

Bevel Gear Cutting Methods

Dr. Hermann J. Stadtfeld

Bevel Gear Technology

Chapter 9

THE FINAL CHAPTER

This is the last in the series of chapters excerpted from Dr. Hermann J. Stadtfeld's *Gleason Bevel Gear Technology* – a book written for specialists in planning, engineering, gear design and manufacturing. The work also addresses the technical information needs of researchers, scientists and students who deal with the theory and practice of bevel gears and other angular gear systems. While all of the above groups are of course of invaluable importance to the gear industry, it is surely the students who hold the key to its future. And with that knowledge it is reassuring to hear from Dr. Stadtfeld of the enthusiastic response he has received from younger readers of these chapter installments.

Gear Technology would like to thank Dr. Stadtfeld for his peerless scholarship, as well as Gleason Corp. for not only allowing the series to publish, but more importantly, for providing the kind of positive and nurturing work environment that enables such needed work as this to flourish.

– The Editors



Introduction

At the beginning of the twentieth century, motion and torque were transmitted to the driving wheels of the first automobiles with straight bevel gears. With slightly curved (episinoid) teeth, bevel gears were an improved alternative. Both straight and curved bevel gear teeth were cut with several different types of two-tool shaping generators. These cutting methods worked in a single-indexing mode. In 1913 The Gleason Works developed a single-indexing face cutter head method. At the same time, Gleason acquired the patents of Paul Boettcher from Hamburg, Germany, which were also based on face cutter heads. Although the subject of the Boettcher patents was the manufacture of bevel gears in single-indexing as well as in continuous indexing methods, company founder James S. Gleason made the strategic decision to concentrate on the single-indexing method only. The American and Asian automotive industry soon adopted this new method for all automotive and truck

axles. The “Gleason method” also spread to Europe—although the European market was shared between Gleason and several local manufacturers with different methods (Ref. 1).

In the mid-1920s the German company Klingelnberg introduced the continuous working “Palloid” cutting method, using a tapered hob that was applied by many European automotive manufacturers until the late 1940s. It is interesting to note that some companies had their own developed bevel gear cutting methods, like Fiat (“Mamano method”) and Renault (“Rochat method”) (Ref. 2).

After World War II, the special methods from Fiat and Renault disappeared, along with the Palloid method from the automotive and truck industry. Mass-produced bevel and hypoid gear transmissions were now being produced, with a few exceptions, by single-indexing methods on Gleason machines. Many of the bevel gears that have been produced in Europe after 1945 on non-Gleason machines were manufactured with newly

developed methods from the Swiss company Oerlikon-Bührle. The so-called “N” and “G” methods from Oerlikon were continuous indexing cutting methods (Refs. 2–4).

The first modern face hobbing process based on machines with cutter head tilt and cutters with HSS stick blades was developed by Oerlikon-Bührle in the 1970s, and caught the interest of European and American manufacturers of heavy trucks. More than 10 years went by before the first face hobbing machines were installed in U.S. automotive gear labs to try out this “new process.”

In the meantime, Gleason had also developed a version of the face hobbing process. The Gleason method was also based on stick blade cutter heads and was offered together with the world's first CNC-controlled bevel gear cutting machines (G-MAXX). What started out very slowly in some gear labs in Detroit gained in popularity during the following decade. Desirable attributes like low cutting times, good tooth spacing, and an

easy to lap surface structure helped face hobbing break through to the U.S. market. It must be mentioned that — without exception — all face hobbing methods are completing processes that reduce cutting times even further.

In Europe, on the other hand, the old face milling, five-cut was replaced by the Gleason face milling completing. The single-indexing completing method also uses cutter heads with stick blades, which in connection with fast indexing CNC machines achieves a similar productivity as the face hobbing process. The reason for European manufacturers to change to this new single-indexing method was the possibility to grind the manufactured bevel gears after heat treatment. The grinding tools are cup wheels that are dressed so that they duplicate the enveloping surface of the face mill completing cutter blades used in the cutting operation. All attempts to find ways to also grind the face hobbled gears in a completing cycle failed, which is the reason why most face hobbled bevel gears are lapped, or sometimes skived, and in very few cases ground in two single side setups.

The Trend in the United States and Europe

Bevel gear grinding in fixed setting mode (single flank grinding) was already introduced by the 1920s for the hard finishing of aircraft gears. However, the stable grinding of automotive bevel gears in a cost-effective completing mode has evolved in production and as a commonly used process only during the past 15 to 20 years. European manufacturers turned away from traditional lapping and converted more and more bevel gear designs to face milling completing. These manufacturers liked the small variations in the finish geometry of the manufactured bevel gears, which is nearly independent from the varying heat treat distortions. The scrap rates for grinding production are lower than that for lapping. Further advantages of grinding are the simplified manufacturing logistics, higher efficiency in operation, and less cleaning effort.

Lapped bevel gearsets show lower efficiency (higher operating temperatures) and in some cases more wear because of the lapping grit that can embed in the flank surfaces.

At the same time, the bevel gear manufacturers in the U.S. converted more than 90% of their five-cut face milling applications to face hobbing completing. The American vehicles with bevel, i.e. — hypoid gearsets — are mostly pick-up trucks and sport utility vehicles (SUVs). This category of vehicle with the consumer requirements of the 1980s and 1990s was particularly well suited for the application of face hobbled and lapped hypoid gears.

The Asian automotive industry didn't adopt either of the two trends. The same company might apply the five-cut method on 40-year-old (well maintained) Gleason No. 116 machines, practice completing wet cutting with grinding after the heat treatment, or apply face hobbing dry power cutting with lapping as a hard finishing operation. This variety enables the Asian manufacturer to choose the optimal manufacturing scenario for every batch size and each application case.

Which of the two camps — face hobbing and hard finishing by lapping or face milling and hard finishing by grinding — will establish itself in the future will depend on the technological developments of the next years (Ref. 5). One thing is certain, however — a compromise between face hobbing and face milling is obviously not possible.

