Guidelines for Modern Bevel Gear Grinding

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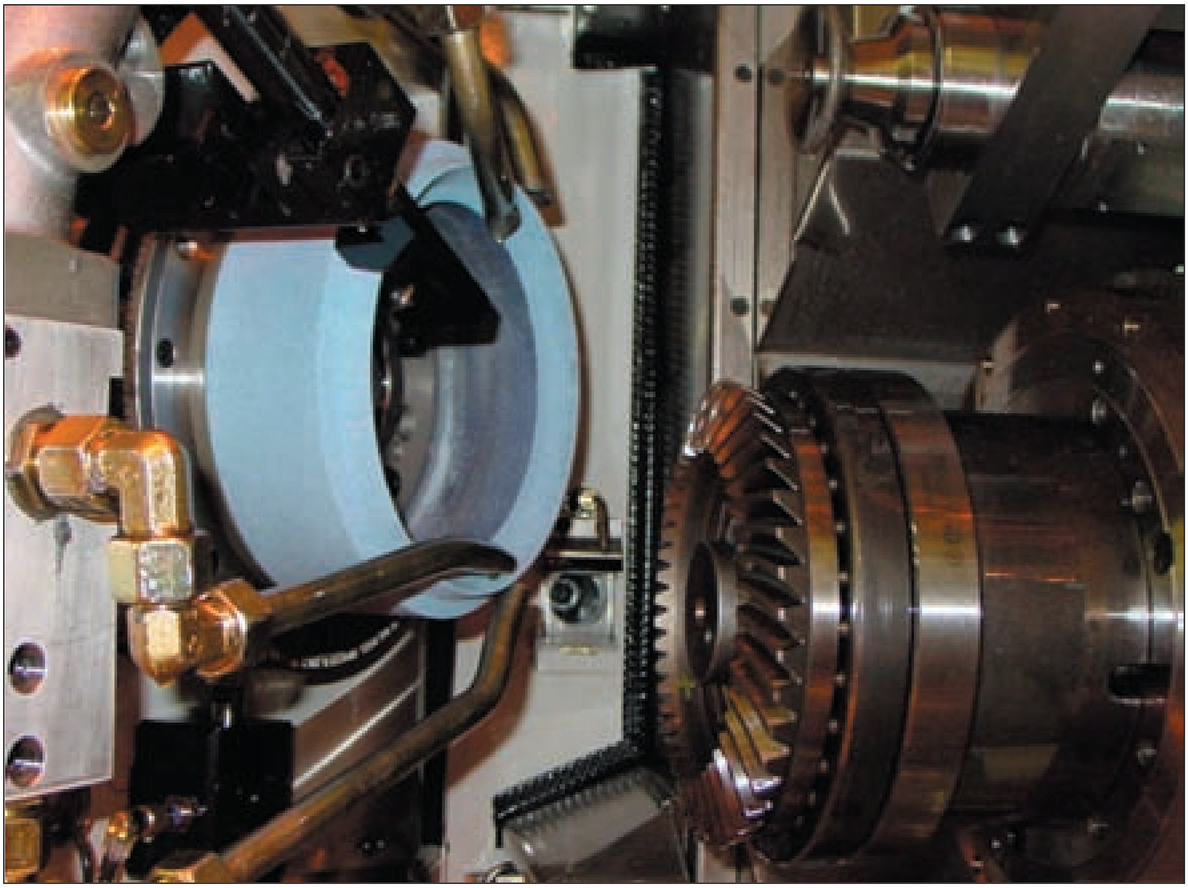


Management Summary

This paper acknowledges the wide variety of manufacturing processes—especially in grinding—utilized in the production of bevel gears and that gear designers and engineers cannot always be expected to have an informed understanding of them. To address that information gap, guidelines—both documented and as yet unwritten (experiential)—are presented here in support of state-of-the-art grinding of bevel

Introduction

Guidelines are insurance against mistakes in the often-detailed work of gear manufacturing. Gear engineers, after all, can't know all the steps for all the processes used in their factories, especially those used in the grinding of that most complicated type of gear—bevels.

