CNC Bevel Gear Generators and Flared Cup Gear Grinding

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New freedom of motion available with CNC generators make possible improved tooth contact on bevel and hypoid gears. Mechanical machines by their nature are inflexible and require a special mechanism for every desired motion. These mechanisms are generally exotic and expensive. As a result, it was not until the introduction of CNC generators that engineers started exploring motion possibilities and their effect on tooth contact.

This article covers the exploitation of new motion freedoms to improve tooth contact patterns on gear sets manufactured by a face-milling duplex process, a manufacturing method where both flanks are completed in a single operation.

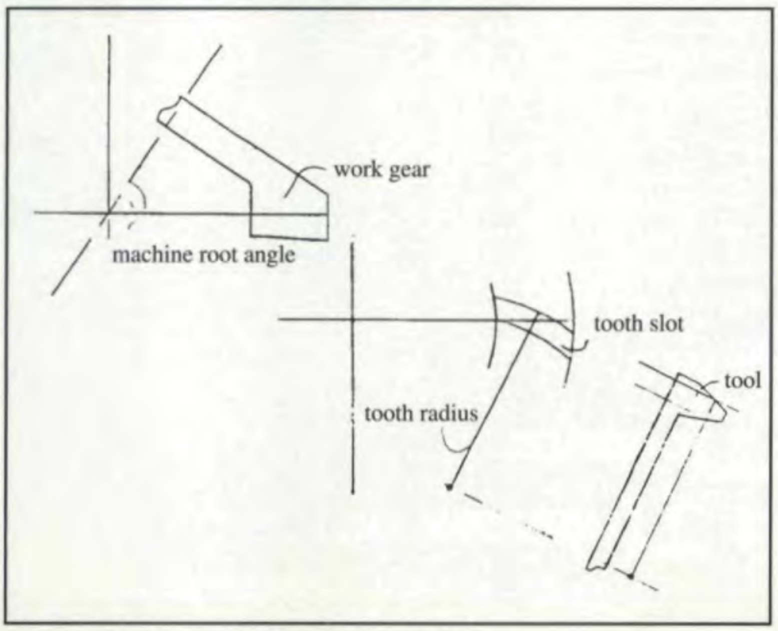

Fig. 1 — Conventional face milling duplex setup.

Starting with a brief background of the flared cup process, the article proceeds to describe the possible linear and angular motion variations and their effect on the gear tooth surface. The article concludes with the use of Tooth Contact Analysis (TCA) to evaluate the enhancement of this duplex process made possible by applying these motions.

Flared Cup Process

When cutting face milled gears using this operation, the cutter is positioned relative to the gear blank, so that the correct spiral and pressure angles will be produced. The gear blank is held stationary, and a tooth slot is form-cut by infeeding the cutter. The part is indexed one pitch, and the process is repeated. See Fig. 1. When the cutter is replaced by a grinding wheel, contact exists over the entire length and depth of the tooth surface. Heat buildup results, causing a tendency for surface damage because ofburning. The flared cup grinding process is used to overcome this problem.

The flared cup process uses a wheel which is tilted out of the work (30°s of tilt is commonly used). The outside wheel surface has a normal radius of curvature less than the conventional tool, and the inside wheel surface has a normal radius of curvature greater than the conventional tool. Line contact exists between the work and the wheel. The wheel is positioned relative to the gear blank so that at the calculated mean position on the gear tooth surface, the correct spiral and pressure angles are produced. The tilted axis of the wheel is in a plane normal to the tooth surface. In achieving this setup the tilted axis is offset from the conventional tool axis. The tooth is swept out by rotating the flared wheel about the axis of the conventional tool axis. See Fig. 2.

As the wheel is dressed its radii change, which requires compensating machine changes to maintain the proper tooth geometry. Making these setting changes manually on mechanical machines is a problem. Tooth geometry often varies from part to part. Full CNC machines, where wheel radius can be accurately determined, are programmed to automatically compensate for wheel size changes resulting from dressing.

Wheel life is a function of the radius change which occurs as a result of dressing. Over the useful life of a wheel, the relative curvature decreases between the convex tooth surface and the inside wheel surface and increases between the concave tooth surface and the outside wheel surface. Although the final tooth surface is produced by line contact, at any instant surface contact exists between the wheel and work in proportion to the depth of grind. The contact area is dependent on the relative curvature between the wheel and work and the variation in the contact area between the two tooth sides is used to determine wheel life. As a rule of thumb, good results are obtained when the difference in contact area between the two sides of the tool does not exceed the ratio of 2:1. Fig. 3 shows sections of a tooth and grinding wheel at three stages of wheel life — ideal, new wheel, and spent wheel.

New Freedoms

Three angular and three linear motions define the relative motions that can exist between any two bodies, in this case between the flared cup tool and the work gear. One of the angular freedoms is used to sweep out the tooth surfaces; therefore, effectively only two angular freedoms are available for contact pattern control.

At any instant in sweeping out the tooth surfaces, the CNC generator has the capability to change the relative orientation between the contact line and the gear tooth. Motions to achieve a change could be defined in any number of reference systems. For this case all of the motions are defined based on the instantaneous radial plane; that is, the plane containing the conventional tool axis and the radial line to the mid-height point on the contact line.

