CNC Face Milling of Straight and Spiral Bevel Gears

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Introduction

Contrary to what appears to be popular belief, 5-axis CNC gear manufacturing is not limited to milling with end mill, ball mill or *CoSIMT* (*Conical Side Milling Tool — it is the generic form of the Sandvik InvoMill and Gleason UpGear tools*.) tools, where throughput is too low to prevent production at any significant level.

Straight and spiral bevel gear manufacturing on 5-axis CNC machines using face mill cutters provides essentially the same throughput as conventional gear cutting machines — with these added benefits:
- Machine setup time is near zero, as opposed to mechanical machines
- Different gear types can be cut on the same CNC machine
- Blank turning can be done on the same CNC machine prior to gear cutting
- Deburring and chamfering can be performed on the same machine after tooth flank generation

The end result can be a part with only one chucking operation, which pretty much eliminates material handling, intermediate storage and repetitive runout adjustments at chucking.

The part programs for each step, i.e. — blank turning, tooth cutting (generation or plunge cut), and deburring/chamfering — can be combined so that only one program need be fed to the CNC controller to completely produce a part. This significantly reduces the risk of errors and enables storing the complete manufacturing definition of any part in a single file.

Currently, CNC face milling is dominated by Gleason's Phoenix and Klingelnberg's C-series machines — both 6-axis-capable. (*In the following, the Gleason Phoenix and Klingelnberg C-series machines will be referred to as "Phoenix-type" machines*.) While both offer superior machining quality and reliability, they cannot be used for any other purpose — blank turning, for example — because the proprietary interface between user and controller does not allow it.

It is also an expensive proposal to cut small-size, straight and spiral-bevel gears — say in the 1 to 3.5 mm module range — on machines targeted for more noble tasks.

The CNC machines found on the market vary in size and capability, and can handle blank diameters anywhere from less than 10 and up to 2,500 mm.

In face milling, one major limit is related to the capacity of the spindle to deliver the torque required by the face mill cutter and provide sufficient stiffness to guarantee vibration-free cutting and, accordingly, a good tooth surface.

Standard Coniflex (*Coniflex is a registered trade mark of the Gleason Works, Rochester NY*.) dish-type cutters for straight-bevel gears come in diameters of 4.25", 9" and 15". Therefore, modules above 5 to 6 mm, where cutter diameter is likely to exceed 9", cannot be accommodated on most 5-axis CNC machines, given the large cutter diameter and associated mass.

Standard face mill cutters for spiral bevel gears range from 1" to well above 15", in variable steps. A practical upper limit for a 5-axis CNC machine appears around 6" because of cutter mass and required spindle torque, which allows the face milling of spiral bevel gears up to around 6 mm module. For larger modules, CNC machines become as large and expensive as comparable Phoenix-type machines.

Both Coniflex cutters for straight bevel gears and face mill cutters for spiral bevel gears can be purchased from different vendors, either in solid form or with adjustable blades that can be reground separately, if tool procurement is not an issue.

However, the generation of the part programs that replicate exactly face milling cutting processes such as fixed setting, spread blade and duplex helical (*all registered trade mark of the Gleason Works, Rochester NY*) is a significant issue faced by manufacturers willing to cut Coniflex or spiral bevel gears on 5-axis CNC machines.