And even when the steps are known, there are all the unwritten guidelines, the ones learned through experience rather than from a design or manufacturing handbook. Those guidelines are numerous and require time to think about—and finally see—whether the time to do so is taken while standing on the shop floor or by going back to an office desk. Gear engineers' work would be much easier if some of the major guidelines were documented, and thus the reason for this presentation.

Semi-Finish Strategy

Several technological and geometrical factors are central in guaranteeing high-quality ground gears. The first factor is a smart strategy for semi-finishing gears. This strategy requires a gear manufacturer to think about its processes in reverse order, making certain the gears it wants to work on at the start of step four are the ones created by the end of step three. For example, uniform stock allowance on the flank surface is important, but only if the semi-finish cutting summary is derived from the finish grinding summary. Figure 1 shows the basic idea—how the semi-finish soft profile relates to the finish profile.

Also, sections of progressively increasing ease-off should not be ground without preparing them in the previous cutting operation. This particularly applies to universal-motion heel or toe sections (UMC) as well as to second-order protuberance (blended Toprem) and flank relief.

With heel or toe relief sections, a gear grinder sometimes has to remove 50% or more stock in some areas of the tooth if the sections are not prepared properly during soft cutting. For example, a green gear may have a regular stock removal of 0.13 mm per flank. Variation from heat treat distortion may add 0.07 mm in certain areas. Also, the hardened gear may require removal of an additional 0.10 mm of stock within the relief section. If the green gear isn't cut properly, a worst case could require the removal of 0.30 mm of stock in one grinding pass.

Possible results of such grinding include burn marks, new hardening zones, or a reduction of surface hardness due to the reduced thickness of the case depth. The case depth of bevel gears in the module range of 3–6 mm is recommended to be between 0.8–1.2 mm after heat treatment. The worst-case scenario would reduce the case depth during grinding to 0.5 mm, perhaps less, reducing the surface and subsurface strength.

Also, grinding of root relief, the so-called blended Toprem, leads to a critical condition on the grinding wheel because the small, sensitive tip of the grinding wheel might have to remove 10–30% more stock than the main profile section. Heavy material removal at the tip of the wheel causes a deterioration of the protuberance section and the edge radius after grinding only a few slots. Subsequently, the remaining slots have reduced or no root relief, and an unacceptable blend into the root-fillet radius. This effect cannot be cured by subsequent redressing.

An important part of the semi-finish strategy for modern bevel gear grinding is a root fillet area which is not ground. The optimal protuberance of the cutting blades relieves the transition between flank and root by a value between 60% and 100% of the stock allowance on the active flanks. The cutting blades should have an edge radius 0.1 mm smaller than the edge radius of the final grinding wheel profile. They also should cut 0.1 mm below the theoretical grind depth.

The transition between the grinding profile and the unground root area can be optimized on the drive side of both members, using a grinding wheel tip extension and a setover, to get a smooth blend of the ground to the unground root surface and clean up the root radius to the area of 30° tangent.

Figure 2 shows the superimposition of an outside blade profile (blue), an inside blade profile (green) and the finish grinding profile (red). The cutting silhouette cuts 0.1 mm deeper, and in this example relieves 100% of the stock, in that a blend between cutting and