Continuous Indexing (Face Milling) with Lapping or Single-Indexing (Face Hobbing) with Grinding

The question as to which method delivers the better rolling performance and higher strength of the manufactured bevel gearsets has often been asked. The answers are as different as the people asking the question, and the answers have changed over time. The most significant influence upon the changing properties of the two methods was the development of bevel gear grinding. Today's bevel gear grind-

ing improves, in general, all important properties such as strength, noise characteristics and efficiency. A global rating of the strength of bevel gearsets that have been manufactured with various combinations of manufacturing methods can be rated using the following grades (1→excellent, 4→poor):

1. → Face milling completing and hard finishing by grinding
2. → Face hobbing and hard finishing by lapping
3. → Face milling with five-cut and hard finishing by lapping
4. → Face milling completing and hard finishing by lapping

A rating regarding noise emission and efficiency is basically the same. The rating list makes it clear that the real question is not face hobbing or face milling, but rather lapping or grinding. A ground gearset with an epicycloid flank line might have achieved the best rating — if it were possible to manufacture. The mathematical function of the flank form, the taper of slot width and tooth thickness in face width direction, as well as the tooth depth taper (parallel or conical), play an important role, which makes it important to clarify the following parameters:

- Macrogeometry
- Flank surface topology
- Ease-Off topography
- Root fillet geometry
- Microstructure of surface

These parameters and their influence on the rolling performance and strength of a bevel gearset are discussed in the following sections. This leads to head-to-head comparisons of the functionality and economy of the two methods, which will finally lead to a recommendation for the method best suited for a certain manufacturing environment, i.e. — which geometry best fulfills the requirements of the mechanical gear properties. The analytical explanations concentrate on the most commonly used method combinations, with the ratings 1 and 2 in the list from the previous page.

Single Indexing

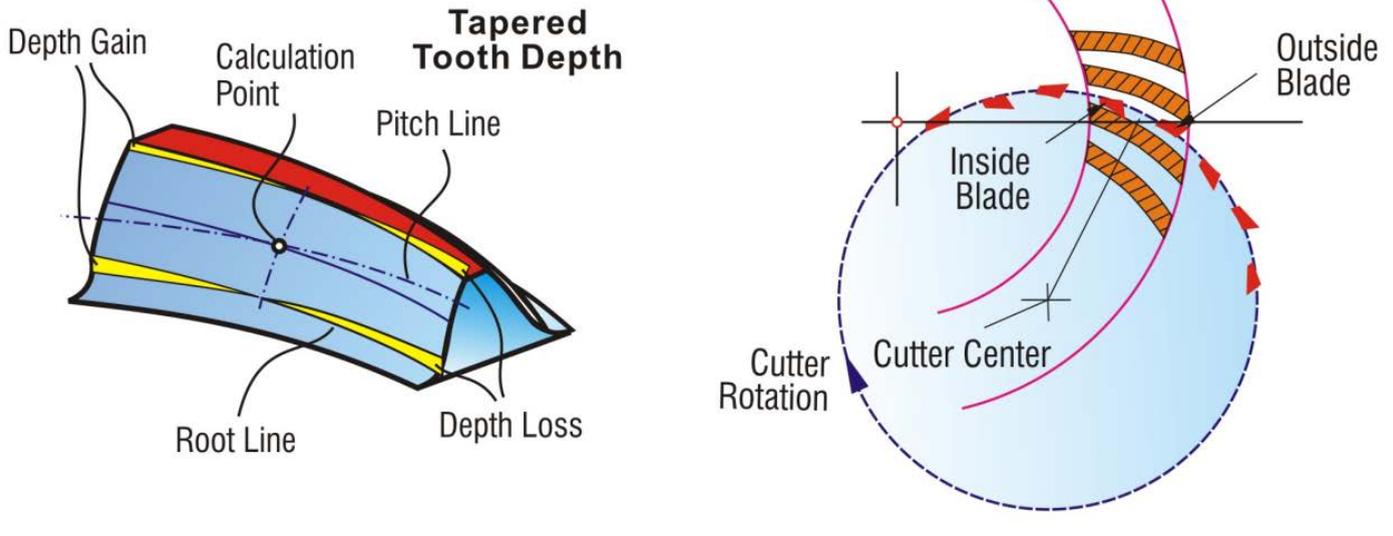


Figure 1 Single-indexing (face milling) Formate.

Observation of Differences in Macrogeometry

Macrogeometry of face milled bevel gears. Face milled gearsets are manufactured in single-indexing — one slot at a time. The right side of Figure 1 shows how all the inside and outside blades of a face mill cutter head pass through one slot of a plane gear, while the cutter moves perpendicular to the drawing plane until the full depth position is reached. For a simple explanation, it is assumed that the manufactured bevel gear is cut in Formate. In this case there is no additional motion and the cutter

rotates around its center, while the center is also fixed relative to the generating gear axis. The flank line's mathematical function is a circle. The distance between the cutter center and the gear center results from the desired mean spiral angle in connection with the cutter diameter. In the case of bevel or hypoid pinions and gears, the circular flank lines wind around a conical or hyperbolic pitch element, similar to the straight flank lines that wind around the pitch cylinder of a helical gear.

The curvature of the teeth, as well as the relative curvature of the meshing

teeth, is constant along the face width of the teeth. The slot width, equidistant to the root, is also constant. Consequently if both flanks are cut with the same cutter simultaneously (completing), the radius of the convex flank is about the amount of the slot width smaller than the radius of the concave flank. Figure 2 shows a schematic of the unrolled flank lines for a pinion.

The difference in outer and inner circumference of the generating gear causes, as seen in Figure 2, an extreme tooth thickness taper that leads to an un-proportionally thin and high tooth in the toe region, and to a short and thick tooth at the heel. Other than the fact that a pointed topland can occur on the toe, the teeth of the one member will not fit and roll in the slots of the other member if both members are manufactured in a completing process. This is why a certain tooth depth taper is applied in all face milled completing bevel gears. The tooth depth taper is calculated in such a way that it generates a slot width taper that splits the difference in circumference between toe and heel in an equal slot width and tooth thickness taper (in the height of the generating gear pitch plane). Figure 3 illustrates this principle using a ring gear as an example. This assures also that the tooth profile changes its size between toe and heel proportionally and, in turn, that

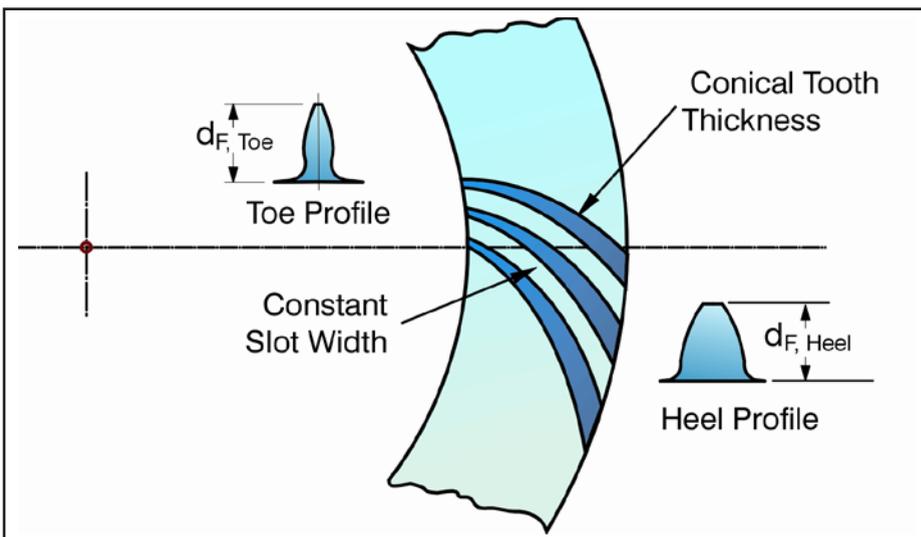


Figure 2 Flank lines in generating gear plane of parallel depth face milling; profiles of resulting pinion tooth.

the teeth of a member fit in the slots of the mating member with a controllable amount of backlash. Given this explanation it becomes obvious that the proportions of tooth depth and slot width for face milled completing bevel gears is not a freedom to be chosen, but a given relationship necessary for establishing a functional gearset.

