

The Basics of Spiral Bevel Gears

Dr. Hermann J. Stadtfeld

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Gearing Principles in Cylindrical and Straight Bevel Gears

The purpose of gears is to transmit motion and torque from one shaft to another. That transmission normally has to occur with a constant ratio, the lowest possible disturbances and the highest possible efficiency. Tooth profile, length and shape are derived from those requirements.

With cylindrical gears, it is easier to understand that the involute profile provides a constant ratio and is insensitive to center distance displacement. The generating principle of an involute is

derived from a straight rack with straight tooth profile. A particular gear, rolling in the rack with constant center distance to the rack, requires involute flank surfaces. A shaping tool with the shape of a rack can machine a gear with a perfect involute flank form. Figure 1 shows a cylindrical gear rolling in a rack.

To understand the bevel gear tooth geometry, one might first observe the case of straight bevel gears. If the generating rack used to derive the cylindrical gear involute is bent in a horizontal plane into a circular shape, it results in a crown gear, which is used to derive the flank form of bevel pinion and gear. In the case of straight bevel gears, the crown gear or generating gear can be placed between the pinion and gear assembly. Its center is located exactly at the intersec-

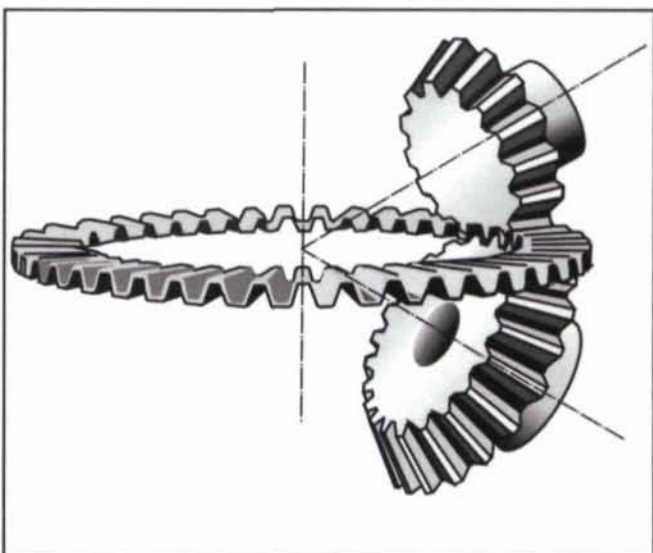


Figure 2—Crown gear arrangement in bevel gear sets.

tion point of the pinion and gear shafts.

As a mental exercise, the crown gear should consist of a very thin material like aluminum foil. In that case, it is possible for all three elements to be in mesh at the same time.

Figure 2 shows how the pinion is located at the back-side of the crown gear and meshes with the "negative teeth," while the ring gear is placed at the front side of the crown gear and meshes with the "positive teeth." If such an arrangement is possible, then the kinematic coupling conditions of the bevel gear set are fulfilled, which means the pinion and gear can mesh with each other, too.

A single profile of the generating gear generates a gear on its one side and the mating member on its other side. The profile and lead are straight,

which causes a straight lead and an octoid profile on the generated teeth. The octoid basically is the bevel gear analog of an involute. The octoid provides a constant ratio and makes the gears insensitive to displacements perpendicular to the pitch line.

Circular Cutting Tools and Spiral Bevel Gears

A face cutter comes with many blades to increase productivity. It generates a curved tooth shape, which provides