The freedoms are defined as follows:

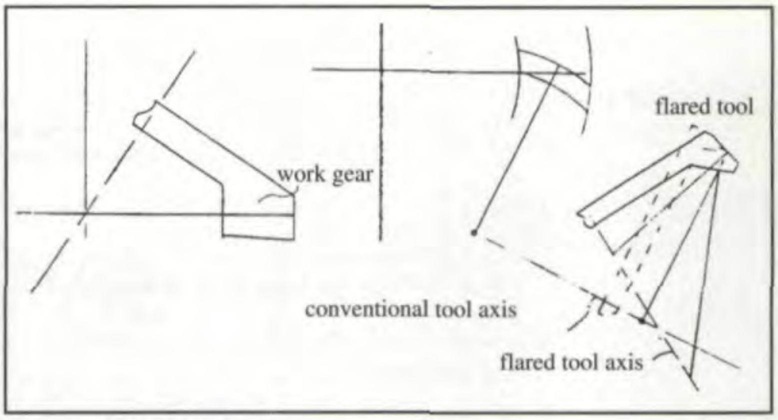

Fig. 2 — Flared cup setup.

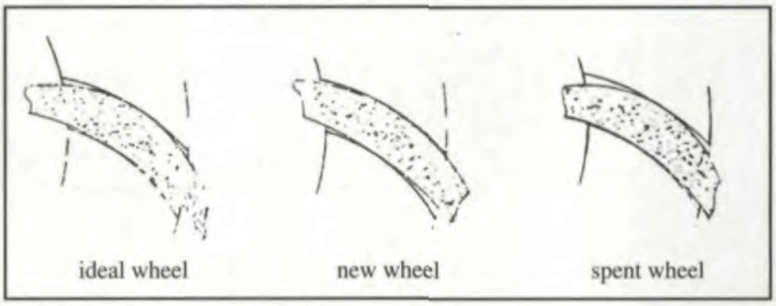

Fig. 3 — Contact area variation.

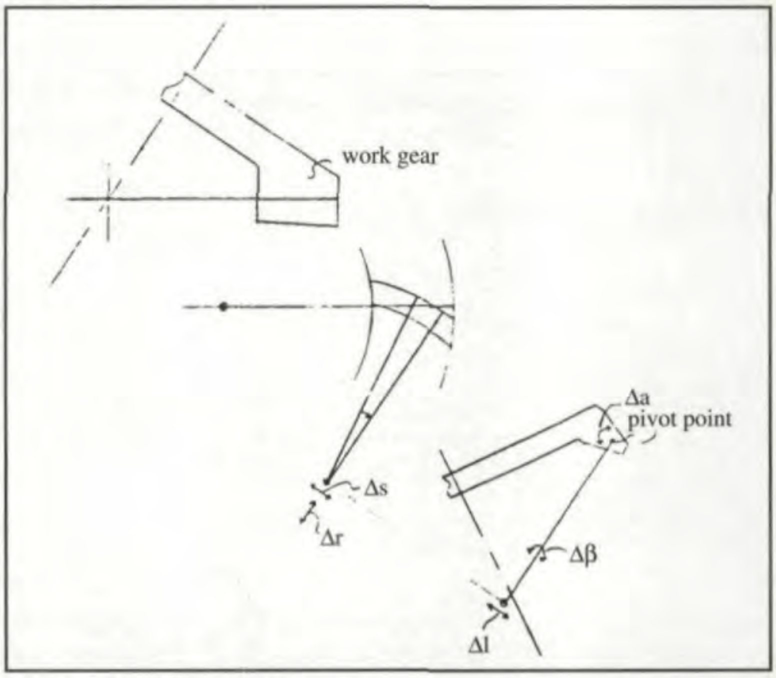

Fig. 4 — Flared cup motions.