If end mill or ball mill tools are used, commercial software such as *SolidCAM*, *MasterCAM*, *GibbsCAM*, etc. can drive the tool if a point-cloud surface — a *STEP* file for example — is provided.
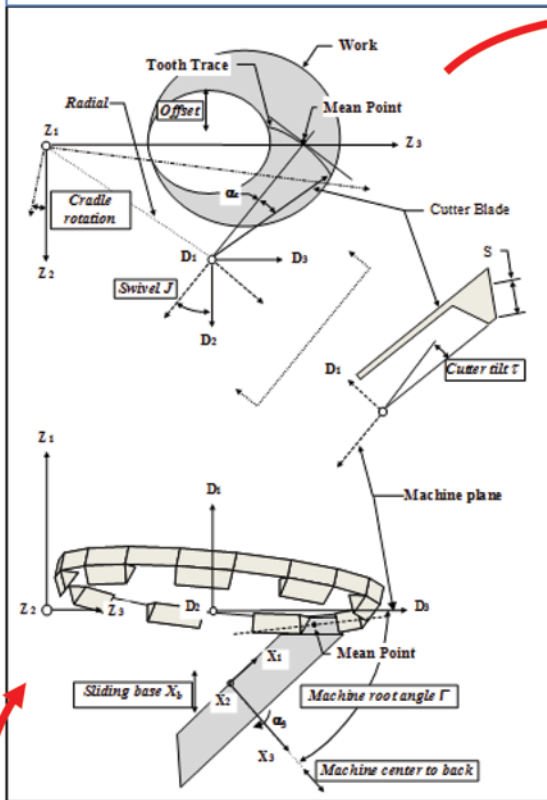
Gleason's *UpGear* process (Ref.1) is intended only for *CoSIMT*-type tools on Gleason-Heller 5-axis CNC machines. While it replicates exactly a spiral bevel gear from its machine settings, it does not allow face milling. Dontyne's *CLGM* (Ref. 2), GWJ's *Gear Engineer* (Ref. 3), *KISSsoft's* CNC module (Ref. 4), and DMG-Mori's *gearMILL* (Ref. 5) all offer spiral bevel gear modules cutting with end mill and ball mill tools, and currently do not replicate the Fixed Setting, Spread Blade and Duplex Helical (all *registered trade mark of the Gleason Works, Rochester NY*.) cutting cycles from the basic machine settings.

On the other hand, aside from Gleason's *CAGE* and Klingelnberg's *KIMoS*, *HyGEARS* (*HyGEARS is a registered trade mark of Involute Simulation Softwares, Quebec, Canada*) (Ref. 6) is the only software capable of generating the same exact Coniflex straight bevel gear and face milled spiral bevel gear tooth surfaces when using the same machine settings — for any cutting process. *HyGEARS* has been in use on conventional and Phoenix-type machines since 1994 and on 5-axis CNC machines since 2012, with results consistently identical to those of *CAGE* and *KIMoS*.
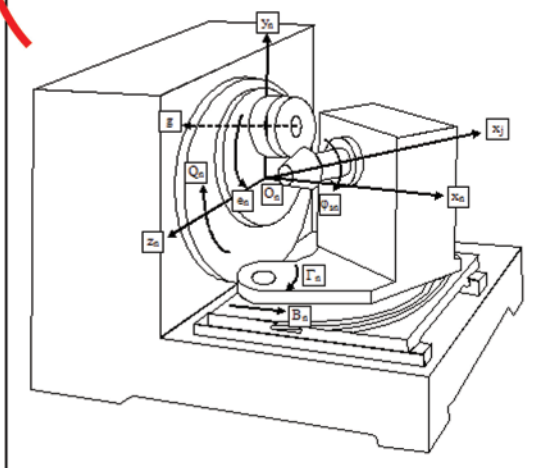
The next paragraphs introduce some *HyGEARS* basics, such as the *Tooth Flank Generator* (*TGF*) and the closed loop. Examples illustrate actual use in industry.
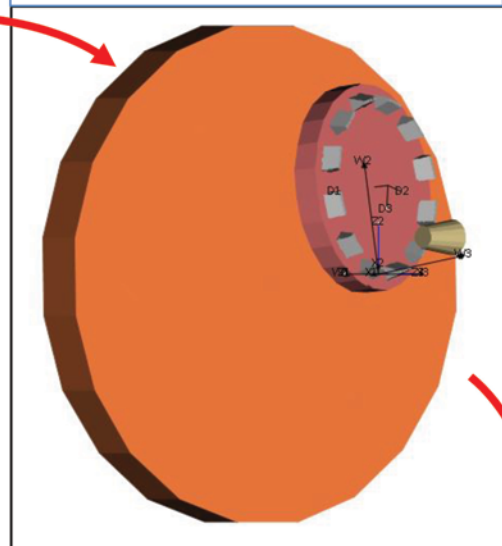
The HyGEARS Tooth Flank Generator

