The Two-Sided-Ground Bevel Cutting Tool

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Introduction

In the past, the blades of universal face hobbing cutters had to be resharpened on three faces. Those three faces formed the active part of the blade. In face hobbing, the effective cutting direction changes dramatically with respect to the shank of the blade. Depending on the individual ratio, it was found that optimal conditions for the chip removal action (side rake, side relief and hook angle) could just be established by adjusting all major parameters independently. This, in turn, results automatically in the need for the grinding or resharpening of the front face and the two relief surfaces in order to control side rake, hook angle and the relief angles of the cutting and clearance side. Figure 1 explains the nomenclature of the process-relevant angles on a cutting blade for a face cutter head. The effective hook angle was also manipulated to control the bias condition of the tooth contact, which seemed to make it impossible to avoid front face grinding, since the front face differs from one job to the next.

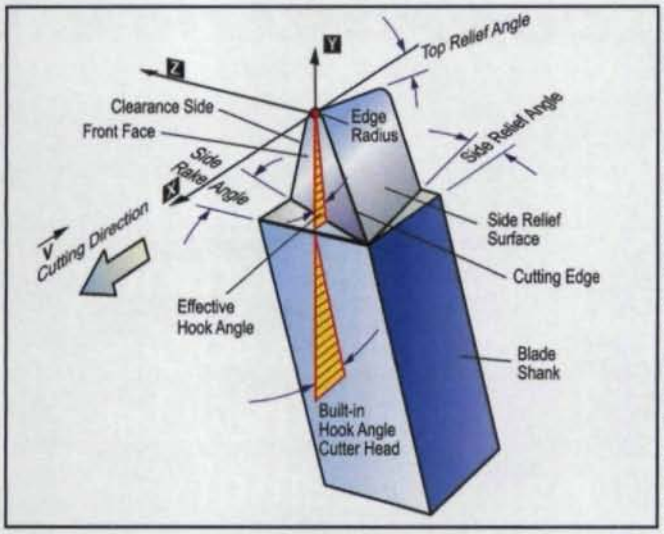

Figure 1—Process-relevant angles on a bevel gear cutting blade.

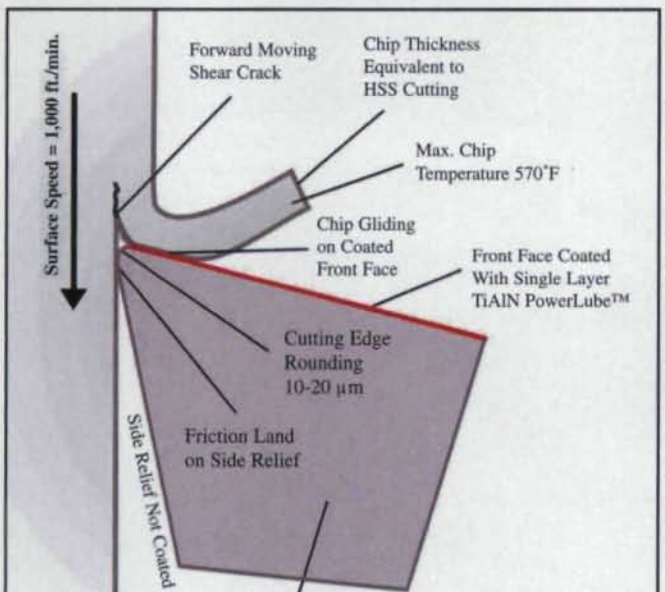

Figure 2—Chip forming mechanisms and specifications.

The face hobbing cutter head has the following design specifications:

- Slot radius
- Slot offset
- Number of blade groups
- Blade spacing
- Built-in hook angle
- Cutter height

At the time, it seemed to be impossible to replace the bias control using hook angle changes by other geometric alterations in blade or cutter head. Gleason Corp. found that a cutter head offset that allows for a permanent front face along the blade shank could be chosen. This would accommodate a wide range of different gear set designs with small deviations from the theoretically optimal side rake angle. This relationship, together with an additional idea that also controls the bias condition, will be explained in the following sections and is the key for the two-sided sharpened cutting tool.