1. Rotational motion in the instantaneous radial plane;

2. Rotational motion about the instantaneous radial line;

3. Linear motion along the conventional tool axis;

4. Linear motion along the instantaneous radial line;

5. Linear motion perpendicular to the instantaneous radial line.

Fig. 4 is a sketch of a flared cup setup

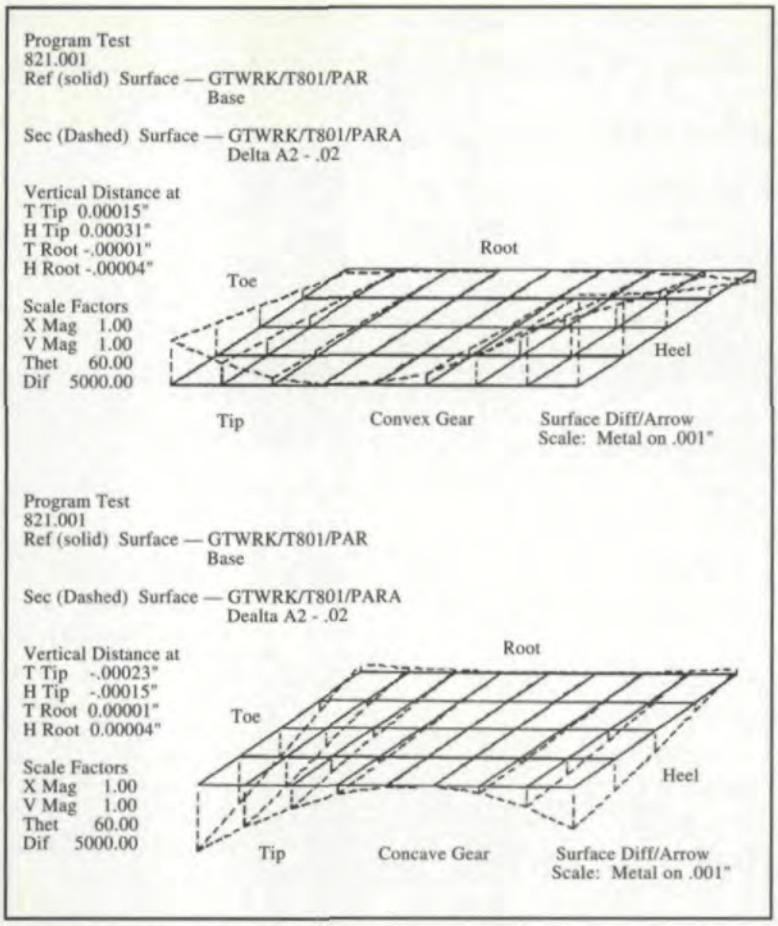

Fig. 5 — Topology graph of second order Δa change.

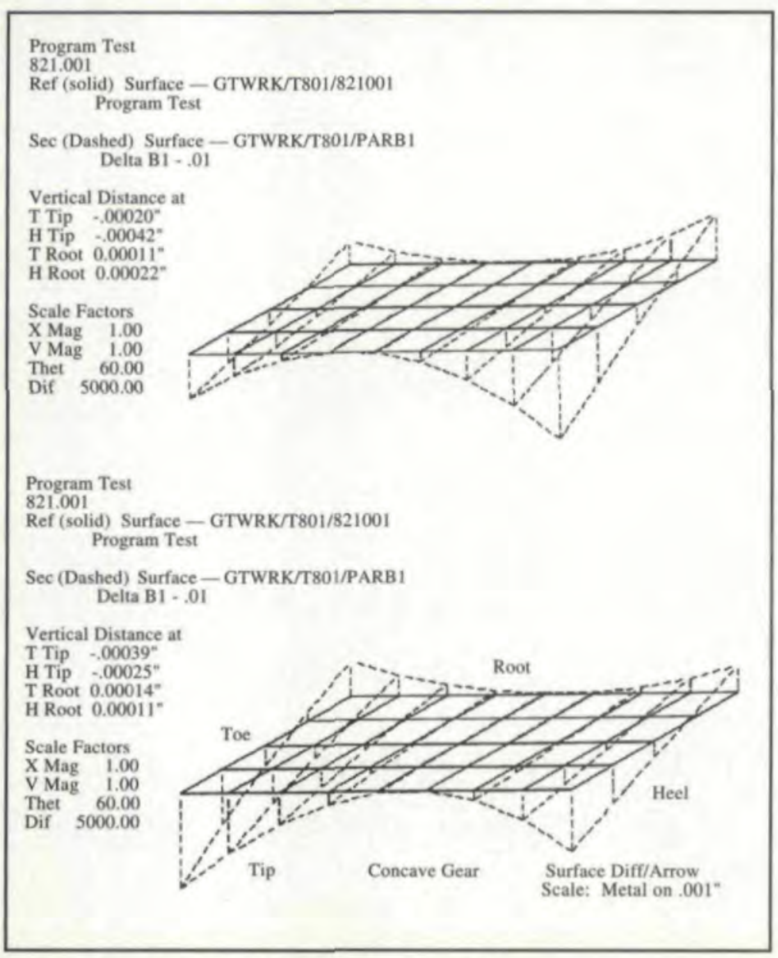

Fig. 6 — Topology graph of second order Δβ change.

showing these motions. The angular motions pivot about a point at mid-tooth depth and mid-slot width. A timed relationship exists between the motions and the angular position of the wheel as it is swept through the tooth slot. Although a number of functions could be used to define the relationships, polynomial expressions were selected.

Radial Tilt. This angular motion is a tilting of the tool in the instantaneous radial plane as the tooth is swept out. The effect is to change the pressure angle on both flanks of the tooth as the grind line moves from the tooth center section. The change increases the pressure angle on one flank, and decreases the pressure angle on the other flank as compared with the conventional tooth. At any tool phase angle position designed by Δa, the radial tilt of the tool is given by:

$$\Delta a = A_1\,\Delta\alpha + A_2\,\Delta\alpha^2 + A_3\,\Delta\alpha^3 + A_4\,\Delta\alpha^4$$

where A_1, A_2, A_3, A_4 are the coefficients that control the motion.

Fig. 5 schematically illustrates the change in surface topology on the convex and concave flanks of a gear tooth. The solid lines represent the baseline surface, and the dashed lines represent the surface resulting from a second order change in Δa. It can be seen that metal is removed on each side of the center section at the bottom of the convex flank and at the top of the concave flank of the gear teeth. The opposite effect occurs at the top of the convex side and at the bottom of the concave side.

The A_1 coefficient produces a velocity in the normal direction at $\Delta\alpha = 0$, the setup must be altered to accommodate the velocity when this coefficient is used.

Tangential Tilt. This angular motion is a tilting of the tool around the instantaneous radial line as the tooth is swept out. Again the effect is to change the pressure angle on both flanks of the tooth as the grind line moves from the tooth center section. In this case the pressure angle is increased or decreased on both flanks, as compared with the conventional tooth. At any tool phase angle position designated by Δ, the tangential tilt of the tool is given by:

$$\Delta_\beta = B_1\,\Delta\alpha + B_2\,\Delta\alpha^2 + B_3\,\Delta\alpha^3 + B_4\,\Delta\alpha^4$$

where B_1, B_2, B_3, B_4 are the coefficients that control the motion.

