The New Freedoms: Three- & Four-Face Ground Bevel Gear Cutting Blades

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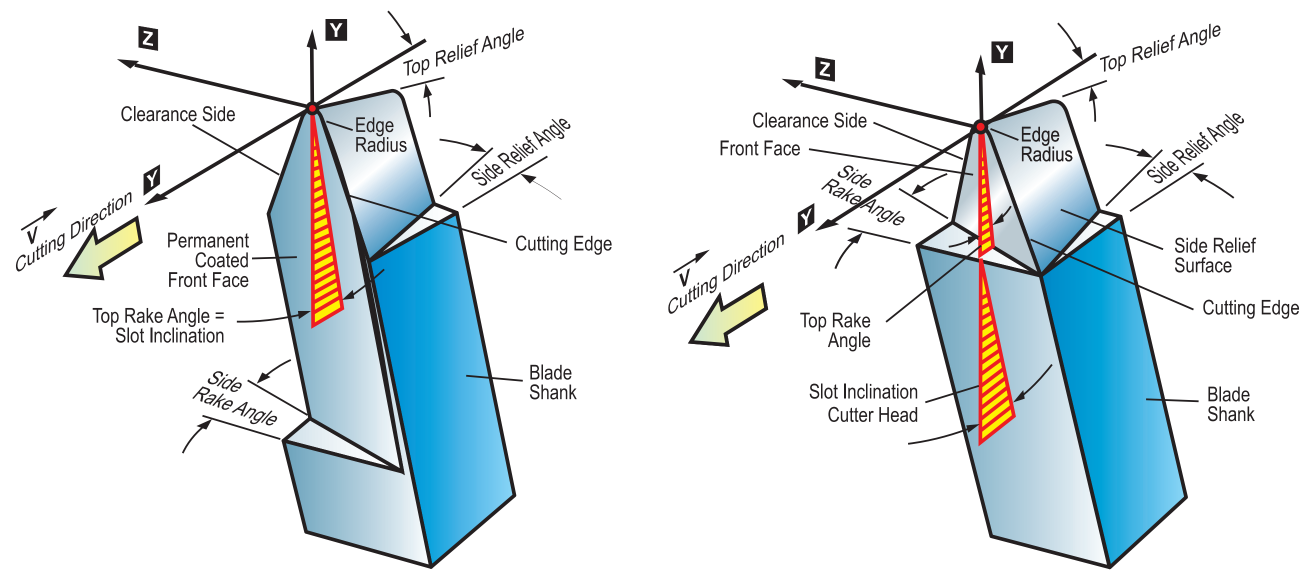

Figure 1—Blade angles and blade nomenclature: left, two-face; right, three-face-ground.

Management Summary

In the 1970s, three-face-sharpened HSS blades were used effectively in bevel and hypoid gear cutting, providing flexibility in blade geometry. When TiN coatings became available, the three-face sharpened blades gave way to two-face sharpened blades with the front face permanently coated. Because of the cost of coating and the turnaround time required, all-around coatings of three-face-sharpened baldes were not economically justifiable—even into the late 1990s when TiAlN coatings and carbide stick blades became the norm.

Today, because of reduced cost of coatings and quicker turnaround times, the idea of all-around coating on three-face-sharpened blades is again economically viable, allowing manufacturers greater freedoms in cutting blade parameters, including three-face-sharpened and even four-face-sharpened blades.

Introduction

Three-face sharpening was used in older face hobbing systems in order to provide the ultimate flexibility in blade geometry, but also to have the freedom to compensate for the discrepancy between the fixed-blade offset in the cutter head and the kinematic offset required for the cutting of individual gear sets (Ref. 1). This system was very successful at the time where uncoated powder metal high-speed steel (HSS) was used and advanced coatings were not available.

