Three-Face Blade Technology

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Three-Face vs. Two-Face

In order to utilize the full potential of 3-face ground and all around coated blades the cutter head slot inclination of 4.42° as it is used in the Pentac-FH cutter system is not sufficient. In case of 2-face ground blades, the front face remains untouched during the re-sharpening of only pressure angle and clearance side of the blade. The front face of 2-face blades is parallel to the blade shank and has a permanent coating. After re-sharpening, the blades are ready to be built in the cutter head.

If blades should be all around coated, then it is recommended to grind in addition to the side relief surfaces also the front face. The reason is the continuous buildup of coating layer on the front face if no stripping between coatings occurs. Although it is possible to strip the front face coating chemically before every re-coating, this would involve additional cost and results in a degradation of the carbide under the repeatedly stripped surface. In case of all-around coating it is recommended to grind the front face of the blades also in order to remove the previous coating and utilize the possibility to achieve more optimal top rake and side rake angles with a different front face orientation. The "package" 3-face grinding and all-around coating can double the tool life, compared to 2-face grinding with permanent front face coating.

Three-face grinding of blades which will be utilized in a cutter head with 4.42° of slot tilt angle is very limited with the maximal achievable top rake angle, which is around zero in the left graphic in Figure 1. If the same blade was used in a cutter head with a 12° slot tilt angle as shown to the right in Figure 1, then the achieved top rake angle would be 7.58°. This freedom allows in all cases of different gear geometries and cutting kinematics to maintain a slightly positive top rake angle.

Another important factor for manufacturing cost per part is the relationship between slot tilt angle and number of re-sharpenings. In order to accomplish an effective top rake angle of e.g. 2° on a blade which is built in a cutter head with a 4.42° slot inclination angle, a Δ_δ (Fig. 1) of 2.42° is required. This is represented by the left graphic in Figure 2. The cleanup amount of Δs normal to the surface will require a large blade top down Δl_1. If a top rake angle of 2° in the cutting process should be realized in a cutter with 12° slot tilt angle, then the blade hook angle in blade grinding will be 10°, as shown in the right graphic in Figure 2. The relationship between top down Δl_2 and front face clean up Δs is becoming more favorable by increasing the slot tilt angle. The number of resharpenings for 3-face grinding in case of a 12° cutter slot tilt angle is 2.7 times higher than that of a 4.42° cutter slot tilt angle.

The limits for the highest realistic slot inclination angles in cutter heads are given

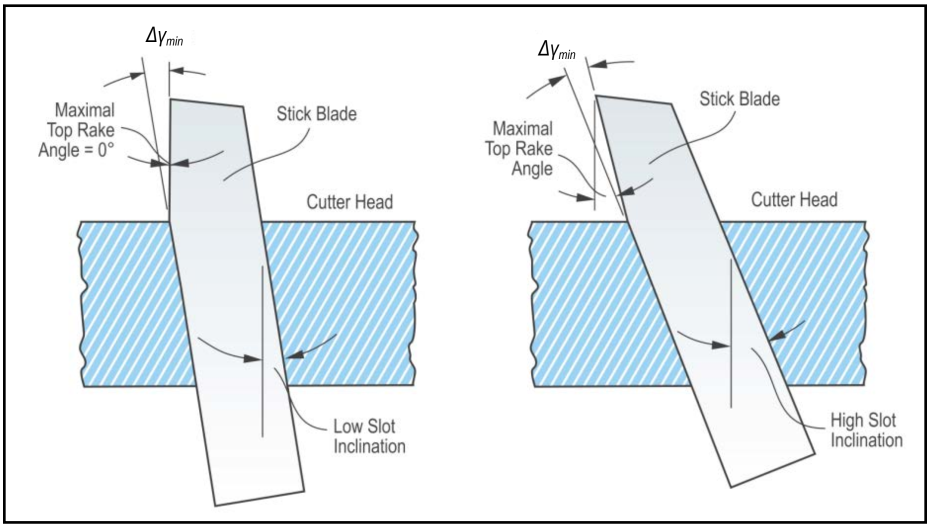

Figure 1 Top rake angle as function of slot inclination (slot tilt angle).

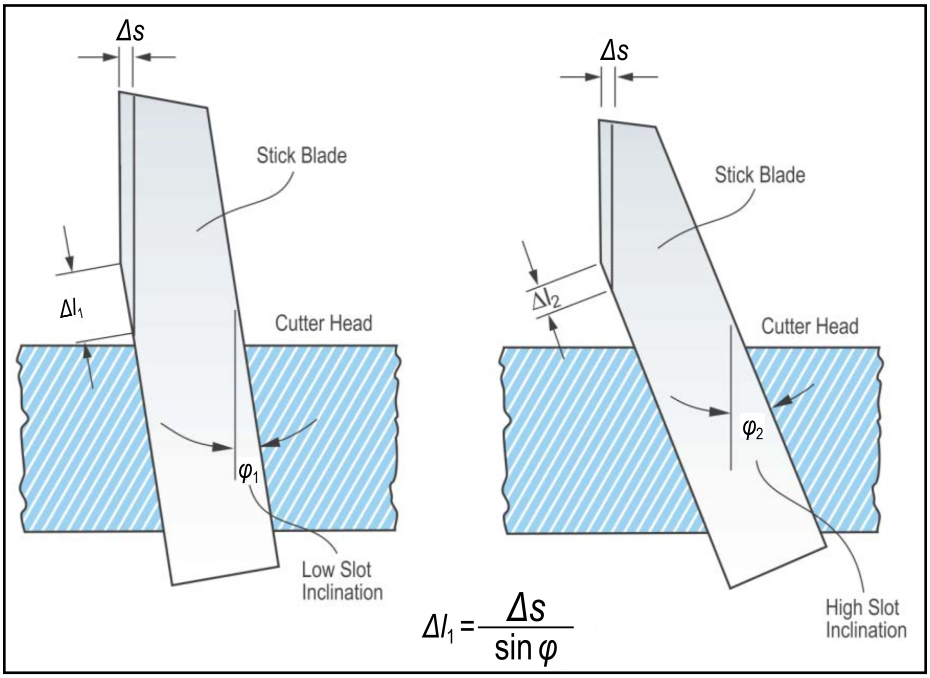

Figure 2 Relationship between top down amount and blade hook angle.

by the cutter design and manufacturing, as well as the higher tendency of the cutting forces to push the blades axially into the slots during the cutting process.

Blade Parameter Definitions and Geometry Calculation

Two of the most important input parameters of the blade geometry calculation after the pressure angle are the effective side rake angle, which indicates the "sharpness" of the blade, and the effective cutting edge hook angle, which indirectly defines the top rake angle. It might be important at this point to mention that for cutting performance and good tool life, the effective cutting edge hook angle is the most important parameter. Because top rake angle and effective cutting edge hook angle are connected, the 3-face blade calculation program attempts to define a blade geometry which achieves the desired effective cutting edge hook angle. Only in cases where this is not possible due to geometry limitations, the closest possible value will be used as the result.