Fig. 6 schematically illustrates the change in the surface topology due to a second order change in $\Delta\beta$. It can be seen that metal is removed on each side of the center section at the top of both tooth flanks. The opposite effect occurs at the bottom of both tooth flanks.

Axial Motion. This linear motion is one that has been described previously in Refs. 1 and 2. It is an advance or retreat of the work along the conventional tool axis. The effect is to modify the surface topology in the same manner on both tooth flanks. More metal is either removed or left on the tooth flanks in the lengthwise direction than in conventionally formed teeth. At any tool phase angle position designated by $\Delta\alpha$, the change in position of the tool relative to the work in the direction of the cutter axis is given by:

$$\Delta l = L_1\,\Delta\alpha + L_2\,\Delta\alpha^2 + L_3\,\Delta\alpha^3 + L_4\,\Delta\alpha^4$$

where L_1, L_2, L_3, L_4 are the coefficients that control the motion.

Since the L_1 coefficient produces a velocity in the normal direction at $\Delta\alpha = 0$, the setup must be altered to hold spiral and pressure angle at the mean point when this coefficient is used.

Fig. 7 schematically illustrates the change in surface topology due to a second order change in Δl. It can be seen that metal is left on at the inside and outside of both tooth flanks.

Radial Motion. This motion is a movement of the tool along the instantaneous grind radius between the tool and the work gear. The effect is to modify the surface topology in the opposite manner on the tooth flanks. Metal is removed on one flank and metal is left on the other, unlike the case of conventionally formed teeth. At any tool phase angle position designated by $\Delta\alpha$, the change in position of the tool relative to the work in the instantaneous radial direction is given by

$$\Delta r = R_1\,\Delta\alpha + R_2\,\Delta\alpha^2 + R_3\,\Delta\alpha^3 + R_4\,\Delta\alpha^4$$

where R_1, R_2, R_3, R_4 are the coefficients that control the motion.

Since the R_1 coefficient produces a velocity in the normal direction at $\Delta\alpha = 0$, the setup must be altered to accommodate the velocity when this coefficient is used.

Fig. 8 schematically illustrates the change in surface topology, due to a second order change in Δr. It can be seen that metal is removed on the convex side and left on the concave side on each side of the tooth center section.

Tangential Motion. The tool can also be moved in a direction perpendicular to the instantaneous grind radius. The effect is to modify the surface topology in the opposite manner

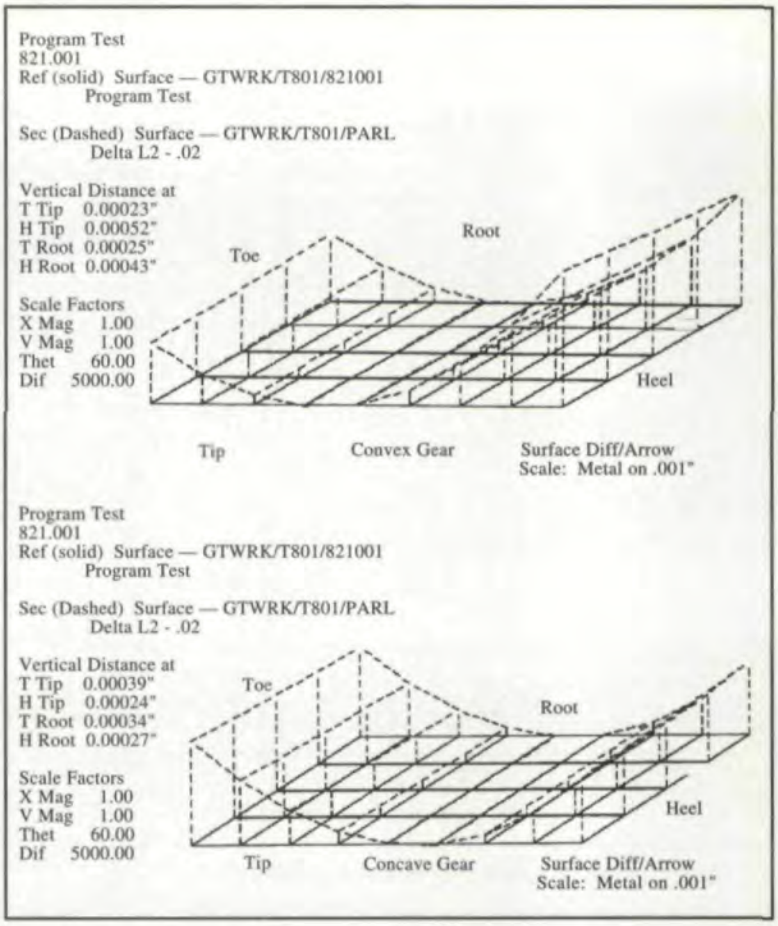

Fig. 7 — Topology graph of second order Δl change.

