). The profile is defined by the intersecting lines between the plane and channel, and it represents the reference profile of the tool. This tool reference profile is used in order to generate the involute in the tool cutting front (Fig. 4, bottom right).

The machine setting calculation is shown (Fig. 5, top) on the example of a bevel gear cutting machine. The explanation of the formula symbols are:

- X, Y, Z Machine axis directions (Y is perpendicular to the drawing plane)
- Σ Shaft angle between cutter and work
- *CRT* Cutter reference height
- B Cutter swing angle
- P_Z Pivot distance to spindle front in Z direction if $B=0°$
- P_X Pivot distance to spindle center line in X direction if $B=0°$
- Z_1, Z_2 Components in Z direction

Depending on the helix directions in work and cutter, the cutting takes place below or above the work gear center line in order to keep the B axis angle below 90°. Should there be no corrections needed, the crossing point between the cutter axis and the work axis lies in the cutter reference plane. The bottom section of Figure 5 shows the cutting blade definitions as reference.

Chip Formation and Optimization of Chip Load

Although the chip formation process of skiving appears different when compared to traditional gear cutting operations, understanding it is a fundamental task in recognizing weaknesses or strength of the skiving process. Power skiving has been called a combination of "cold forming"

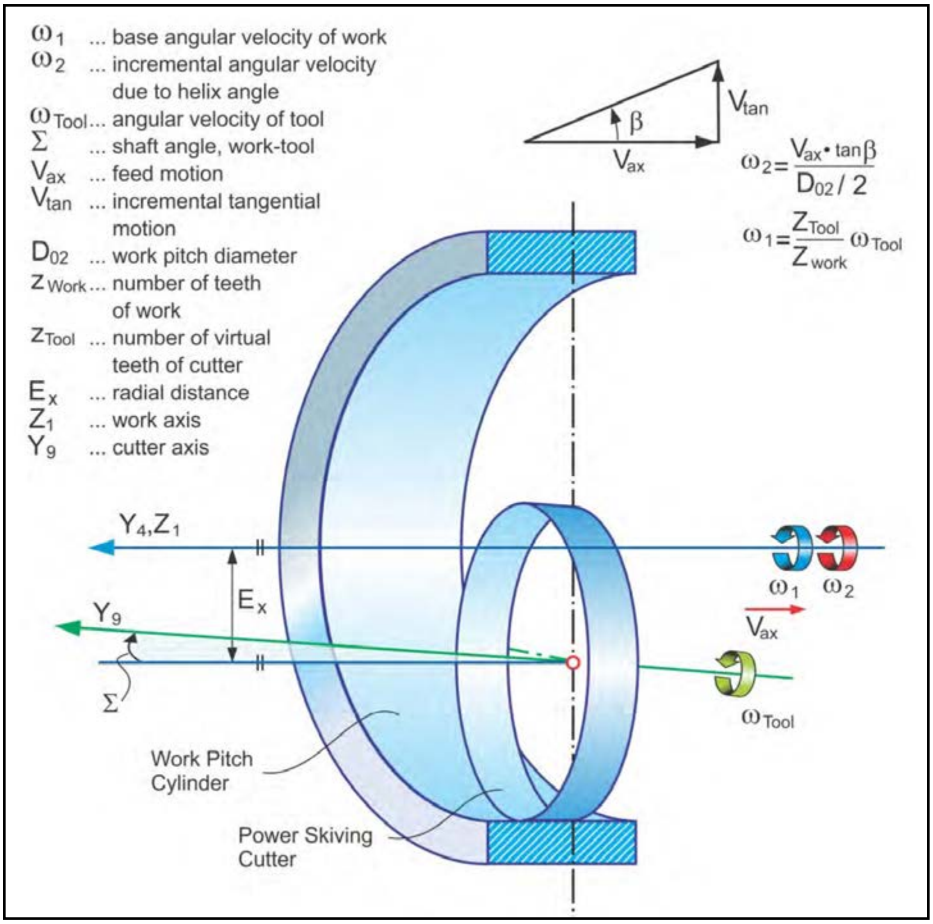


Figure 2 **Pitch cylinders of work and tool.**

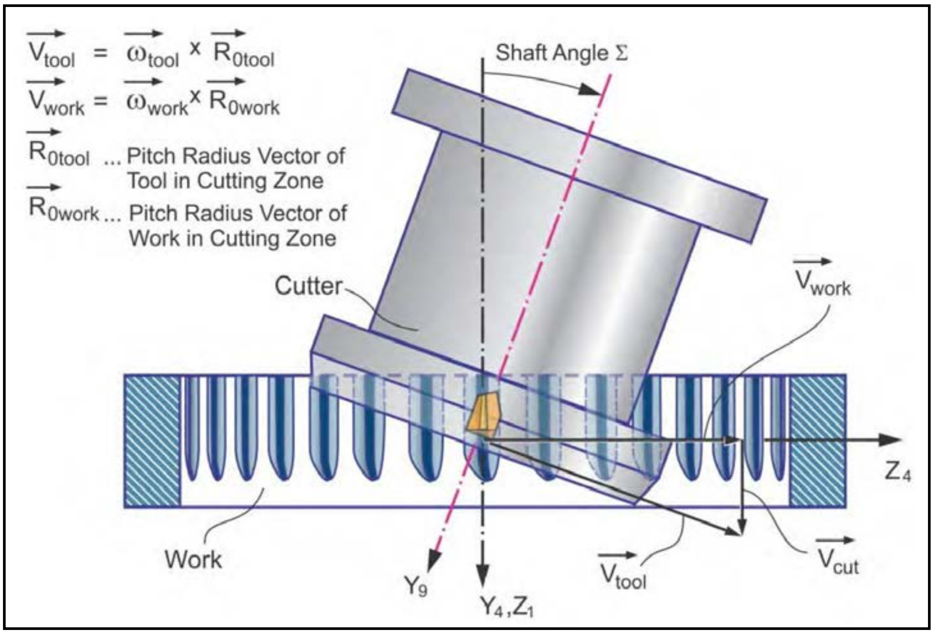


Figure 3 **Calculation of cutting velocity.**

and cutting. But is not every metal removing process such a combination? The task of a successful process is an economical combination of speed, part quality, tool life (tool-cost-per-part), and of course the investment in the machine tool.

The plane in Figure 6 shows a segment of an internal ring gear to be skived, and it is defined along the face width at the point where the last generating occurs. The second cutting tooth from the left has just entered into a part of the slot which is already rolled out from the previous cutting action. The third cutting tooth is advanced towards the observer and just begins a generating cut (see top view of unrolled partial slots). The generating cut continues to cut tooth number six. The lowest scallop in the top view was generated between the second and sixth cutting blade position. Cutting blades seven and eight finish the form cut end section of the slot.