In order to obtain the effective angles, the relationship between the cutting velocity vector (Fig. 3) and the blade coordinate system in Figure 4 has to be considered. The blade side rake angle shown in Figure 4 is equal to the effective side rake angle, if the indicated cutting direction is equal to the x-axis of the blade coordinate system. The effective cutting edge hook angle (vs. the blade hook angle) is shown in Figure 5. Each material removal from the blade front will change the cutting velocity vector direction in Figure 4 and therefore will also change the orientation of the cutting plane. This will in turn change the effective side rake angle as well as the effective cutting edge hook angle. If the gear engineer chooses a particular effective side rake angle, then the blade related side rake angle target has to be reduced or increased depending on the relationship between the cutting velocity vector and the X-axis of the blade coordinate system. This still would not deliver the desired kinematic side rake angle in one calculation step, because the slightly changed blade side rake angle will require a different front clean-up amount, which in turn changes the relative cutting velocity direction again. A complete and a partial front clean-up is shown in Figure 6.

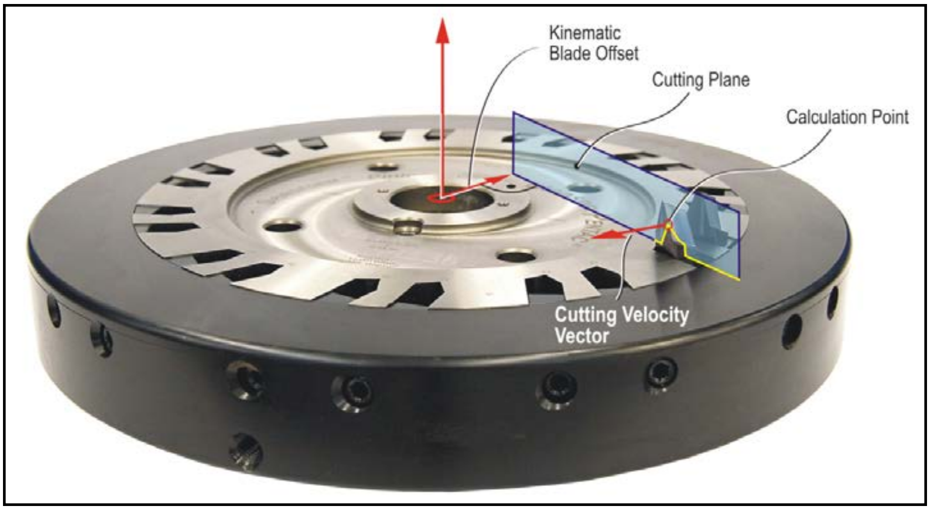

Figure 3 Cutting plane and kinematic velocity vector.

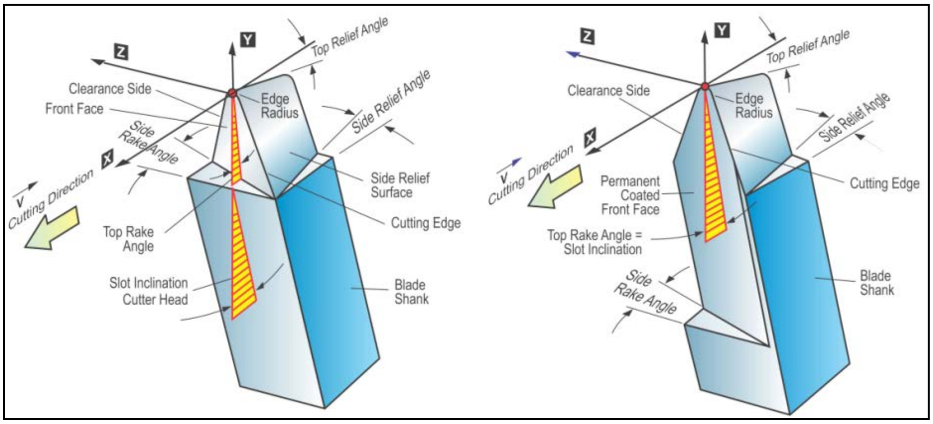

Figure 4 Blade coordinate system of 2-face blade (left) and 3-face blade (right).

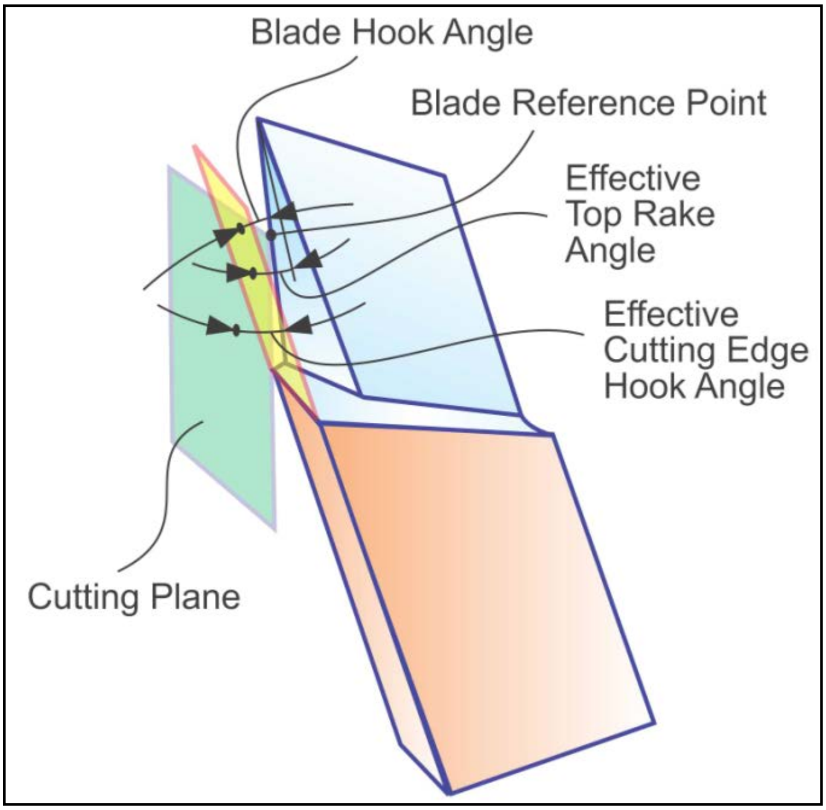

Figure 5 Effective cutting edge hook angle and effective top rake angle.