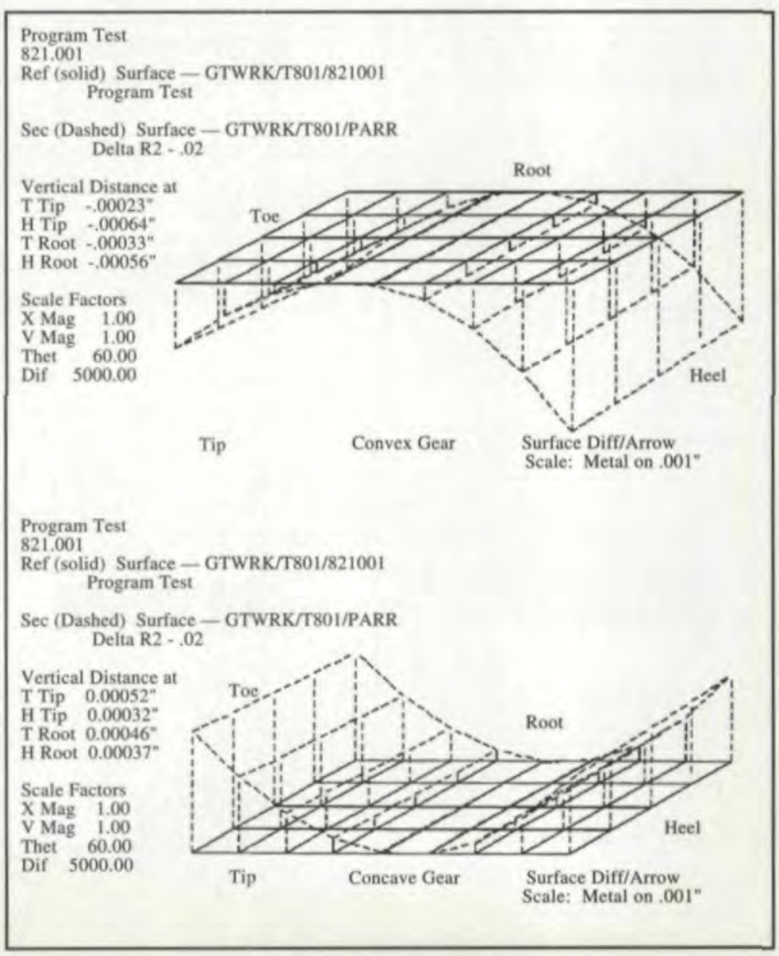

Fig. 8 — Topology graph of second order Δr change.

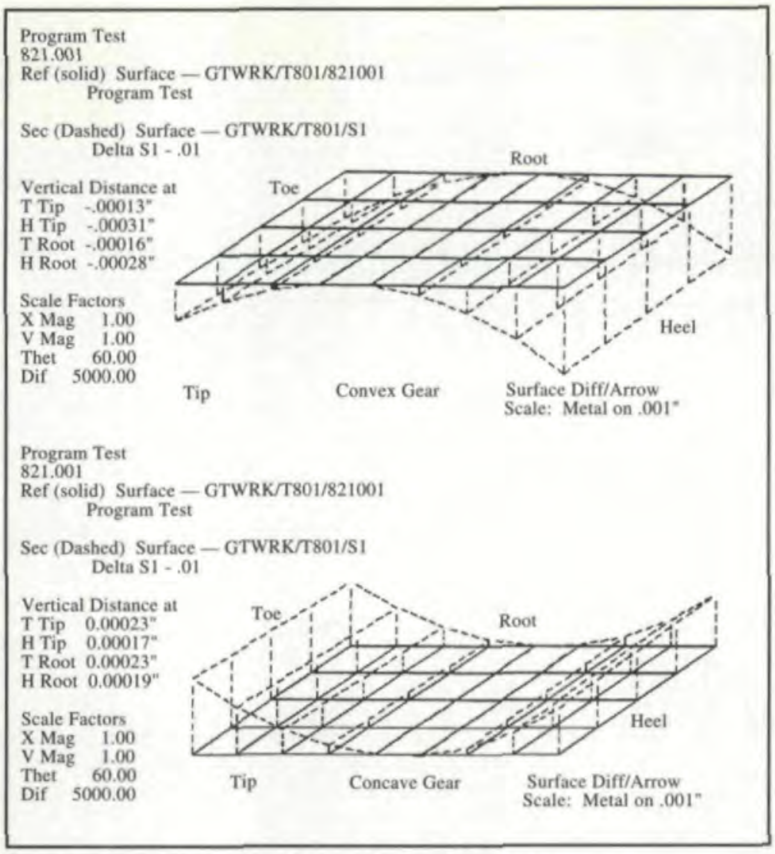

Fig. 9 — Topology graph of second order Δs change.

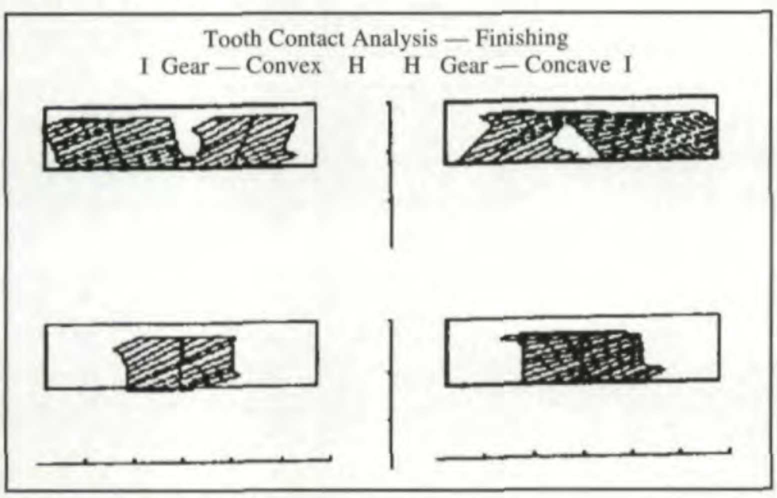

Fig. 10 — Baseline TCA.