2: *A Vector Model is created from the reference frames of the machine in* **1:**

3: *A digital machine is obtained from the Vector Model in* **2:**

4: *A digital gear set is obtained using the digital machine in* **3:.**

1: *The reference machine is discretized as a series of reference frames connected by rotations and translations.*
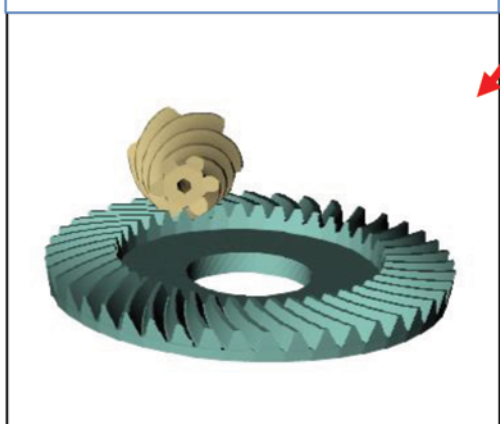

Figure 1   Logic of *HyGEARS* Tooth Flank Generator.

The *HyGEARS* Tooth Flank Generator

HyGEARS is built around an advanced *Tooth Flank Generator* (*TFG*) (Ref. 7) that can be described as a group of software functions defining the shape of a tool and its movements relative to a workpiece, i.e. — the functions replicate the generating process.

The generating process describes one cutter blade, representing one tooth of a theoretical generating gear that meshes with the workpiece. The fundamental relation is:

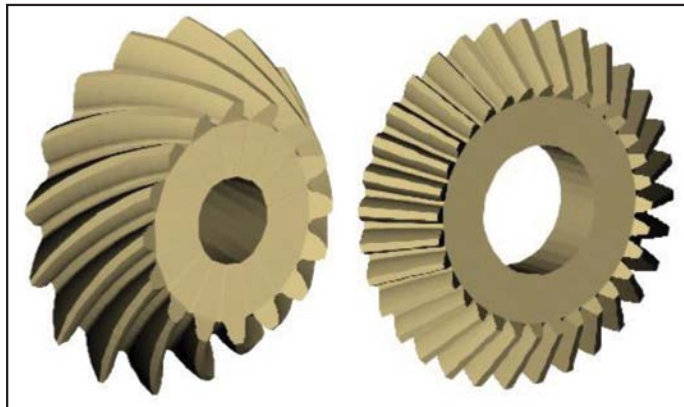$$\overline{N} \cdot \overline{V}_r = 0 \tag{1}$$

Figure 2   Spiral bevel and Coniflex pinions.