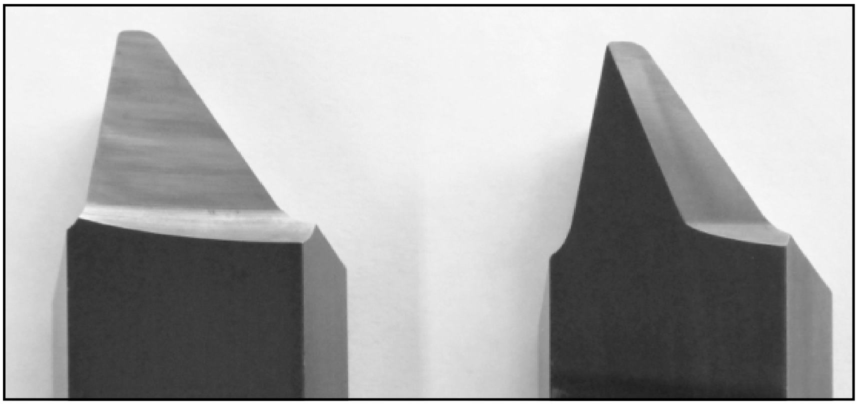

Figure 6 Complete front clean-up (left), partial but sufficient front clean-up (right).

Figure 7 Blade angle and clean-up iterations.

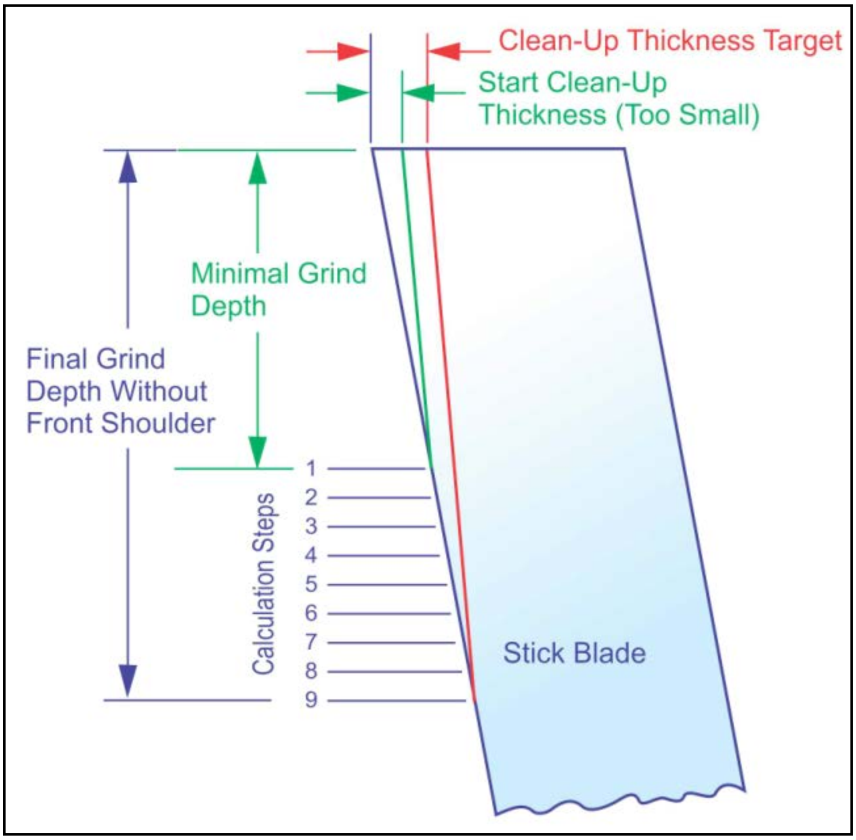

Figure 8 Front clean-up calculation strategy.

Because the amount of front clean-up depends on the chosen side rake and cutting edge hook angle, the physical blade offset (Fig. 3) will change, which also changes the cutting plane orientation relative to the blade. Because of the cross influences between the three parameters which are present in the solution formulae, a closed analytic solution of the 3-face blade geometry is impossible. In order to achieve a sufficient front clean-up and realize the effective input values, three imbedded iterations are required. The problem with imbedded iterations is to achieve a stable and convergent behavior of the calculations while keeping the iterations fast. This goal was achieved with the iteration strategy, symbolized in Figure 7.

The inner iteration loop No. 1 (Fig. 7) influences the top rake angle on the blade front face in order to achieve the given effective cutting edge hook angle. At the end of each calculation step, the effective cutting edge hook angle is calculated and the difference between this number and the desired input value is multiplied with a damping factor and then subtracted from the top rake angle used in the last step. After that, the calculation loop is repeated until the deviation between the actual and the nominal value is below the pre-determined limit.

The iteration loop No. 2 (Fig. 7) is next in the arrangement of iterations. The lead parameter of this iteration is the grind depth (Fig. 8). The calculation begins with the minimally required grind depth. This iteration has to accomplish two things at the same time. Firstly, the front clean-up has to cover the entire length of the cutting edge in order to correctly cut the whole depth of the gear. Secondly, the clean-up thickness at the tip of the blade needs to be equal or above a given minimal value. The calculation is a single direction step approximation rather than a true iteration. Figure 8 shows 9 steps, starting at the minimal grind depth to the final grind depth. After each step the clean-up thickness is checked if it is still below the minimal value, which will enable the next step with an incrementally increased grind depth. If the clean-up thickness calculated at the end of the loop passes for the first time the target value, the front clean-up loop ends and loop No. 3 (Fig. 7) completes the first step of calculating the effective side rake angle for a blade geometry which already shows the correct effective cutting edge hook angle as well as the correct front clean-up.

The result of the effective side rake after finishing the first step of the iteration will not deliver the desired value because the two inner loops (Fig. 7) sufficiently changed the cutting direction relative to the blade coordinate system that several corrective repetitions of this loop are required. Corrective input is the deviation (with negative sign) between actual and nominal effective side rake angle. Although this procedure makes this loop an iteration, the loop ends either if the deviation limit is satisfied or after maximally 5 steps.

In the first generation of 3-face blade geometry calculation, the resulting geometry of the above described calculations was used for the blade grinding, but with one exception for face hobbed bevel gears. The blade spacing between the reference points of outside and inside blade is in the ideal blade definition for face hobbing equal to 360° divided by twice the number of blade groups. The final 3-face blade bases on a blade positioning in a real cutter head and on a different front face geometry of outside and inside blade (Fig. 9). The result is a blade spacing S_X that is not equivalent to the theoretical value of 360° divided by twice the number of blade groups. Figure 10 explains how a blade spacing error of F_d causes in face hobbing a radial error of N_e. In other words, the deviation from equal spacing caused by a physically given cutter head and the 3-face blade geometry of outside and inside blade results in a tooth thickness error of the produced bevel gears. For face hobbing blades, the 3-face program uses a radial correction of each of the inside and outside cutting edge locations of $N_e/2$ (with alternating signs).

The initial gear design calculation either used a theoretical blade or a standard 2-face blade design. Although the radial compensation of the 3-face blade will re-establish the tooth thickness, there will be some side effects which are discussed in the following section.