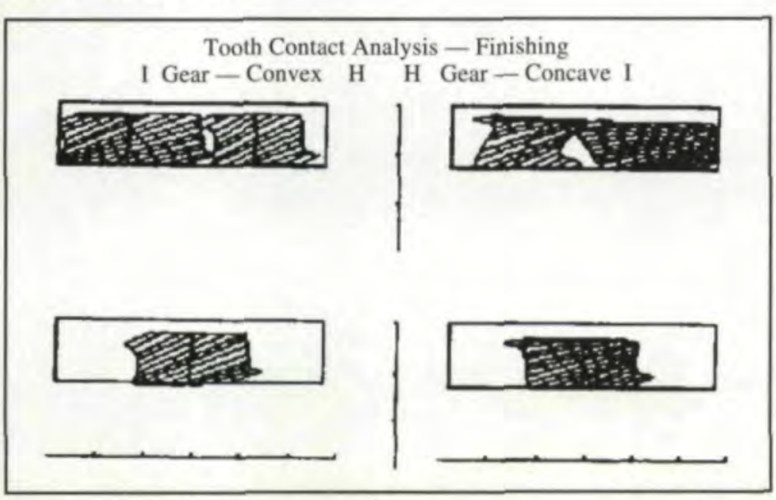

Fig. 11 — TCA of second order Δα change.

on the tooth flanks. It has a effect similar to the effect described above for a change in radial motion. At any cutter phase angle position designated by $\Delta\alpha$, the change in position of the tool relative to the work, in a direction perpendicular to the instantaneous radial is given by:

$$\Delta s = S_1 \Delta\alpha + S_2 \Delta\alpha^2 + S_3 \Delta\alpha^3 + S_4 \Delta_\alpha \alpha^4$$

where S_1, S_2, S_3, S_4 are the coefficients that control the motion.

Fig. 9 schematically illustrates the change in surface topology due to a second order change in Δs.

Tooth Contact Analysis (TCA)

A second illustration of the five motion freedoms is shown using TCA. To aid in the comparison, the same job is used, and the effect of second order changes of the same magnitude are evaluated. Fig. 10 is the baseline TCA. It represents a conjugate gear set with only lengthwise mismatch. Fig. 11 is the TCA of the radial tilt change. Fig. 12 is the tangential tilt change. Fig. 13 is the axial motion. Fig. 14 is the radial motion. Fig. 15 is the tangential motion.

Duplex Enhancement

The face milling duplex process is successfully used in many applications; in particular on fine pitch jobs and jobs where the contact pattern is enhanced by lapping. When grinding is the final finishing operation, the desired contact pattern length needed for most automotive applications cannot be achieved easily. Often a contact pattern, where the contact length varies from top to bottom, called a diamond pattern, results. This has been a factor in limiting the success of grinding as the final operation in the manufacture of hypoid gear sets for land applications. Enhancement of the duplex process by exploiting the new motion freedoms should make grinding more attractive as a final finishing process because of the ability to develop contact patterns with a wide range of characteristics.

Typically, gear sets used in automotive and

TABLE I — BLANK DATA	SMALL AUTOMOTIVE		
	Inch		MM
Pitch/Module	6.154		4.13
Pitch Diameter	7.638		194.01
Number of Teeth		12/47	
Face Width	1.300		33.02
Offset	1.250		31.75
Spiral Angle		48°	
Cutter Radius	3.000		76.20

truck applications cover the range from two to seven diametral pitch. Three sets within this range were designed using the standard duplex method plus the new motions. Blank data for the sets is given in Table I.

Small Automotive — When the diametral pitch is six or higher, the need for added flared cup motions can be questioned. Fig. 16 is a TCA comparison of the duplex job designed without added motions on the left and with added motions on the right. The jobs were designed with very little transmission motion variation. Both designs are similar. Substantial pattern length was obtained without the introduction of flared cup motions. However, even for this case, greater pattern length was achieved on center, while limiting the length when the contact moves to the inside or outside of the blank. The long center contact is beneficial when gear noise is a concern.

Large Automotive — For coarser diametral pitches, the benefits that can be achieved are more easily seen. Fig. 17 is a TCA comparison of the large automotive set designed without added motions on the left and with added motions on the right. The standard development is reasonably acceptable, and enhancement of the contact pattern as a result of the lapping could result in a set that would be very acceptable relative to noise quality. However, if the development is for a final finish grind, the contact pattern has more than the desired lengthwise mismatch.

Lengthening the pattern by conventional duplex methods would result in an unacceptable diamond pattern.

The introduction of additional motions can substantially increase the on-center pattern length while controlling the diamond condition. Also, note that pattern length at the toe and heel is held to a reasonable length to maintain adjustability.