Macrogeometry of face hobbled bevel gears. Face hobbled gearsets are manufactured as continuous indexing; while the outside blade and following inside blade of one blade group cut one slot, the following blade group will enter the next slot (Fig. 4, right). This is accomplished by the simultaneous rotation of the cutter and workpiece, where the work rotates per cutter revolution for as many pitches as the cutter has starts. The resulting mathematical function of the flank lines of a plane generating gear is an extended epicycloid. In this case the curvature radius of the flank line is increasing from toe to heel and the average curvature depends not only on the cutter radius, but also on the number of starts of the cutter head (see also original text chapters 2.3 and 2.4).

The constant relative indexing motion between cutter and work results in an equal split of the inner and outer circumference on the toe and heel—as well as an equal split between toe and heel along the entire face width. This leads to a “natural” slot width taper and equal tooth thickness taper. If the tooth depth along the face width is designed constant (parallel depth), then the pitch cone is equidistant to the root cone, which with no Ease-Off corrections results in a perfectly conjugate geometry between produced pinions and gears.

The fact that face milled gears have no slot width taper—but a large tooth thickness taper—and face hobbled gears have an equal slot width and tooth thickness taper, is the one reason why it is impossible to grind face hobbled gears (using a cup-shaped grinding wheel) simultaneously on both flanks of a slot in a completing process. And, the reason why face hobbled gears cannot even be ground on even *one* side of a slot at a time with a cup-shaped wheel is demonstrated in Figure 5. The difference between an epicycloid and a circle has a nearly sinusoidal appearance. Single side grinding

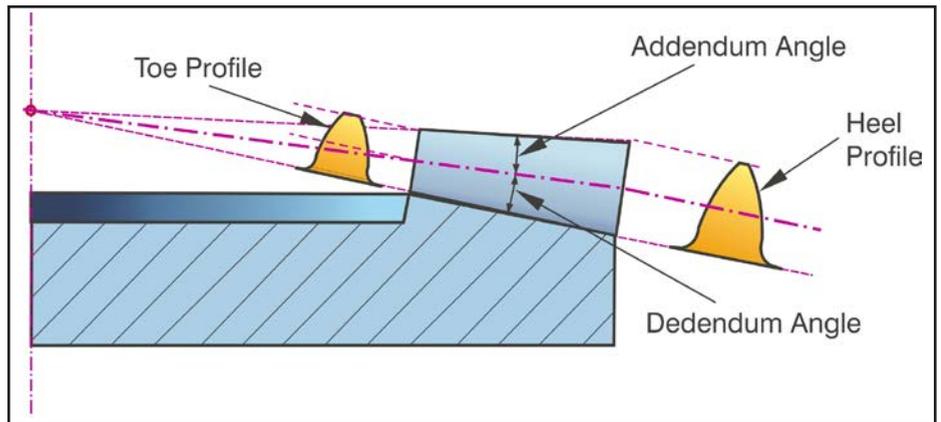


Figure 3 Tooth proportions—tapered depth face milling completing.

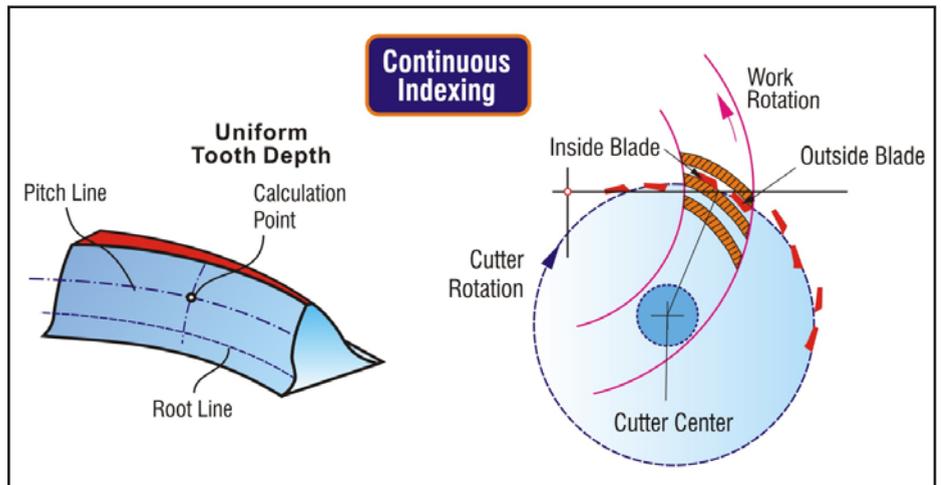


Figure 4 Continuous indexing (face hobbing) Formate.

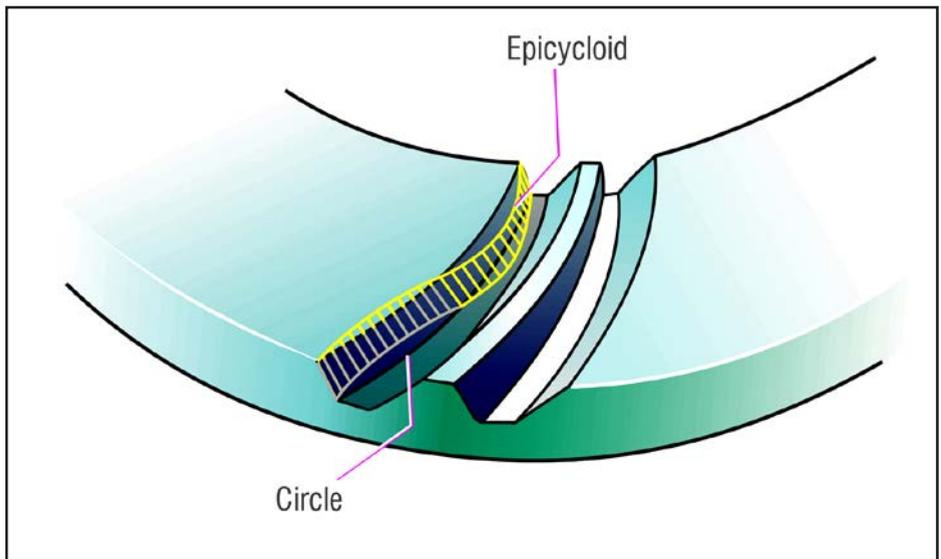


Figure 5 Circular arc vs. extended epicycloid.

might be possible with big variations in stock removal along the face width, but a change in the properties of the ground gearset must be expected because it will destroy the epicycloid and replace it with a circle. The specifically favorable displacement properties of the face hobbled, soft manufactured geometry will be removed due to the grinding.