Three-sided sharpening not only introduces higher tool cost per manufactured part, it also prevents the application of a permanent coating on any of the active blade surfaces. The front face is the most exposed to friction, pressure and the heat resulting from the chip removal action. Therefore, a coating of blade front faces with a protective layer enhances tool life and allowable cutting speeds significantly. Coating of the side relief surfaces could also be considered, but shows far less improvement in the performance of the cutting process. In cases of carbide blades applied for high-speed bevel gear cutting, it was imperative to use coatings on the front face for protection of the carbide grid from deterioration. The mechanical effect of the friction as well as the temperature generated by it is isolated from the carbide by the protective layer. The coating reduces friction and has a high temperature resistance compared to the raw carbide material. Figure 2 schematically shows the chip forming action.

Figure 2 makes clear that the front face of the blade is exposed to compressive stress, friction and temperature. The cutting edge has its highest exposure in the metal removal process during the start of a cut, when it penetrates in the surface and plasticizes the steel, generating the forward moving shear crack that forms the chip. The corner around the cutting edge is partially relieved from the contact to the workpiece material as soon as the shearing of a chip begins. Instead of coating, the cutting edge can be rounded with a 10-micron radius. This reduces wear and chipping. Tool life similar to the case of an all-around coating can be achieved.

The Relationship between Cutting Velocity Direction and Effective Side Rake Angle

In face hobbing, each bevel or hypoid gear set requires a certain blade offset or offset angle. The offset angle δ_W determines the difference between the circumferential cutter velocity and the direction of the effective cutting velocity. The following formula shows all parameters that have an influence in the value of δ_W:

$$\delta_W = \arcsin[\, z_W \cdot m_n / 2R_W \,]$$

where: z_W ... number of blade groups
m_n ... normal module
R_W ... radius, cutter center to calculation point on blade

The formula above shows that changes of the number of blade groups (starts), the module (or pitch) and the cutter radius influence the offset angle. Provided that the number of starts as well as the cutter radius cannot change in one given cutter design, the module or the size of the teeth to cut will have the only influence in δ_W. To establish a new cutter design, the average tooth size expected for that cutter is used to calculate the value of m_n, which leads to a number for δ_W. The relationship between tooth size and normal module is:

$$m_n = \text{circular pitch}/\pi$$

The conclusion of the formula relations above is an increased δ_W for a coarse-pitch job and a decreased δ_W for a fine-pitch job, where the average job that was used to design the face hobbing cutter requires exactly the nominal value of δ_W. Figure 3 gives an example.

Job #1 requires an offset 1, derived from δ_{W1}. Figure 3 also shows that the inclination between the cutter speed vector (circumferential velocity) and the relative cutting velocity (effective cutting velocity) is labeled δ_W. If a cutter head is designed according to the parameters of Job #1, then the blade slots have to be machined in the position of the upper blade. For easier explanation, a front face with no side rake angle was chosen; the cutting velocity vector is therefore perpendicular to the blade front faces in Figure 1. If a cutter with the same radius and an identical number of starts should be used to cut fine pitch Job #2, then it would be required to machine the blade slots with a much smaller offset 2 of the lower blade in Figure 3 into the cutter body. This would accommodate the smaller inclination

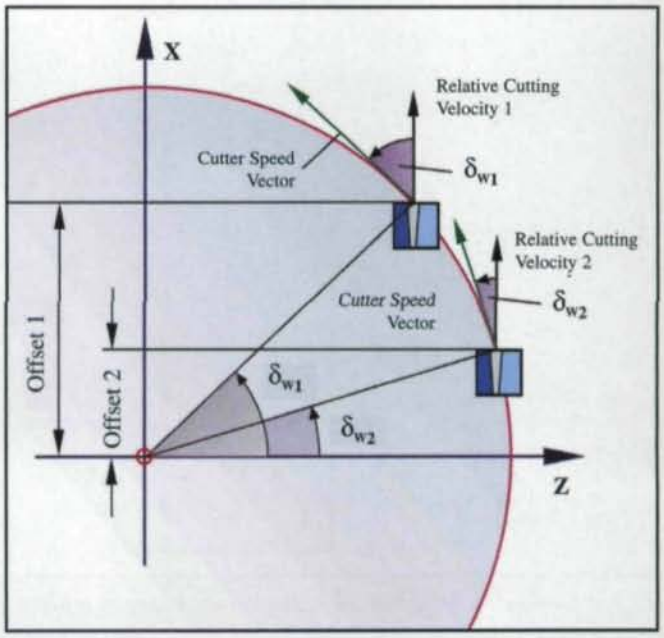

Figure 3—Optimal blade positions for two different-sized jobs using the same cutter radius and an identical number of blade groups.