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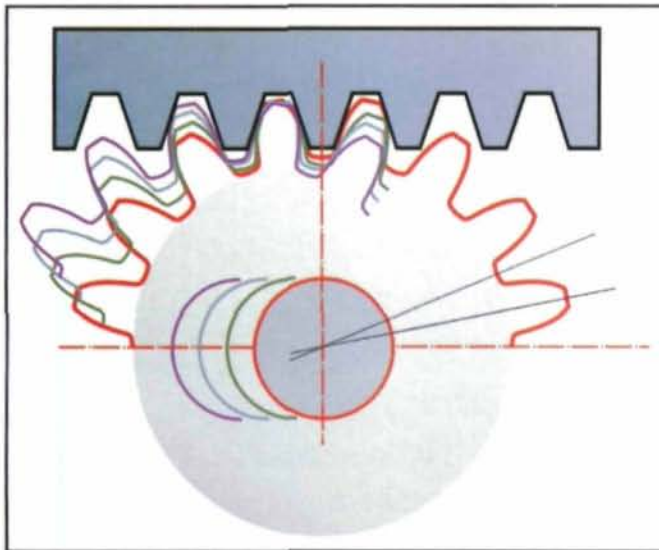



Figure 1—Cylindrical gear generating principle.



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increased face contact ratio, tooth rigidity and adjustability to load-dependent deflections.

In the case of a single index face milling method, the tooth lead function is circular, as the blade in the cutter performs a circular motion, while the generating gear rests in a fixed angular position.

The tooth profiling between the cutter and the generating gear does not require any rotation of the generating gear. The virtual generating gear is formed by the cutter head in a non-generating process. In Figure 3, the rotating blades in the cutter head can be understood to represent one tooth of the generating gear.

As explained earlier, the generating gear is the bevel gear equivalent of the straight rack for generating a cylindrical gear tooth. Therefore, it is understandable that the generating gear tooth profile is a mirror image of the blade profile (it is not an involute or octoid).

If a pinion blank without teeth is positioned in front of the generating gear and then moved towards the cutter, the blades will cut the same trapezoidal profile of the generat-

ing gear into the pinion. The pinion slot produced in that way has two defects. First, the profile will not allow rolling between pinion and generating gear (compare to the rack and cylindrical gear tooth in Figure 1). Second, the pinion slot does not have the proper depth along the face width. As soon as the teeth have a spiral angle and the slot inclines to an angle on an axial plane, the teeth wind around the work gear body. In a fixed angular position, just the heel section, for example, is cut to the proper depth.

The roll motion rotates the virtual generating gear and the work gear with the proper ratio while they are engaged (similar to the linear motion of the rack, Figure 1, in conjunction with the gear rotation).

Since the generating gear is just virtual and doesn't physically exist, the cutter that simulates one tooth of the generating gear has to rotate around the generating gear axis. With this rotation (roll motion), the cutter blades work their way from the heel to the toe and generate the proper octoidal profile along the entire face width. The start

A SINGLE PROFILE OF THE GENERATING GEAR GENERATES A GEAR ON ITS ONE SIDE AND THE MATING MEMBER ON ITS OTHER SIDE. THE PROFILE AND LEAD ARE STRAIGHT, WHICH CAUSES A STRAIGHT LEAD AND AN OCTOID PROFILE ON THE GENERATED TEETH. THE OCTOID BASICALLY IS THE BEVEL GEAR ANALOG OF AN INVOLUTE. THE OCTOID PROVIDES A CONSTANT RATIO AND MAKES THE GEARS INSENSITIVE TO DISPLACEMENTS PERPENDICULAR TO THE PITCH LINE.

roll position is normally on the side of the tooth with the big diameter (heel). The roll motion ends when the profile generating "arrives" at the opposite side of the face width (toe).

That procedure was for machining one slot. To machine the next slot, the cutter withdraws, and the work indexes one pitch. The spiral angle is the inclination angle of the curved tooth tangent to the radius vector from the intersection point of pinion and gear axis (see Figure 4). Because of the curved shape of the tooth length, different points along the face width have different spiral angles. The nominal spiral angle of the spiral bevel gear or pinion is the angle measured from the center of the tooth.

It is possible to use a bevel generating gear that is identical to the ring gear. The pinion is in that case generated by rolling with the bevel generating gear, and the gear is manufactured simply by plunging the cutter to full depth without rolling (non-generated form cutting).