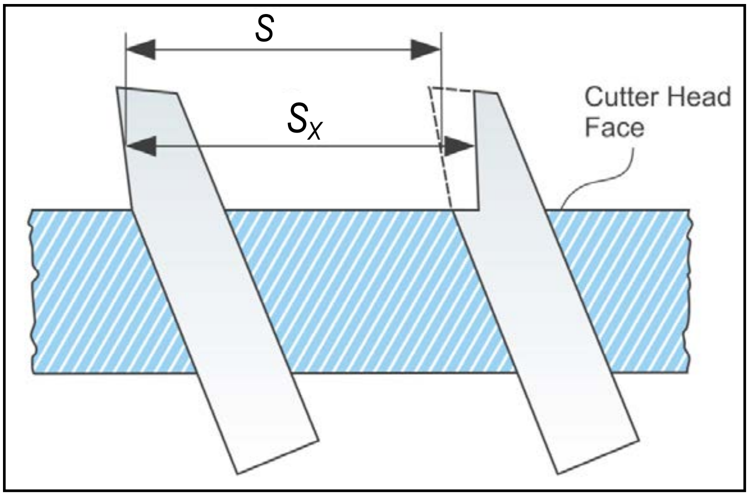

Figure 9 **Blade spacing value changes due to 3-face grinding.**

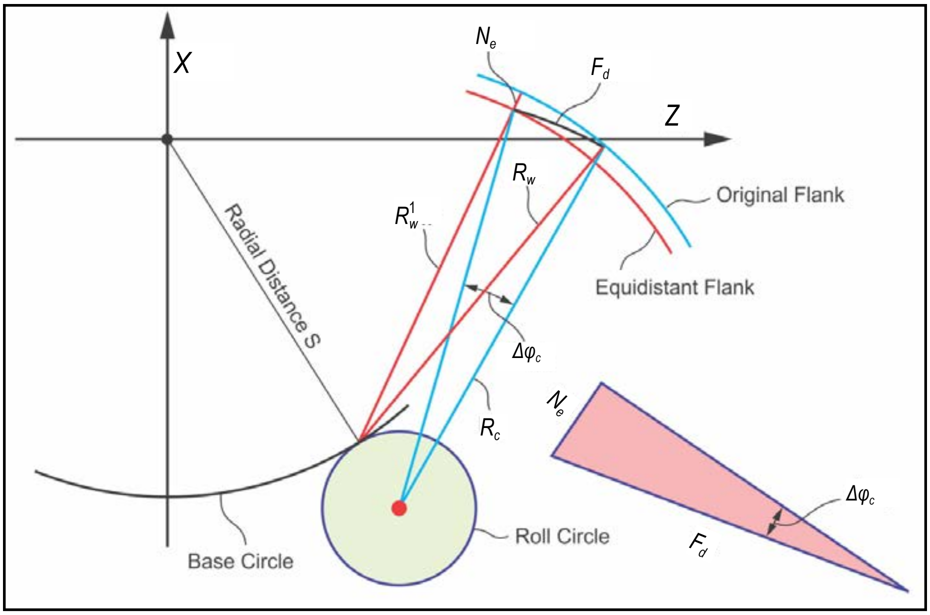

Figure 10 **Radial compensation of spacing discrepancy F_d.**

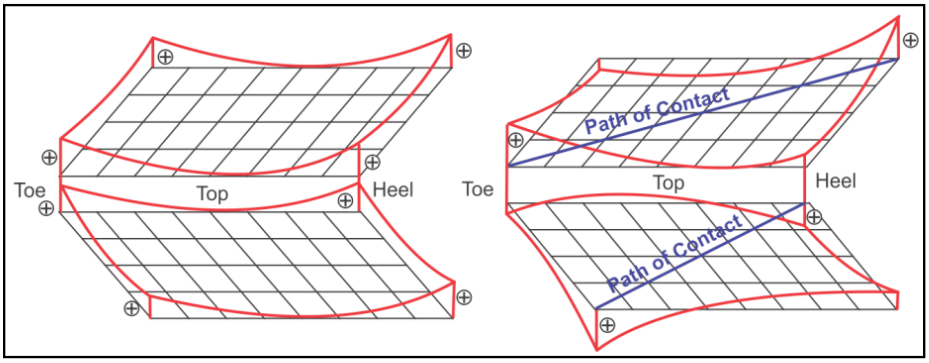

Figure 11 **Side effect length crowning (left) and flank twist (right).**

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Length Crowning and Flank Twist Phenomenon

The change from 2-face ground blades in Pentac-FH cutter heads to 3-face ground and all-around coated blades in PentacPlus-FH cutter heads also requires a relocation of the blade front faces, as described in the previous section. Different front relocations of outside and inside blades cause a tooth thickness change, which can be compensated with small changes of the inside blade and outside blade radii as mentioned above. The alteration of the blade point radii compared to the calculated values causes a major side effect which is a length crowning error on both flanks (Fig. 11, left). The second side effect relates to the change of the effective cutting edge hook angle versus the initial 2-face value (or theoretical blade definition) which results in a flank twist (Fig.11, right).

An effective possibility to reduce the twist in the measurement result is to adjust the 3-face blade geometry closer to the standard 2-face blade geometry. This requires maintaining the original effective cutting edge hook angle; however, the length crowning error still remains in the flank surfaces without any available correction freedoms.

Influence of Blade Stepping

If the outside and inside blades in a face hobbing cutter are built to equal height above the cutter head, then a degradation of the tooth root geometry will occur if a gearset member has length crowning which is created by a cutter head tilt κ (Fig. 12). Figure 12 also aids in the understanding that if the lower outside blade was built to the same blade height above the face of the cutter head as the upper inside blade, then the root of the work would be severely stepped between the two flanks. In order to eliminate the stepping in the work gear root fillet, a stepping between the outside and the inside blade height above the cutter head face is required.

The initial blade stepping calculation uses the length crowning tilt component and applies the objective to keep the blade tips within the vertical generating plane (Fig. 12). After the stepping amount in the direction of the cutter head axis is determined, the cutting edge tangent vector is used to calculate the precise, extended or shortened blade tip locations by maintaining the correct radius and offset at the blade reference point. The effective blades with their original calculation point locations and their stepped blade tips (Fig. 12) are used in the generating software to calculate the correct effective tooth slot and root fillet geometry.

The described blade stepping procedure will not influence the blade reference point location and the geometry of the cutting edge surrounding surfaces. The blade stepping merely extends or shortens the blade dedendum S890 (Fig. 12).