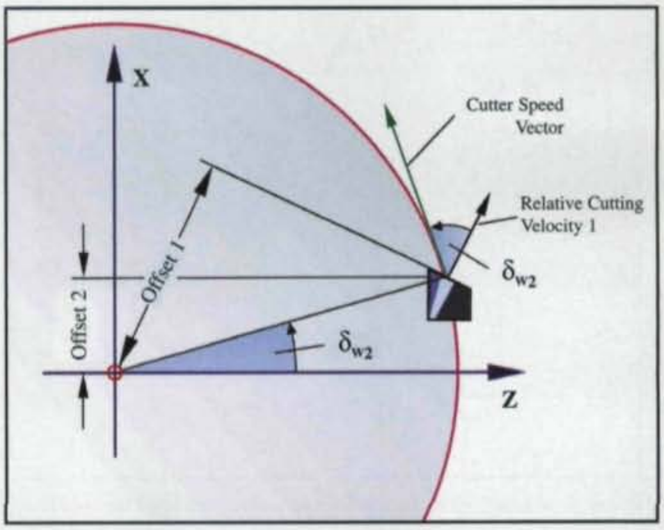

Figure 4—Blade with Offset 2 accommodates offset angle 1 by front face modification.

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started his career as head of engineering research and development at Oerlikon Geartec in Switzerland. From 1992–2002, he worked as vice president of research and development for The Gleason Works of Rochester, NY. Stadtfeld established Bevel Gear Industries (BGI) in Eisenach, Germany, in 2002.

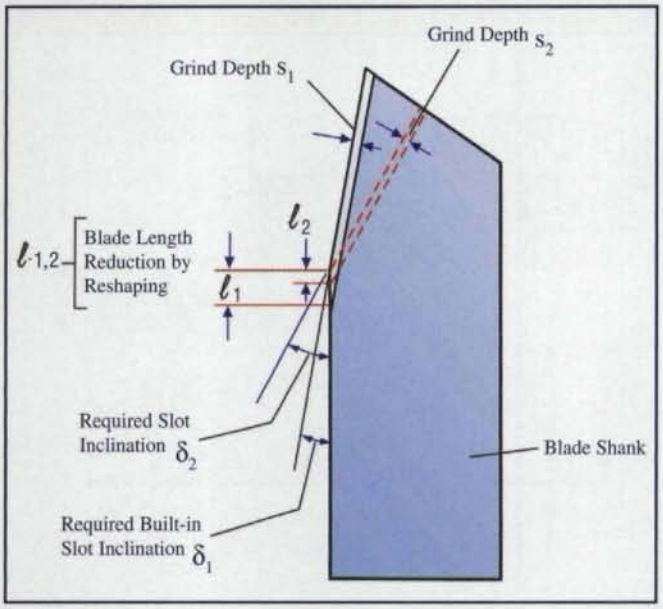

Figure 5—Blade length reduction after resharpening as a function of slot inclination.

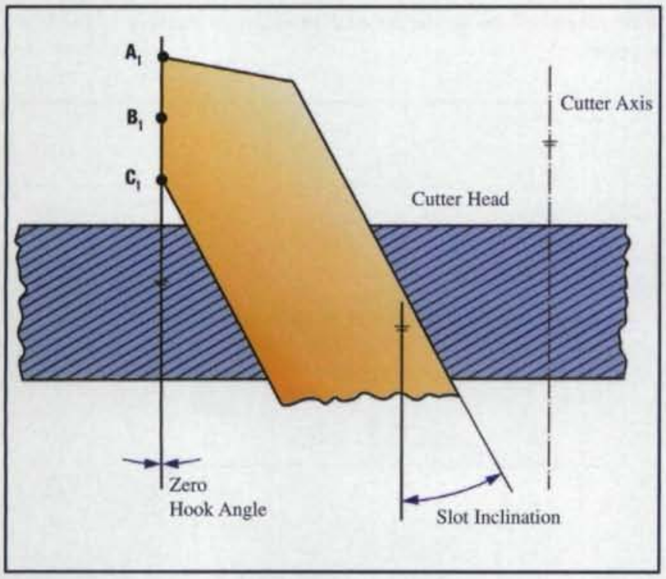

Figure 6—Cutter with slot inclination and zero effective blade hook angle.

