First Part Right—Fiction or Reality?

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Introduction

The manufacture of spiral bevel and hypoid gears is considered one of the most complex metal cutting operations in the industry. Many factors contribute to the accuracy of the flank surfaces. In the early 1980s, when the *G-AGE* correction software was introduced, it was possible, for the first time, to employ a closed correction loop. Before that, so-called proportional changes helped to make approximate changes, which after many trials resulted in a good part. But with the *G-AGE* closed loop correction software it was now possible—with basically one single correction step—to eliminate 80% to 95% of the practical influences from the machines, the workholding, and the cutting tool.

With the manufacturing of spiral bevel and hypoid gears in larger batches, it seems widely accepted that several development parts are required in order to match the theoretically developed geometry. If the once-developed gearset is repeated at a later time, the first-cut part in many cases does not reflect the theoretically developed geometry; the reasons in both cases are related to the cutting machines and the cutting tools.

Today's understanding of lean manufacturing—and the generalized quality teachings of "do it right the first time"—makes it difficult to accept that still some development parts continue to be required—especially for environmentally aware manufacturers.

This paper analyzes the different influences of the deviations between nominal and actual geometry for a first-cut bevel gear. In each section, the customary tolerances are quantified and the possibilities to reduce them are discussed.

The Influence of the Cutting Machine to Workpiece Accuracy

Gaging of the cutting machine like the Phoenix II 600HC (Fig. 1) is an important task that must be repeated after each incident on the machine between cutter head and part. Plunging with the wrong index position, prompting such blades into an aggressive first-cutting contact with the part, or worse—even situations where one or several blades breaking might require a re-gaging of the machine.

A gaged machine achieves axes positioning in the single micron range accuracy. Every part, based on its design specifications, is cut with axes positions that differ from the gaging position. All tolerances of machine components such as rails and trucks, bearings, ball screws and encoders, as well as the interface surfaces of frame and spindle housing castings, accumulate error commensurate with the distance of the axis position away from the gaging position. Six-axes, free-form machines also have kinematical deviations depending on the axes speeds and the combination of three linear and two or three rotational axes. The machine fingerprint commonly causes flank form errors between 0.010mm and 0.020mm.

The accumulated machine deviations that require specific corrections for one particular gear design are commonly called the "machine fingerprint." If the workholding and the cutting tool have no deviations from the nominal specification, then the nominal, actual deviation plot of the first-cut part from a CMM represents this machine finger print. Each CMM-based machine fingerprint is linked to a corresponding set of *G-AGE* corrections. The *G-AGE* corrections, which represent the machine fingerprint, could be stored in the respective machine

Figure 1 **Influences to absolute part accuracy from the cutting machine.**

and be superimposed on the theoretical settings of each new job.

In most cases, the final touches to the contact geometry of a bevel and hypoid gear development are made between roll tester and cutting machine. After such a "Gear-Lab" development is finished, the developed machine settings still include the machine fingerprint. If the machine fingerprint is known for a similar job, then this set of fingerprint corrections could be subtracted from the newly developed basic settings, which results in machine-independent settings. Those settings can be stored on the network and sent to any different machine at a later time for the repeated manufacture of this job. In this case the machine receiving the machine-independent settings will superimpose the newly received settings with the fingerprint for cutting this particular job.

Because each job has a unique set of fingerprint corrections, the basic data of a large number of gearsets must be stored in a database — together with the fingerprint corrections of every machine on which they have been cut; every new job sent to a particular machine will activate a data mining tool. Even though the new job has never been cut on any of the machines, the data mining tool will apply a list of similar criteria and find a set of fingerprint corrections for the new job in combination with the selected machine, thus assuring that the flank surfaces of first-cut parts fall within the specified tolerances.

Workholding influences. Workholding (Fig. 2) can introduce runout or part slippage. Influence to the flank surface geometry is basically limited to differences between the labeled arbor distance and the real value. It is possible that the axial draw, depending on the condition of an arbor, changes the effective arbor distance by small amounts.

Cutter head influence to work gear accuracy. Slot bottom radii of cutter heads have a certain tolerance that influences the actual point radius of the cutter head. Commonly, Gleason cutter heads are held in a tight tolerance band. The ability to measure the absolute radial blade position in a cutter head is limited due to a number of factors.

The following procedure is required to predict the radial location of the corner point between top width and blade distance (Fig. 3, left):

The tip of the blade must be captured — not at its high point — but at the blend of the tip edge radius to the top slope. Then the cutting edge must be scanned and approximated with a circular function. This function must then be extrapolated to intersect with the horizontal tangent to the blend point — between top slope and tip edge radius — because the corner point between top width and blade distance is virtual, as it physically does not exist (Ref. 1). The distance between the virtual corner point and the cutter axis is the point radius of the cutter head as it is specified in the summary. The possible measurement accuracy of a stick blade mounted in a cutter head in connection with the extrapolation can only deliver accuracies in the range of ±0.006 mm.