Pinion [Finishing]/Th.Err:-0.0016 [Nominal] [Meas.Surface : pinnom0337.teo/1]
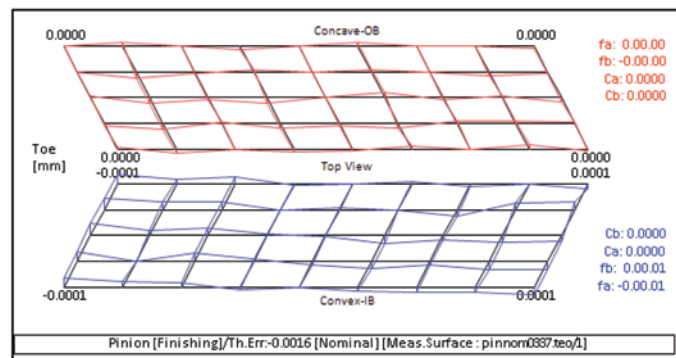
Figure 3   Software comparison: Gleason's *CAGE* vs *HyGEARS* Simulation.
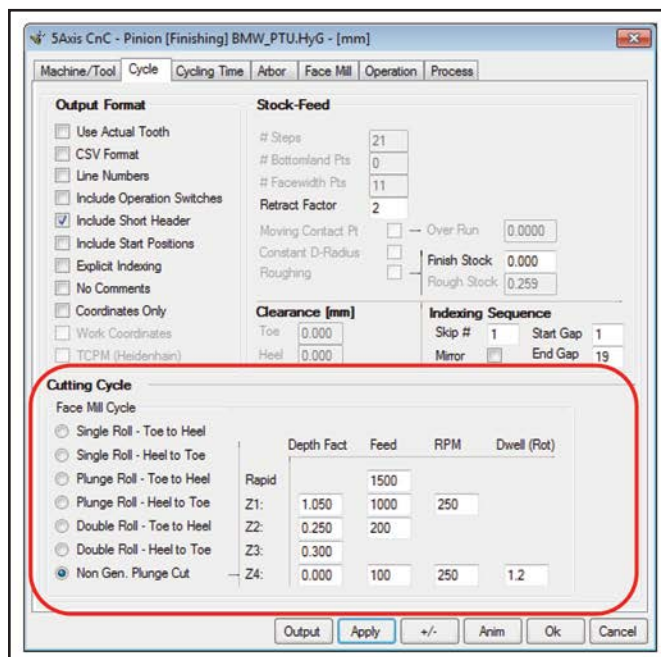

Figure 4   *HyGEARS* face milling cycles.

Where — the relative speed vector between tool and work surfaces is in a plane perpendicular to the common normal vector.

When applied to the reference frames (Fig. 1, upper-left), Equation 1 yields an unbounded surface in a reference frame attached to the workpiece. The surface is a function of the machine settings and three variables, respectively — cutter position α_c (angular or linear), workpiece roll angle α_3 and S, the position of a point along the edge of the cutter blade:

$$S = f(\alpha_c, \alpha_3) \tag{2}$$

The solution (Eq. 2) is a series of contact points between cutter blade and workpiece describing a line along the path of the cutter blade. The envelope of a series of such lines is the generated tooth. Figure 2 shows a spiral bevel and a Coniflex straight bevel pinion obtained by replicating one generated tooth around the axis of rotation.

The *TFG* includes work and tool adjustments and movements found in conventional and Phoenix-type cutting machines. In all CNC machines, machine settings can be continuously altered during cutting to allow improvements in gear kinematics; these alterations include modified roll and helical motion — both supported by the *HyGEARS TFG*.

Figure 3 compares the pinion IB and OB tooth surfaces simulated by Gleason's *CAGE* (red and blue lines) and *HyGEARS* (black lines) for the same machine settings. Clearly, the *HyGEARS* tooth surfaces match those of Gleason's *CAGE* within 0.1 µm. This is true for all face mill cutting processes when the same machine settings are used.

It can be debated whether the parametric definition of a gear tooth from machine settings and cutter tool geometry is better or worse than a point-cloud, such as a *STEP* file. The machine settings-based definition allows creating a point-cloud that can be fed to commercial CAM software, capable of generating part programs; the opposite of course is not possible. In addition, point-cloud-based surfaces are subject to mathematical waviness caused by interpolation. Surface waviness affects surface coordinates and normal and tangent vectors, which often leads to some level of inaccuracy in the resulting tooth flank topography.

Beyond these debatable considerations, *TFG* software (such as that used in *HyGEARS*) ensures that production — in small, medium or large batches — can be dispatched to any conventional, Phoenix-type, or 5-axis CNC machine with the same end result, as the tooth is defined with the same parameters.