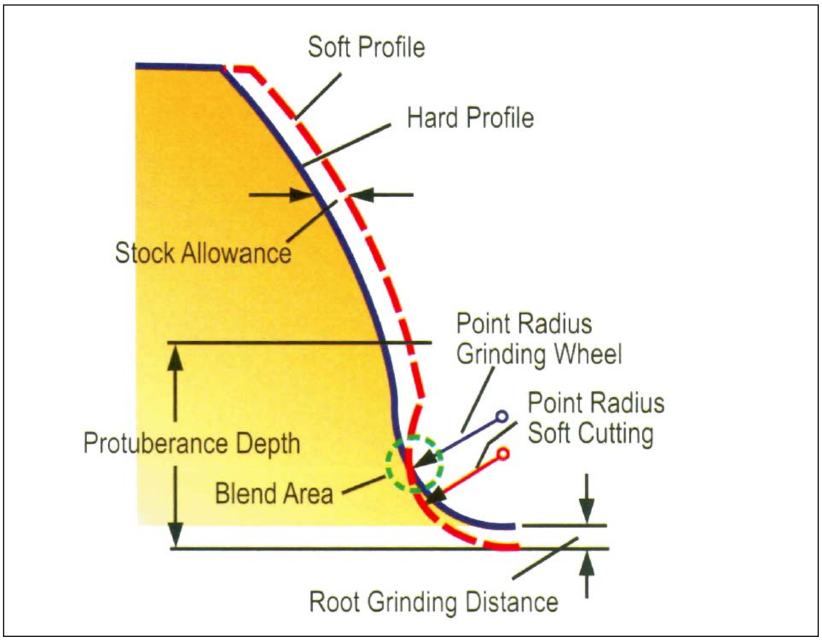


Figure 1—Root fillet relief, derived from finish profile.

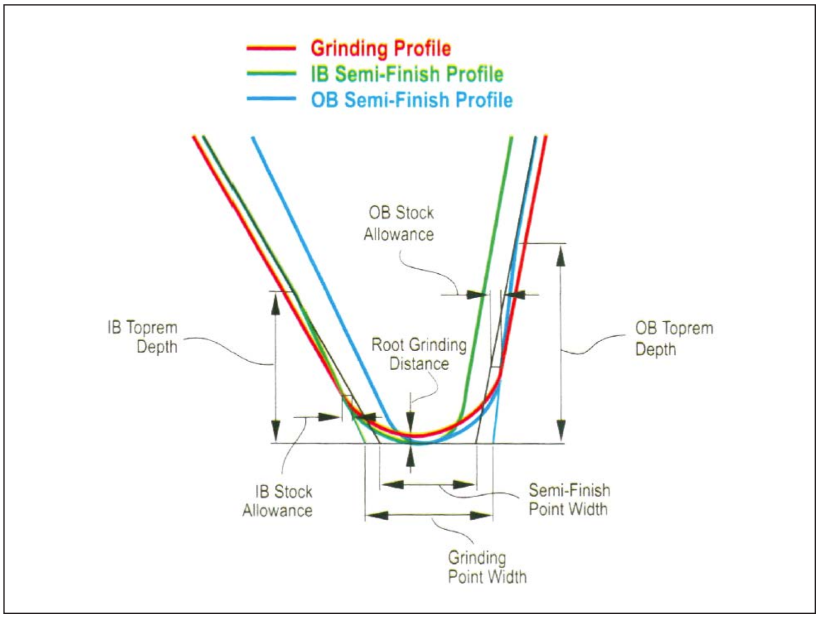


Figure 2—Superimposed profile plots, cutting blades and finish grinding profile.

grinding surfaces occurs below the active flank working area. All parameters of the correct semi-finish blades follow a tight rule as soon as the amounts of relief on flanks and root are defined. For example, the edge radii of the blue and green cutting sides should blend seamlessly with each other, as should the clearance side radii with the same side (same color) cutting edge radii. This is necessary in order to achieve the maximal radii on the cutting blades but also to avoid fins and grooves in the root bottom. Gleason has developed a software module called *Semi-Finish Calculation*. This module will automatically calculate blade parameters and new basic settings for semi-finish cutting from a few input items such as stock allowance percentage of relief, applied Toprem angles and amount of deeper cutting. If no input is given to the semi-finish input screen, default values that represent best practice in bevel gear grinding are instead used.

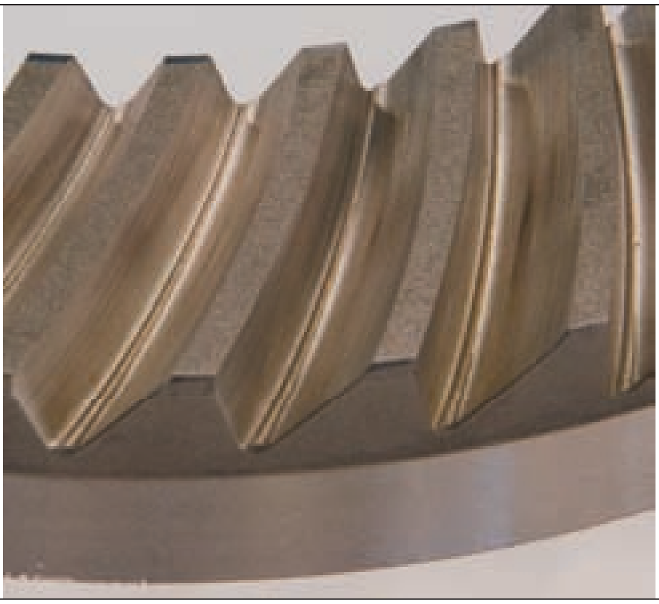


Figure 3—Unground root bottom in a ring gear.