A straight tooth bevel gear set has contact lines that are parallel to the pitch line (Figure 5, top). The first contact between a generating gear tooth and a pinion tooth starts, for example, in the root and moves during the rotation of the two mating members along the path of contact straight up to the top. The contact lines represent the momentary contact between the two flanks in mesh.

With a spiral bevel gear set, the contact lines are inclined relative to the pitch line orientation. Unlike the contact lines of the straight bevel gear set, the contact lines of the spiral

bevel gear set have different lengths. The bottom of figure 5 shows the movement of the contact from heel top to toe root. The very short contact length increases from the beginning of the roll towards the center of the face width and reduces as the roll approaches the exit at the toe end.

The contact lines between pinion and generating gear are identical to the contact lines between cutter blades and pinion flanks.

Single Index Process—
Face Milling

In a single index process, just one slot is cut at a time. For the non-generated member only, the cutter rotates and is fed into the work gear to the full depth. After reaching the full depth, the cutter withdraws and the work indexes one pitch to the next desired slot position (Figure 6, right side). The process repeats until all slots have been machined. The resulting flank lead function is a circular arc.

Machining a generated member is done by plunging at the heel roll position first. After plunging, the roll motion begins, and generating of the flanks from heel to toe occurs. The flank lead function for a face milled, generated gear is a circular arc that is wound around a conical surface.

The manufacturing of a face milled bevel gear pair is possible in a five-cut process or in a completing process. The five-cut process consists of the following five independent operations:

1. Gear roughing (alternate roughing blades),
2. Gear finishing (alternate finishing blades),
3. Pinion roughing (alternate roughing blades),



Figure 3—Circular cutting tool and virtual generating gear.

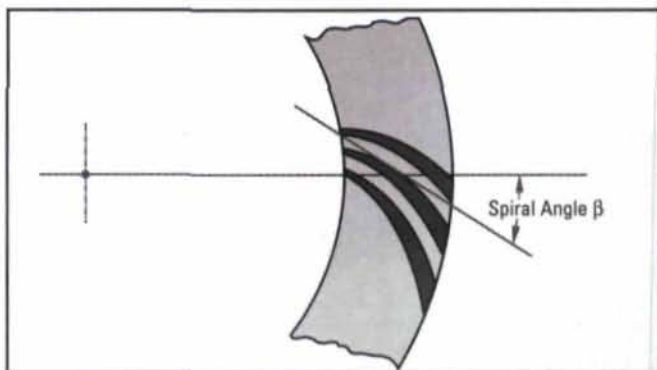


Figure 4—Definition of spiral angle.

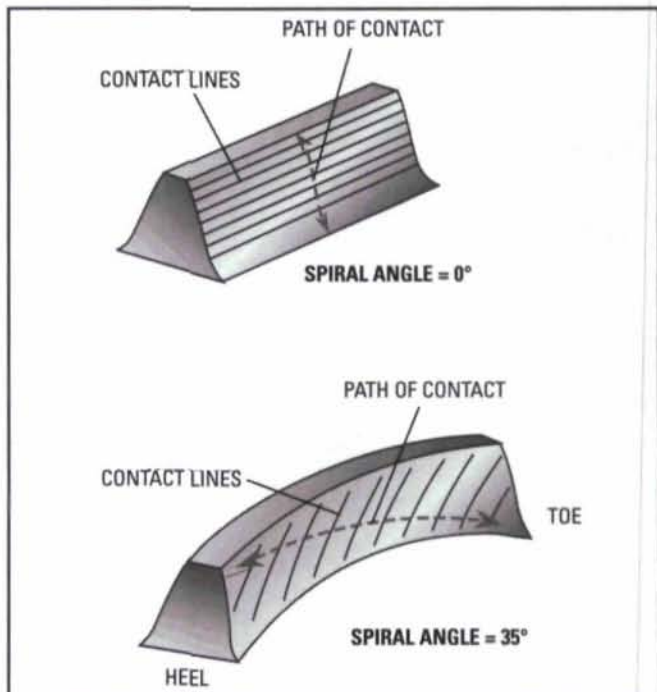


Figure 5—Contact lines for different spiral angles.