The longitudinal macrocurvature is constant in face milling and changes along the face in face hobbing. However, an interesting longitudinal shape for a flank line is an involute. Teeth with such a shape would be insensitive to longitudinal displacement between pinion and gear flank, similar to the insensitivity of regular cylindrical gears with respect to a center distance change. For example, Klingelnberg Palloid gearsets have an involute flank line function. Neither face hobbing nor face milling is able to produce involute flank lines; nevertheless, there is always one point along every curved flank line that fulfills the so-called involute conditions.

Figure 6 shows the curvature required to achieve involute conditions at different points along the flank line. Independent from the mathematical flank line function of the bevel gears discussed in this

paper, which are epicyclic or circular, the position of the involute point relative to the center of the flank or relative to the initial contact position is significant for noise and load behavior. It is perceived as ideal if the initial contact for light load is positioned towards the toe and moves under increasing load to the heel, while the contact spreads. Under 100% nominal load the contact area should use the entire flank — without hard contact at the teeth boundaries. The positioning of the involute point allows control of the contact movement under load. It is recommended to choose an involute point location between the flank center and the heel. If only small displacements are expected, the involute point should be positioned at the heel border. Large displacements require an involute point between center and heel. However, the involute point should not be positioned at the center of the face width because this would prevent contact movement and therefore cause surface fatigue at the flank center. The contact pattern tends to move under load towards the involute point; this movement becomes smaller as the contact pattern approaches the involute point. No contact movement will occur, even under severe overload due to

matching locations of contact pattern and involute point. In spite of the significance of the involute point, an involute-shaped flank line is not desirable.

Face hobbled bevel gearsets tend to have their involute point location between the flank center and the heel, which gives them the reputation of being forgiving with respect to gearbox and gearset deflections. The design practice for modern face milling completing gearsets takes advantage of the relationship described in Figure 6 and has adopted smaller cutter radii than were used until some years ago (with the five-cut process), in order to achieve a predetermined position of the involute point. The so-called ratio of involute-to-mean-cone (A_x/A_m , Fig. 6) should be above 1.0, while the ratio of involute-to-outer-cone has to be below one, or should at least not exceed 1.0. Face milling bevel gearsets designed according to this rule achieve the same forgiveness for high deflections as face hobbled gearsets.

Surface Topology

Surface topology of face milled bevel gears.

Face milled gearsets have machining marks (generating flats) that are parallel to the lines of contact between pinion and gear. In other words, the cutter blades cause traces on the flank surfaces during the cutting process with a spacing that depends on the roll rate and angular distances of the blades in the cutter head; the contact lines between pinion and gear flanks are parallel to those machining marks. Figure 7 offers a simplified visualization of the relationship between the generating flats and a contact line. Case 1 (Fig. 7, left) shows a plane as a simplified ring gear flank and a pinion flank, simplified to a cylinder. The contact line between cylinder and plane is parallel to the machining marks of both surfaces; this is typical for two flank surfaces machined in a single indexing generating process. The surface combination in case 1 leads to a “rough” rolling of the cylinder on the plane. There is a high risk that lapping compound between the two surfaces will be pressed out and wiped away from the contacting zone; smoothness of rolling and lappability are not good in case 1.

The smooth surface in case 2 represents a Formate ring gear flank that does not show any generating flats. The con-

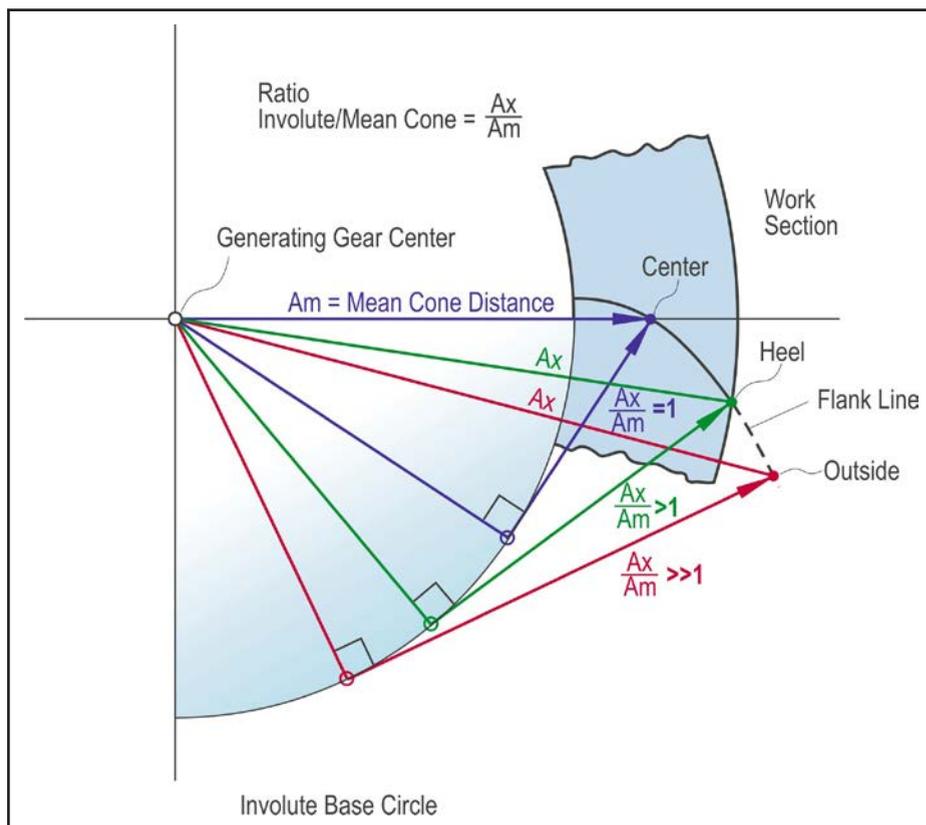


Figure 6 Involute-shaped flank line and relationship between involute and cutter radius.

tact line between cylinder and plane is, as with case 1, oriented in the direction of the generating flats of the cylinder. This resembles the surface analogy to a bevel gear pair of a generated pinion and a Formate ring gear. Also in case 2, the result is a “rough” rolling of the cylinder; however, lapping compound between the surfaces has a better chance of remaining in the contact zone. Case 2 leads therefore to poor rolling performance but has better lappability than case 1. In order to achieve good lapping results in face milling, the surface waviness (flat amplitudes) is required to have only about 10% of the surface waviness of face hobbled gearsets after cutting. While here the surface roughness is basically non-critical, the opposite is true regarding ground face milled gearsets. Flank form and surface condition of semi-finished face milled gears is less critical than with face hobbled gearsets prepared for lapping.