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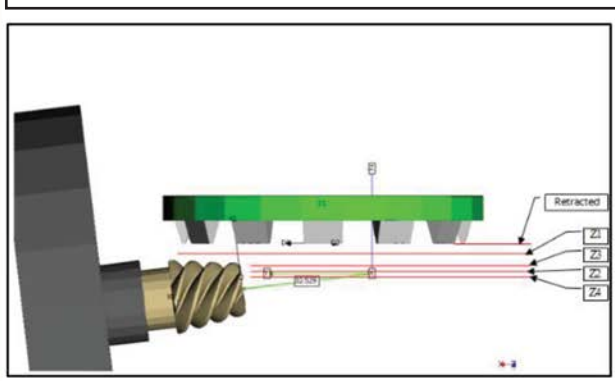
Cutting Cycles

In order to completely cover the tooth, conventional and Phoenix machines may plunge the face mill tool slightly before generation begins and retract the tool slightly after generation ends; or plunge at center roll and then roll in each direction before retracting and indexing. Tool plunge is critical since too fast a movement may damage the cutting blades when hitting the blank. Plunge is also critical in cycle time since it creates a bottleneck because of the usually slow plunge feed rate. Up-roll and down-roll in single and double roll cycles are also required to cover LH and RH cutters.

HyGEARS offers a comprehensive set of face mill cutting cycles (Fig. 4).

Toe-to-heel and heel-to-toe cycles for single roll, plunge roll, double roll and non-generated plunge cut can be selected for generated gears, and non-generated plunge cut for non-generated gears. By selecting an appropriate toe or heel clearance the tool can be plunged outside the part and thus allow fast plunge, thereby reducing cycle time. Return from end to beginning of cycle is done at high feed rate, again to reduce cycle time. Finally, the non-generated plunge cut cycle offers a comprehensive set of possibilities to guarantee excellent results (Fig. 4).

For Coniflex gears, only one cutting cycle is offered in which the flanks on one side are generated, after which the tool changes sides and cuts the opposite tooth flanks (Ref. 9). Thus only one Coniflex tool is used — as opposed to the cutter pairs found on Gleason mechanical machines. Using a CNC machine allows setting up each flank differently in order to obtain specific kinematics, if desired. As shown by Stadtfeld (Ref. 9), cycle times of CNC versus mechanical machines can be slightly longer; but since the same machine can be used to cut other gear types, the time disadvantage is out-weighed by the flexibility advantage.

The Closed Loop

The *Closed Loop* (Ref. 10), i.e. — *Corrective Machine Settings* — calculates the required changes in machine settings to remove manufacturing errors and match the manufactured tooth surface to the design. This implies that the theoretical tooth flank surface is known from the cutter definition and the machine settings, and therefore excludes a point-could approach.

Given machines vary from one to another, and are not always exactly identical to their definition, and given actual tools can be slightly different from their design values; *Closed Loop* is usually required to eliminate manufacturing errors when face milling gears. *Closed Loop* requires a coordinate measuring machine; *HyGEARS* supports all major CMMs on the market.

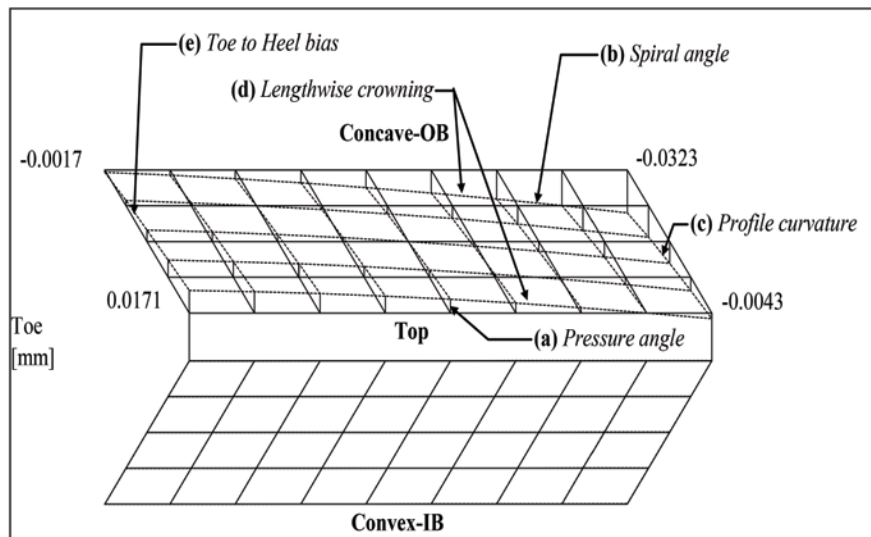Surface errors can be classified in two broad categories (Fig. 5):

Figure 5   Typical surface errors.