between cutter speed vector and cutting velocity 2, δ_{W2}.

If a cutter head with slot offset 2 should be used to cut Job #1, a larger offset angle would be required, which presents a problem. This problem can be solved with a modification of the front face angle (side rake) as shown in Figure 4. The front face inclination in Figure 4 provides a front face orientation perpendicular to cutting velocity 1. The front face manipulation in Figure 3 simulates an offset, different to the built-in offset of the cutter head.

The three-face-ground blades have the freedom to change the front face orientation in a wide range and therefore realize correct front face orientation for a broad spectrum of pitch variation. But do the jobs that cut with one specific cutter size in fact vary from pitch significantly?

Relationship between Cutter Slot Inclination and Effective Hook Angle

All surfaces on a cutting blade need to have an inclination to the shank surfaces of more than 10°. Below 10°, the amount of material removal to clean up a worn cutting edge becomes too high. Figure 5 has a comparison of two different cutter slot inclinations. To result in a zero hook angle, the front face must be ground in about the same angle relative to the blade shank as the slot inclination of the cutter. Figure 5 demonstrates how a higher slot inclination allows a higher angle between front face and blade shank and leads to a smaller amount of blade length reduction.

Figure 6 shows a blade front face with a zero hook angle (connection of points A_1–B_1–C_1 is co-linear with cutter axis). The blade is held in the cutter slot that shows a significant slot inclination. After resharpening, the blade is moved in the slot against a stop in location A_1. The blade shank gets shorter with each resharpening, but the geometry above the face of the head remains identical throughout the life of the blade stick.

The angle between front face and blade shank is reduced, if a blade has a positive effective hook angle like shown in Figure 7. It is possible to increase the slot inclination in the cutter head within limits. The highest realized slot inclination is 20° in the Oerlikon Spirapid® cutter system (Ref. 1).

In most cases, a zero-effective hook angle is desired for an optimal cutting action. In this case, the relationship between the effective hook angle and the slot inclination of the cutter head is simple. It is only dictated by the requirement of an economical and effective resharpening. The 20° angle in the case of the Oerlikon Spirapid cutter system was a good choice for easy and economical resharpening of the stick blades. The measurement of 20° also left enough room for slight modifications of the effective cutting hook angle, e.g. to accomplish some bias modification of the flank form.

Blade System with Permanent Front Face

The Gleason Works introduced a new stick blade system in the 1970s, which did not require any resharpening or reconditioning of the front face (Ref. 2). Gleason called the cutter and the cutting system Relief Sharpened Roughing (RSR®) and later Relief Sharpened Completing System (RSR-C®). Figure 8 shows a three-dimensional graphic of an RSR-C blade with permanent front face. If resharpening of the blade front face is not required, then the rules for defining the cutter geometry are quite different. Since the effective hook angle now depends only on the pressure angle of the blade and the slot inclination in the cutter, the cutter slot is calculated in such a manner that the cutting edge with the highest possible pressure angle does not show a negative hook angle, when assembled in the cutter.

The blade in Figure 9 shows a constant cross section and was the next developmental step that converted the friction seating of the blades in the cutter in a positive form seating condition. Those blades are called PENTAC® because of their pentagon-shaped cross section (Ref. 3).

The variations of the hook angles from job to job caused by different blade pressure angles have only a very small geometrical influence on the generated flank surface in the single index face milling process. Those first order influences are compensated by a pressure angle correction.