A photograph of the tooth sequence from Figure 6 is shown in Figure 7 as a close-up. As one blade rotates through the cutting mesh, the orange-colored scallop is generated and the green-colored section is form-cut. The entire cutting action of one blade produces one chip, which includes the material removal from generating and form cutting. Beginning with its addendum, the right side of the blade gradually engages with the gear slot during the generating motion. It approaches the tip, and at this point it smoothly peels the chip up to the top of the gear. As the generation works its way from the right flank of the gear to the tip, and from this point up to the flank, every section that had at one point chip removing contact with the work now stays in contact to the end of the cut. Only the generating chip removal (within the scallop) converts quickly into form-cutting.

The form-cutting section might seem like an interesting phenomenon but it can be found in a similar form in all other generating cylindrical or bevel gear cutting methods. It is also common in all generating and form-cutting processes, that the tip region of the blades have the longest exposure to chip removal action within the green form-cutting region.

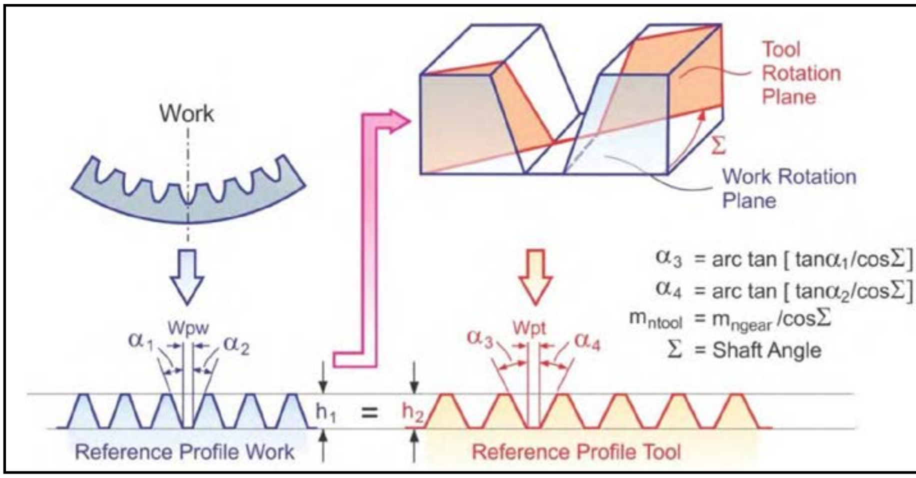
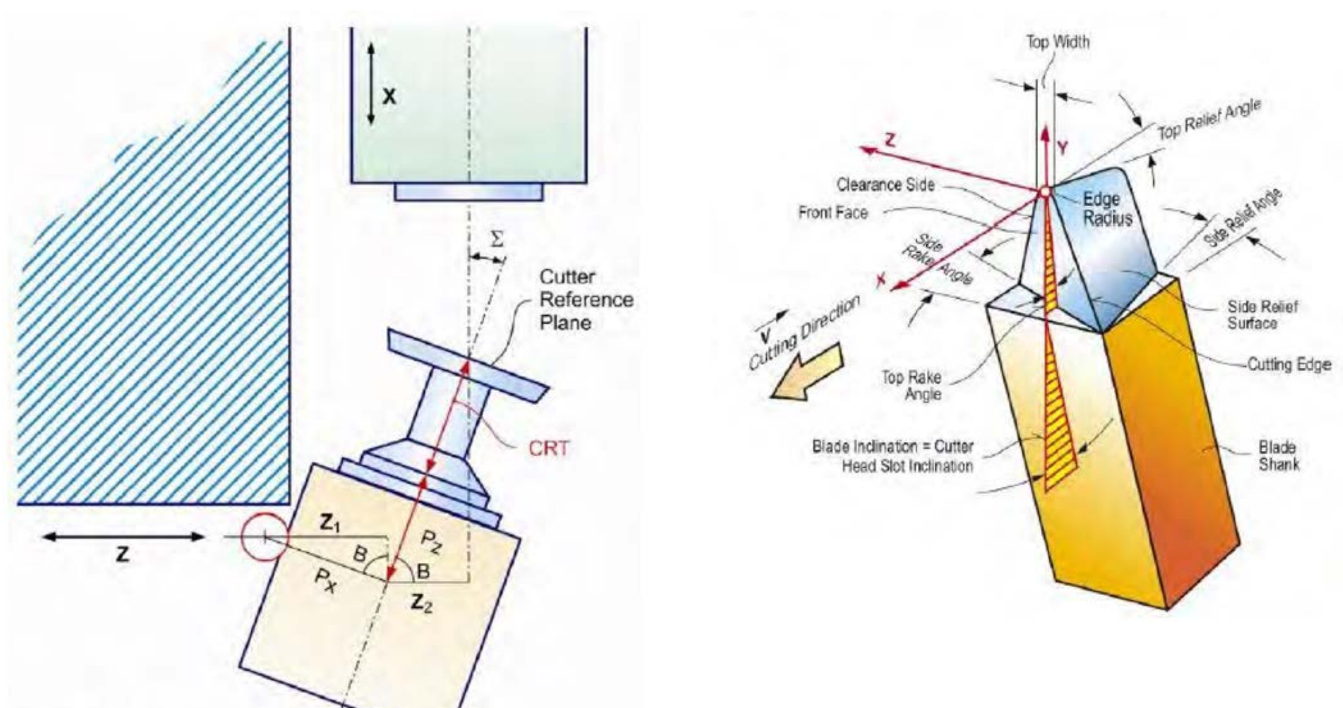


Figure 4 **Procedure for the calculation of the tool reference profile.**



$B = 90° - \Sigma$

$Z_{pos} = Z_1 + Z_2 = (CRT + P_Z)\cos B + P_X \sin B$

X_{pos} = Arbor Height + Gear Width + $(CRT + P_Z)\sin B$

Y_{pos} = Gear Pitch Radius - Cutter Pitch Radius

Figure 5 **Calculation of machine settings (top) and cutting blade definitions (bottom).**

Since the front face of power skiving blades is a plane that connects the cutting edges for both flanks, the side rake angle cannot be positive for both cutting edges. An acceptable compromise is a side rake angle of zero degrees. In order to enhance the cutting performance of the blade tip, a significant top rake angle can be introduced. However, peripheral cutter heads with carbide blades and top rake angles above 4° seem to fail with blade chipping in the tip area (Fig. 5).

Power skiving chips with a 5× magnification are shown (Fig. 8, top). The first chip (A) is a side chip from the first roughing pass of a module 4.0 mm gear with a 5 mm in-feed. The second chip (B) is U-shaped, which means, unlike the first chip, the side chips and the bottom chip have not been separated. This chip is from a second roughing pass with 3 mm in-feed. The third chip (C) is from a finishing pass with 1 mm in-feed. The result of an unrolled and uncompressed chip that is just sheared off is a curved channel like that indicated in the drawing at the bottom left of Figure 8. The two side walls, as well as the bottom section of the channel, are rolled up individually and mostly without breaking into separate pieces.

The microscope photo (Fig. 8, bottom right) shows a cross-section through the left wing of one chip with a magnification of 100×. At the beginning of cutting (center of the chip spiral), the chip thickness is small and increases slightly during the rather short generating section (orange scallop, Fig. 7). A proportional increase of the chip thickness occurs from the beginning to the end of the form-cutting section (Fig. 7, green area).