- First order : pressure angle (a) and spiral angle (b)
- Second order: profile curvature (c), lengthwise crowning (d), toe-to-heel bias (e)

The *HyGEARS Closed Loop* algorithm finds a set of machine settings that minimizes surface errors. The modified machine settings are then used to generate a new part program based on the selections made for the first cut.

Closed Loop is integral to *HyGEARS* for all the supported cutting processes — for both Coniflex and spiral bevel gears.

Global View of *HyGEARS*

Figure 6 shows graphically how *HyGEARS* is integrated: 1) different gear types can be designed (or imported from existing summaries) and analyzed; 2) part programs are created for any tool and saved as parametric operations; 3) the part is cut on any CNC machine; 4) the part is measured on any CMM; 5) *Closed Loop* is calculated from CMM output; 6) the part program is re-generated using the modified machine settings of the *Closed Loop*; and 7) the part is re-cut — if needed.
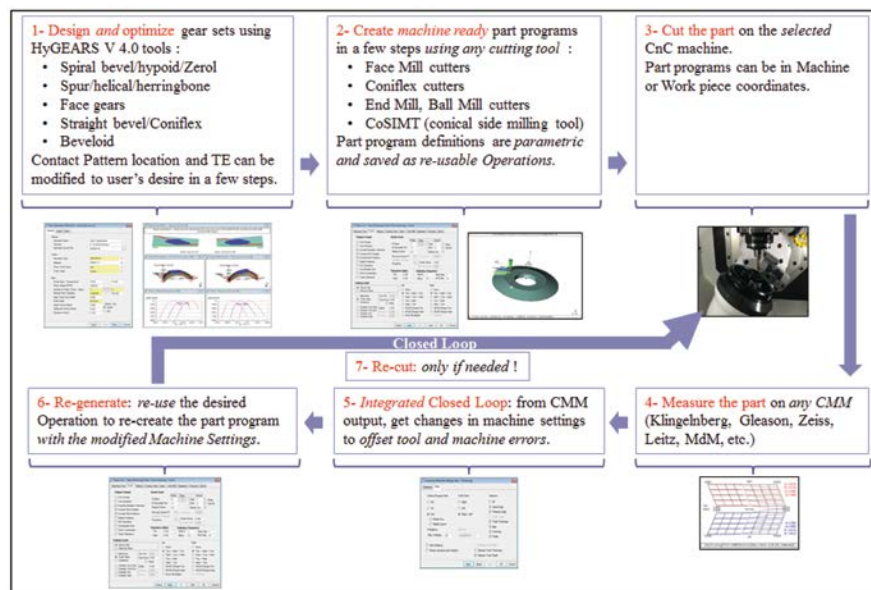

Figure 6   *HyGEARS*: global view.

Applications

The two following application examples show results obtained using *HyGEARS* to face mill different geometries on 5-axis CNC machines; such results are typical of actual production.

Application 1. **32-tooth, 1.25 mm module, Coniflex pinion; 4.25" dish-type cutter.** The pinion was cut on a tilting turntable-type 5-axis CNC machine with a Coniflex dish-type cutter. The first cut yielded the results seen in Figure 7; helix (*fb*) and pressure (*fa*) angle errors are visible on both tooth flanks.