When TiN coating, applied to the front face of the blade, showed a significant increase of tool life and surface finish, the two-face sharpened blades with permanent-coated front face became the state-of-the-art cutting tool of choice. For face milling, this did not require a certain cutter head design. For face hobbing, comprehensive studies that included all possible gear set designs were required to find a cutter design offset which was less than 2° different from the extreme values of the kinematic offset within the expected variety of jobs. Only this could guarantee an adequate side rake angle for all real gear designs because of the fixed-blade front face. Other technological angles such as side-and top-relief angle could still be chosen freely since those surfaces were ground during the sharpening operation.

The high cost of coating and the turnaround time between the coating facility and the gear manufacturer did not justify an all-around coating in connection with a three-face sharpening—not even after 1997, when high-speed cutting with TiAlN-coated carbide blades began its success story (Ref. 2). The PowerCutting process used blades with permanent-coated front face, which were two-face-sharpened at the side relief and clearance side surface.

Already in the late 1990s, some manufacturers tried the advantages of all-around coating; however, this was mostly experimental and no advantage was taken of the possibilities the freedoms of flexible front-face design could provide.

Today, modern coatings are readily available at nearby coating facilities. The cost of re-coating, as well as the turn-around time, has become more reasonable. This led to the desire of many manufacturers to take advantage of both the flexible design of all technological blade surfaces and the protection of the cutting edge from the front face to the side relief surface. Figure 1 left, shows a blade with permanent front face and to the right, a three-face-ground blade.

All-around coating could be questionable or even impossible if all three functional blade surfaces of the cutting blade are not ground before re-coating. The grinding provides a mechanical removal of all coating on the functional blade surfaces. A chemical stripping of the coating is required if two-face-ground blades should be re-coated. The chemical stripping can cause cobalt leaching and can only be repeated about six times before a degradation of the carbide grit is noticeable. In view of this conflict, the mechanical stripping by three-face sharpening in combination with the additional freedoms in the blade parameters seems an ideal combination which is beneficial for all gear sets cut in larger quantities.

Traditional Blade Angle Definition

The precise values of the blade angles are today only known relative to the blade shank and relative to the cutter heads where the stick blades are assembled. Figure 2 shows blades assembled in a cutter head under a certain slot inclination. The left blade in Figure 2 has a positive hook angle. This means the cutting edge, observed from the side, perpendicular to the visible side of the blade shank, is inclined counterclockwise. The blade in the center of Figure 2 has a neutral or zero hook angle, where the graphic at the right side in Figure 2 shows a blade with a negative hook angle.

The definition of the side rake angle is analogous to the hook angle definition. Figure 3 shows a graphic with a positive side rake angle in the top portion, a neutral side rake angle in the center and a negative side rake angle at the bottom. The observer looks perpendicular to the face of a cutter head and measures the side rake angle in a plane parallel to the cutter front face (Ref. 3).

The traditional angle designation is a static or geometric definition, which does not consider the relative cutting velocity nor the direction of chip flow. The relative cutting velocity between work and blade and the cutting plane, which has the relative cutting velocity vector as normal vector and includes the calculation point of a blade as surface point, is introduced in Figure 4. The kinematic or effective blade angles can be calculated and expressed in relationship to the cutting plane. Gleason three-face blade grinding summaries include additionally to the traditional angles the effective blade angles.

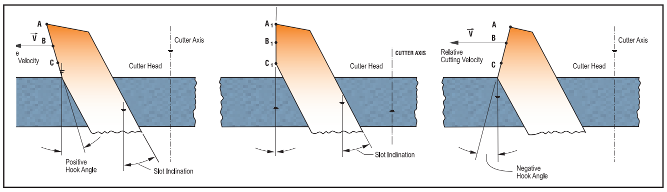

Figure 2—Positive hook angle (left), neutral hook angle (center), negative hook angle (right).