The right sides of the chips are thinner than the left sides, and a crack in the middle of the rolled-up sidewall can be observed. As the bottom left image indicates, the right channel wall has a more complex shape than the left side, and the skiving kinematic provides slightly different cutting conditions on both flanks. This explains differences in chip thickness between the two sides and the additional crack of the right side of the chip.

In order to avoid U-shaped chips, Gleason has developed an in-feed strategy. After each stroke an in-feed amount and a work angle set-over is applied in order to generate L-shaped chips (Fig. 9, left); L-shaped chips reduce the wear on the cutting blades.

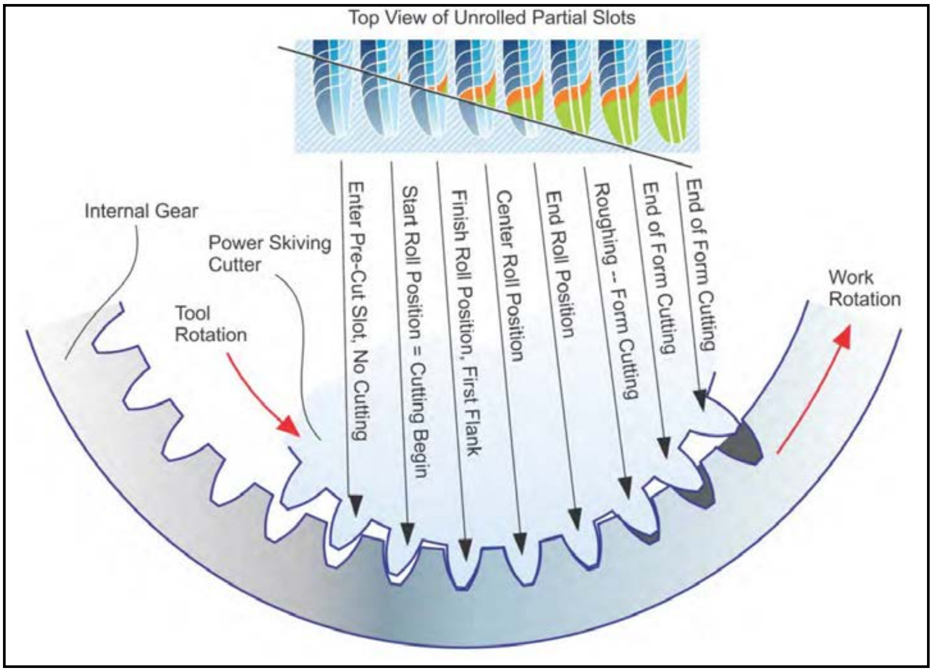


Figure 6 **Cutting sequence from engagement to exit.**

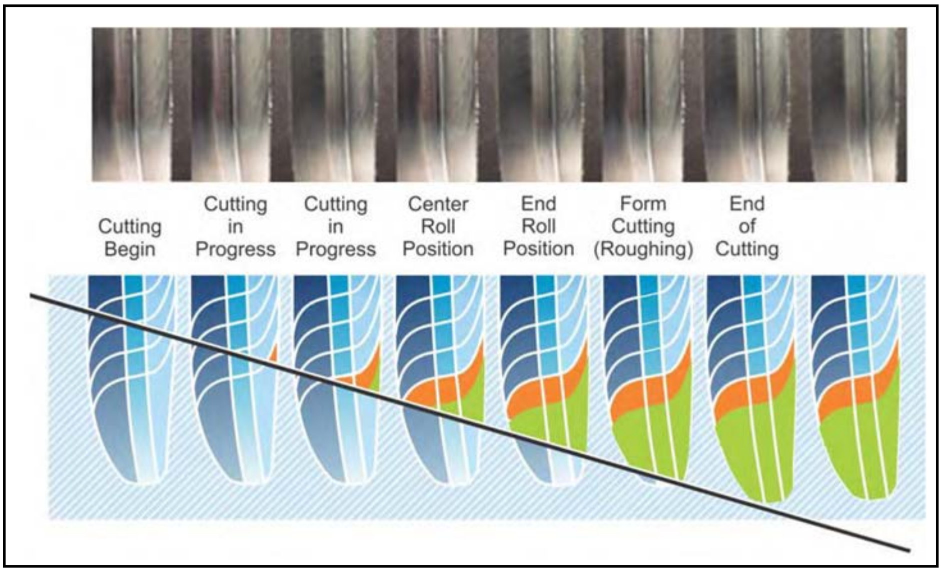


Figure 7 **Top view of unrolled partial real slots (top) and graphics (bottom).**

It is possible to alternate the in-feed work angle set-over direction from part to part in order to achieve even tool wear. Another possibility is to apply a positive side rake (e.g., 2°) to the left side of the blade (Fig. 8) that will enhance the cutting action on this side and generate L-shaped chips. If the resulting feed direction (Fig. 8) is not exactly parallel to the right flank, but about 3° "steeper," then a perfect clean-up of the right flank is guaranteed and the surface finish of the right flank will be equal or slightly better than the finish on the left flank.

HSS Cutters for Power Skiving and Surface Speed Calculation

Traditionally, power skiving is performed with common shaper cutters. However, a variety of different tools used for power skiving is shown; the first cutter (Fig. 10, left) is a shaft type that is slightly tapered without helix angle in the cutting teeth. This cutter can be used for gears with a helix angle. The shaft angle between cutter and work will be set to the helix angle of the work. This also means that the helix angle of the work should be above 10° in order to generate sufficient cutting speed. Due to the straight nature of the cutting teeth, workpieces