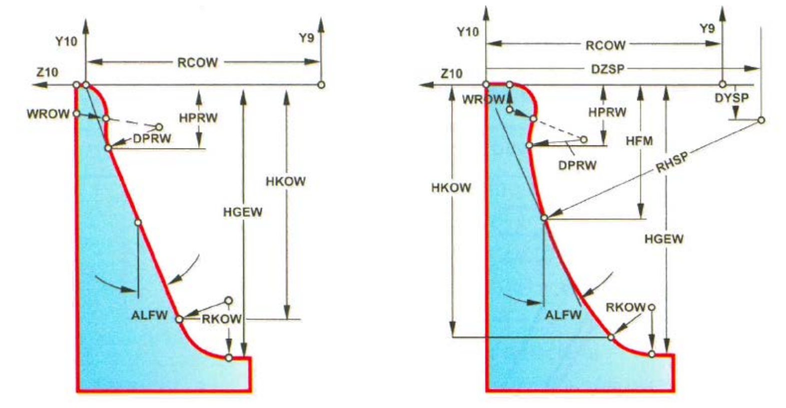


Figure 4—Blended Toprem in straight (left) and curved (right) blade profile.

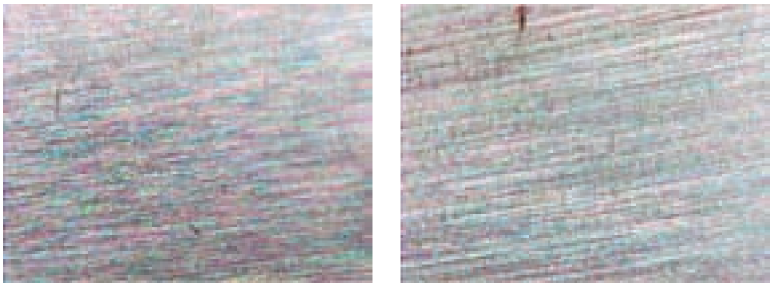


Figure 5—Surface structure after grinding (left conventional, right MicroPulse).

The distortions due to heat treatment cause an unequal cleanup along the face width and from slot to slot around the circumference. Also, the first- and second-order corrections—applied after coordinate measurement to achieve correct flank geometry—influence the angle of the ground root line versus the semi-finish cut root line. This root-angle difference might result in a partially ground root bottom.

The rule is that the root bottom should not be ground in a section that contains 30% or more of the face width. Stock removal in the root bottom should also be contained to a range of 0 to 0.05 mm. The variation from slot to slot can change the unground section between 30% and 100% without disadvantage to the performance of the gear set. Figure 3 shows an example of a completely unground root—with no disadvantages for the strength performance of the ring gear.

Interference and Blended Toprem

If a face-milling geometry shows a high transition line between root and flank that was generated by the profile generating process, and not by a too-large point radius of the tool, then an interference of the top edge of the mating teeth can initiate surface damage and noise excitation. This interference zone can be relieved via a second-order protuberance, which is a radius that connects the grinding wheel main profile and the edge radius with a tangential blend.

The standard definitions associated with the grinding wheel profile include the point radius RCOW; the edge radius WROW; the pressure angle ALFW; and the blade curvature (RHSP). Figure 4 shows these standard profile parameters and the additional parameters required to define blended Toprem in a straight grinding wheel profile (left, Fig. 4) and a curved grinding wheel profile (right, Fig. 4).

Surface Finish and Surface Treatment

A finish-ground bevel gear set should have an R_z equal to or less than 5 μm and an R_a equal to or less than 0.8 μm.

The ground surfaces of hypoid gears always carry the risk of scoring during the initial wear-in period. To eliminate this risk, the flank surfaces of at least the ring gear should be phosphate-coated. (The risk of scoring may also be eliminated during the first operating period through the use of synthetic hypoid oil.) Nevertheless, the risk of scoring during operation is reduced due to the enhancement of the surface finish.