Surface topology of face hobbled bevel gears. Case 3 (Fig. 8, left) is a model of a generated face hobbled flank pair. The contact line between cylinder and plane crosses the generating flats under an angle. This configuration causes a gradual, soft rolling of the cylinder and provides a pumping of the lapping compound through the contacting zone (when the lapping process applies). The result is a high rolling smoothness and good lappability in case 3 (Ref. 6).

The smooth plane in case 4 represents a Formate ring gear flank surface with no generating flats. The contact line between cylinder and plane crosses the generating flats of the cylinder, as in case 3 — under an angle. This is analogous to the surfaces of a face hobbled and form generated bevel gear pair. Also in case 4, the result is a smooth rolling of the cylinder. Lapping compound placed between the two surfaces will be pumped through the contact zone, similar to case 3. Case 4 provides the best rolling quality of the 4 discussed cases, and shows equal lappability to case 3.

The observations in this section lead to the conclusion that face milled gearsets are not suited for hard finishing by lapping. However face hobbled gearsets, in contrast, show excellent suitability for lapping as a hard finishing process.

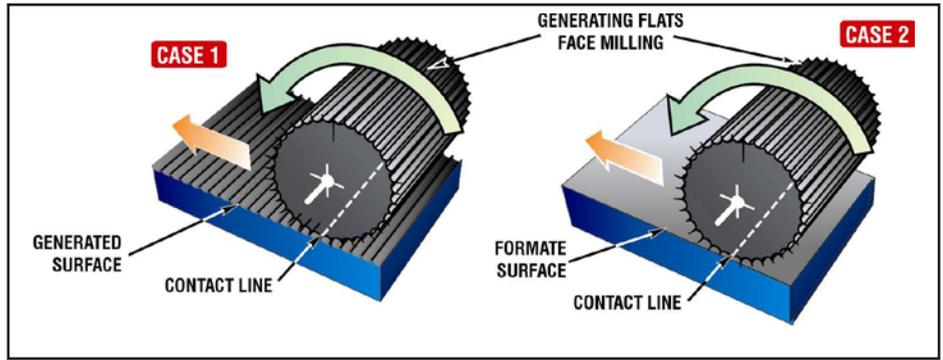


Figure 7 Principal roll condition for face milled gearsets.

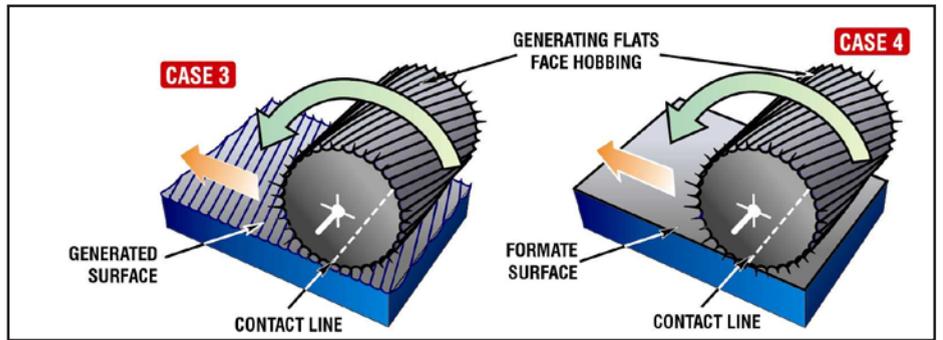


Figure 8 Principal roll condition for face hobbled gearsets.

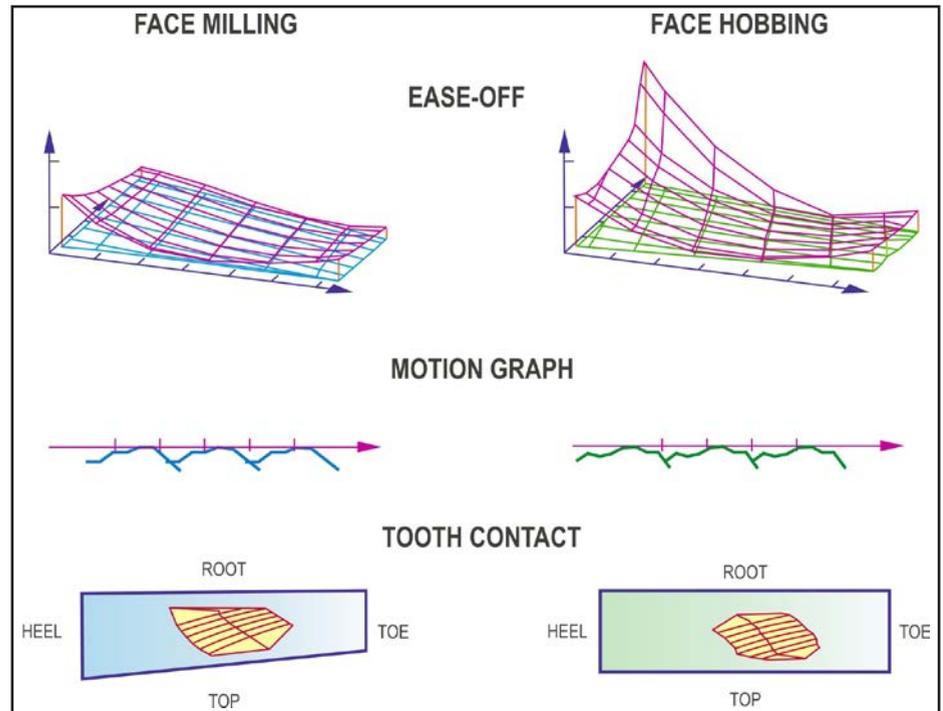


Figure 9 Analysis results of modern designs — left, face milling; right, face hobbing.

Ease-Off Topology of Face Milled and Face Hobbed Bevel Gearsets

The usual design calculation practice applies different tooth contact pattern and Ease-Off topographies for face hobbed vs. face milled designs. This was based in part on the large cutter radii recommended in the past for face milled gears and the small recommended cutter radii in face hobbing. Additional reasons for the design of different contact patterns included the conjugate basis with only simple optimization freedoms of face hobbed gearsets vs. the non-conjugate basis of face milling that offered a variety of geometric and kinematic optimizations.