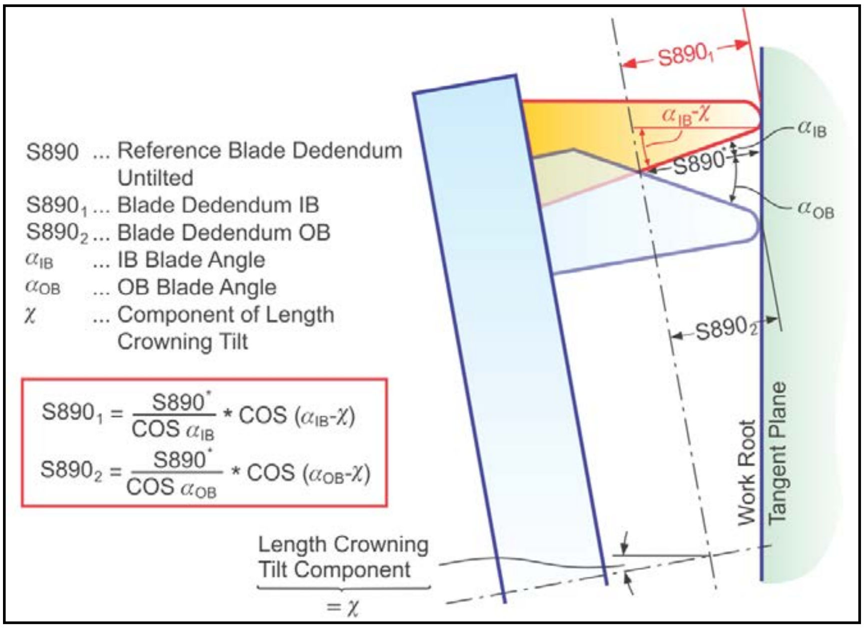

Figure 12 Stepping calculation in blade software.

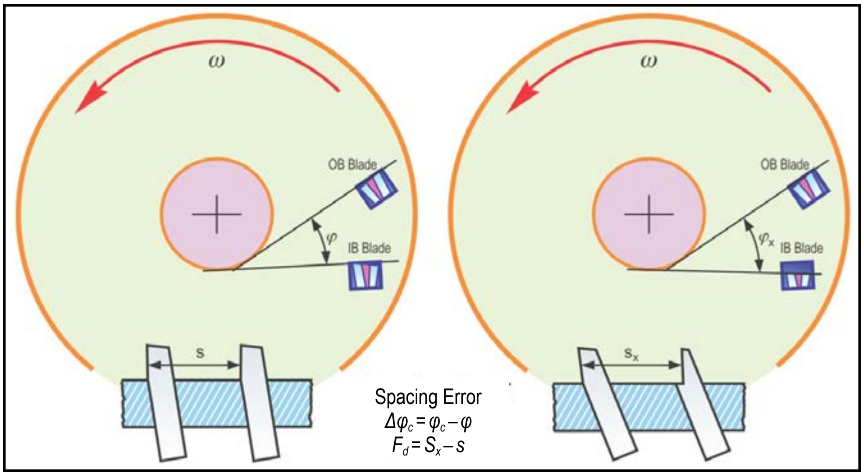

Figure 13 Cutting edge spacing φ.

Blade Spacing Correction in *TREFACE* Program

The 3-face blade calculation program *TREFACE* applies the strategy to establish the required cutter radii at the calculation point and define side rake and top rake angle correctly with respect to the relative cutting direction, given by the kinematic blade offset angle. While providing the requested blade geometry, the program has to assure a sufficient front face cleanup, which has an influence on the resulting timing angle between the outside blade and the following inside blade. The initial timing angle φ (Fig. 13) is derived from the original 2-face calculation that is always exactly or close to 360° divided by twice the number of blade groups (which is the slot spacing angle of the cutter head). This original timing angle in connection with the original point radius adjustment in the 2-face calculation assures the cutting of the correct tooth thickness.

Three-face ground blades result in a spacing angle φ_x, which will—according to Figure 10—lead to a tooth thickness error N_e. As previously mentioned in the section "Length Crowning and Flank Twist Phenomenon," if the correct tooth thickness is re-established with small cutter point radius changes, then a length crowning side effect of gears cut with such a cutter will occur that cannot be corrected without changes in blade geometry and alterations of the machine settings.

An uncommon solution was developed, which achieves the correct blade spacing angle φ instead of φ_x (Fig. 13), and at the same time delivers the desired values for the effective cutting edge hook angle, the effective side rake angle, as well as providing a complete front face clean-up.

The new method is based on the idea that φ_x (Fig. 13) can be increased if the IB-blade receives a larger front clean-up thickness and φ_x can be reduced if the front clean-up thickness of the OB-blade is increased (Fig. 8). Only increasing of the front face clean-up thickness is permissible because only then is the minimal clean-up preserved.

The algorithm of iterations and approximation loops in Figure 7 now becomes even more complex in order to achieve the desired goal of re-establishing the original blade spacing. Two additional outer loops have to be added (Fig. 14). The first added loop (loop No. 4) repeats all previously discussed calculation loops for both blades involved in cutting one pinion or gear slot ("Inside & Outside Blade Loop" in Fig. 14). The additional outer loop (Loop No. 5) will calculate the actual blade spacing angle (which required that both, IB- and OB-blade calculations have been finished at this point) and processes this value in order to decide which blade (inside or outside) has to receive what amount of additional front clean-up thickness ΔS_x. The corrective repetition of all four inner loops uses a dampened amount of ΔS_x (reduced amount). All inner loops are repeated as described in the section "Blade Parameter Definitions and Geometry Calculation."

The outer blade spacing iteration loop repeats the calculations until the actually achieved blade spacing deviation from the original (desired) spacing is below a defined iteration limit, or if the deviation value changes its sign (or it aborts after maximally 6 steps). The dampening factor and the number of steps have been adjusted so that the overall system of loops works stably and the final results in all evaluated cases are within the acceptable accuracy limits (Fig. 15).

Figure 16 is the blade grinding summary output section with the effective blade geometry. The highlighted yellow shows the effective cutting edge hook angle of 1.00° and the effective cutting side rake angle of 4.50°. Those are exactly identical with the input values of the *TREFACE* program where the correct values have been achieved with one single run of *TREFACE*. The blade spacing was kept precisely at the value of the reference cutter. In the output in Figure 16 the blade spacing correction is evident by the fact that the effective tip clean-up thickness of the outside blade varies by a large

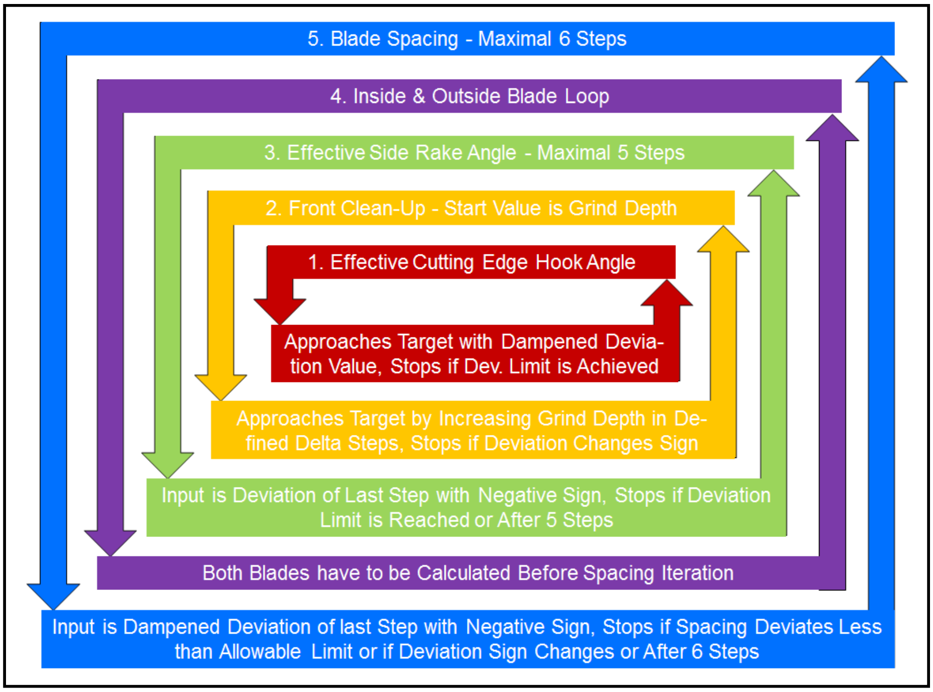

Figure 14 Five imbedded loops for 3-face blade calculation.