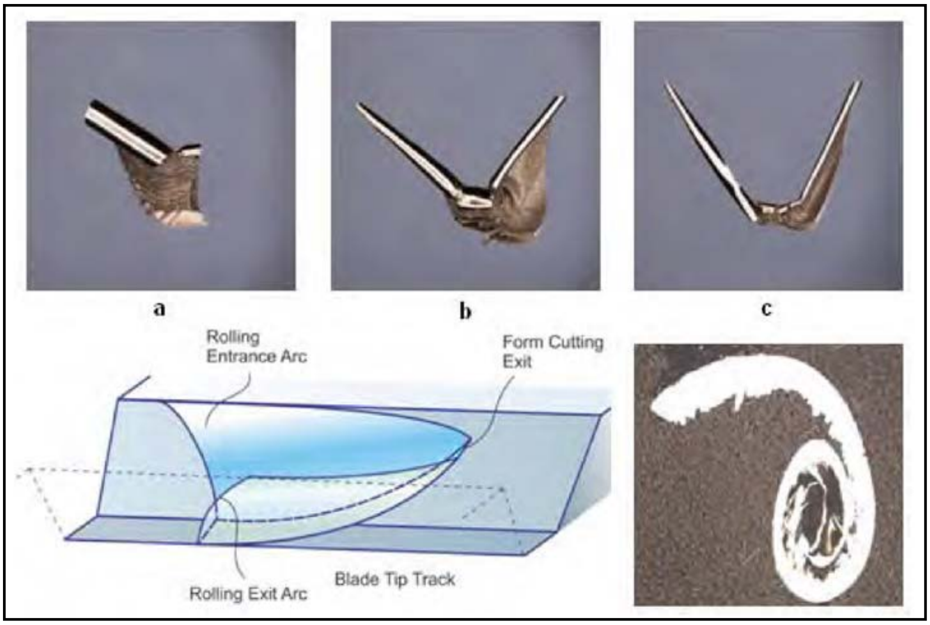


Figure 8 **Analysis of chip formation.**

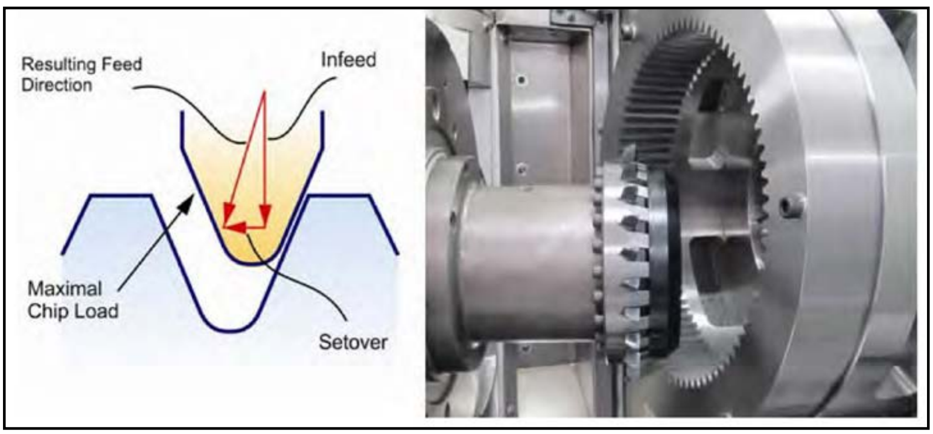


Figure 9 **In-feed strategy for optimized chip formation (Refs. 2, 3).**

Figure 10 **Solid HSS power skiving cutters coated with TiN and AlCroNite.**

with small diameter and large face width might cause interference between the slot and the far end of the cutting blade. The skiving cutter in the center (Fig. 10) is a wafer cutter with only a few re-sharpenings. The cutting teeth are straight, which makes this cutter only suitable for workpieces with a helix angle. The wafer cutter has very short, relieved teeth, which will prevent interference problems in case of helical slots that wind around a small-diameter workpiece.

The skiving cutter on the right (Fig. 10) has serrated blade front faces and teeth that are oriented under a helix angle; the black coatings are AlCroNite and the golden coating is TiN.

If the helix angle of the workpiece is 15° and the tool helix angle is 20°, then the shaft angle between skiving cutter and work has to be set up to 5° (same helix direction). If the helix directions are opposite, then a shaft angle of 35° must be used. An interesting situation presents itself if the gear helix angle of the work is identical to the cutter helix angle (same amount and same hand). In this case the shaft angle between cutter and work is zero, and no skiving motion is generated. The calculation of the cutting surface speed, depending on the helix angle β of the work and the shaft angle Σ, is shown (Fig. 11). The upper graphic represents the unrolled pitch cylinder with teeth and slots indicated (see also Fig. 11, right side graphic) for a spur gear. With $\beta = 0$, the formula is simplified to the first special case. The lower graphic shows the formula simplification for the second special case, which occurs if the helix angle β is equal to shaft angle Σ. The cutting velocity formula also considers — next to the circumferential velocity at the work gear pitch diameter — the helix angle β of the work and the shaft angle Σ between work and skiving cutter. The cutting velocity vector is automatically directed in the flank lead direction if the formula (Fig. 11) is applied. Although the formula indicates some interplay between Σ and β, the major parameter for generation of sufficient cutting velocity is the shaft angle Σ between the work and tool axes.

High-Speed Carbide Cutter Head System for Power Skiving

A new type of cutter head — PentacPS — that uses stick blades has been developed especially for power skiving (Fig. 12). The blade material is carbide and the blade profiles are 3-face-ground and all-around-coated. The blade profile resembles an involute that is derived from the tool reference profile (Fig. 4). The blades can either be ground as full profile blades — just like the profiles of the standard skiving cutters shown in Figure 10 — or as alternating left flank/right flank blades that allow it to realize sufficient side rake angles. This alternate blade arrangement offers very good tool life and an exceptionally smooth cutting operation. However, the productivity is slightly lower than using full-profile blades.

Due to the design of the PentacPS cutter head, the blades have spaces between them that are larger than the tooth thickness of the reference profile. PentacPS cutters are selected for a certain module, such that the blades in the cutter head represent every second, third or fourth slot of the reference profile. Regarding low workpiece run-out and high spacing quality, it is required to avoid a common denominator between the theoretical number of skiving cutter teeth and the number of work gear teeth. The same rule applies for solid skiving cutters as well.

In order to establish a new cutter design, a procedure was developed that allows a minimum of cutter head types. For example, external gears with a maximal pitch diameter of 360 mm or internal ring gears with a minimal pitch diameter of 450 mm and above can be skived with a 9-inch peripheral cutter head. The spreadsheet in Figure 13 uses modules from 2 to 7 mm, in 0.5 mm steps, to calculate a pitch diameter and the theoretical number of teeth z_2. The value for z_2 must be rounded up or down in order to receive an integer number. This requires a change in the pitch diameter of the tool. The developed stick blade system allows adjustment of the blade stick out by some small amount to match the required pitch diameter for the number of teeth selected.

However, the 9-inch-size cutter heads only have blade numbers of 15, 17, 19, 21 and 23. In the next columns of the spreadsheet (Fig. 13), all existing inte-