To use the permanent-front-face blade system for the continuous face hobbing method causes two additional problems (Ref. 4). The effective side rake angle (first problem) might vary from job to job (discussed in Figures 3 and 4) caused by the different offset angles δ_W. The side rake problem can be solved with the blade in Figure 8 by defining a cutter slot offset that is exactly in the center of all jobs expected for the particular cutter. This means that a study of the different jobs cut with previous systems can tell very accurately what the average offset angle δ_W for a new cutter system should be and what the maximally accruing side rake deviations for the extreme jobs are. It is therefore possible to find an optimal slot position for each designed cutter with less than 2° variation of the effective side rake angle.

The second problem is the influence of the effective hook of the cutting edge on the generated flank surface. This influence is a flank twisting (bias effect). A flank twisting changes the direction of the path of contact and therefore causes a different orientation of the contact pattern, but also influences the motion graph amplitude significantly. In case of the three-sided-ground blades, it was possible to control the hook angle of the cutting edge such that it is always zero (or a predetermined desired angle). The following sections will explain the flank deviation effect by hook angle change analytically and present an interesting mathematical solution for this problem.

Analysis of the Geometric Effects to the Flank Form by Controlling the Front Face Orientation

The publications of Kotthaus (Refs. 1 and 5) teach that to maintain a sufficient side rake angle, especially to control the flank surface twist, the front face has to be variable in two angular directions, the side rake angle and the hook angle. The effective hook angle is the inclination around the normal cutter radius (Figure 10) between the cutting edge and the cutter head axis (Figure 7). The blade in Figure 7 is oriented such that the relative cutting velocity vector lies in the presentation plane. The effective hook angle is a function of the front face orientation with respect to the blade shank, as well as the angle of the blade slot in the cutter head (built-in hook angle) and the pressure angle of the cutting edge.

A change of the blade pressure angle has a direct influence onto the pressure angle of the manufactured tooth flank. A change of the hook angle in a face hobbing cutter blade caus-

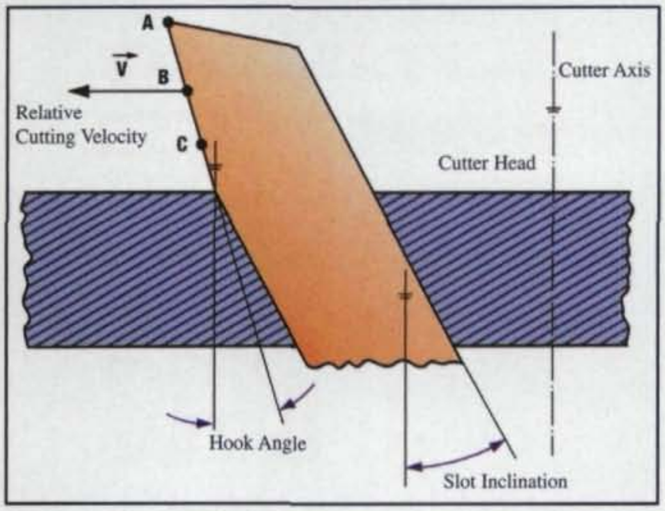

Figure 7—Cutter with slot inclination and positive effective blade hook angle.

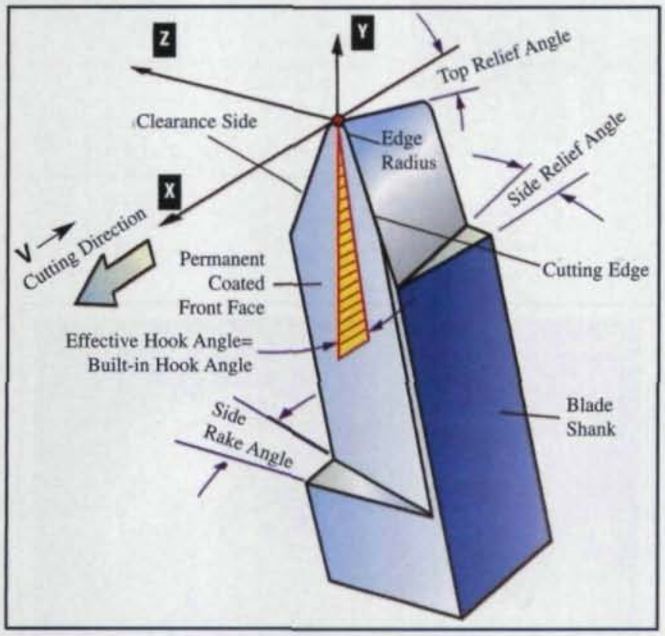

Figure 8—RSR-C stick blade with permanent front face and rectangular cross section.

es a flank twist and a change in profile crowning and pressure angle.