Today's modern bevel gear design defines the cutter radii independent of the cutting method in order to achieve an optimal displacement characteristic. The shape and size of the contact pattern can be chosen nearly independent of the cutting method. Additional *UMC-Motions* and cutter blades with "blended Toprem" and "blended Flankrem" can be equally applied to face hobbed and face milled gearsets (Ref. 7). Figure 9 (left) shows the exotic-appearing Ease-Off of a face milled bevel gear pair. The contact pattern, which only a couple of years back was typical only for face hobbed gearsets, has been calculated using *UMC-Motions*. The complex Ease-Off function of the face milled gearset is realized with excellent repeatability after heat treatment, by grinding.

Ease-Off and contact pattern of the face hobbed bevel gear pair (Fig. 9, right) have also been designed using *UMC-Motions*; cutter blades with blended Toprem were also applied. Modern

flank optimizations adapt very well to face hobbed bevel gearsets if a heat treatment with low distortions is possible, and if high-speed, short-time lapping is applied as a hard finishing operation. High-quality, ground bevel gearsets have to be rolled as individual pairs in order to measure single flank error or structure-borne noise in different pinion cone positions. The final pinion mounting distance, i.e. — the required shim rings — are determined on the roll tester. The logistical cost of ground gearsets is therefore only lower prior to the roll testing.

A lapped surface finish still depends today on the interaction between pinion and gear; it is impossible to achieve the precise mathematical target surface. Heat treat distortion and inconsistent lap removal in different zones of the flank surface result in a final contact appearance that differs significantly from the tooth contact analysis at the stage of the design calculation. Contact patterns of lapped gearsets have a very soft transition to the flank areas without contact and allow realization of excellent, low-motion error. Nevertheless, the variation in one manufacturing batch is high, and every gearset is matched after lapping; yet there still needs to be roll testing, with the possibility of finding an optimal build position that requires individual pinion shimming. The roll testing also serves of course to find and eliminate reject pairs.

This section about Ease-Off and tooth contact optimization has, in summary, four messages to convey:

1. There are Ease-Off limitations in face milled gearsets caused by the tapered tooth depth and the smaller cutter radii, as they are used today. They can

be eliminated with *UMC-Motions* (and three flank sections).

2. The nominal geometry of face milled bevel gearsets can be reproduced by grinding with high accuracy.
3. There are limitations regarding the final Ease-Off for face hobbed and lapped bevel gearsets due to heat treatment distortions and non-uniform material removal of the lapping process.
4. Resulting Ease-Offs and tooth contact patterns look unconventional and exotic from a conventional viewpoint, but are more application-oriented than tooth contacts of the past.

Root Fillet Geometry of Face Milled and Face Hobbed Bevel Gearsets

The face hobbing macrogeometry has a conical slotwidth along the face, which is also true of the root bottom. The blade edge radii and the blade point width must be calculated from the smallest root width on the toe of the slots. Not only are the edge radii and blade points of inside and outside blades limited by the conditions of the smaller slotwidth at the toe, the movement of outside and inside blades along non-concentric tracks causes cross-over between outside and inside blades and leaves a fin — or step — on the root fillet bottom (Ref. 8). Although a step in the root can be averaged out between toe and heel by axial stepping of the blades, a fully rounded root fillet is not possible for a continuous indexing process utilizing face cutter heads (Fig. 10, right).

The strength advantages of face hobbing experienced in the past are based, to a larger extent, on the insensitivity to deflections and tolerances. This insensitivity has its origin in the central location of the involute point due to a small cutter radius and a high number of cutter starts. The subsequent reduction of the load concentration at the heel allows higher loads with reduced risk of tooth fracture. A non-optimized, standard face hobbing design today still delivers a stronger appearing gearset compared to a non-optimized face milling gearset.

The face milling root geometry can be optimized to a stepless, smooth root fillet and, in many cases, even a fully rounded root fillet is possible. Optimized, face milled bevel gearsets gain a definite

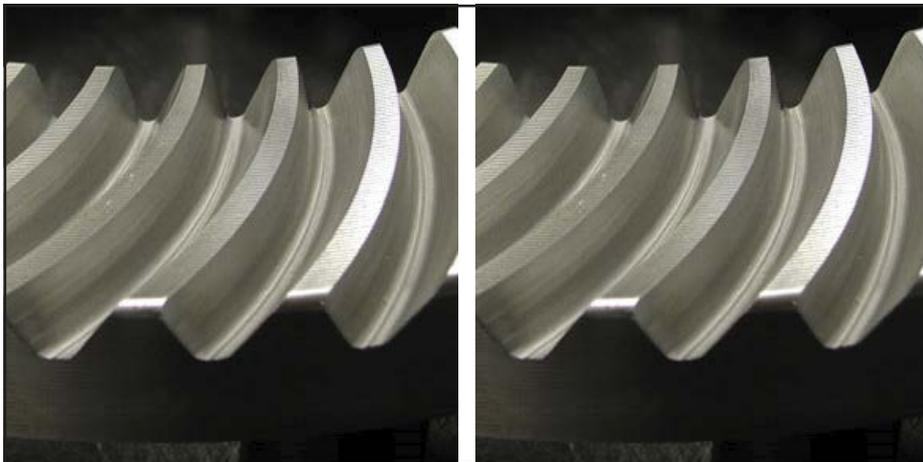


Figure 10 Ring gear root fillet — left → face milling; right → face hobbing.

strength advantage compared to optimized, face hobbed gearsets due to the possibility of a more optimal root design (Fig. 10, left).

Face milled bevel gearsets must be relieved with protuberance blades at the flank-root transition areas on the pinion and gear flanks in order to keep the grinding removal in these areas low and in order to achieve a soft flank-root transition.

Lapping of flank surfaces utilizes the top of the one member to lap the root of the mating member, and vice versa. The transition between flank and root must be relieved in the cutting operation by using protuberance in the pinion blades, whereas the ring gear flanks do not require this relief. This feature accounts for the lap removal that is on the pinion flanks because of the higher number of pinion revolutions, a multiple of the ring gear lap removal. The high material removal on the pinion would cause a lapping step between flank and root. The protuberance relief differs along the face width as a result of the generating process and the changing pinion diameter between toe and heel. Small protuberances will leave a partial lapping step along the face width, where in a case of too much protuberance some relieved section will not be lapped out. Both cases require a compromise in the design of the transition area between flank and root that either causes interference (lapping step) or weakening of the root. Interferences are often not recognized in the roll tester, and result in unexpected noise phenomenon under load. Good pre-corrections for heat treatment distortions and the use of pinion and ring gear blades with blended Toprem instead of protuberance limited to the pinion can eliminate the disadvantages of the conventional protuberance — if lapping time is kept short.

The message regarding strength in this section is that a more optimized root fillet can be machined by grinding. Also, interferences that can cause noise as well as strength problems can be avoided by grinding.