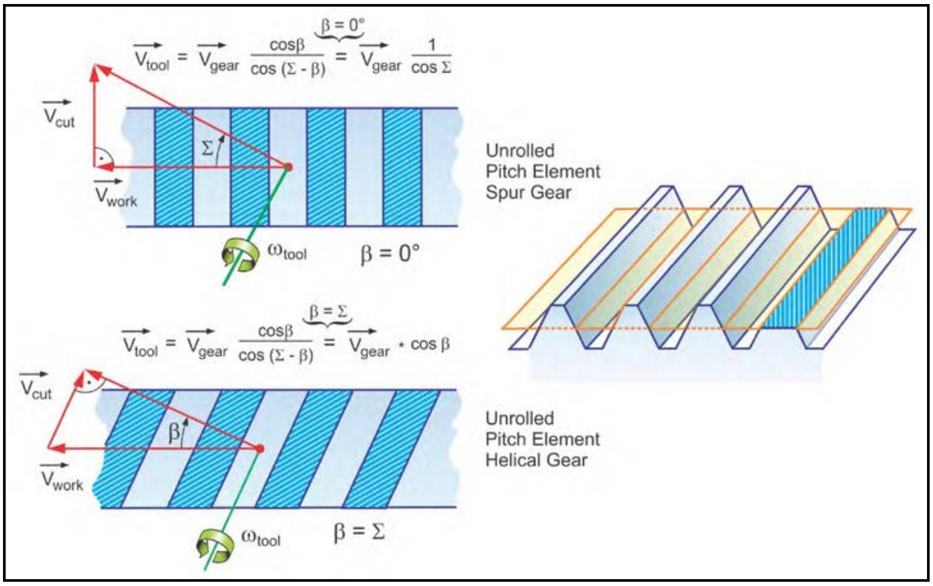


Figure 11 **Cutting velocity calculation.**

Figure 12 **Stick blade cutter PentacPS for power skiving with carbide blades.**

Module	D_{02}	Z_2			D_{02}*	D_{02}*(Selected)	Fraction Generating Gear						Fraction Gear		Cutter Slots
		Calculated	Rounded	Selected			Calculated	Divisors				Selected			
2	223.7433	105.1250	106	105	225.6057	223.4773	105	5	0	3	0	5	1	5	21
			105		223.4773		21						21	105	
2.5	222.6791	83.7000	84	84	223.4773	223.4773	84	0	4	3	2	4	1	4	21
			83		220.8169		21						21	84	
3	221.6149	69.4166	70	69	223.4773	220.2848	69	0	0	3	0	3	1	3	23
			69		220.2848		23						23	69	
3.5	220.5508	59.2143	60	57	223.4773	212.3035	57	0	0	3	0	3	1	3	19
			59		219.7527		19						19	57	
4	219.4866	51.5625	52	51	221.3490	217.0923	51	0	0	3	0	3	1	3	17
			51		217.0923		17						17	51	
4.5	218.4224	45.6111	46	46	220.2848	220.2848	46	0	0	0	2	2	1	2	23
			45		215.4960		23						23	46	
5	217.3582	40.8500	41	42	218.1564	223.4773	42	0	0	3	2	2	1	2	21
			40		212.8356		21						21	42	
5.5	216.2940	36.9545	37	38	216.5602	222.4132	38	0	0	0	2	2	1	2	19
			36		210.7072		19						19	38	
6	215.2299	33.7083	34	34	217.0923	217.0923	34	0	0	0	2	2	1	2	17
			33		210.7072		17						17	34	
6.5	214.1657	30.9615	31	30	214.4318	207.5147	30	5	0	3	2	2	1	2	15
			30		207.5147		15						15	30	
7	213.1015	28.6071	29	30	216.0281	223.4773	30	5	0	3	2	2	1	2	15
			28		208.5788		15						15	30	

Figure 13 Calculation scheme for cutter diameter and number of blades.

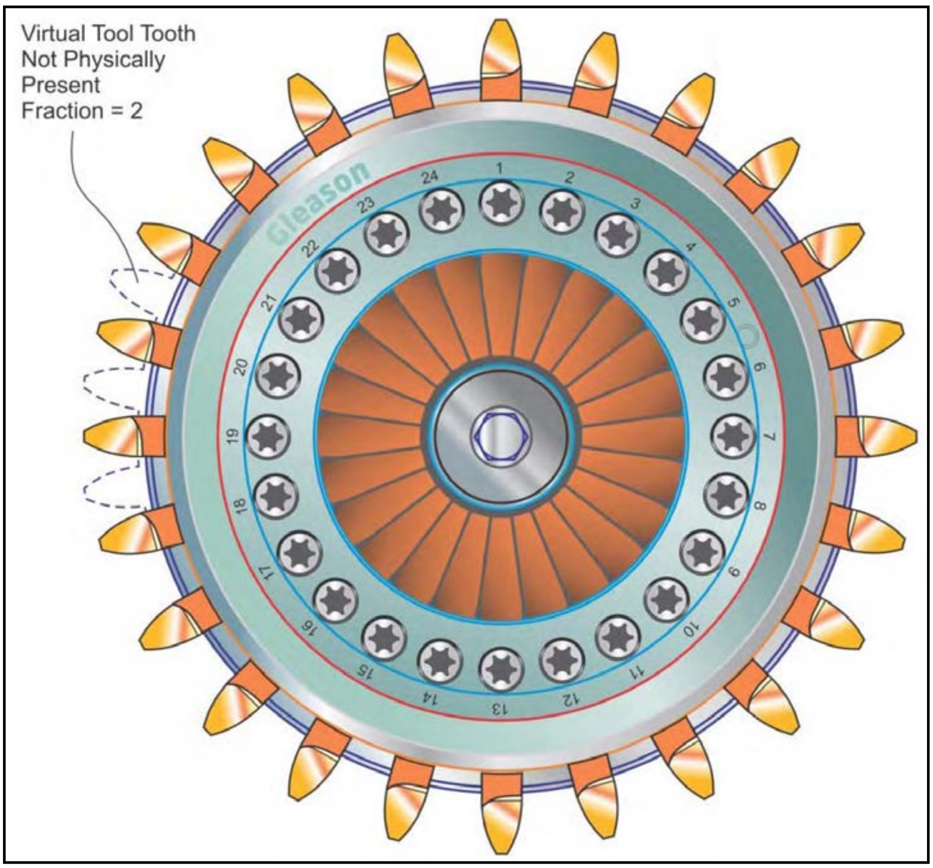


Figure 14 Virtual tool teeth.

ger fractions between two and five are determined. The goal is to find the largest number of slots available in the 9-inch PentacPS line of cutters to assure the maximal productivity. In other words, the PentacPS cutter never represents the theoretical tool tooth number with the number of slots — rather, only a fraction thereof. The theoretical number of tool teeth becomes the virtual tool tooth number of which only a fraction is represented on the cutter head. If a number is selected and typed in the spreadsheet next to the actual fraction of slot and theoretical tooth number, the resulting number of cutter slots is shown in the last column. If this number does not match an existing cutter head, then a second or third number has to be chosen until a matching cutter is found.

Depending on the number of teeth of the work gear, the virtual number of tool teeth may be even, and never is a prime number. This will not be of any disadvantage as long as a hunting-tooth relationship between work and virtual cutter exists. In such cases the hunting-tooth principle exists between work and real cutter. The peripheral stick blade cutter design will physically prevent a fit of the virtual number of blades next to each other. The cutter drawing in Figure 14 represents each other tooth, as indicated with the dashed drawn (virtual) blades between the real blades.

Power Skiving Machines and Software

During the last years dedicated power skiving machines have been introduced, starting from very small gear sizes (below 100 mm) up to 600 mm gear diameter (Fig. 15, left). A technology software was developed that calculates machine settings from part geometry and chosen tool parameters; the software also determines the chip removal volume, depending on the shaft angle between work and tool. The optimal in-feed strategy utilizing an involute roll simulation also features an interference check by comparing the tool path with the simulated slot surfaces (Ref. 4).