Figure 10 shows a blade with the Points *A*, *B* and *C* along a cutting edge that has a positive hook angle. The figure also shows a cutting edge without any hook angle (Points A_1, B_1 and C_1). The epicyclical path generated by *A* is different than the one generated by A_1. The curve associated with A_1 has a similar, but not identical, shape to the one generated by *A*. The two curves are inclined and shifted relative to each other in z-direction. That means the spiral angle of curve *A* decreases relative to A_1. The opposite happens for curve *B* relative to B_1.

The conclusion of the last paragraph is that the hook angle causes a positive flank twist between heel and toe. This, together with the already mentioned change in profile, represents crowning as a rather complex flank form modification.

The blade systems that allow a change of the hook angle use this freedom for flank form and contact movement (adjustability) optimizations. Studying the literature shows that the inventor of those systems found it physically impossible to allow the same optimizations by avoiding the individually controlled front face. All attempts during the past 30 years to develop a permanent front face cutter system with the same freedoms of the one with front-face-ground blades failed.

New SPIROFORM™ Cutter and Blade System

An interesting technical challenge was the attempt to develop a cutter and blade system that allows all the freedoms of the three-face-sharpened blade, yet using a blade that is shaped and sharpened on the two side relief surfaces only.

Finally, a discovery was made that relates the epicycloids, generated by different hook and side rake angles. The idea is to find the radial location of one point along the cutting edge of a given blade that lies on the same epicycloid, generated by a blade with different hook and side rake angle. It is assumed that the given blade consists of a permanent front face, no hook angle and a side rake that is constant along the shank. The hook angle of this system is created by an inclination of the slot in the cutter head.

Figure 11 shows the two different blade types with the roll circle-base circle kinematic "attached" to the front-face-sharpened blade.

The Points *B* and B_1 of the two blade types are identical (Figure 10). The problem to solve is to find the locations of the Points A_1 and C_1, along the existing front face of the simplified blade. The geographic height of the blade, with respect to the cutter head front face, remains constant.

To find the location of Point A_1, the epicyclical kinematics with roll circle and base circle are rotated clockwise until *A* contacts the front face of the new blade. This is the location of A_1. The movement from *A* to A_1 requires a rotation around the roll circle center, superimposed by a rotation around the center of the base circle. The relationships for the solution of this problem are shown in Figure 6 and expressed by the following formulas:

$$E_{X0x} + R_{B0x} = E_{X3x} + R_{B3x} \qquad (1)$$

or:

$$S \cdot \sin(-\Phi_0 - j + \delta_w) + R_{B0} \cdot \sin(\delta_w) = S \cdot \sin(-\Phi_0 - j + \delta_w + \varphi_w) + R_B \cdot \sin(\delta_w + \varphi_{Hook} + \varphi_c) \qquad (2)$$

where:

$R_{b0x}\cdots$ x-Component of Cutter Radius Vector (Blade without Hook)

$R_{b3x}\cdots$ x-Component of Cutter Radius Vector (Blade with Hook, rotated into zero Hook Plane)

$E_{X0x}\cdots$ x-Component of Vector from Machine Center to

Cutter Center (Blade without Hook)

E_{X3x}... x-Component of Vector from Machine Center to Cutter Center (Blade with Hook, rotated into zero Hook Plane)

S... Radial Distance (Scalar of E_{X0x})

Φ_0... Cutter Phase Angle

j ... Swivel Angle

δ_w... Offset Angle (Face Hobbing)

R_{B0}... Scalar Cutter Radius (without Hook)

φ_w... Rotation of Cutter Center around Base Circle

R_B... Scalar Cutter Radius (with Hook)

φ_{Hook}... Angle between R_B and R_{B0}

φ_c... Rotation of Blade with Hook Angle around Roll Circle (Cutter Center)