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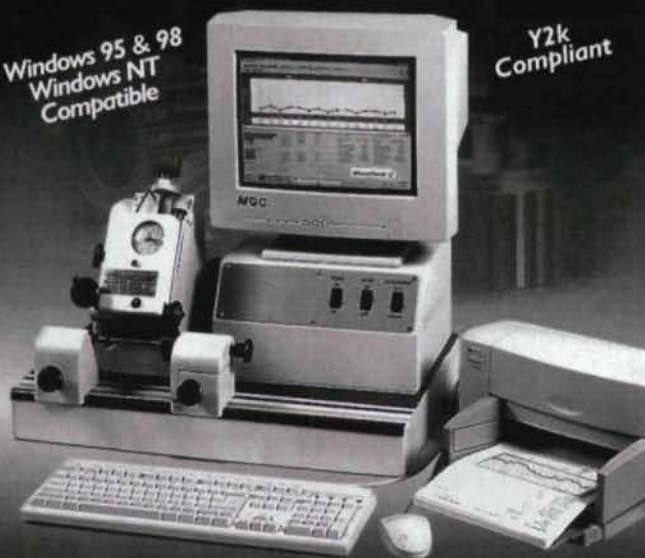
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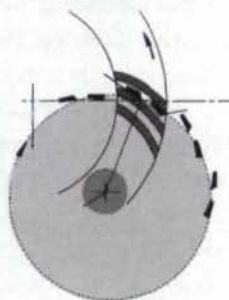
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Continuous Indexing



Single Indexing

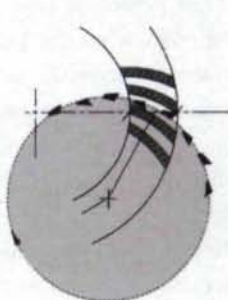


Figure 6—Kinematic principle of continuous indexing vs. single indexing.

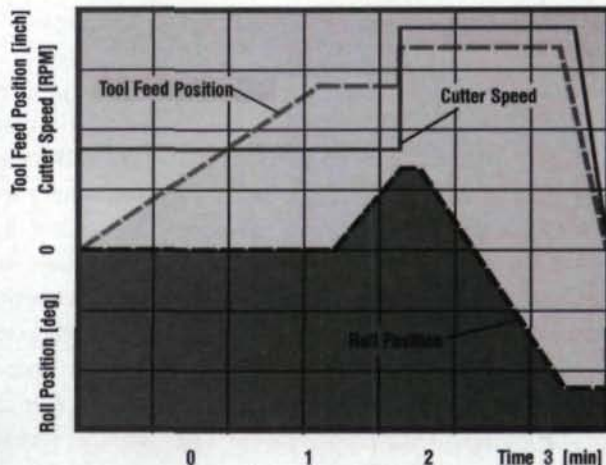


Figure 7—Cycle diagram for generating a face hobbed pinion.

4. Pinion finishing convex (inner blades only), and
5. Pinion finishing concave (outer blades only).

A completing process uses two combined operations:

1. Gear roughing and finishing (alternate roughing-finishing blades) and
2. Pinion roughing and finishing (alternate roughing-finishing blades).

Continuous Indexing Process—Face Hobbing

A continuous cutting process consists of continuous rotations and a feed motion only. While an outer and an inner blade move through a slot of the work gear, the work gear is rotating in the opposite direction. The relation of the cutter rpm and the work rotation is equivalent to the ratio

between the number of work gear teeth and the number of cutter head blade groups (starts). The resulting flank lead function is an epicycloid. The effective cutting direction of the blades in the cutter head is not perpendicular to the cutter radius vector (like in the single indexing process). The blades are moved in the cutter head tangentially to an offset position to accommodate the correct orientation with respect to the cutting motion vector. The pitch points on the cutting edge of inner and outer blade have an identical radius. The right slot width is achieved with the angular distance between the outer blade (first) and the following inner blade. The left portion of Figure 6 shows the kinematic

relationship and the orientation of the blades relative to cutter and cutting motion.