Large Truck — For diametral pitches in the range of two, the benefits are dramatic. Fig. 18

LARGE AUTOMOTIVE			TRUCK		
Inch		MM	Inch		MM
4.178		6.08	2.226		11.41
10.500		266.70	16.625		422.28
	11/41			7/37	
1.600		40.64	2.000		50.80
1.500		38.10	1.750		44.45
	48°			47°	
3.750		95.25	6.000		152.40

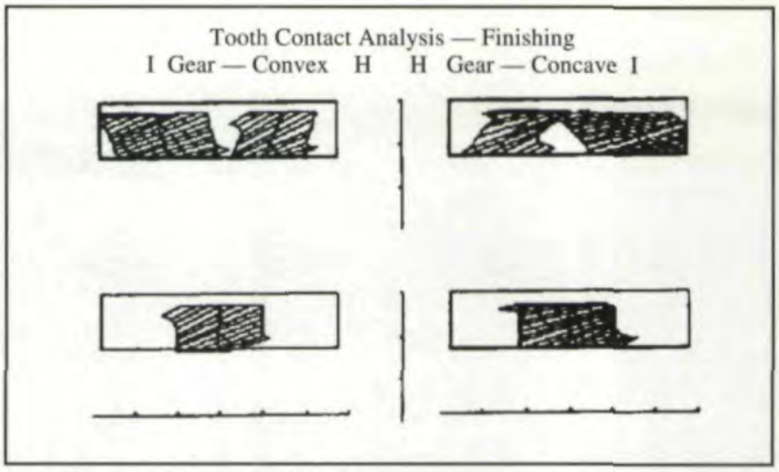

Fig. 12 — TCA of second order Δβ change.

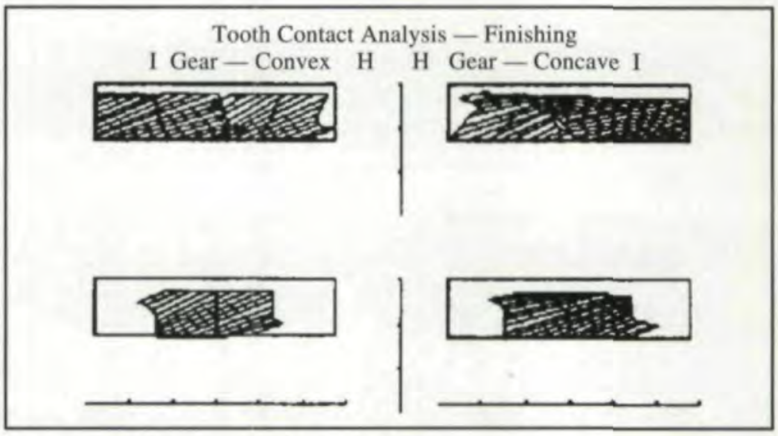

Fig. 13 — TCA of second order Δ*l* change.

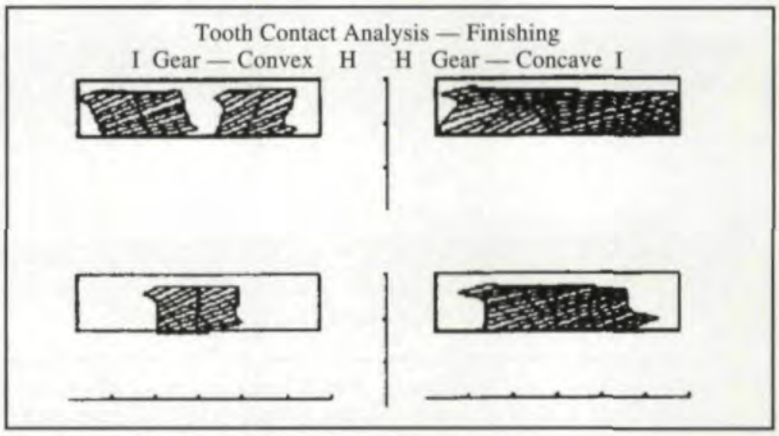

Fig. 14 — TCA of second order Δr change.

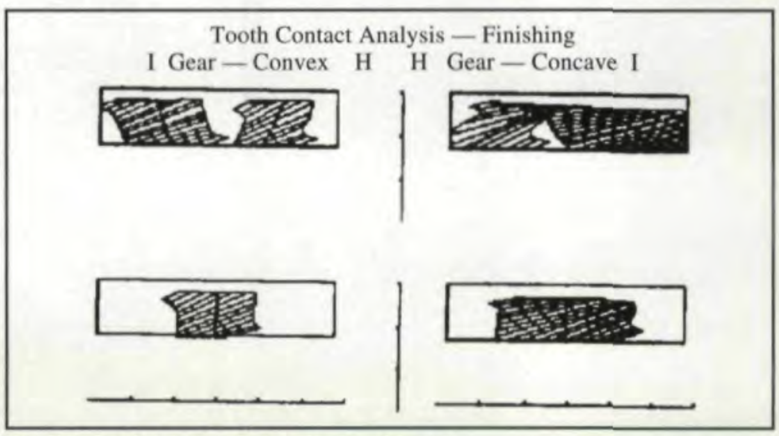

Fig. 15 — TCA of second order Δs change.