Stick blade seating. The seating between stick blade and cutter head slot introduces potential for radial errors that are minimized by the prismatic seating surfaces of the Pentac cutter heads. The blade seating can introduce radial

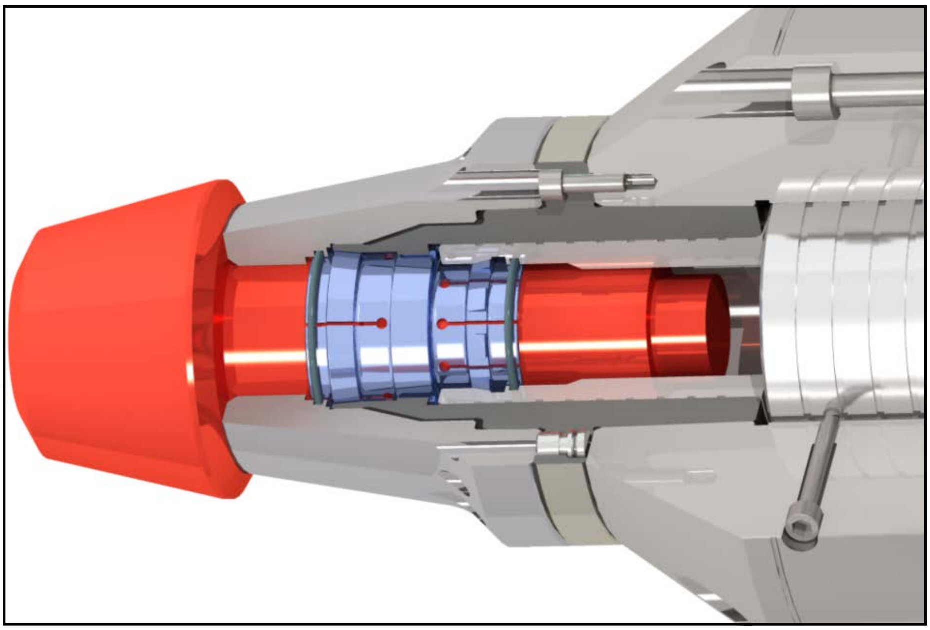

Figure 2 Influence to absolute part accuracy from workholding.

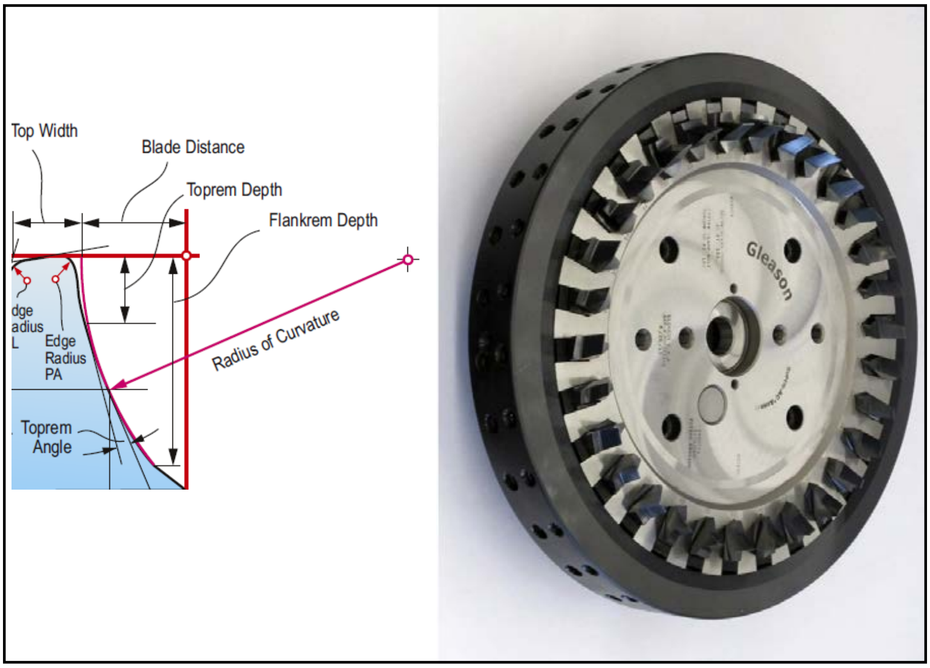

Figure 3 Influence to absolute part accuracy from cutter head.