Balancing of the tooth thicknesses between pinion and gear can only be realized by different radii of inner and outer blade pitch points, since the spacing between the blades is given by the cutter head design and therefore remains constant.

While one blade group (like shown in Figure 6) is moving through one slot, the work rotates in the opposite direction, such that the next blade group enters the next slot. That way, all the slots around the work gear are cut at about the same time. The feed motion to feed the cutter to the full depth position is therefore slower than in the single index process.

A non-generated work gear is finished when the full depth position is reached. To get the highest possible spacing accuracy, a dwell time is applied to the non-generated member. The aim of the dwell motion is to allow each blade to move once more to each slot, which takes N slots to pass by, where

N is the number of cutter starts times the number of gear teeth. N is equivalent to as many ring gear revolutions as the cutter has starts.

For a generated pinion, a roll motion follows the plunging cycle in the center roll position (the cutter does not cut the full depth yet). The roll motion after plunging moves the cutting action to the heel; both plunging and rolling to heel is part of the roughing cycle. At the heel roll position, the cutter advances to the full depth position, the cutter rpm increases to a finishing surface speed, and a slow roll motion from heel to toe follows. When arriving at the toe (end roll position), all teeth of the generated work gear or pinion are finished (see Figure 7).

Heat Treatment of Bevel Gears

Heat treatment follows the soft cutting operation. The generally used low carbon steel has to be carburized on the surface, by case hardening for example. The heat treatment is finished with the quenching operation that provides a surface hardness in the



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A NON-GENERATED WORK GEAR IS FINISHED WHEN THE FULL DEPTH POSITION IS REACHED. TO GET THE HIGHEST POSSIBLE SPACING ACCURACY, A DWELL TIME IS APPLIED TO THE NON-GENERATED MEMBER. THE AIM OF THE DWELL MOTION IS TO ALLOW EACH BLADE TO MOVE ONCE MORE TO EACH SLOT, WHICH TAKES N SLOTS TO PASS BY, WHERE N IS THE NUMBER OF CUTTER STARTS TIMES THE NUMBER OF GEAR TEETH. N IS EQUIVALENT TO AS MANY RING GEAR REVOLUTIONS AS THE CUTTER HAS STARTS.

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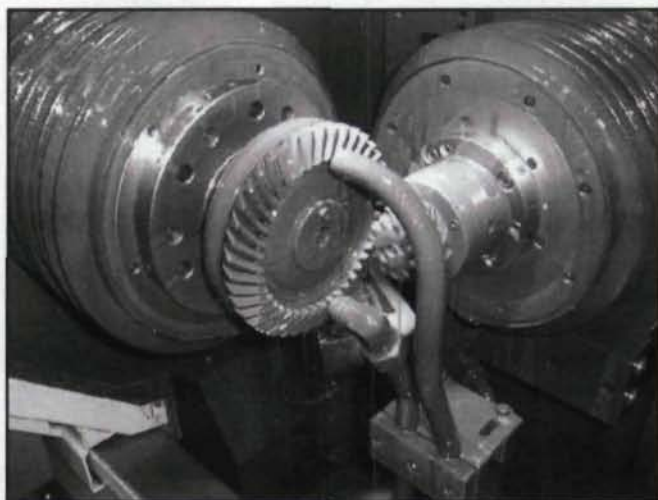


Figure 8—Lapping of a bevel gear set.



Figure 9—Grinding of a bevel pinion.

range of 60 to 63 Rc (Rockwell C). The pinion may be 3 Rc harder than the ring gear to equalize the wear and reduce the risk of scoring. The core material stays softer and more ductile, with a hardness in the range of 30 to 40 Rc.