Between φ_w and φ_c is the following relationship:

$$\varphi_w = \varphi_c/(1 + z_{generating\ gear}/z_{cutter}) \qquad (3)$$

where:

$z_{generating\ gear}$... Number of Teeth Generating Gear

z_{cutter} ... Number of Starts Cutter

Wanted is φ_w out of formula (2). The mathematical solution is conducted with an iteration algorithm. The difference between A_1 and A_2 is Δ. Δ is calculated as shown:

$$\Delta = | R_{B3} - R_{B0} | \qquad (4)$$

Δ is the displacement of the normal radius (along z-axis) of point A_2 to come to point A_1 that cuts the same epicycloid as point A. The epicycloid cut by A_1 will differ to some extent from the desired one, cut by A. The shown approach is the physically closest possible approximation, that infinitesimally observed still represents a mathematically precise solution. In practice, it causes differences over the entire flank surface of only a few microns and therefore can be neglected.

The analog scheme is applied to find point C_1 (Figure 7), a rotation of the epicyclical kinematic in counterclockwise direction brings C (Figure 7) to the front face of the new blade.

According to the above shown solution, any desired number of points along the cutting edge with one particular hook angle can be converted into a point on a cutting edge without hook angle or any other chosen hook angle.

Depending on the mathematical function of the new cutting edge (circle, ellipse or higher order), three, five or more points can be transformed from the original to the new cutting edge. Three points, one on the tip, one in the center and one on the end of the cutting edge, deliver a sufficient definition of the cutting edge function to capture the characteristics of the different front face hook angles.

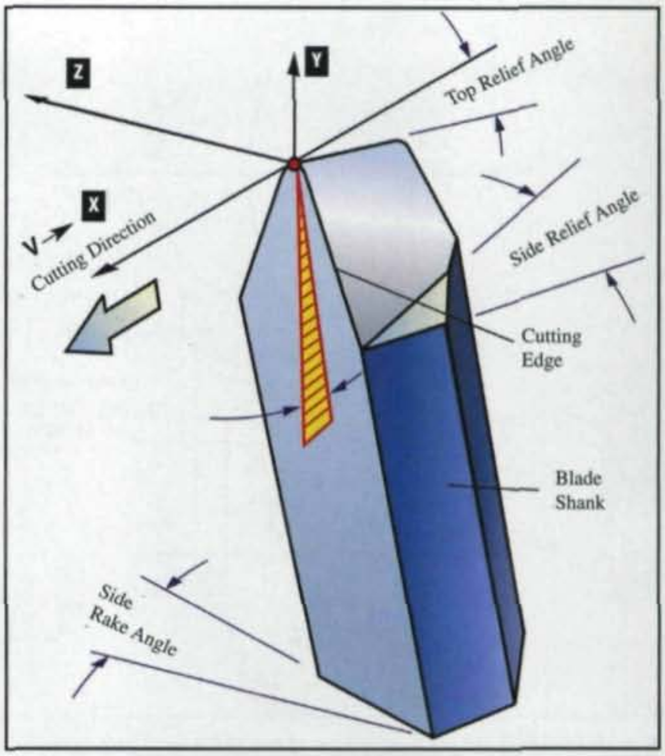

Figure 9—Pentac stick blade with permanent front face and pentagon-shaped cross section.

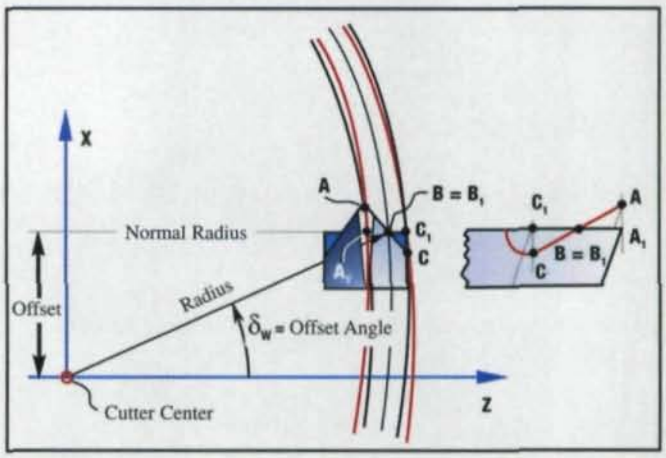

Figure 10—Relationship between hook angle and cycloidal path of different blade points.