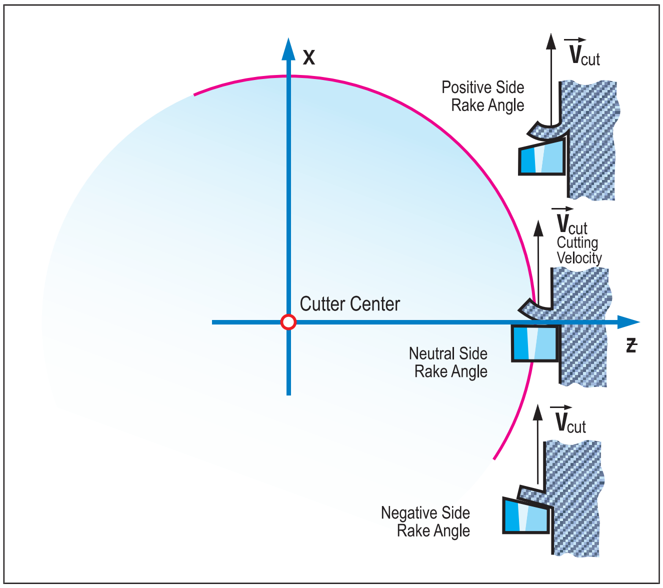

Figure 3—Side rake angles: positive at top, neutral in center, negative at bottom.

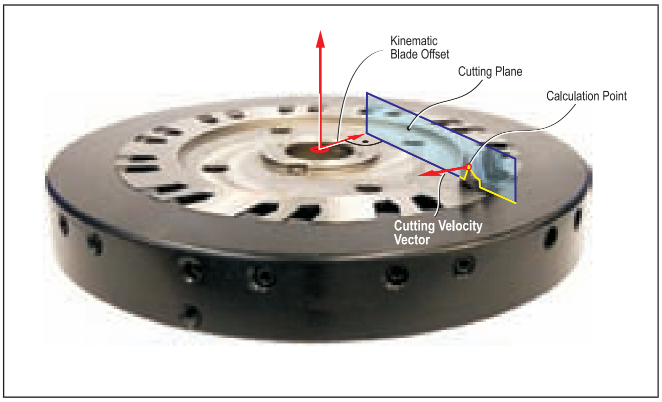

Figure 4—Kinematic blade angle definition using cutting plane.

Blade Geometry Features

In face milling—but more so in face hobbing—the kinematic blade geometry differs from the aforementioned static blade geometry and in most cases is not shown in summaries. In the past, it was not possible to optimize or even change the kinematic angles, sometimes also referred to as dynamic blade angles.

Extensive studies of the cutting action in connection with three-face blade designs have led to important discoveries and are supported in new software tools for the design of

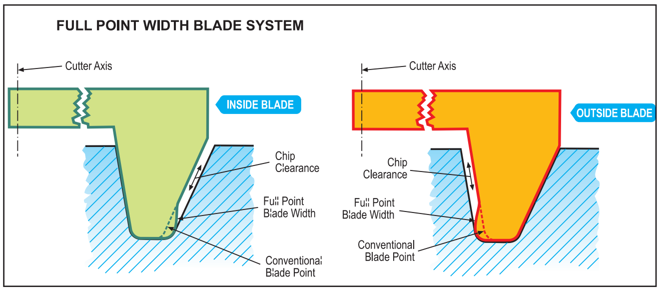

Figure 5—F-point blades use the entire root width.

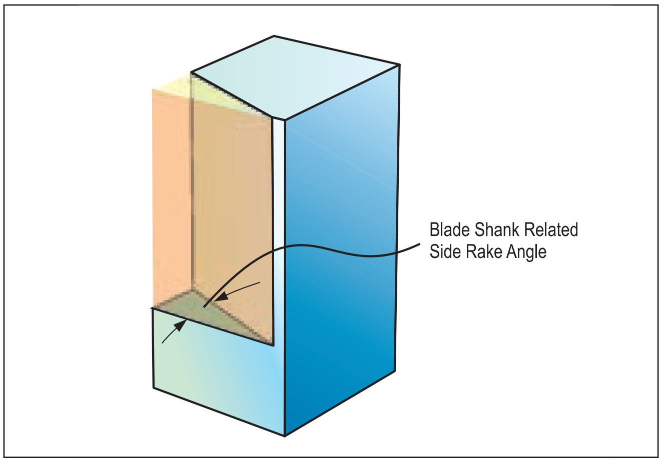

Figure 6—Traditional definition of side rake angle.