Enhancement of the surface also can be achieved through a Gleason method called MicroPulse (patent pending). Certain additional machine movements in the micron range can generate a more irregular surface texture. In Figure 5 (right side), such a texture is compared to a conventionally ground surface finish (left side). The irregular texture reduces higher harmonic amplitude levels and creates desirable side bands in the frequency spectrum. MicroPulse-treated surfaces are superior to the conventional grinding structure on bevel gear flanks (Ref. 1).

Grinding Wheel Specifications and Performance

Keys to efficient grinding are the abrasive material and the abrasive bond. Recommended for bevel gear grinding are grinding wheels with an 80-grit, sintered, aluminum oxide abrasive with an open-pore, soft-ceramic bond. Results of extensive process development have shown that non-uniform particle size, e.g.—80-grit wheel specification that contains particles between 80 and 240 size—increases the grinding wheel wear and the need for redressing. Uniform particle size, say between 80 and 120 grit (for an 80-grit wheel specification), requires fewer redressings because the grinding wheel retains shape and dimension longer.

The automatic resharpening effect of a wheel is based on the radial and tangential cutting forces on a grinding grain. The three cases of wheel wear are:

Case 1: Grain breaks out of ceramic bond (bulk wear)—Wheel stays sharp, but loses size.

Case 2: Grain dulls (attritional wear)—Wheel keeps dimension; surface finish improves; grinding force is high; risk of burning.

Case 3–a: Grain fracture of mono crystal (fracture wear)—Wheel dulls somewhat and loses some dimension.

Case 3–b: Grain fracture along particle boundaries of sintered grain—Dimension is stable; wheel is always very sharp.

Sintered aluminum oxide grains consist of particles in a size range of a tenth of a micron. This explains the difference in fracture characteristic between conventional aluminum oxide and sintered grains. Conventional grains, as shown in Figure 6a, left-break like a mono crystal (see indicated fracture). A grain, sintered from several hundred million aluminum oxide particles—as shown in Figure 6b—will develop a fracture that nearly preserves the original size of the grain and creates a high number of cutting edges. It often appears that the sintered grain structure has rake and relief angles. The wheel wear rate versus the metal removal rate is an indication of how much wheel wear occurs during a certain material removal. This