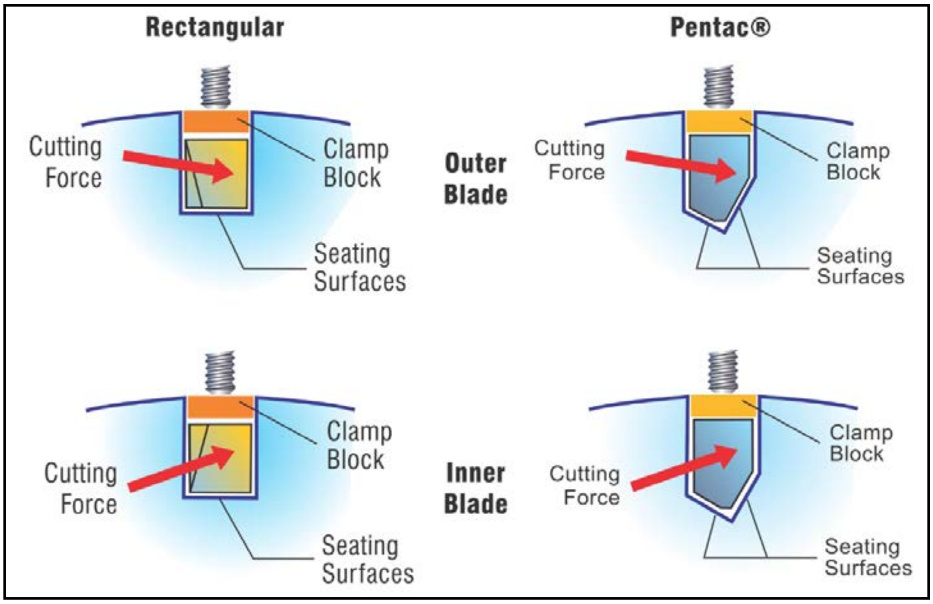

Figure 4 Influence to absolute part accuracy from blade seating conditions.

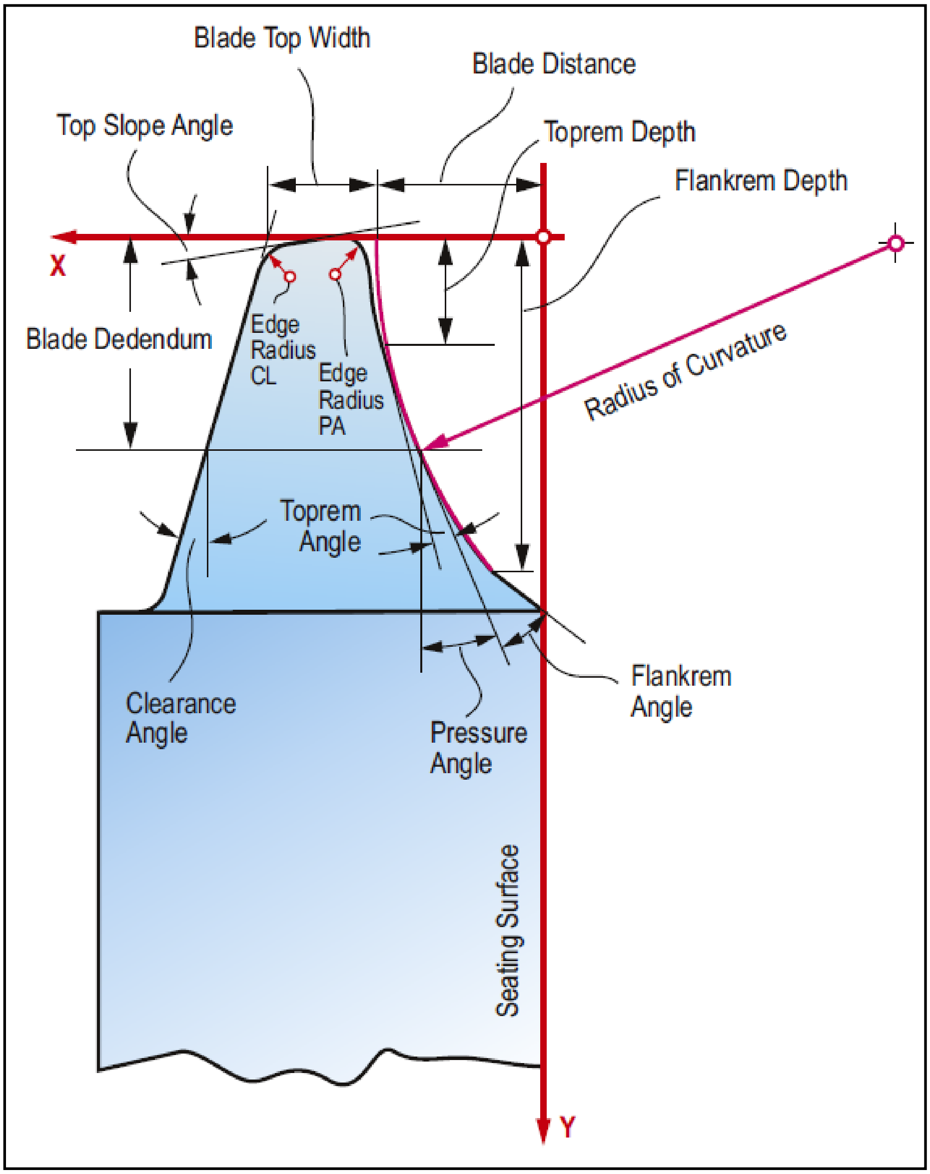

Figure 5 Influence to absolute part accuracy from blade geometry deviations.