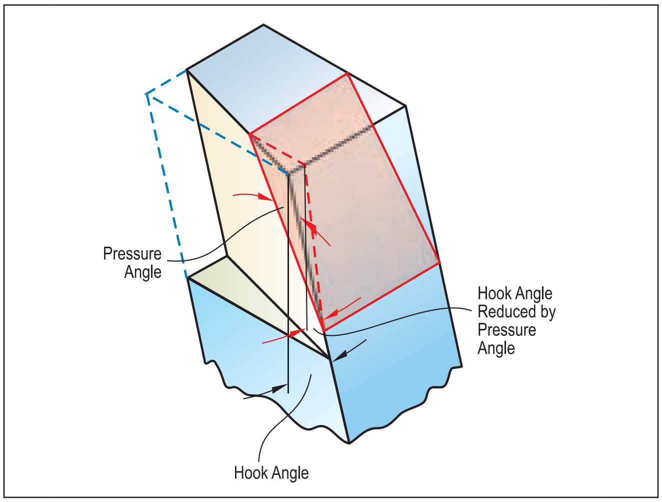

Figure 7—Hook angle reduction due to side rake and pressure angle.

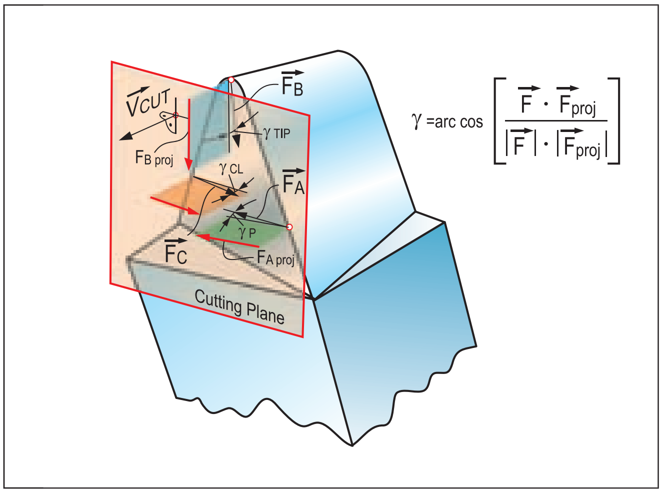

Figure 8—Calculation of effective normal rake angles.

optimal performing tools.

At first, existing tool life data of two-face-ground blades were used to analyze issues such as why inside blades had a shorter tool life than outside blades; under which condition the largest blade pressure angle wear occurred; and in which cases the tip or the edge between tip and cutting edge showed a fast degradation. In order to understand the cutting mechanism better, several additional terms were added to the three-face blade grinding summaries.

The duplication of two-face ground blades with three-face mathematics allowed analysis of a large amount of older data and led to a better understanding of the wear mechanism, which allowed the establishment of a set of recommendations for good blade design.

Next to the blade geometry input parameter, the new summaries show the following effective kinematic values of:

- Side rake angle
- Cutting edge normal rake angle
- Top rake angle
- Cutting edge hook angle
- Wedge angle of cutting edge
- Effective blade point
- Effective cutter point radius
- Effective side relief angle of cutting edge
- Effective side relief angle of clearance side
- Effective pressure angle

Other geometry features for the optimal use of three-face geometry are the full use of the root fillet width and the proper relief from the clearance side edge radius into the clearance blade edge. The recommendation is to back away from the flank surface on the clearance side to avoid the cutting action with a negative rake angle γ.

Blades designed with maximal blade point that avoids negative angles for clearance side cutting (as mentioned above) are called F-Point design. The advantage of F-Point blades is a smooth root fillet without steps and fins and a roughing action of the clearance side edge radius in order to reduce the wear of the edge radius of the following blade.