For the convenience of both gear engineer and machine setup personnel, the power skiving technology software resides on the control of the power skiving machine. Coincidentally, during development of the power skiving process, it became apparent to Gleason that there was interest in applying this successful process to bevel gear cutting machines as well. Manufacturers who wanted fuller optimization of their Phoenix bevel cutting machines began utilizing the power skiving process for prototyping or manufacturing of small- and medium-batch sizes as a value-added task for this rather versatile machine. In order to address this interest, Gleason applied the power skiving developments that had been conducted until 2012 — and strictly on dedicated machines — to all current Phoenix bevel gear cutting machines (Fig. 15, right); Figure 15 shows a power skiving setup in a Phoenix 600HC.

Along with this significant step, the Gleason power skiving development team was expanded from only cylindrical gear experts to a mix of cylindrical and bevel gear experts. The experience in bevel gear manufacturing using carbide stick blades then led to development of the PentacPS peripheral skiving cutter system, which in turn was applied to the dedicated power skiving machines as well.

As for power skiving, the Gleason bevel gear cutting machines use the same software as used on the PS machines. Summary development, cycle optimization, and corrections are conducted on the machine — not on a remote desktop — as is common in bevel and hypoid gear manufacturing. Figure 16 shows the main screens for gear data, process parameter and workholding entry.

The power skiving technology software can also be used as a standalone package on the gear engineer's desktop. This allows the gear engineer to conduct experiments and pre-optimizations of future gear designs that will be soft-machined by power skiving. The desktop software version is also more suitable for the stick blade geometry calculation. This calculation delivers a blade-grinding summary following the same standards used for bevel gear cutting blades. The blade-grinding machine accepts those summaries like summaries for regular bevel gear cutting blades.

The technology software for power skiving on Phoenix machines allows the input of tooth thickness, depth and helix angle corrections. Tooth thickness and

Figure 15 **Different machines with power skiving setup.**

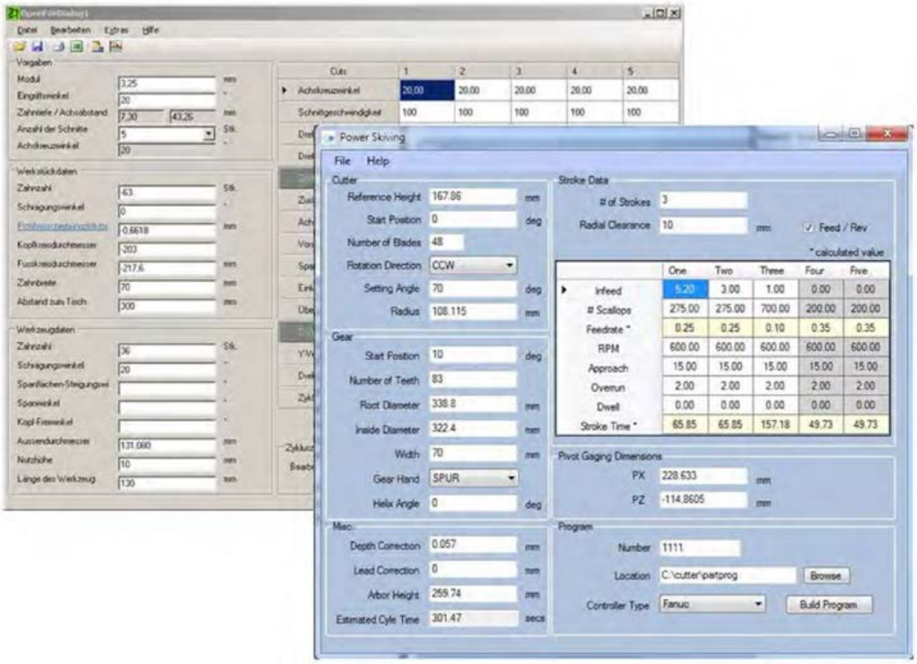


Figure 16 **Technology software process input screens (Ref. 4).**

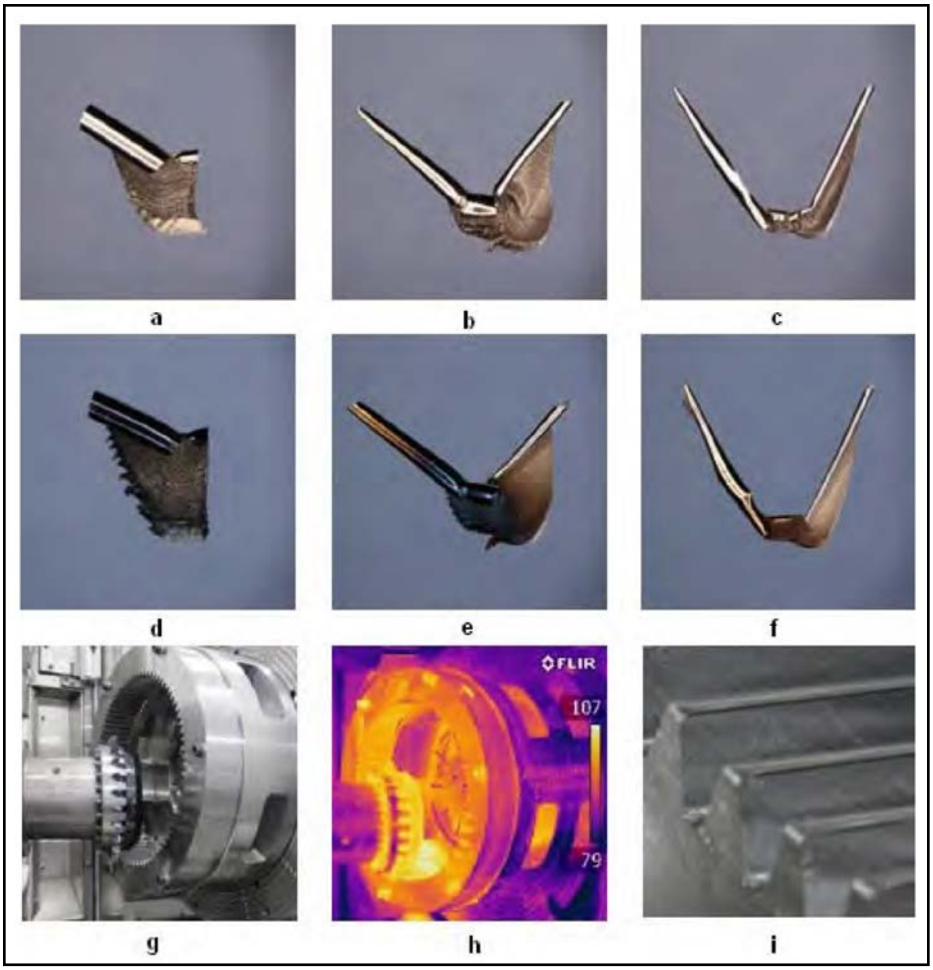


Figure 17 **Chips from wet/dry skiving and process temperature.**

depth are coupled corrections that follow a certain strategy. The correct tooth thickness has the higher priority than the depth. In order to achieve the correct thickness, the slots can be cut deeper within the limit the gear engineer allows. It is not recommended to cut the slots shallow because of implications like roll interferences in the operation of the gearset. If the correct slot width cannot be achieved within the given possibilities, then the blades have to be corrected; or, in case of an undersized slot, a side cutting in a second pass is possible, although it adds unwanted cutting time. If both flanks have similar, small unidirectional pressure angle errors (same sign), then a correction via the cutter tilt angle (Fig. 1) is possible; larger pressure angle errors with inverse signs must be executed by grinding corrected blades.