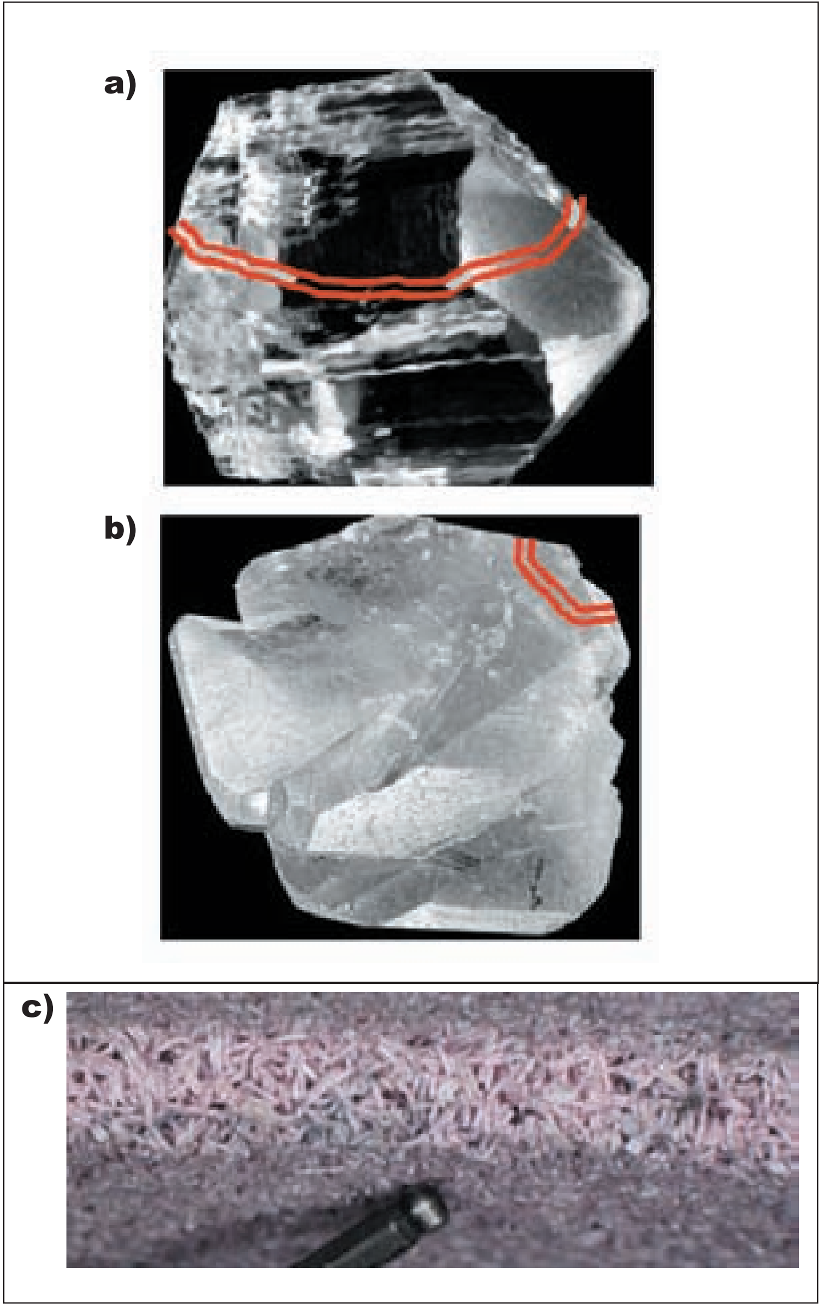


Figure 6—a) conventional aluminum oxide grain; b) SG sintered aluminum grain; c) ZG grinding wheel structure with worm shaped grains.

indicator also reveals how frequently redressing is required and what the life will be of a complete grinding wheel. Regarding sintered aluminum oxide, the wheel wear is almost independent from the metal removal rate. Usual metal removal rates in bevel gear grinding lead to about a third of the grinding wheel wear, as compared to conventional aluminum oxide.

Modern, high-performance sintered aluminum oxide grinding wheels may contain optimized grain shape and advanced ceramic binders, allowing higher surface speeds and much higher removal rates compared to standard sintered aluminum oxide wheels. Examples of these advanced wheels include the Targa TG and TG 2 brands from Norton/Saint-Gobain Abrasives. Today, Gleason and Norton collaborate in grinding research in order to qualify the Targa wheel technology for bevel gear grinding. It is anticipated that grinding with Targa wheels will not require any wheel wear compensation, and will reduce dressing frequency to every third to tenth part (instead of dressing after every part today) for high-quality automotive bevel gear grinding applications. Other new and promising types of grinding wheels worth mentioning are Altos and Vortex brands, with aluminum oxide grains Norton refers to as ZG. The grains of those wheels are "worm shaped" with a radial orientation, and the binder provides a very open wheel structure that allows light to pass through the wheel (Fig. 6c). These types of grinding wheels—similar to the Targa wheels—require low dressing frequency and work best above 30 m/min.

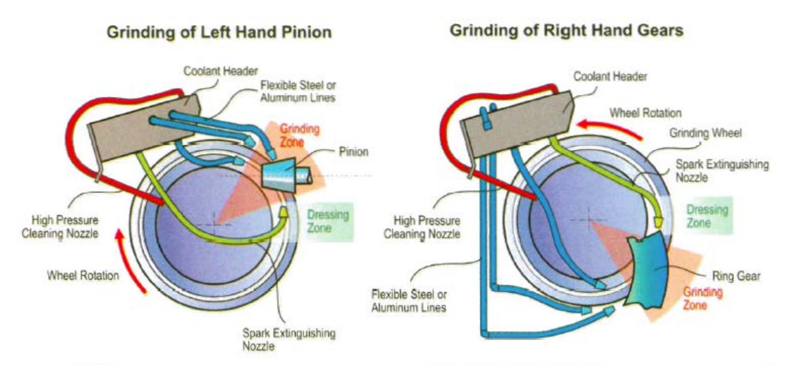


Figure 7—Coolant application (Ref. 2).