Blade Sharpness

The blade sharpness is a new expression, which defines the effect of the rake angle to the chip forming and chip removal process. For pre-raked blades with permanent-coated front face, a side rake angle of 20º was used for high-speed-steel blades used in face milling and 12º was used in face hobbing. This side rake angle was defined relative to the blade shank as the angle between the actual front face and the front surface of a virtual block blade (Figure 6).

The side rake angle of a pre-raked blade and the blade shank inclination due to the slot tilt angle in the cutter head define the general sharpness of a blade. For two-face-ground blades, this is an adequate strategy, which allows the use of standard blade blanks as well as standard cutter heads across the board for all bevel gear cutting jobs.

In the transition from HSS wet cutting to carbide dry cutting, short of deeper experiences, the 12º side rake angle of TRI-AC® face hobbing was chosen for the pre-raked carbide blades. The experiences that have been gathered in the past several years have shown that, besides the fact that the 12º blade side rake angle was too large, a general definition of technological blade angles according to "one size fits all" does not result in optimal tool life and best cutting performance.

The slot inclination in the carbide, high-speed cutter heads was chosen so that the cutting edge inclination vs. the cutting plane would always have positive values, and in borderline cases be permitted to be zero. The interaction of pressure angle and side rake angle will always reduce the angle given by the slot tilt angle value as shown in Figure 7.

The aforementioned considerations lead to slot tilt angles for Pentac® Cutter Heads of 7.42º for face milling cutters and 4.42º for face hobbing cutters.

Process research of The Gleason Works has discovered that only the effective sharpness reflects the chip forming mechanics correctly and explains the phenomena of tool life differences between cutting jobs that seem similar, yet deliver dramatically different tool lives.

If the total chip width along the cutting edge and blade tip is observed in infinitesimally small increments, three fundamentally different areas can be identified. A, B and C in Figure 8 show those areas. Chip flow vectors, which lie in the plane of the blade front face, are displayed in Figure 8 and are perpendicular to the cutting edge tangent at the specific points.

Figure 9 shows how the chip flow vectors such as FA are calculated as cross products of the front face normal vector VF and the local cutting edge tangent vectors like TA. The angle between the chip flow vector and the cutting plane shown in Figure 8 is the true rake angle relevant to the cutting action.

Chip Wrinkle Dynamics

There are three fundamentally different chip flow and wrinkle mechanisms depending on one of the following blade types (Ref. 4):

- Side blades, IB/OB-Blades
- Full profile blades
- Dual cut, double side and bottom blades

Side blades produce an L-shaped chip. As the chip is formed by the shearing action and flows away from the cutting edge, a plastic deformation wrinkles the chip (Figure 10, center). In case of a positive cutting edge hook angle, chips are less wrinkled and flow without obvious disturbances. The side chip part is pulled away from the top, which reduces the load on the edge radius and, in turn, reduces edge radius wear, but also eliminates catastrophic failure like the so called "banana peel" as it is shown in the photograph in Figure 11.

Highly positive cutting edge hook angles can lead to a separation of top and side chip or cracks between them. This is a positive sign of a desired load reduction in the major wear zone of the blades.

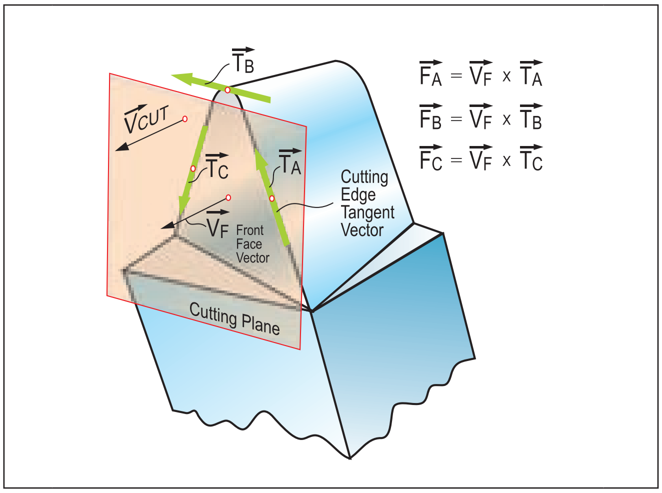

Figure 9—Cutting edge tangent vectors, cutting plane and cutting velocity.