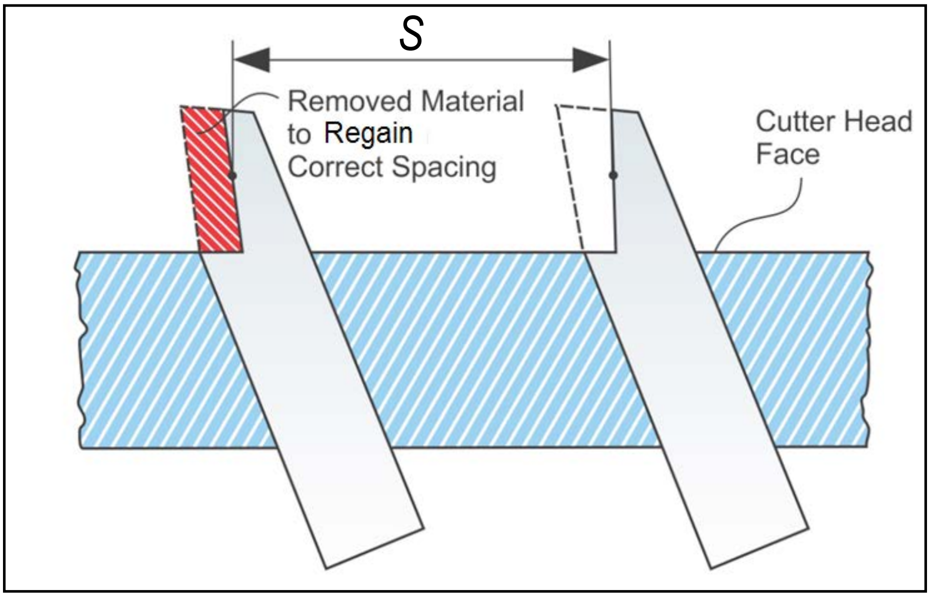

Figure 15 Regaining of correct blade spacing.

amount from the target value (2.47 mm versus 1.00 mm).

Face milling designs do not require the outer iteration loop in Figure 14 because the tooth thickness is independent from the blade spacing.

A3F Feedback File to Create Relevant CMM-File

The goal of a 3-face ground blade is to duplicate the theoretical blade geometry used during flank form and tooth contact analysis development. This theoretical blade has in all common cases a standard, 2-face geometry. The decision of which system is used (2-face or 3-face) and the decision of which particular angles (especially the effective cutting edge hook angle) will be chosen for a 3-face blade geometry is made long after the original design calculation was conducted. In cases where the effective cutting edge hook angle of a 3-face blade geometry deviate largely from the original 2-face blade, a specially calculated feedback file (*A3F-file*) can be used to calculate the actual flank form of the gears that will be later manufactured with these blades (software function "create effective design"). The *A3F-file* contains the effective 3-face blade geometry and is processed in the standard flank form generator.

GLEASON BLADE PROFILE GRINDING SUMMARY V. 3.0
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EFFECTIVE VALUES IN CUTTER HEAD

	OUTSIDE	INSIDE
01. KIN. TOP RAKE VELOCITY ANGLE	-1.60deg	-1.60deg
02. EFF. CUTTING EDGE HOOK ANGLE	1.00deg	1.00deg
03. EFFECTIVE TOP RAKE ANGLE	2.88deg	2.66deg
04. EFF. TOP RELIEF ANGLE.	15.00deg	15.00deg
05. EFF. CUTTING SIDE RAKE ANGLE.	4.50deg	4.50deg
06. MIN. TIP CLEAN UP TARGET	1.00 mm	1.00 mm
07. EFF. TIP CLEAN UP THICKNESS.	2.47 mm	1.00 mm
08. CUTTING PRESSURE ANGLE.	22.53deg	20.53deg
09. CUTTER POINT RADIUS.	86.41 mm	90.37 mm
10. CUTTER POINT WIDTH	.80 mm	.80 mm
11. EFF. RELIEF ANGLE P.A. SIDE.	15.00deg	11.00deg
12. EFF. RELIEF ANGLE CLEAR SIDE	9.00deg	13.00deg
13. FRT CLEAN UP LENGTH W/O SHLDR.	11.70 mm	12.21 mm

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Figure 16 Effective blade geometry output in program *TREFACE*.

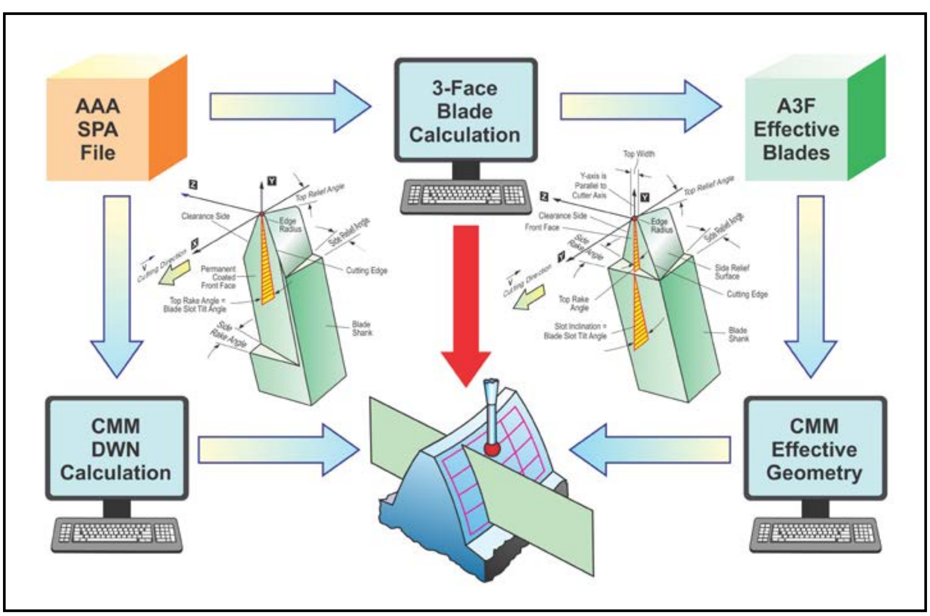

Figure 17 Two-face vs. three-face nominal CMM data file.