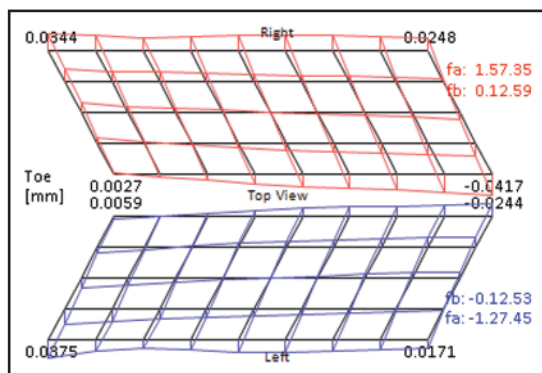| Table 1 Averaged surface errors after first cut			
AVERAGE ERRORS		**(Right)**	**(Left)**
Tooth Thickness	:	0.0087	
Pressure Angle	:	1.57.35	-1.27.45
Helix Angle	:	0.12.59	-0.12.53
Crowning	:	-0.0029	-0.0050
Profile Curvature	:	-0.0024	-0.0032

Figure 7 Error surface after first cut.

Figure 8 shows the same part after the first *Closed Loop* iteration; pressure and helix angle errors have all but disappeared.

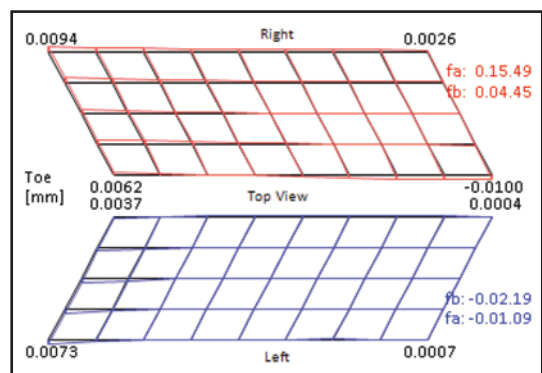| Table 2 Averaged surface errors after correction			
AVERAGE ERRORS		**(Right)**	**(Left)**
Tooth Thickness	:	0.0087	
Pressure Angle	:	0.15.49	-0.01.09
Helix Angle	:	0.04.45	-0.02.19
Crowning	:	-0.0024	-0.0049
Profile Curvature	:	0.0017	0.0019

Figure 8 Error surface after correction.

Application 2. **26-tooth, 1.5 mm module, duplex helical spiral bevel pinion.** The pinion was cut on a tilting turntable-type 5-axis CNC machine using a 2" face mill cutter. The first cut yielded the results seen in Figure 9; pressure (*fa*), spiral (*fb*) angle and bias errors are visible.
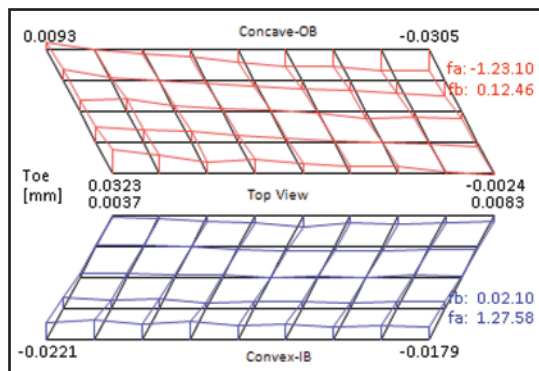

Figure 9 Error surface after first cut.

Figure 10 shows the error surface after the first *Closed Loop* iteration; clearly, pressure, spiral and bias errors have been corrected.
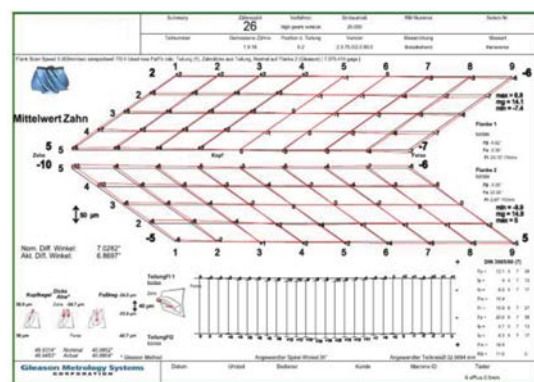

Figure 10 Error surface after correction.