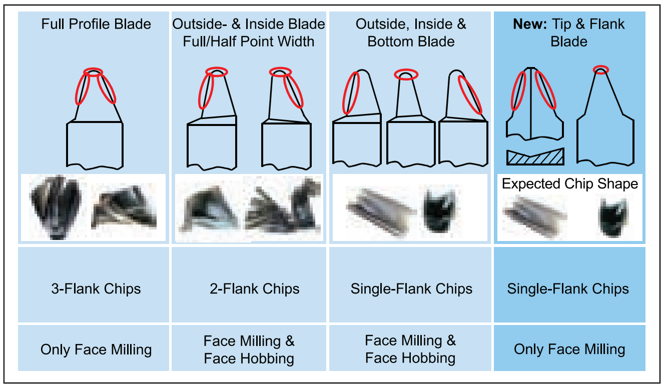

Figure 10—Left side: full profile chips; center: side blade chips; right: dual cut chips.

Figure 11—Large blade top chipping called "banana peel."

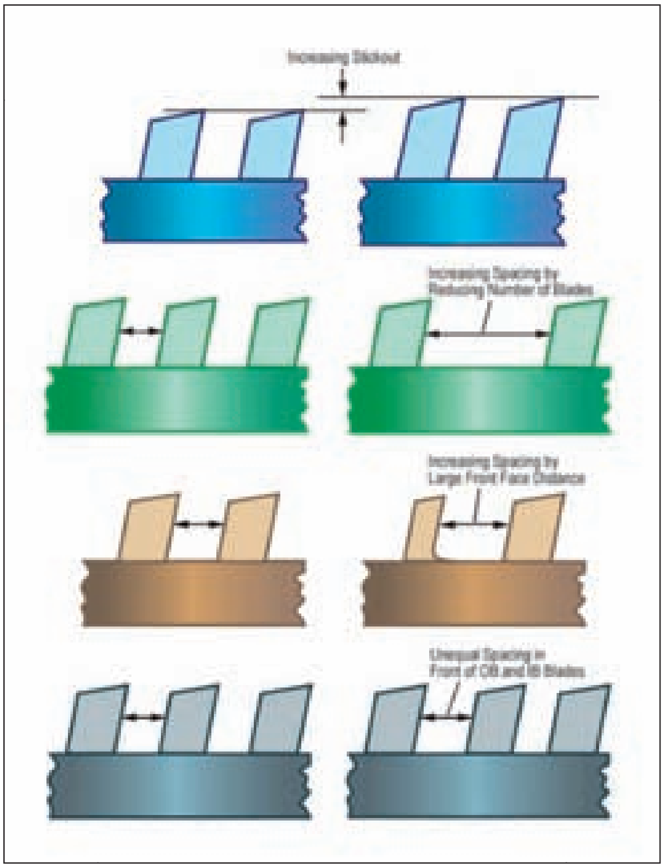

Figure 12—Different possibilities to increase the chip gap volume.