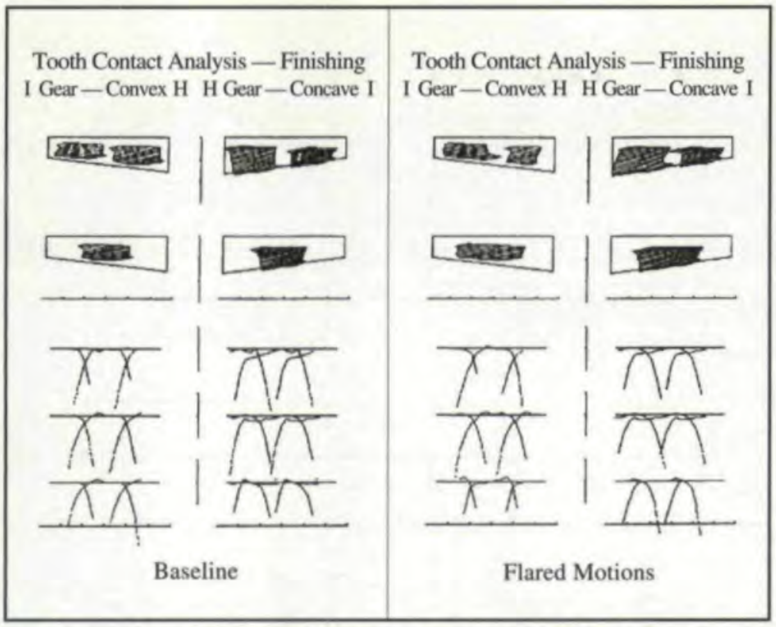

Fig. 16 — TCA of comparison of small automotive duplex design.

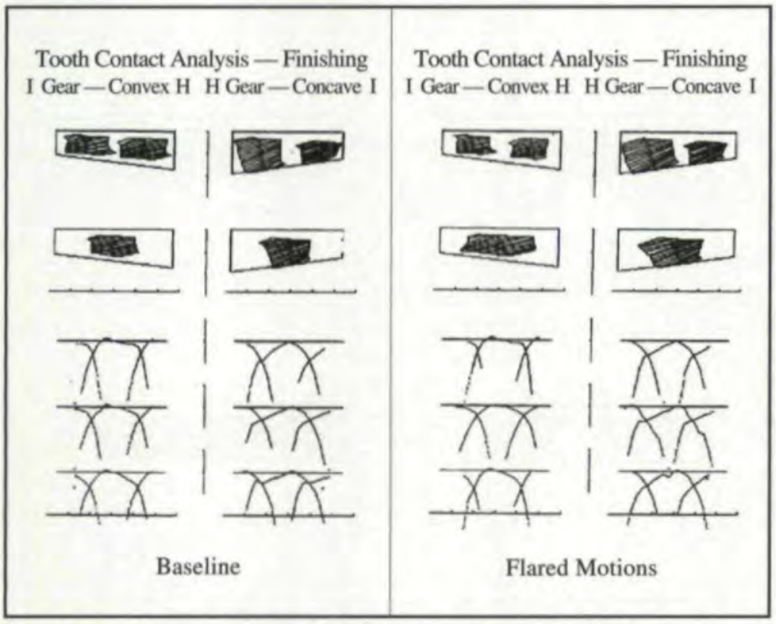

Fig. 17 — TCA comparison of large automotive duplex design.

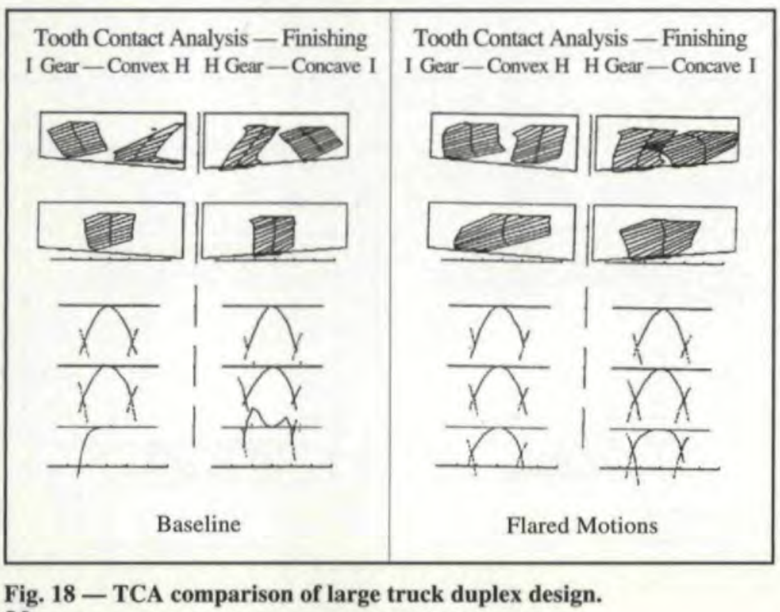

Fig. 18 — TCA comparison of large truck duplex design.

is a TCA comparison of the large truck job without added motions on the left and with added motions on the right. Pattern length on the standard development is short. Typical bias-in at the toe and bias-out at the heel contact patterns exist. Any further attempt to lengthen the pattern by conventional means would cause severe diamond problems. Note that more transmission motion variation was introduced into this design on the assumption that the set is more highly loaded and, as a result, requires increased adjustability.

With the added motions, the lengthwise pattern was increased at the central position, the diamond patterns at the toe and heel were controlled, and the lengthwise mismatch at the toe and heel were held.

Summation

The article presented a theoretical description of the freedoms available on full CNC generators and their application to the flared cup gear grinding process. Surface topology and TCA were used to graphically define the effects of motion variation on the tooth surfaces. Finally, the application of the motion freedoms to enhance the flared cup duplex process was demonstrated using TCA.

In automotive and truck applications the amount and distribution of the mismatch between mating surfaces has a critical effect on sound quality. Theoretically, the flared cup process combined with a full CNC hypoid generator offers the motion freedoms that provide the necessary mismatch control for the duplex process allowing both pinion and gear members to be finished ground in one operation. ■

References:

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