dislocation of the blades in the single-micron range; often it is perceived to average out between all the blades of one set. In the case of Formate ring gears, this is incorrect because the "high blade" takes the last chip and leaves its influence on the entire flank form. Blades sticks are not perfectly straight, which causes the blade tips to vary. This variation can be eliminated with radial, truable cutter heads, which, however, will influence the cutter point radius in the 0.010 mm range.

Stick blade geometry. Regarding the blade definitions provided in Figure 5, the pressure angle and the blade distance are the relevant features that assure accurate flank geometry of the manufactured gears. Blade distance and pressure angle of ground stick blades have to be within a certain tolerance. In particular, in the case of curved blades, the deviations between the real blade and the theoretical blade have allowable deviations in pressure angle of 0.05° and in blade distance of 0.015 mm. The BPG blade grinding machine and the GBX measurement machine can assure finish deviations below this magnitude.

Blade grinding measurement and correction. Blade grinding accuracy is influenced by the frequency of machine gaging, grinding wheel dressing, and the condition of the blade clamping fixture. Also, if blades are close to their kill length, the accuracy of the blade geometry is reduced significantly. The closed loop in Figure 6 assures precise blades in the range of less than 0.005 mm — well below the tolerances specified in the last paragraph. However, there may be variations within one set in the magnitude of 0.015 mm and, as mentioned above, the "high blade" will dictate the final part geometry — especially in Formate (Ref. 2).

Blade measurement strategy. The question of measuring the blades on the GBX blade measurement machine on the cutting edge or below the cutting edge can be answered rather easily if geometrical conditions between cutting edge and the spherical tip of the probe in Figure 7 are observed. It becomes evident (Fig. 7) that a measurement between the cutting edge and the measurement sphere results in a metastable condition. This metastable condition degrades if an attempt is made to measure above the cutting edge (red dashed path in Fig. 7). Because of the tolerance of the front face, the effective path of the probe tip versus the cutting edge will be inclined, which is shown exaggerated (Fig. 7).

The path of the measurement sphere will never be able to follow the cutting edge precisely — even if the front face is measured before the cutting edge scanning. In the case of three-face blades, this is even more significant because of the slightly curved front face, which is approximated in the *GABE* software with a plane.

A measurement of 0.005 mm or even more below the cutting edge will provide stable contact conditions between the side relief surface and the measurement sphere. The small differences in blade distance direction due to the side relief angle are compensated by the *GABE* software.

Cutter building. Deviations in overall cutter height (Fig. 8) are the only obvious cause of part inaccuracies. Due to the procedure in cutter build machines like the Phoenix CB or the 500CB, inaccuracies in cutter head thickness are entirely filtered out. The blades are built to the overall cutter height, which reference the blade tip directly to the mounting interface between cutter head and cutting machine spindle.

Figure 6 Influence to absolute part accuracy from blade grinding and measurement.

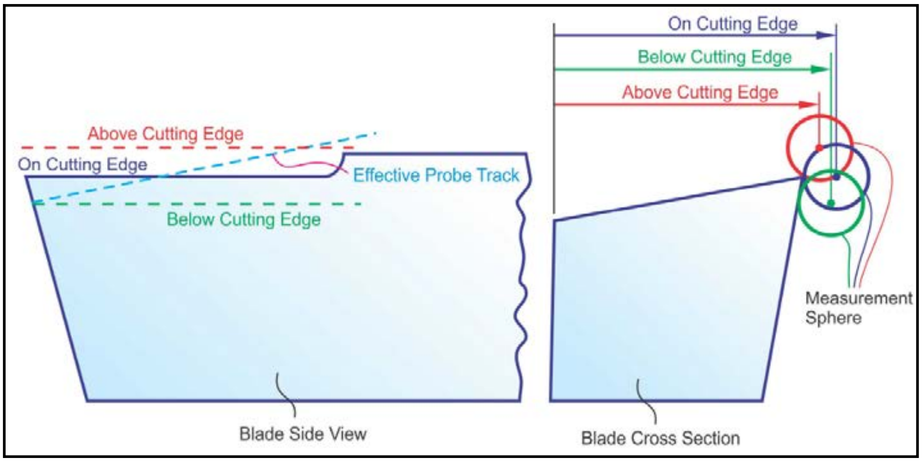

Figure 7 Influence to absolute part accuracy from blade measurement strategy.