The distortions from heat treatment are critical to the final hard finishing operation. The kind of heat treatment facility (salt bath, furnace or continuous furnace), as well as the differences between the charges of blank material, has a significant influence on the gear distortion. The gear, which is mostly shaped like a ring, loses its flatness (it gets a face run-out) via the hardening procedure. The pinion, in

most cases, is shaped like a long shaft that loses its straightness (radial run-out).

In addition to the blank body distortions, heat treating causes a distortion of the individual teeth. The spiral angle changes, the flank length curvature is reduced and the pressure angle changes. To achieve the best results, attention has to be paid to processing and handling of the parts through the furnace. Quenching the ring gears with a quench press assures good flatness of the heat-treated ring gears, for example.

Hard Finishing of Bevel Gears

The final machining operation after heat treatment

should provide a good surface finish and remove flank distortions. The most common process used is lapping. Pinion and gear are brought into mesh and rolled under light torque. To provide an abrasive action, a mixture of oil and silicon carbide is poured between the teeth (Figure 8). A relative movement of pinion and gear along their axes and a movement in offset direction is created, such that the contact area moves from toe to heel and back numerous times.

The lapping process improves the surface finish, leaves a desirable micro-structure on the flank surfaces and removes heat treat distortions to some extent. The metal removal is not uniform in the different flank sections and varies from set to set, since the pinion and gear are used as tools to hard finish each other. This is the reason why lapped sets have to be built as a pair; lapped pinions and gears are not interchangeable.

The lapping surface structure is not oriented in the direction of the contact lines, thus providing a good hydrodynamic oil film between the contact areas. The lapping structure also tends to deliver side bands in a noise frequency analysis, which makes the gear set appear to roll more quietly.

During the lapping process, a pinion and a gear are always machined and finished at the same time. The time to lap a pair is equal to or shorter than the time to machine one member using another finishing method. Therefore, lapping is often called the most economical bevel gear finishing process.

Another finishing option is grinding of bevel gears, which is limited to face milled (single index) bevel gears. The grinding wheel envelops a single side or an alternate completing cutter (Figure 9). Today's technology does not allow the use of a grinding tool in a continuous indexing process. The advantage of grinding is the manufacturing of an accurate flank surface with a predetermined topography. The process allows the constantly repeated production of equal parts. Building in pairs is not necessary.

Lapped pairs used in vehicles require an oil change after the first 1,000 miles because of abrasive particles introduced to the tooth surfaces during lapping. A further advantage of grinding over lapping is that such an oil change is unnecessary with ground spiral bevel gears.

A process between lapping and grinding with respect to surface speed and relative motion is honing. Honing trials on bevel gears have been done, but they haven't been proven successful.

Skiving is a hard cutting process. A tool material such as carbide or boron carbonitride is used on the cutting edge. The cutting machine setup is identical to that for soft machining. The blade point dimension is wider than the one for soft cutting, such that a 0.005-inch uniform stock removal per flank takes place. Skiving delivers a high quality part accuracy and a fine surface finish. Skiving is applied to small batches of mostly larger gear sets. The advantage of skiving is the use of the same cutter head (only with different blades) and the

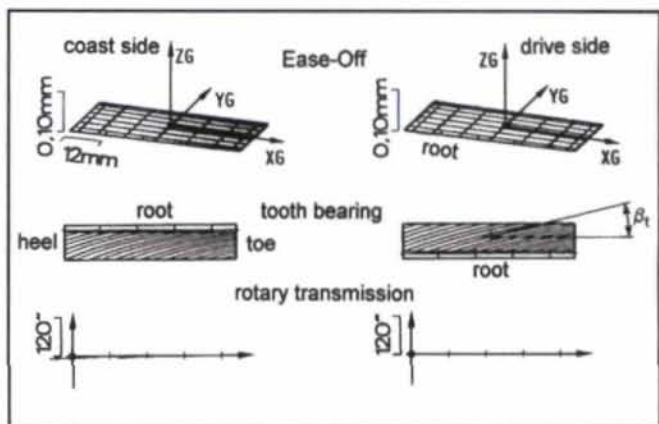


Figure 10—Tooth contact analysis result of a conjugate bevel gear set.

possible use of the same cutting machine. That makes the investment in machines and tools a minimum.