Wet or Dry Power Skiving?

A solid cutter from G50 (Rex76) material with an AlCroNite coating is suitable for a surface speed of 100 m/min in a wet skiving environment. Carbide stick blades (H10F) with an ALCRONA-Pro coating allow about 300 m/min surface speed. However, regarding tool wear it has to be considered that in skiving very high rpms are required in order to achieve the desired surface speed. This in turn creates a profile sliding which is superimposed to the cutting speed. The profile sliding might have its highest value at the blade tip, which has already a long chip removing engagement path and experiences due to the sliding and additional side relief wear.

Cutting trials in Power Skiving have shown it is possible to reduce the surface speed down to numbers between 150 and 200 m/min (Under-Critical Speed, UCS) and increase the in-feed and feed rate in order to keep the productivity high, and at the same time achieve a significant improvement in tool life.

Chips from wet UCS skiving with Alcrona-Pro coated carbide blades and 172 m/min surface speed are shown in the top row of Figure 17. The first roughing pass used an in-feed setting of 5 mm and a feed rate of 0.045 mm per blade. The chips (Figure 17a) are large and only slightly curved. Each chip represents one flank and part of the slot bottom. The second pass used an in-feed setting of 3 mm and a feed rate of 0.28 mm per blade. This chip consists of the two flank chips connected by the bottom chip (Figure 17b). The finishing pass used an in-feed of 1.00 mm and a feed rate of 0.015 mm per blade, and this chip has the two flank and the bottom chip connected to a U-shaped appearance.

Chips d through f in Figure 17 have been created also with Alcrona-Pro coated carbide blades and 172 m/min surface speed in a three-pass dry cutting process using the same in-feed values and feed rates as applied in the wet cutting (Figure 17 a through c). The dry chips seem to have the same appearance as the chips from wet cutting except for the brown and blue color from the process heat.

The comparison between the wet and dry versions of power skiving with coated carbide blades shows a clear advantage of the dry process. The process heat helps to plastically deform the chip during the shearing action. If the process parameters and tool geometry are chosen to move the process heat into the chips and with the chips away from tool and work piece, then a cool skiving process is the result. Dry power skiving delivers a better surface finish and causes equal or even lesser tool wear than the "wet" process version. However, the chip surface on the side adjacent to the sheared off side is smoother, and the machine power reading showed about 15 percent lower spindle power during dry skiving. The current skiving developments indicate the dry process version will deliver the better tool life, which is expected to be more significant than in bevel gear cutting.

Dry high-speed UCS power skiving with coated carbide blades result in the optimal combination between low tool wear and low skiving times. The additional advantage is, that machines with medium-speed, high-torque spindles (e.g., 1,000 rpm max for machine size 600 mm OD) can be applied without compromising the performance of the machine e.g. for bevel gears which require low rpm and high torque. This argument is important if a manufacturer applies power skiving to bevel gear cutting machines.

The bottom row in Figure 17 shows a dry UCS setup "g," and it shows a thermographic photo taken during the roughing pass at mid-face. The highest temperatures of 107°F (42°C) occur around the cutter and at the work gear sections, which move away from the cut. These temperatures can also be measured on part and cutter after the cycle. It can be concluded that the dry UCS process has an optimal heat transfer into the chips and quickly reaches a rather low and steady-state temperature of cutter and work holding.

A productivity comparison between the traditional processes hobbing and shaping with three variations of the new power skiving process is shown (Fig. 18). The goal of this chart is to compare the preferred embodiment of the different processes. In order to establish the same basis for each process, an external ring gear with the gear data shown in the diagram was used for all processes. The objective was a finishing quality with scallop or generating flat amplitudes at or below 5 μm. The shaping process used an AlCroNite-coated shaper cutter from G50 material with 34 teeth and it was set up as a 3-cut finishing cycle. The identical shaper cutter was used for the wet power skiving where the cutting was done in four passes. For the hobbing process, a one-start hob with 16 gashes, also from AlCroNite-coated G50 material, was utilized in a 2-cut cycle. Dry power skiving with ALCRONA-Pro-coated H10F carbide blades is represented in the diagram as UCS-skiving with 172 m/min and as high-speed skiving with 300 m/min — both set up as a three-pass cycle. The dry power skiving bars are based on a 24-blade and 9" diameter PentacPS cutter head. The chip thickness in the case of UCS-skiving is 10 percent-to-20-percent higher than in the case of high-speed skiving, which reduces the productivity difference between the two process variations, yet gives the UCS-skiving a tool life advantage. Figure 18 indicates that power skiving has between 6-to-12 times the productivity of shaping and between 1.6 and 3.3 times the productivity of hobbing.