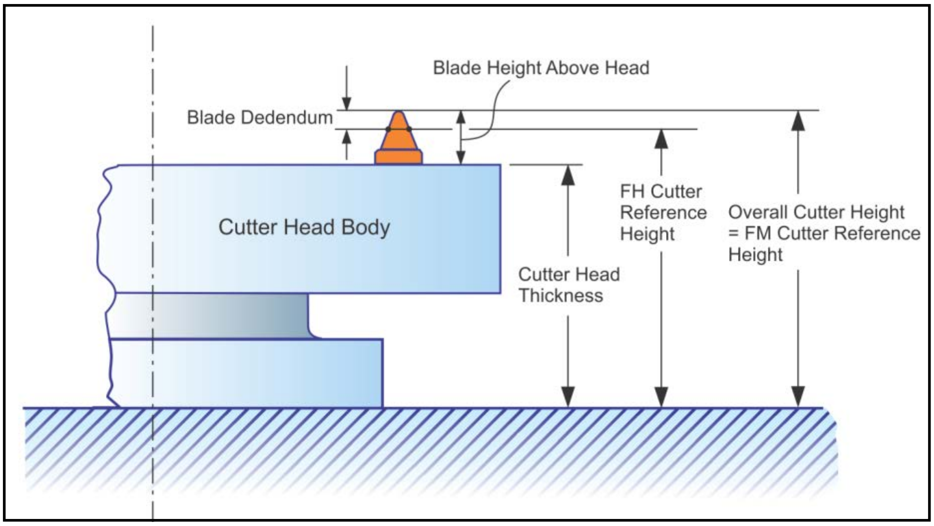

Figure 8 Influence to absolute part accuracy from cutter head building.