Cycle Times and Quality

The idea of cutting face milled spiral bevel gears on a 5-axis CNC machine rather than a dedicated gear machine is valid as long as cycle times and gear quality are up to standards. Table 3 shows the cycle times required to cut a 9×59 spiral bevel gear set on a small 5-axis CNC machine; the module is 2.5 mm and cutter diameter is 6". The pinion is generated duplex helical, while the gear is plunge-cut (Formate); Figure 11 shows the gear after soft cut.

Table 3	Sample cycle times and DIN quality	
	Pinion Z=9	**Gear Z=59**
Grinding only	3m 52s	16m 29s
Quality achieved	DIN 4	DIN 4
Cutting & chamfering	7m	15m 30s
Quality achieved	DIN 6	DIN 6

Figure 11   Z = 59 gear after soft cut.

Conclusions

Face milling of spiral bevel and straight bevel gears on 5-axis CNC machines is a practical and economically advantageous solution for the manufacturing of small module bevel gears in any kind of batch size, because it allows cutting different gear types on the same machine. Gear blank turning before — and chamfering after — tooth generation can also be performed on the same machine to yield a net part with only one chucking operation.

The *HyGEARS* software uses a *Tooth Flank Generator* tested in the gear industry for more than 2 decades. The *TFG* produces exactly the same micro-topography as Gleason's *CAGE* and Klingelnberg's *KIMoS,* when given the same machine settings. This ensures total compatibility between production on 5-axis CNC machines and other machines, conventional or Gleason Phoenix /Klingelnberg C-series.

CMM nominal target files are produced from the *HyGEARS TFG* for any CMM on the market and are thus perfectly compatible with those of Gleason's *CAGE* and Klingelberg's *KIMoS.*

Gears can be designed and optimized from scratch in *HyGEARS*, or the machine settings of existing gearsets can be entered/imported to produce the same tooth surface as that obtained on a conventional or Phoenix-type machine.

HyGEARS generates machine-ready face milling part programs for any 5-axis CNC machine available on the market, and is thus manufacturer-independent. The integrated closed loop allows correction based on CMM output.

HyGEARS, being manufacturer-independent, allows the use of CNC machines already available, or the flexibility to shop around for the CNC machine best-suited size-wise, cost-wise and flexibility-wise for the intended applications — a clear advantage for the manufacturer.

For more information. Questions or comments regarding this technical paper? Please contact **Claude Gosselin**; *hygears@gmail.com.*

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Dr. Claude Gosselin is president (1994–present) of Involute Simulation Software, a developer and distributor of *HyGEARS* software. Previous experience includes work as a designer for Pratt & Whitney Canada Ltd (1978-1980) in gearbox design; computer software; and R&D. He also held a longtime professorship in mechanical engineering (1988–2007) at his alma mater, Laval University, Quebec, and elsewhere did post-doctoral studies in the department of precision engineering at Kyoto University (1987) Japan, hosted by Professor Aizoh Kubo. Gosselin has also served (1996–1998) as an associate editor for the ASME Journal of Mechanical Design.

Dr.-Ing. Joachim Thomas is managing director (2015–present) of ZG Hypoid GmbH in Dietersheim, Germany. His work experience includes stops at MAN Truck Company (1998–2000) — team manager; Klingelnberg (2000–2008) — manager, application engineering; and Voith Turbo (2009–2014) — various manufacturing-related managerial roles. He has also served (2006–2015) as convener of the FVA bevel gear committee and has been (2009–present) a visiting lecturer at Technical University of Munich. Since 1995 Thomas has served as a member of the ISO committee for the rating of bevel gears and tolerances.

B. Ing. Nicolai Meixel was named this year (2018) production manager for custom gearboxes at Neugart GmbH, Germany. Previously (2012–2018), at Neugart's Gearing Competence Center, he was responsible for setting-up and managing a new department for bevel gear design and manufacturing using *HyGEARS* V4 simulation software; calculation of macro- and micro-geometry of straight, spiral bevel and hypoid gears; management of production control on 5-axis CnC machines, including Closed Loop; and development of grinding and fast deburring solutions on 5-axis CnC machines.