Some Bevel Gear Conventions

The expression "bevel gears" is used as a general description for straight and spiral bevel gears as well as hypoid gear sets. If the axes of the pinion and gear do not intersect but have a distance in space, the gear set is called a hypoid gear set. The name is derived from the hyperbolic shape of the "pitch cones." For simplification, the blanks are still manufactured with a conical shape.

The convex gear flank rolls with the concave pinion flank. This pair of flanks is called the "drive side." The direction of rotation where those flanks contact the pinion drives is called the drive direction. The drive side direction is always used in vehicles to drive the vehicle forward. The reverse direction is subsequently called the coast side (vehicle rolls downhill, foot is off the gas pedal, wheels drive the engine). In some cases, the coast side is used to drive the vehicle, but it is still called the coast side.

Ease-off is the presentation of flank form corrections

applied to pinion and/or gear. The ease-off topography is defined in the ring gear coordinate system, regardless of where the corrections were done (pinion, gear or both).

Protuberance is a profile relief in the root area of the flank, which prevents flank damage resulting from "digging in" of the mating tooth's top edge. Protuberance is realized with a cutting blade modification.

Localized Tooth Contact

When bevel gear sets are cut according to the crown gear or generating gear principle, the result is a conjugate pair of gears. Conjugate means pinion and gear have a line contact in each angular position. While rotating the gear in mesh, the contact line moves from heel top to toe root. The motion transmission happens in each roll position with precisely the same constant ratio. Roll testing is done in specially designed bevel gear test machines. If a marking compound (paint) is brushed onto the flanks of the ring gear member, a rolling in mesh under light torque makes the contact area visible. In the case of a conjugate pair, the contact area is spread out over the entire active flank. That is the official definition of the