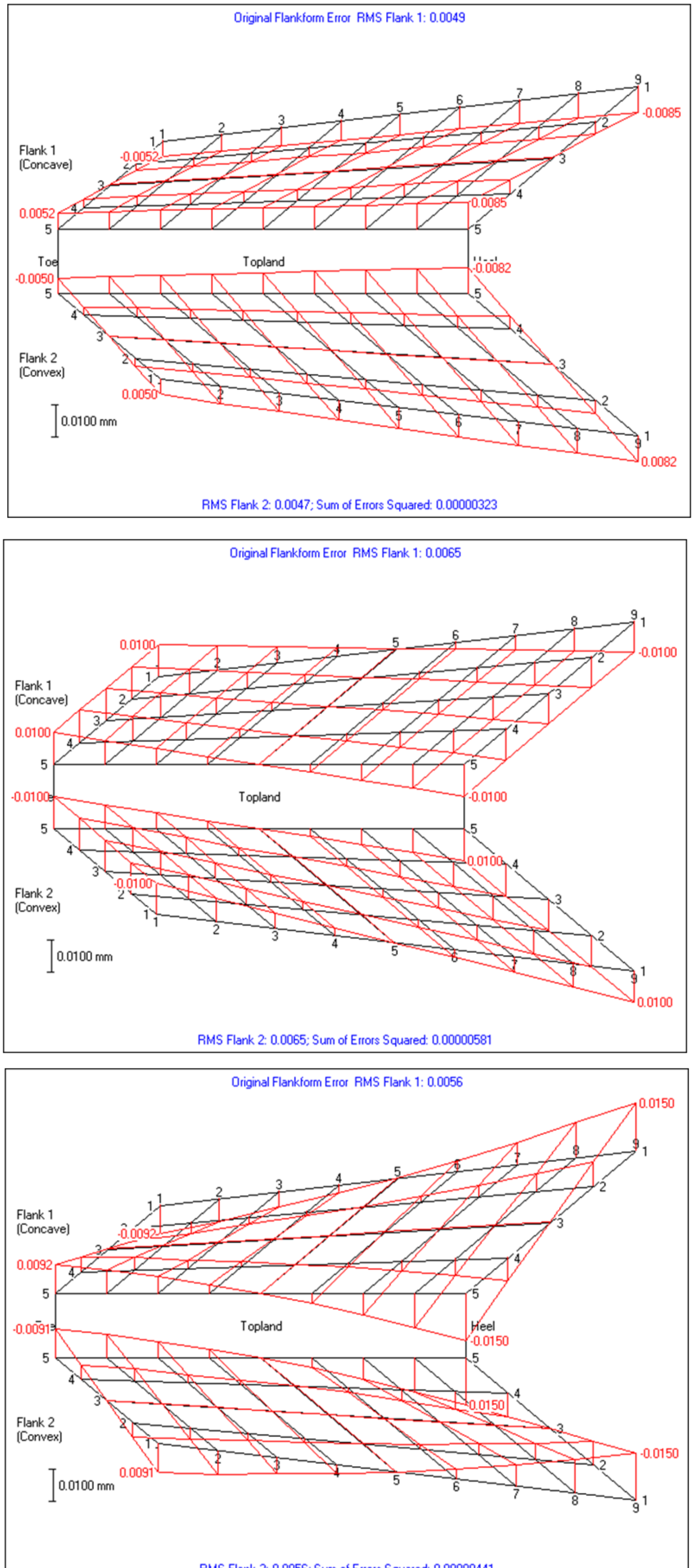

Figure 9 Flank form deviations resulting from machine fingerprint.

Summary of all Workpiece Accuracy Contributing Factors

In this final paragraph, the different flank form errors caused by the single deviations discussed above are modeled with *G-AGE4Win* order to quantify the different sources of deviations (Ref. 3).

Cutting machine errors can be expressed in components that lead to spiral angle errors, pressure angle errors and higher-order errors (Fig. 9).

The workholding can be neglected because — even after re-work — it is always possible to adjust the distance value to the actual number.

The blade pressure angle in the case of a deviation of 0.05° will cause a flank form deviation between 0.020 mm and 0.030 mm (Fig. 10).

The collective influence of the slot bottom radius tolerance and the blade distance deviation of blades ground within the recommended tolerance are shown (Fig. 11). Both the influence of the cutter head and the influence of the blade distance variation result in a length crowning error of 0.004 mm, as shown in the deviation plot.

In order to gain a statistically realistic overall deviation from nominal, caused by all machine and tool influences, the worst-case combination of the graphics in Figures 9, 10 and 11 are superimposed (which is an unrealistically high deviation) and then reduced to 60%. The result, shown in Figure 12, reflects the probable nominal-actual deviation if all elements of the manufacturing are within tolerance and no *G-AGE* correction has been made.

The graphics in Figure 12 show realistic results with a dominating pressure angle error on the concave side, and a dominating spiral angle error on the convex side. However, both sides contain elements of spiral angle error, pressure angle error and twist. The maximal corner point amplitudes are 0.029 mm and 0.026 mm.

If the manufacturing cutting machine is eliminated, then the remaining 60% deviation probability of the cutter head and blade influence are shown (Fig. 13); the maximal corner deviations are 0.021 mm for both sides.

One attempt to eliminate the cutting machine is to develop for a new design the ring gear and the pinion — each on a particular machine. However, the cutter head cannot be eliminated because, as shown above, even pressure angle errors can be caused by the cutting machine fingerprint. If the first part of a new batch (previously developed job) is measured against the nominal data in the theoretical CMM download file, then a certain "base load error" is already contained in the first-developed reference part; statistically, 60% of all occurring cutter deviation will add to the base load error of the development part. In other words, the cutter deviations were never separated from the machine deviations.

Philosophical or Rational Conclusion?

If it has been decided to always use the same machine for a particular pinion or gear, then the machine and cutting tool fingerprint is *partially* eliminated from the deviation graphic in Figure 12, because the developed machine summary contains both. This statement is correct if the last-developed summary — which was developed on the respective machine — is used to cut the first part of a new batch. Remaining errors in the nominal-actual CMM deviation plot are the only flaw. Those deviations are caused by the cutting machine, as well as by the cutting tool.

If a new cutter head with re-ground blades is used, the cutting tool fingerprint changes. Depending on the location of the developed blade geometry within the tolerance band, the next ground set of blades might fall at the opposite border of the tolerance band. Because the remaining nominal-actual CMM deviations contain part of the cutting machine fingerprint and part of the cutting tool fingerprint, the new cutter head and the new set of blades are confronted with this "base load error."

If a manufacturer permits ±2' of pressure angle error with a "base load error" of +1' and a tolerance of blade grinding of ±1.5', then the realistic likelihood of cutting a good first part is 50%. But it is more realistic that small, additional machine-inflicted deviations, plus additional deviations from the use of a different cutter head, will reduce the likelihood of a good first part to 25%.