Surface Roughness, Waviness and Texture

Microsurface topology and microsurface structure are related properties of a surface characteristic. The generating

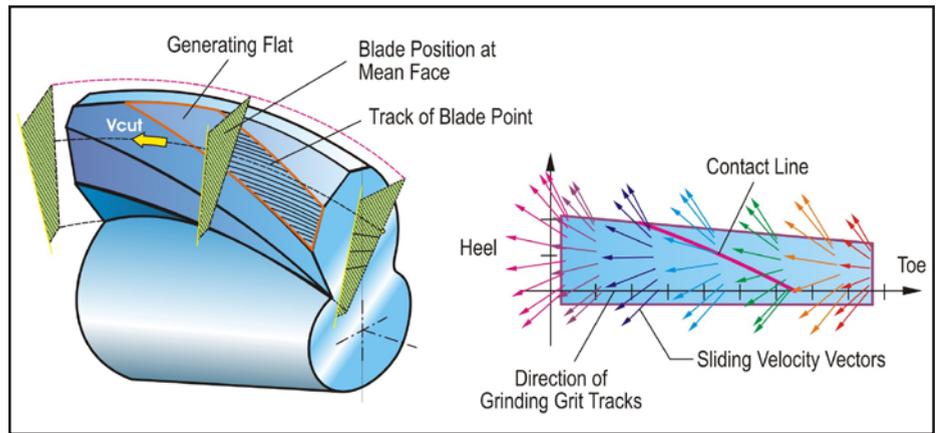


Figure 11 Generating flats and blade roughness traces, sliding velocity vectors, and contact line.

flats that are crossed to the contact lines between pinion and gear in face hobbing have been mentioned in (*original text, chapter/section 9.5.2*). The characteristic of the generating flats in face hobbing helps to reduce excitations of higher multiple tooth mesh frequencies in the operation of a bevel gearset. The sources of those excitations are low because of the crossed arrangement, i.e. — contact line → generating flat; the generation of additional high frequency excitations is reduced and the flat structure (Fig. 11, left) is eliminated with lapping. The remaining structure after lapping is generated by the lapping grit and the relative motion between pinion and gear. The relative motion can be captured by the relative sliding velocity, shown for a hypoid gearset (Fig. 11, right). The surface texture generated by lapping is consistent with the vector map of the sliding velocities, which shows a different orientation than the contact lines between the pinion and gear flanks. This also reduces the excitation of higher harmonic frequencies during operation of a gearset; but this excitation is not completely eliminated, as the flank surface structure between pinion and gear match exactly due to the manufacturing process, where the pinion is the finishing tool of the gear, and vice versa. The lapping motion can also induce long wave surface modulations. Further modulations that have a shorter wave length are leftovers from the generating flats caused during the cutting process. If all the mentioned possible imperfections are considered — and can possibly be avoided — the result is a remarkably quiet, lapped gearset.

In face milling the generating flat

structure is removed by the grinding operation, but the traces from the grinding wheel grit are left. On the pinion and gear flanks those traces are parallel to the root and extend along the entire face width (see “Track of Blade Point,” Fig. 11). Although the traces have an inclination to the contact lines, the valleys and crests of the longitudinally oriented roughness of pinion and gear are almost a match in their direction. The sliding component in profile generates a higher order excitation that presents a scoring risk. The goal is to achieve surface roughness values of $Ra \leq 0.8 \mu\text{m}$ and $Rz \leq 5 \mu\text{m}$; the roughness values of lapped surfaces are smaller. Certain imperfections, e.g., in the grinding wheel profile, repeat with high accuracy from flank to flank on all teeth of a ground gear. If the number of imperfections is, say, three, even though the magnitude of the imperfection might be below one micron, the likelihood of an excitation of a third harmonic frequency will be high. Gleason has developed a package in order to improve the surface texture of ground bevel gear surfaces. Under the trade name MicroPulse — a combination of dressing parameters, machine motions and dynamic effects are utilized to generate a surface texture during a “regular” grinding operation that gives the pinion and gear surfaces different, non-matching surface textures that in the past could only be realized via honing processes.

In concluding this section, it can be stated that the surfaces of lapped bevel gears are more optimized regarding roughness and rolling performance than the surfaces of ground gearsets. In contrast, measurement results seem to prove

that the efficiency of a broken-in, ground bevel gearset is higher than the efficiency of comparable lapped pairs.

Global Strength Considerations

When face hobbing and face milling designs are compared, finite element calculations and strain gauge measurements prove that idealized teeth and root fillets with no or little surface roughness, optimal blend between flank and root, and optimal rounded root fillet without steps and fins in the root bottom, both deliver identical results.

The higher precision of the flank form and the more favorable root fillet of the face milled and ground gearset are therefore compared to the advantage gained from the more optimal surface structure of the face hobbled flank surfaces. Some of the possible advantages of the face hobbled flanks cannot always be realized due to variations in the lapped flank surfaces. Consistency in the grinding process is obtained through a strong effort regarding grinding cycles, grinding oil filtering, condition of the grinding machine, dynamically sound machine placement on the shop floor, etc.

In a highly consistent grinding production, it is possible to make gears that correspond in both surface durability and root bending strength — and extremely close to predictions calculated with sophisticated finite element programs. It is also possible to address single properties, such as sub-surface stress, in order to reduce them without sacrificing other properties.

Fine-Tuning and Optimization During a Lifecycle

During initial prototype testing, and also during the following lifetime of a gear design, it is often necessary to address specific parameters or features in order to eliminate a certain problem without having negative side effects on other features. At the beginning of the lifetime of a new design, the field of attention might be tooth fracture, pitting, or case crushing. For ground gearsets it is possible to change the root fillet radius, eliminate an interference with blended Toprem, change the contact size or position, modify the displacement characteristic, or add a UMC heel section in order to eliminate edge contact under high load, without a

cross influence of the one optimization on all other features of the flank and root geometry.

The face hobbing finish geometry (including the flank > root blend) still depends in today's lapping to a large extent in the inconsistencies of the lapping process, and also is a result of the difficulty in controlling the material removal mechanism of lapping in general. Making small changes to the lapped tooth contact on the drive side may also cause some change on the coast side and could generate an unwanted change in the high load contact pattern. The transition between flank and root (lapping step) can also be influenced because the lapping process connects all the geometrical features of flank and root transition together. Changing the contact displacement characteristic by optimizing the lapping motions is almost impossible. In such a case a slightly modified new design calculation is required. This also means that most of the development that had been conducted to get from the theoretical design to a functional bevel gear or hypoid transmission will be scrapped and the development work will have to start all over again.

The advantage of ground bevel gear designs during the lifecycle of the gearset becomes obvious, due to the possibility of controlling nearly every single parameter independently without the risk of destroying other positive features of the gearset.

Manufacturing Cost Comparison

So far this chapter might seem to some readers as a “white paper” dedicated to grinding. However, the diligent, conscientious reader will have noticed that the last sections presented many facts that were not known or considered in the context of the evolution that grinding has experienced during the past 15 years, and particularly during the past five years. Some time ago, the manufacturing stability of automotive and truck production grinding was not at an acceptable level, which made in the comparison with lapping, face hobbing lapping the winner not only in manufacturing cost but also in noise and strength.