The two possibilities to arrive at a coordinate file for 3-D flank form measurement are shown in the data flow and processing chart in Figure 17. It begins with the basic settings and basic blade geometry *AAA-file* or *SPA-file*. The standard case is the CMM-download file calculation in *CAGE*, for example (Fig. 17, left). Parts cut with 2-face blades in a cutter head with 4.42° slot inclination are measured directly with this CMM-download file (right pointing blue arrow to the center bottom graphic in Fig. 17).

In the case of 3-face ground blades used in a cutter head with 12° slot inclination to cut a bevel gear, it is possible to use the parallel generated *A3F-file* with the effective blade geometry and go the path to generate the CMM-effective geometry calculation (Fig. 17, right) and measure the parts with this coordinate file (left pointing blue arrow to center bottom graphic in Fig. 17).

In cases where the post-revision 3-face blade calculation is used, and if the effective blade hook angle is between -1° and +1°, then the manufactured bevel gears can be directly measured with the standard CMM-download file (calculated for 2-face blades in a cutter with 4.42° slot inclination) which is indicated with the red arrow (Fig. 17).

Example Results: Pre- and Post-Revision Software

In order to judge the cutting results after the software revision, some baseline calculations have been made and will be discussed in the following paragraph. All measurement results in this section result from blades ground on the same BPG blade grinder which have been used to cut sample pinions on the same Phoenix cutting machine by utilizing a cutter head with 4.42° slot inclination and a cutter head with 12° blade inclination. The "sum-of-errors-squared" is defined as the summation of the squared deviation amounts of all 90 surface grid points (of both flanks, measuring a 9 × 5 grid). Per convention, the unit "inch²" is used — even if the surface evaluation is done in metric units, as in the present case.

The flank form measurement results in Figure 18 are the baseline for a pinion cut with a 2-face ground blade built in a cutter head with 4.42° slot inclination and measured with the standard *CAGE* download file, which is also based on a 2-face blade in a cutter with 4.42° slot inclination. The corner point deviation of less than 4 µm (Fig. 18) lead to a sum-of-errors-squared of 0.000 000 40 inch², which is an excellent result for cutting before heat treatment.

The second baseline measurement also uses the standard *CAGE* download file, but the measured pinion was cut with a 3-face ground blade that was built in a cutter head with 12° slot inclination; the blade grinding summary for this test had been calculated with the pre-revision software. Figure 19 shows the deviations of the cut pinion, which are nearly 14 µm. The sum-of- errors-squared is 0.000 00 231 inch², which is still acceptable for a soft cut pinion before heat treatment. However, the surface deviations are significantly larger than the ones in Figure 18. The 3-face blade geometry featured 4.5° effective side rake angle and 1° effective cutting edge hook angle, which compares to the 2-face blades with side rake angles of 12° and effective cutting edge hook angles between +1° and -1°. In particular the effective cutting edge hook angle causes the flank surface twist, visible on the concave flank (Fig. 19). The ΔR_W blade point radii correction that was used in the pre-revision software to maintain the correct tooth thickness causes the length crowning, which is more visible on the convex flank.

As a first step to represent the 3-face blade geometry and subsequently the flank geometry of the manufactured gears, a file that contains the effective blade geometry was created (so-called *A3F-file*). The same 3-face cut pinion measured before with the standard *CAGE* download file (Fig. 19) was also measured with a download file generated with the new *A3F-file*. The results of this measurement are shown (Fig. 20). This measurement achieved a sum-of-errors-squared of 0.000 000 20 inch², with corner point deviations in the single micron range — an excellent result.

However, the intention of using 3-face blades is the improvement of the cutting conditions without changing the initially developed flank surfaces. If the *A3F-file* was used to re-run the tooth contact analysis, then small changes in the path of contact bias direction, as well as changes in the length crowning amount, could be observed.

The development goal of the revised *TREFACE* software was to eliminate or reduce any differences between 2-face and 3-face blades and subsequently eliminate the differences between cutter heads with different slot inclination.

It became evident during a theoretical study of the cause of flank twist and length crowning that side rake angle and top rake angle are only indirect parame-

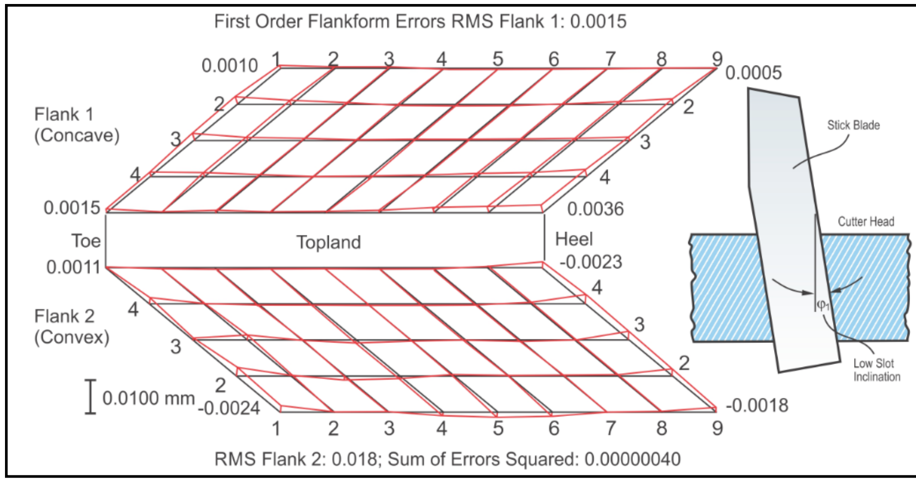

Figure 18 Standard ***CAGE*** download file, part cut with 4.42° cutter slot inclination and 2-face blade.

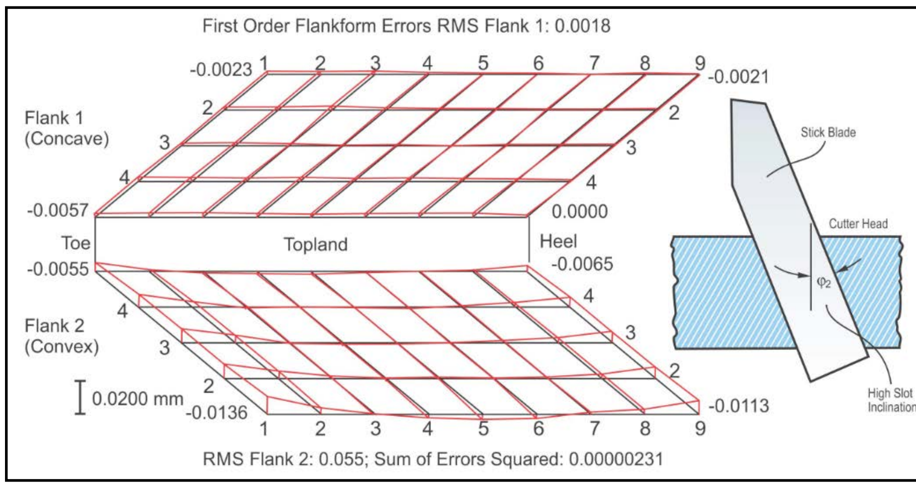

Figure 19 Standard ***CAGE*** download file, part cut with 12° cutter slot inclination and 3-face blade with blade calculation before software revision.