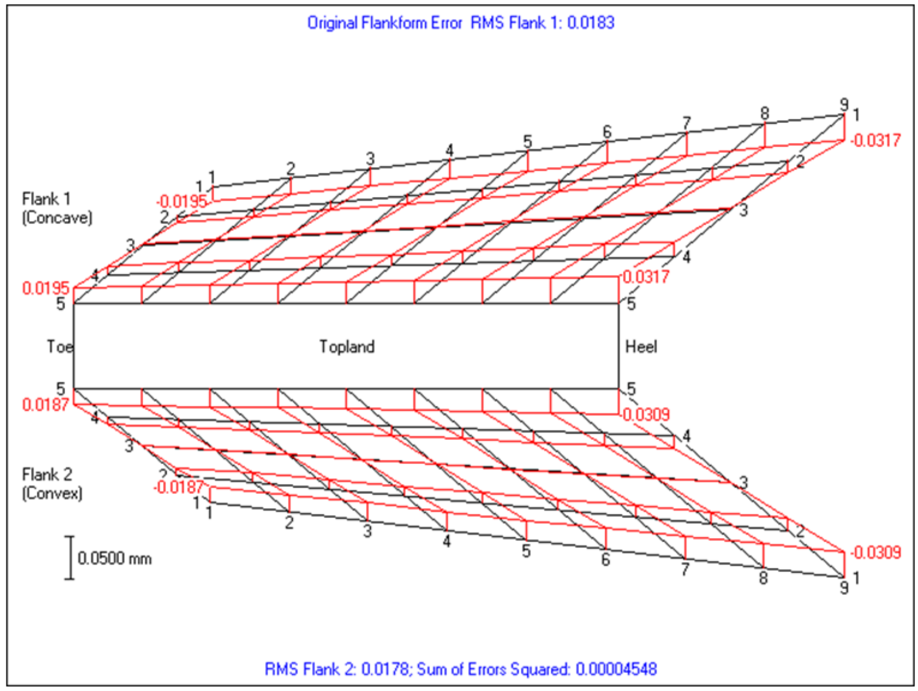

Figure10 **Flank form errors resulting from blade pressure angle deviations.**

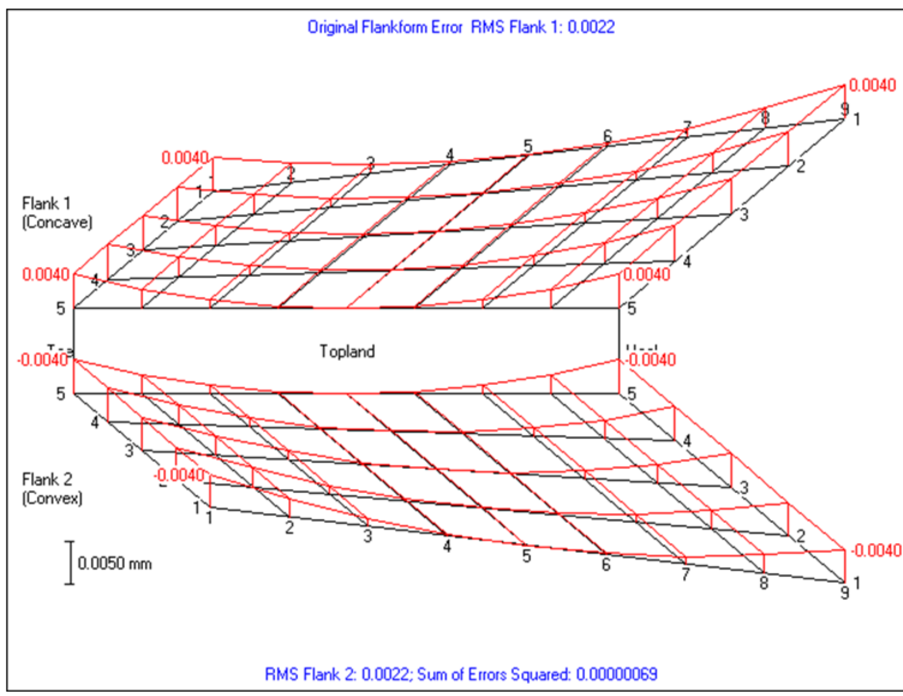

Figure11 **Flank form errors resulting from cutter head and blade distance deviations.**