The progress in grinding, some of which has been reported in this chapter, is significant. It begins with a grinding friendly basic geometry with suitable

parameters for a good displacement characteristic and a low noise excitation. The development of the Ease-Off is targeted today at conjugate flank center and sufficient crowning towards the boundaries of the teeth. The result is a highly effective contact ratio for high strength and smooth rolling, yet sufficiently robust to accept manufacturing variations and deflections. The right semi-finish strategy and heat treat pre-corrections are also important to guarantee good input for an efficient grinding operation. That does not at all mean grinding is the better process; it might only emphasize that grinding today is comparable with lapping regarding process stability and noise quality. To out-perform good, lapped gearsets regarding low noise emission, for ground bevel gearsets it is not yet possible — or at least very difficult. The strength of ground bevel gears is only better if the latest rules with respect to flank form and transition between flank and root are followed. Lapping can also benefit from the advancements made in grinding. UMC *Motions*, with three sections as well as a more advanced root relief, has been tried successfully in combination with short-term lapping and low heat treat distortions.

An attempt at a cost comparison between lapping and grinding was made (Fig. 12). Continuous face hobbing under comparable conditions is somewhat faster than the single indexing face milling. In spite of this, face milling is a semi-finish operation while face hobbing in preparation for lapping is considered a finishing process, and the reason the cost of the soft cutting operations for both scenarios can be estimated as equal. This also applies to heat treatment and grinding, or hard turning journals and seating shoulders. The cost estimations (Fig. 12) are therefore limited to hard finishing operations, including final measurement and roll testing. The hourly machine rates were calculated using a depreciation period of five years with a one-shift, 5-day operation.

Manufacturing cost of lapping. It has been assumed that one operator handles two lapping machines, and one operator attends to one testing machine for a 100% testing. The lapped gears are handled in pairs after lapping. The scenario in the (Fig. 12) spreadsheet assumes that all

Light trucks, pick-ups, sport utility vehicles. Seventy percent of all produced bevel gearsets are lapped; 20% are ground.

Passenger cars with all-wheel-drive. Almost 100% of all-wheel-drive passenger cars manufactured in Europe are ground; in the U.S. and Asia, 65% are lapped and 35% are ground.

Passenger cars with front- or rear-wheel-drive. Seventy-five percent of the bevel gearsets applied are ground; 25% are lapped.

Motorcycles. The three manufacturers who build motor cycles with a propeller shaft between transmission and rear wheel (instead of chain) use lapped bevel gearsets between the propeller shaft and the rear wheel.

The question of which combination of processes is best suited for a certain application (i.e. — an existing infrastructure) is discussed in a different light in the following two sections:

When are face hobbing and lapping the best process combination?

- Good for small manufacturer with continuously changing jobs
- Design calculation in-house, but complex optimizations are not practical
- Lowest investment in machines and tools is more important than production in a closed loop
- Manufacture of heavy truck axles
- Short development times, but must produce above-average bevel gearsets

When is face milling and grinding the best process combination?

- High numbers of equal bevel gearsets
- Bevel gearsets for premium passenger cars and SUVs
- Large numbers of different but repeated small batches
- Manufacturing of aircraft bevel gearsets
- Large high-precision bevel gears; e.g. — for marine applications (below 1,000 mm OD)
- If the efficiency of bevel gears is a particularly important factor

Summary

It is obvious that both process combination — face milling/grinding and face hobbing/lapping — have their unique strengths and weaknesses, and that both have a future in the modern manufacturing of bevel gearsets.

Lapping is a process used for certain kinds of fittings, like valve seats, in order to achieve a highly individual fitting accuracy between two functional machine elements. Lapping had its breakthrough in the hard finishing of bevel gears, at a time when highly qualified workmanship and manual labor in industrial production was available, as well as acceptable. The closed control loops desired in today's production are not applicable to lapping, as the quality of lapping production is only verified by rolling on a testing machine. Coordinate measurement against theoretical target data is without much meaning, because the flank form errors of the single members can only be judged in connection with the flank form errors of the mating member. Even if such an error consolidation was realized, the result could only be noticed because of the absence of a determined correction of flank form errors by corrective lapping (see also original text, chapter 11.1.6).

Grinding enables measurement against theoretical flank surface data and the correction of the found errors in a closed loop between coordinate measurement machine and manufacturing machine. The cost difference in the manufacture of ground gearsets vs. that of lapped pairs is negligible, as reflected in the tables of Figure 12. Grinding is therefore justifiable economically, and more suitable for modern bevel gear production than lapping regarding repeatability as well as AGMA, DIN, JIS or ISO quality.

Rear-wheel drive, premium-class passenger cars have made a comeback, and cars with all-wheel drive have enjoyed increasing popularity. Because these automobiles are considered to be high-tech products, ground bevel gearsets can be well justified, just as in aviation equipment.

What does this all mean?

It means that there are a number of reasons why ground bevel gearsets have become more desirable during the past years. Companies that specialize in the manufacture of lapped bevel gears are undoubtedly positioned to match ground bevel gearsets regarding strength and acoustic and NVH (noise-vibration-harshness). 

References

1. Hoffmann, F. "Gleason Spiralkegelräder," Verlag Julius Springer, 1939.
2. Rochat, F. "Die Verzahnungsmaschinen für Kegelräder," Company Publication, Oerlikon Bühler & Co. Zurich, 1957.
3. Krumme, W. "Klingelberg Spiralkegelräder," Springer-Verlag, Berlin, Heidelberg, New York, 1976.
4. Keck, K.F. "Die Zahnradpraxis," Band II, Verlag Oldenburg, München 1958.
5. Stadtfeld, H.J. "What to Know About Bevel Gear Grinding," *Gear Technology*, Elk Grove Village, IL, September/October 2005.
6. Landvogt, A. "Einfluss der Hartfeinbearbeitung und der Flankentopografie-Auslegung auf das Lauf und Geräuschverhalten von Hypoidverzahnungen mit Bogenförmiger Flankenlinie," Dissertation, RWTH Aachen, 2003, Volume 20/2003, Shaker Publishing.
7. Stadtfeld, H.J. "Good Basic Design or Sophisticated Flank Optimizations? Each at the Right Time," *Gear Technology*, Elk Grove Village IL, January/ February 2005.
8. Pitts, L. and M. Boch. "Design and Development of Bevel and Hypoid Gears Using the Face Hobbing Method," Company Publication, The Gleason Works, Rochester, New York, October 2001.

Dr. Hermann J. Stadtfeld received

in 1978 his B.S. and in 1982 his M.S. degrees 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.

