

CNC Bevel Gear Generators and Flared Cup Formate Gear Grinding

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American Gear Manufacturers Association



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ABSTRACT:

Full CNC bevel generators achieve the relative position between the tool and work with simple mechanisms and electronic controls. As a result, the gear engineer has new freedoms for the control of gear tooth shapes and contact characteristics. This paper defines the flared cup Formate gear grinding process and the motions that can be applied to the process. Surface comparison charts and tooth contact analysis are used to demonstrate the effects of the freedoms. Comparisons of jobs designed with and without the motions are included.

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CNC BEVEL GEAR GENERATORS AND FLARED CUP FORMATE GEAR GRINDING

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New freedoms 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 paper covers the exploitation of new motion freedoms to improve tooth contact patterns on gear sets manufactured by the Formate® face milling duplex process. (The duplex process is a manufacturing method where both flanks are completed in a single operation.)

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

Flared Cup Process

When cutting face milled gears using the Formate process, 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 formed cut by infeeding the cutter. The part is indexed one pitch and the process is repeated. See Figure 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 due to burning. The Formate flared cup grinding process was developed to overcome this problem.

The flared cup process uses a wheel which is tilted out of the work. (Thirty degrees 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 Figure 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 was a problem. Tooth geometry often varied 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, 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 to 1. Figure 3 shows sections of a tooth and grinding wheel at three stages of wheel life; ideal, new wheel and spent wheel.

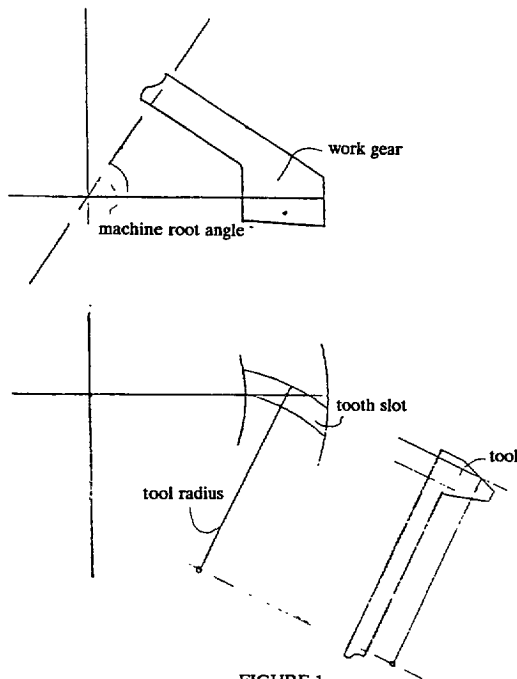


FIGURE 1
CONVENTIONAL FORMATE SETUP

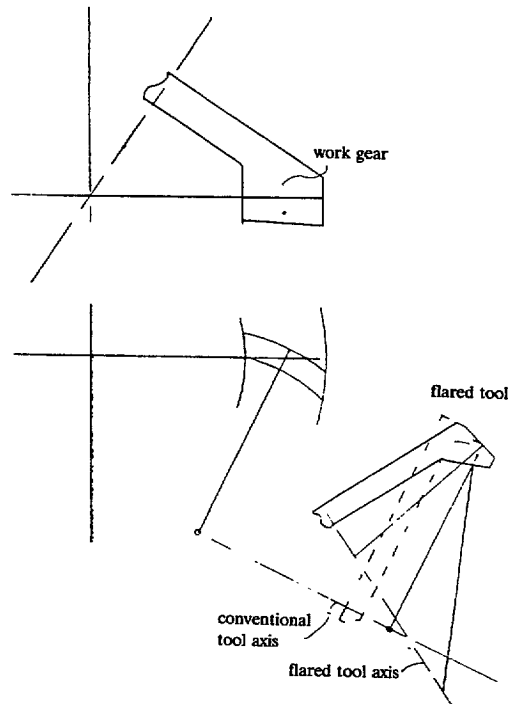


FIGURE 2
FORMATE FLARED CUP SETUP

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:

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.

Figure 4 is a sketch of a flared cup setup 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.

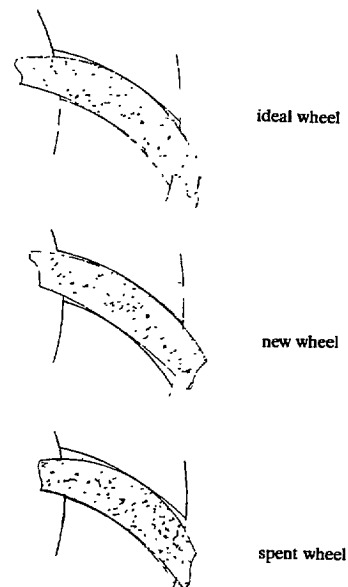


FIGURE 3
CONTACT AREA VARIATION

1. 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 Formate tooth. At any tool phase angle position designated by $\Delta\alpha$, 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.

Figure 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.

2. Tangential Tilt

This angular motion is a tilting of the tool around the instantaneous radial line as the tooth is swept out. The effect again, 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 $\Delta\alpha$, 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.

Figure 6 schematically illustrates the change in 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.

3. Axial Motion

This linear motion is one that has been described previously^{1,2}. It is an advance or withdraw 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 as compared with the conventional Formate tooth. 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:

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

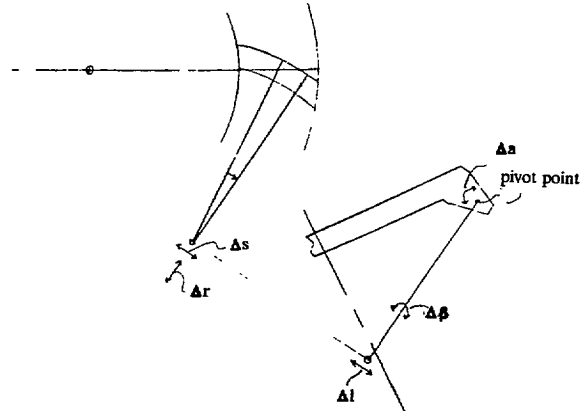
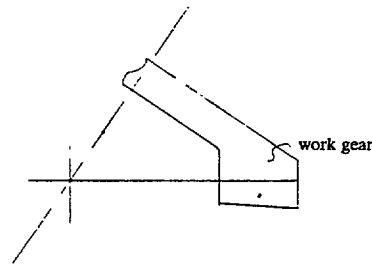


FIGURE 4

FLARED CUP MOTIONS

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.

Figure 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.

4. 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 flank, as compared with the conventional Formate tooth. 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.