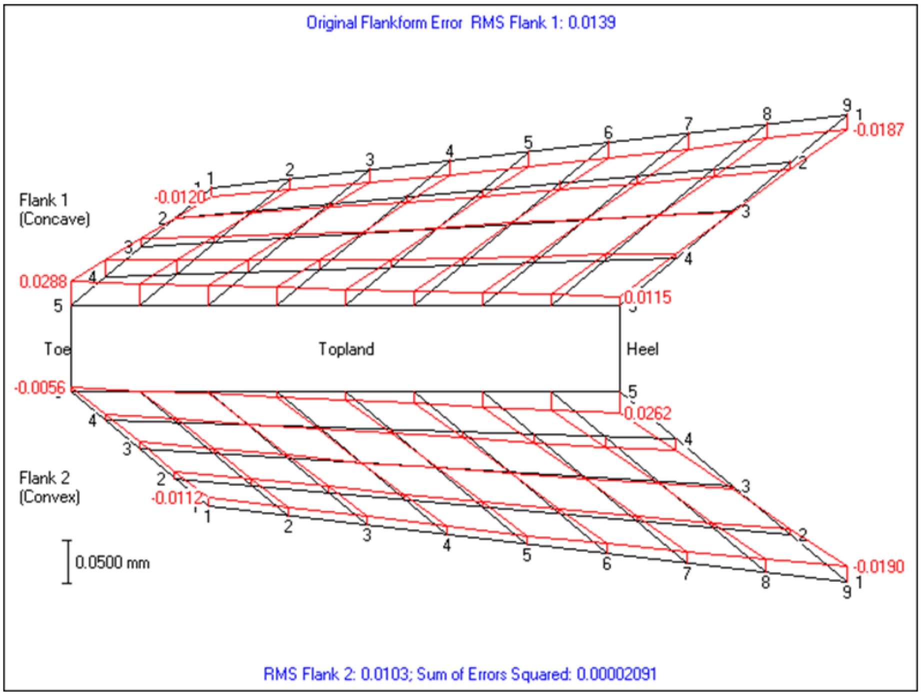

Figure12 Statistically probable total deviation in first part without any corrections.

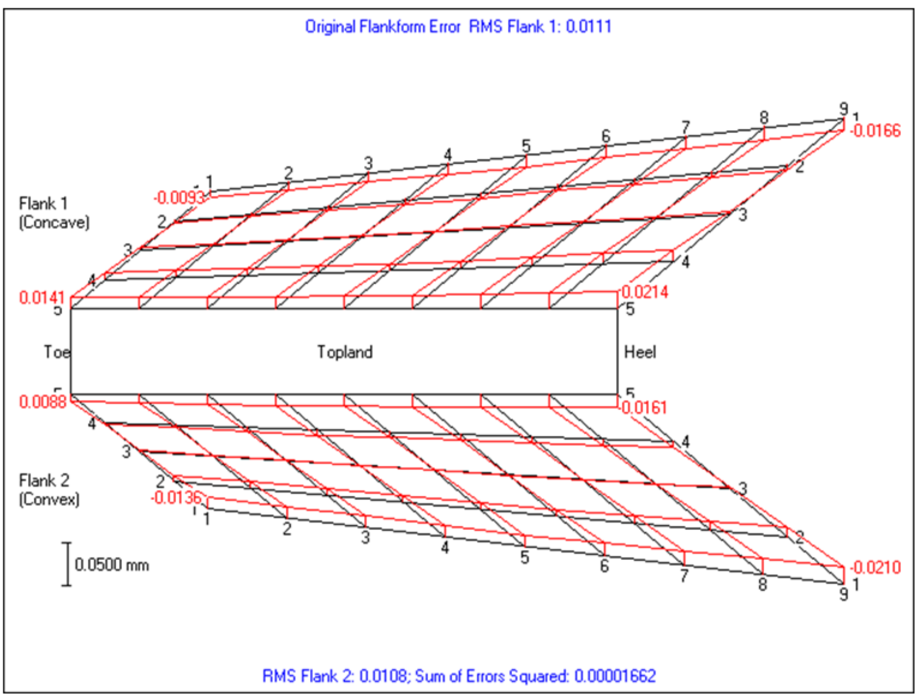

Figure13 Statistically probable deviation from blades and cutter head.

The solution of the problem is the RF30 of the flank surface deviation after finishing a development and creating the original reference set. The RF30 function sets all deviations between nominal and final development to zero, and with that produces a reference for all future gearsets of this particular design.

In many cases, duplicates of the reference gearset have been qualified in NVH and strength investigation. From this point on it is no longer desirable to manufacture parts with zero deviation versus the original theory, as the original theory has slightly different specifications than the qualified geometry of the reference parts.

The physical reference gearset, often with a rolled tooth contact, is used as the ultimate master for future batch manufacturing; it is good engineering practice to create the corresponding electronic master. The RF30 function after 3-D measurement of the reference gearset delivers the electronic masters. This procedure is applied by 90% of all bevel and hypoid gear manufacturers who use coordinate measurement machines for their gearset development and manufacturing control.

The argument that the theoretical basis (SPA-File) no longer exists as soon as the RF30 function is applied is false. Gleason-developed software allows backfeeding of the "nominal-actual" deviations of the final reference gear, thereby creating an effective/developed SPA-File.

Applying the RF30 function will promote the "first part right" strategy and establish a clean basis by which reference part, CMM electronic master file, and SPA-File are identical.

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For more information.

Have questions or comments regarding this technical paper? Contact Gleason Corp's Dr. Hermann Stadtfeld at *hstadtfeld@gleason.com*.

Dr. Hermann J. Stadtfeld received in 1978 his B.S. and in 1982 his M.S. in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994—joining The Gleason Works—also in Rochester—first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002–2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to *Gear Technology*), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents on gear design, gear process, tools and machinery.