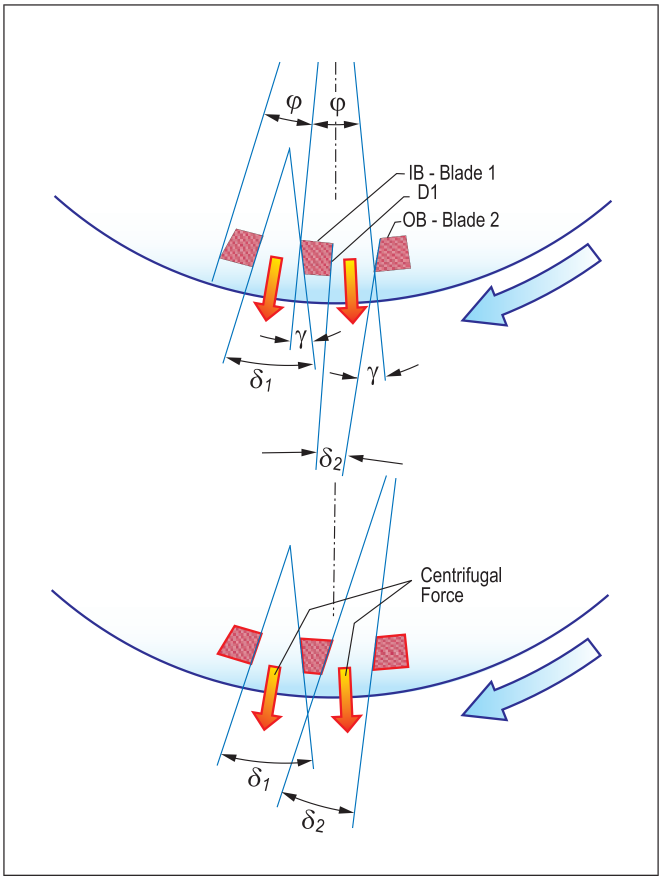

Figure 13—Regular chip gap (top), optimized chip flow by four-face grinding (bottom).

Full-profile blades are traditionally three-face ground. It is recommended to give the IB side 0.5º positive normal rake angle (which will result in a slightly negative value for the normal OB rake angle). Figure 10 shows typical full-profile blade chips. The top rake angle of full-profile blades should be maximized because this will change; e.g., a zero degree normal rake angle of the cutting edge to a positive value. The top rake angle is limited due to the cutter slot tilt angle. Figure 1 shows that the maximal possible top rake angle is equal to the slot inclination angle, which for three-face-ground blades needs to be at least 0.5 degrees smaller than the slot inclination angle because of grindability.

Dual cut blades allow the choice of independent rake angles between side and bottom blades. The side chips roll up without any wrinkling, independent from the hook angle (Figure 10). The bottom blades require the maximal possible top rake angle, similar to the full-profile blade system. Full-profile blades and dual cut blades would benefit from chip flutes, chip groves, chip breaker, etc., designed in order to provide both blade sides with a sharp cutting edge with a positive normal rake angle.

Chip Flow

Highly aggressive dry cutting cycles lead to large chips, which are often highly wrinkled. There is a potential that those chips will not always leave the gap between a blade and the blade in front of it. It has been observed that this phenomenon occurs only in front of outside blades. The chip gaps in front of outside blades are mostly tapered, getting smaller towards the outside (Figure 13).

The centrifugal force in high-speed cutting is up to 100 times the gravitation force g. If the first chip is caught in a chip gap, the following chips from the following cutter revolutions are not able to leave the gap toward the outside of their openings (keystone effect), but the accumulated chips compress to a hard pack, which fills out the entire gap. Chip packing leads to catastrophic failure, blade breakage or in the best case to a cycle abort due to an extensive power draw.

The change of the physical gap size by larger blade stick out, reduced number of blades, increased blade front distance or unequal IB/OB blade spacing lowers the blade stiffness or requires a special cutter head design, as shown in Figure 12. However, it has not been proven that the mentioned changes of the gap size eliminate chip packing, but negative side effects like chatter marks and consequently lower tool life have been recorded during cutting investigations.

Gleason discovered that the size of a chip gap is of less importance than the ability of the chips to flow toward the outside and leave the gap. Chip packing can be avoided if the gap is formed in order to enhance this flow by a gap opening in front of all outside blades. The flow of chips can be analyzed using the basic principles of fluid mechanics. A chip gap formed like the chamber between two blades of a turbo compressor will provide enhanced chip flow. In order to achieve such an effect, the back side of inside blades have been modified with a fourth ground surface (see bottom part of Figure 13).

The fourth blade surface is defined by three parameters, the back face distance DBF, the back side rake angle ε, and the back hook angle η. Figure 14 is a view onto the back side of an inside blade, which shows the three parameters for a sufficient definition of the orientation and location of the fourth blade surface. The blade in Figure 14 shows a "positive" value for the back hook angle η, which provides an additional gap opening away from the cutter head body.