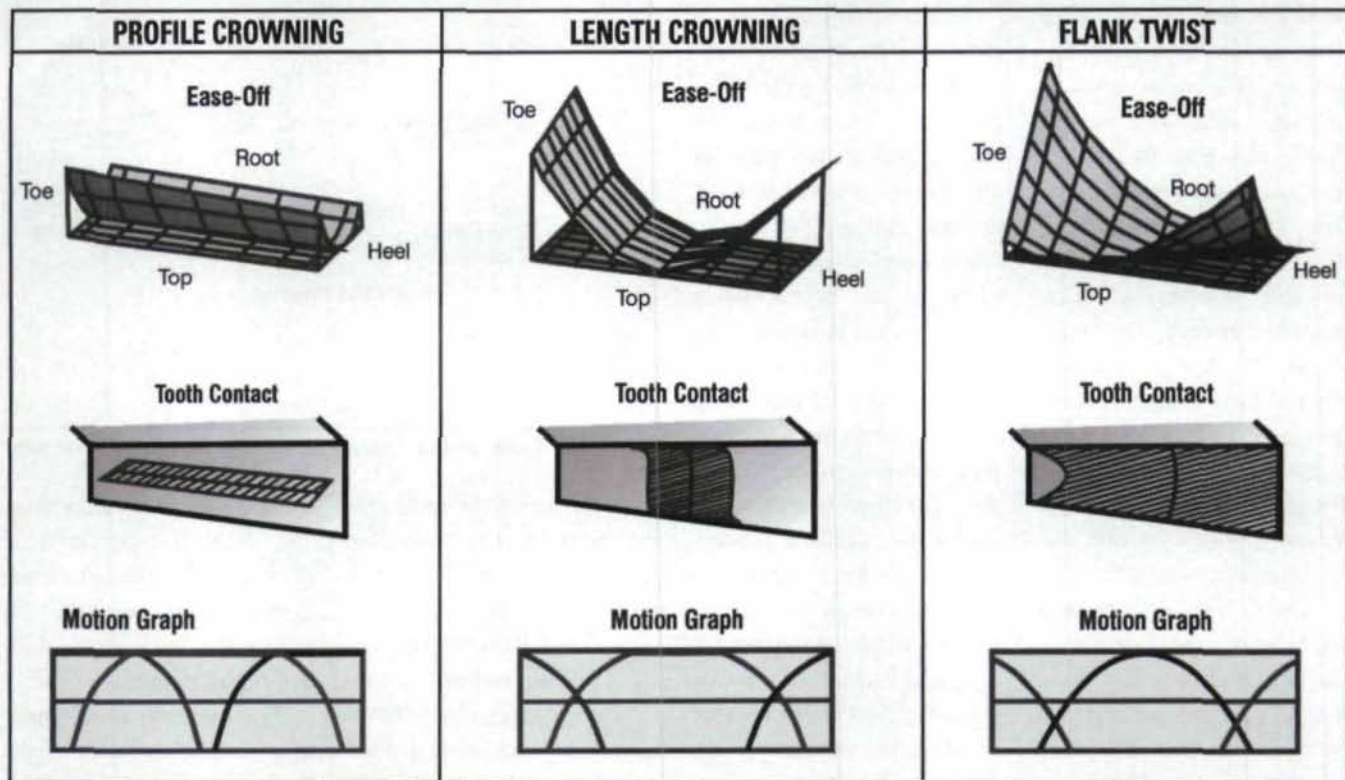


Figure 11—Tooth contact analysis of profile crowning, length crowning and flank twist.

contact area. It is the summation of all contact lines during the complete roll of one pair of teeth.

Conjugate bevel gear pairs are not suitable for operation under load and deflections. Misalignment causes a high stress concentration on the tooth edges. To prevent those stress concentrations, a crowning in face width and profile direction is applied to nearly all bevel pinions. The amount of crowning has a relationship to the expected contact stress and deflections.

To analyze tooth contact and crowning, computer programs for tooth contact analysis (TCA) were developed. Figure 10 shows the TCA result of a conjugate bevel gear set. The top section of Figure 10 represents a graphic of the ease-off. The ease-off represents the sum of the flank corrections, regardless of whether they were done in the pinion or gear member. The

octoidal profile and curved lead function are filtered out. Therefore the ease-off is a "flat" zero topography for conjugate gears. The tooth contact is shown below the ease-off. Tooth orientation is indicated with "heel, toe and root." The coast and drive sides show a full contact, covering the entire active working area of the flanks. The lower diagram in Figure 10 is the transmission error. Conjugate pairs roll kinematically exactly with each other. That roll is reflected by points on graphs that match the abscissas of the diagrams. Each point of those graphs has a zero value (ZG-direction), so they cannot be distinguished from the base grid. The base grid and graph are identical and drawn on top of each other. That characterizes a conjugate pair of gear flanks. The transmission graph always displays the motion variation of three adjacent pairs of teeth.

To achieve a suitable flank contact, today's flank corrections mostly consist of three elements, shown in Figure 11. Profile crowning (Figure 11, left) is the result of a blade profile curvature. Length crowning (Figure 11, center) can be achieved by modification of the cutter radius or by a tilted cutter head in conjunction with blade angle modification. Flank twist (Figure 11, right) is a kinematic effect resulting from a higher order modulation of the roll ratio (modified roll) or cutter head tilt in conjunction with a machine root angle change.

The three mentioned flank modifications can be combined, such that the desirable contact length and width, path of contact direction and transmission variation magnitude are realized. The TCA characteristics (contact pattern and transmission variation) are chosen to suit the gear set for the expected amount of con-

tact stress and gear deflections. ☉

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