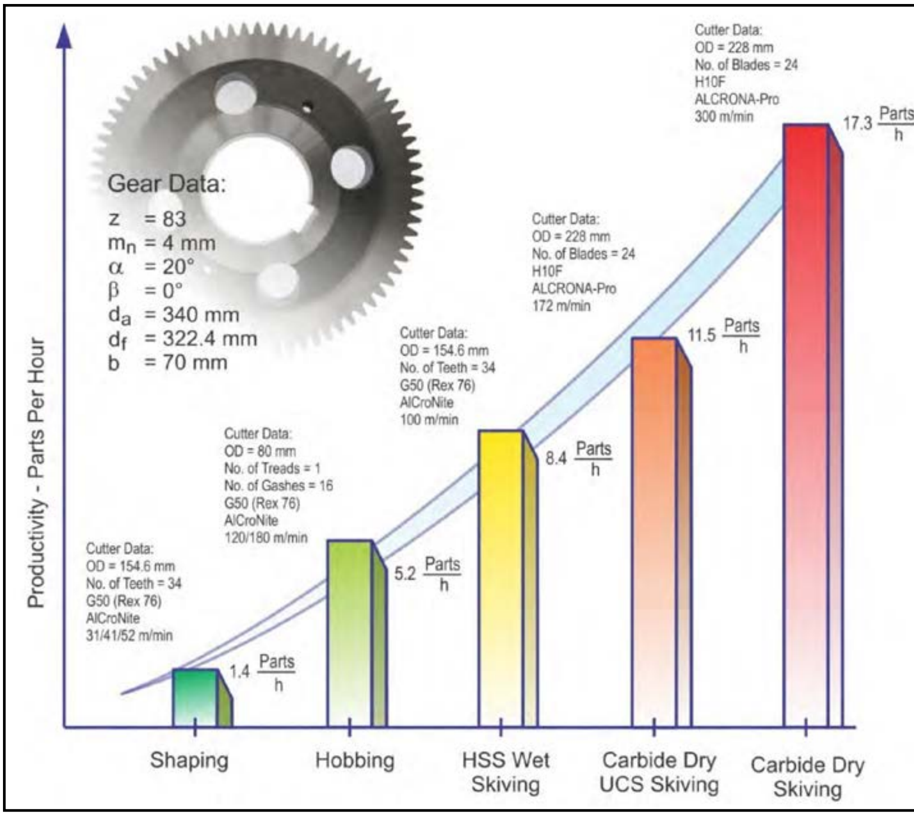


Figure 18 **Productivity comparison.**

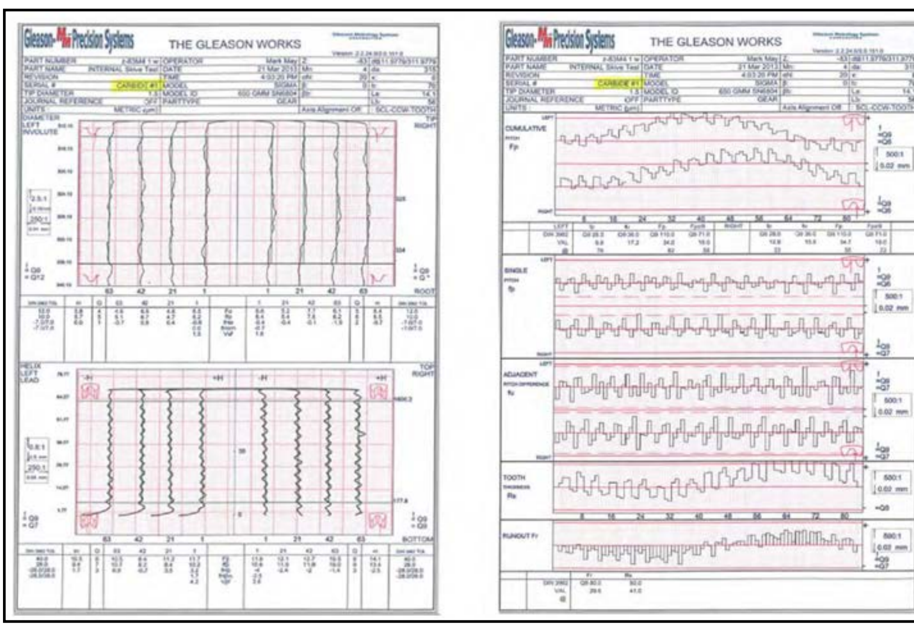


Figure 19 **Measurement: profile, lead and spacing.**

Measurement Results

This section discusses measurement results from the newly developed UCS power skiving with Pentac PS tools. As mentioned earlier in this paper, corrections of the lead angle can be accomplished with machine motions and corrections of tooth thickness and depth are possible within limits using machine settings. Unlimited tooth thickness and depth corrections, as well as pressure angle corrections, are possible by regrinding the stick blades. The measurement results (Fig. 19) show profile (top) and lead (bottom) measurement in the left-side evaluation sheet. The measurement was taken after a pressure angle correction on the skiving blades. The lead direction showed a perfect result after the first sample cutting. The waviness of the

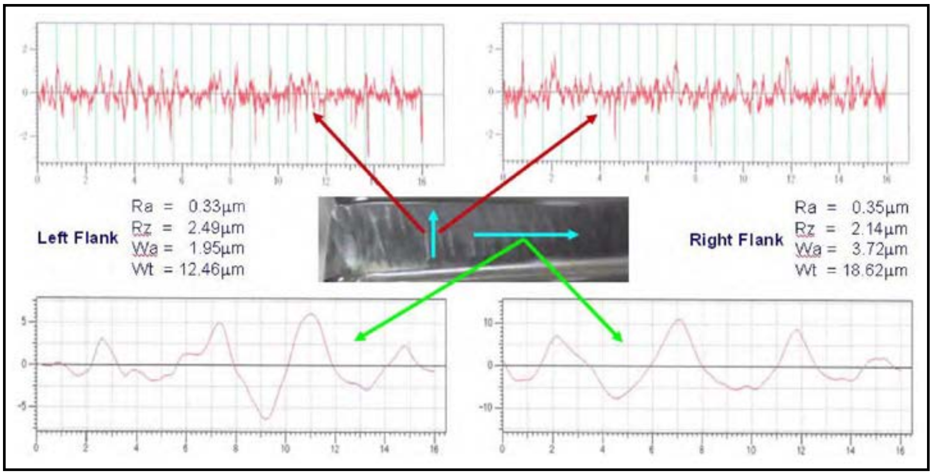


Figure 20 **Measurement: surface roughness and waviness.**

lead graph is typical for power skiving and reflects the skiving scallops; however, their amplitudes are below 5 μm.

Surface roughness and waviness measurement results from a Zeiss surface tracer are shown (Fig. 20). The profile roughness results in the two graphs on top of Figure 20 delivered excellent values for R_a and R_z. The waviness in lead direction is basically the result of the scallop amplitude of 5 μm (theoretically). Due to the different cutting condition on the two flanks, the waviness on the right flank shows about 1.5 times the magnitude of the waviness of the left flank.

The right hand chart (Fig. 19) show good results regarding f_p and f_u, considered the skiving scallops are phase-shifted from tooth to tooth. Cumulative pitch error F_p and run-out F_r reflect the imperfect temporary workholding (Fig. 17g). Improved gear quality can be achieved by using production workholding or individual run-out truing in case of small manufacturing quantities. Single and adjacent tooth spacing numbers can be improved by a lower feed rate, which will reduce the tooth-to-tooth variation due to the "moving" scallops.

Summary

Complex solid skiving cutters lack some flexibility for lower quantities and for larger parts. Next to the solid cutter disks, Gleason developed a second solution that offers a high-speed dry power skiving based on peripheral cutter designs. The new cutter system consists of three different cutter sizes where each size is available with different blade numbers. Depending on the part size, this combination allows coverage of a range between module two to module seven, with five different cutter bodies; and the stick blades can be ground on every modern blade grinding machine.

The power skiving process with stick blade cutters is performed on 6-axis CNC bevel gear cutting machines. Feed and stroke motion are optimized in connection with the particular stick blade geometry in order to create an optimized chip formation. All parameters for feed and stroke are calculated in advance in order to assure high cutting performance, even tool wear and high tool life.

Lead correction, pressure angle balance and anti-twist correction can be achieved via delta value input directly from the K- and lead-chart into the technology software screen on the skiving machine. Although the perception in the market is that power skiving seems to compete only with shaping, and is particularly suitable only for internal gears, it can also be applied to external gears and is also equal — and perhaps faster — than hobbing.

In the case of a power skiving process performed next to bevel gear cutting on a Phoenix 6-axis machine, the conflict of compromising the machine's ability for bevel gear power cutting with a high-speed spindle, which suits the high-speed dry power skiving, was solved with the development of under-critical-speed (UCS) skiving. Power skiving with UCS only requires 150 to 200 m/min effective surface speed, is highly productive, and has excellent tool life.

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