The possibility to influence the blade spacing in the cutter head by grinding the front face of either inside or outside blade further back results in a tooth thickness or slot width change. The SPIROFORM blades can account for that feature, too. A tooth thickness adjustment is done by splitting the required amount and, for example, increasing the radius of the outer blade cutting edge and decreasing the cutting edge radius of the inner blade by half the amount each.

Summary

A method was found to convert a side relief and front-face-sharpened blade, held in a face hob cutter head into a blade that has a permanent front face and is profile shaped or re-sharpened

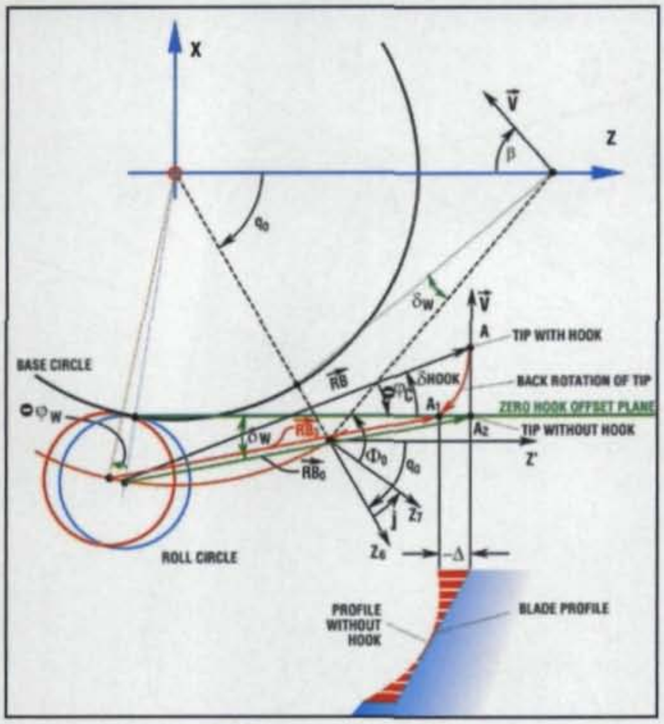

Figure 11—Epicyclical kinematics of two different blade types.

Figure 12—The Spiroform cutter head with a 160 mm radius and 13 starts.

Figure 13—Left side–conventional, right side–cut with Spiroform cutter head.

on the side relief surfaces.

The advantage of replacing the old style three-face-sharpened blade is in particular the permanent character of the front face and its coating. The new carbide high-speed cutting depends to a large extent on the correct front face coating. All gear sets, designed with a system using three-face-sharpened-blades can hardly be manufactured using high speed carbide cutting by replacing the high speed steel blades with carbide blades of the same geometry. To send a set of blades to a coating facility after resharpening requires more expensive carbide blades in storage and includes the cost of up to 100 recoatings of each blade. This procedure increases the tooling cost by a factor of eight.

The new SPIROFORM blades allow conversion of all older "three-face-ground" jobs into a two-face-sharpened blade system with a permanent front face coating. Gear sets do not have to be re-qualified after the conversion since the flank surface geometry stays identical to the original.

Figure 12 shows a photo of a SPIROFORM cutter with 160 mm radius and 13 starts. The SPIROFORM system uses no bottom blades. This provides a very solid and stiff cutter construction. The blades used (TRI-AC® or PENTAC) provide sufficient roughing action on the secondary cutting edges (clearance sides).

Front face coated blades provide good surface finish and improved productivity. The SPIROFORM blades are stepped in their building height, such that the tracks from outside blade and inside blade blend smoothly together in the root fillet.

Figure 13 shows an example of a conventionally cut ring gear. The gear to the right is cut using a SPIROFORM cutter and a Phoenix® free-form machine. Surface finish and root blends are superior for the new cutting system. Cutter heads and blades of the newly developed system are not limited to a certain machine tool brand, but can be applied on CNC bevel gear generators of The Gleason Works, Oerlikon Geartec AG and Modul-SU with no limitations. ❍

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