The approach of a fourth face grinding of inside blades is a proprietary, patent pending technology of The Gleason Works utilized with Pentac® cutting tools.

Edge Treatment

The cutting edges of three-face-ground blades are treated differently than two-face-ground blades. The edge-rounding radius before all-around coating is recommended to be below one micron versus five to ten microns for the edge rounding of two-face-ground blades. In reality, a one-micron edge rounding is a rather academic value. The treatment before all coatings is a vapor blasting which is done as part of the cleaning process, prior to coating. Basically, the vapor blasting eliminates surface particles with low adhesion to the carbide grit. The cratering along the cutting edge is cleaned from loose particles during the vapor blasting where the following vapor deposition coating develops a thicker coat around all corners, which has the effect of a certain rounding and smoothing of the cutting edge roughness. ○

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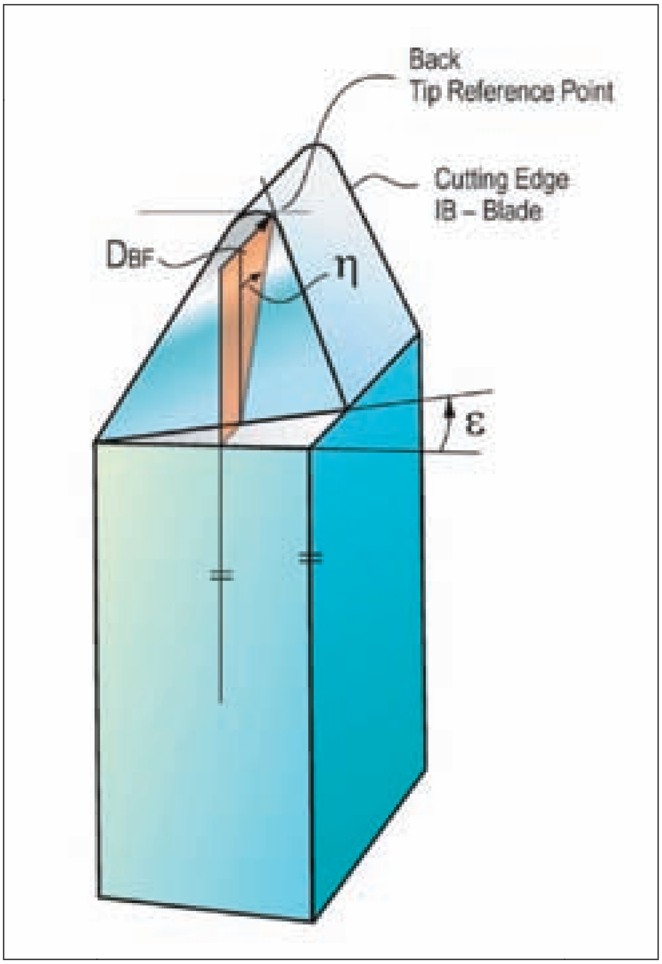

Figure 14—Parameters for back face definition.

		Blade Tilt Angle	Cutting Edge Hook Angle	Effective Side Rake Angle	Effective Top Rake Angle	Normal Rake Angle - Cutting Edge	Normal Top Rake Angle	Normal Rake Angle - Clearance	Wedge Angle - Cutting Edge	Wedge Angle - Top	Wedge Angle - Clearance Side
Car/Truck **Face Hobbing**	OB	4.42°	1°	3°	4.4°	5°	3°	-4.5°	72°	63°	81°
	IB	4.42°	1°	3°	4.4°	5°	3°	-4.5°	79°	63°	81°
Car/Truck **Face Milling**	OB	7.42°	3°	5°	4.5°	5°	5°	-4.5°	82°	69°	79°
	IB	7.42°	3°	5°	4.5°	5°	4°	-4.5°	76°	68°	81°

Figure 15—Three-face parameter table.

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