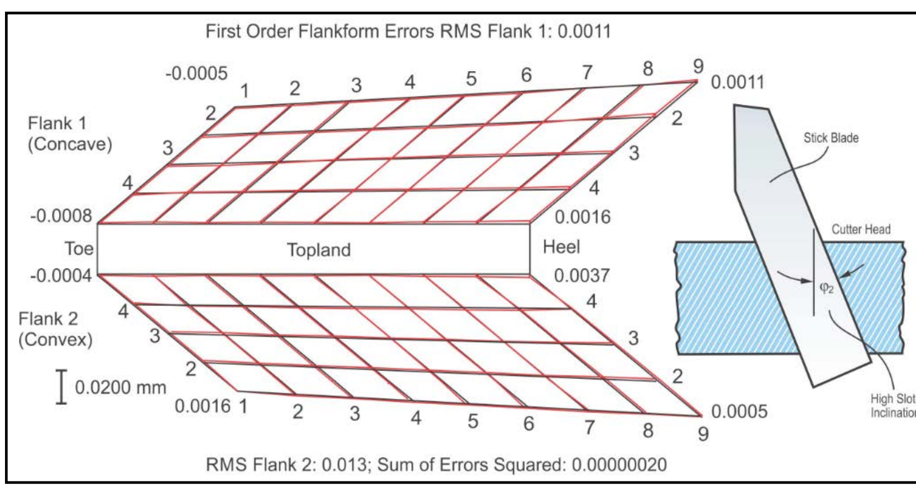

Figure 20 A3F download file, part cut with 12° cutter slot inclination and 3-face blade.

ters with limited significance to the flank twist. The investigations resulted in the acknowledgement that the effective cutting edge hook angle is the sole blade feature causing the flank surface twist. And yet the theoretical investigations and the verification in practical cutting trials also showed that the flank twist is minimized if the effective cutting edge hook angle is selected between 0° and +1°.

The addition of the two outer calculation loops (Fig. 14) with the strategy of increasing one of the front clean-up depths (either on the inside blade or on the outside blade) resulted in a 3-face blade spacing that duplicated precisely the original 2-face reference blade. Calculations with the post-revision *TREFACE* program in connection with an input value for the effective cutting edge hook angle between 0° and +1° deliver new-generation 3-face blades that eliminate all length crowning errors and reduce about 85% of the flank twist experienced with the pre-revision software.

Practical proof of this is shown in the flank deviation graphic (Fig. 21). The 3-face blade calculation was repeated with the post-revision *TREFACE* program. As input for the effective hook angle values of inside and outside blade, the recommendation above was applied. Pinions manufactured with the new 3-face blade geometry in a cutter head with 12° slot inclination angle are measured with the standard *CAGE* download file (based on 2-face blades with 12° blade side rake angle used in a cutter with 4.42° slot inclination) result in a single micron flank form deviation with an excellent sum-of-errors-squared of 0.000 000 46 inch².

In face hobbing the cutting edge hook angle — as well as the spacing between outside and inside blades — has an influence on the flank geometry of the manufactured bevel gears. In an industrial environment the basic blade geometry (reference blade) is defined with the original job design early on, but the decision "2-face or 3-face blades" is made much later in the process. Manufacturers were not comfortable with the fact that their decision to use 3-face ground blades could change the flank geometry development of their already approved designs. This was the reason for a major revision of the Gleason blade summary

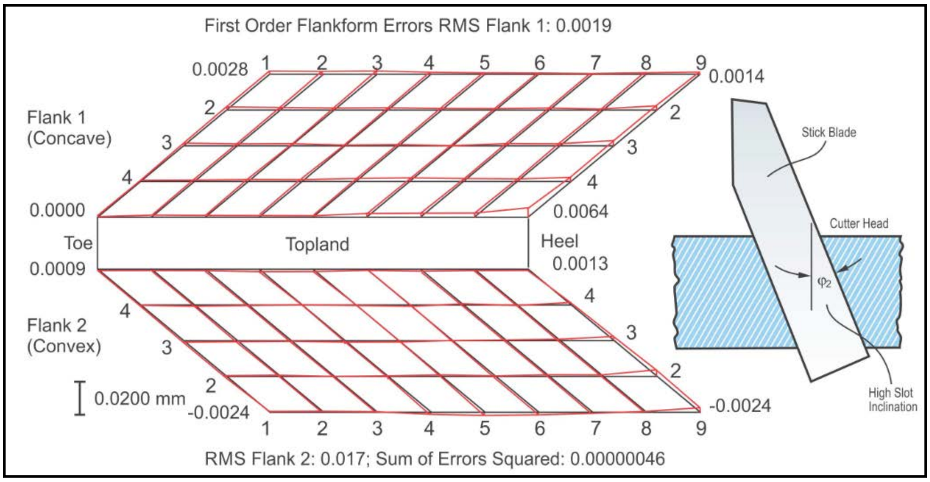

Figure 21 **Standard *CAGE* download file, part cut with 12° cutter slot inclination and 3-face blade with bade calculation after software revision.**

calculation program *TREFACE*.

Three-face blades ground with summaries calculated with the post-revision *TREFACE* software do not create length crowning differences, compared to the 2-face reference blade. All flank twist or bias differences between gears cut with 3-face blades versus the 2-face reference blade can be eliminated, or greatly reduced, if the effective cutting edge hook angle is chosen between 0° and 1°. The new calculation allows the user to make the decision to use cutters with slot inclinations higher than the reference cutter in connection with 3-face ground blades much later than the development of the gearset design. This enables a manufacturer to develop and manufacture in different location without the potential of discrepancies between desired and achieved flank geometry. It also makes manufacture of the same gearset design possible in different locations without noticeable differences.

In cases where a manufacturer likes to apply an effective cutting edge hook angle that is several degrees away from the recommendation, a certain flank surface twist in the manufactured parts versus the original development (and the standard *CAGE* download file) will occur. This problem can be resolved by utilizing the *A3F-file* with the effective blade geometry. A tooth contact analysis using the *A3F-file* will confirm that Ease-Off and tooth contact still reflect the original development, or will show that fine tuning is required in order to adjust the 3-face generated (and manufactured) gearsets to the original development. In either case, a download file generated with the basic data of the *A3F-file* (no standard *CAGE* download file) has to be utilized for the coordinate measurement.

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