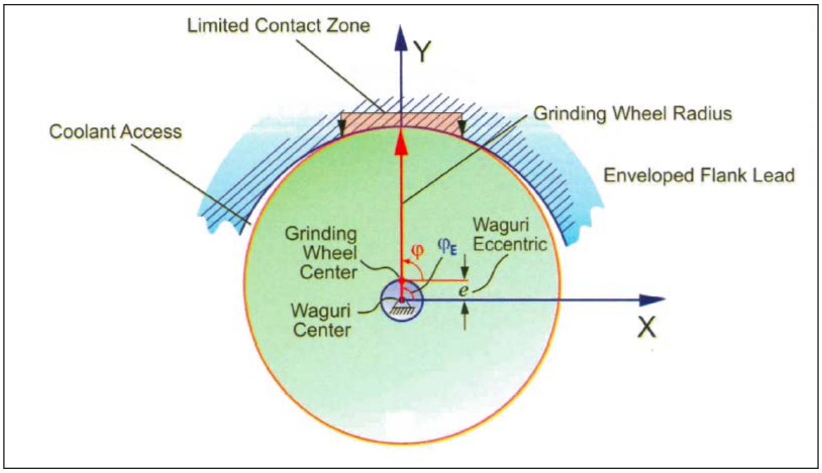


Figure 8—Waguri eccentric principle with coolant access and limited wheel contact.

Coolant and Grinding Wheel Cleaning

Applying the proper amount of coolant to the correct area between the work and grinding wheel is of great importance in avoiding surface defects and achieving good surface finish and flank form accuracy. Three or four coolant pipes are directed tangentially to the grinding wheel circumference—with a coolant speed of 75% to 100% of the grinding wheel surface speed—to apply a layer of coolant to the grinding profile surface just before it engages the grinding zone. Additional pipes are located behind the grinding zone and are directed opposite to the grinding speed to extinguish the sparks, which would burn into the wheel bond and get into the grinding zone (Fig. 7). The coolant pipes are connected to the high-volume coolant pump. This pump has a pressure of 4.5 bar, but it is rated for a high flow of 130 liter/min (Phoenix II 275 G) or 150 liter/min (Phoenix II 600 G). The utilization of more coolant pipes than is shown in Figure 8 will reduce the flow through the process-critical nozzles. Here, the rule is "less can be more."

In addition, the wheel's surface has to be cleaned continuously with a high-pressure coolant jet that's connected to an extra pump, which supplies the coolant at a pressure of at least 20 bar. The minimum required flow of the high pressure system is 24 liter/min (275 G), or 36 liter/min (600 G). The high-pressure jet has to be located roughly opposite the grinding zone and has to shoot coolant perpendicular to the profile surface (Fig. 7). Because of centrifugal force, the chips tend to clog up the inside profile more, so appropriate attention must be paid to the design and function of the high-pressure cleaning system.

The recommended grinding oil requires a flashpoint above 190°C. The viscosity for bevel gear grinding should be greater than, or equal to, 20 c St at 40°C. Lower viscosity, e.g., 10 c St, is better, but the available oils have flashpoints below 190°C. The grinding oil must not contain any sulfur (active or inactive). Even inactive sulfur, which typically is bound in compounds like the ones contained in the EP package, become active after grinding oil is used. Sulfur reacts with machine components and may, over time, cause deterioration.

Grinding Cycles

In the automotive industry, bevel gear grinding requires only one rotation of the gear, and each slot requires generally only one pass. The so called double roll cycle may be required if heat treat distortions are large. This cycle consists of one prefinishing pass, during which the grinding machine moves the grinding contact from toe to heel (uproll), and one fine-finishing pass, rolling from the heel back to the toe. Dressing should be done after a rotation is finished, not before, while a part is being ground.

In contrast, some gears for high-quality machine tools require two rotations, and aircraft parts are ground in four or more rotations.

In all cases, though, the rule is: After each rotation, the grinding wheel should be redressed. However, skip indexing should be avoided. This technique was developed in order to distribute wear more uniformly around the work in order to avoid ramp-shaped spacing errors. Rather than grinding successive slots, skip indexing skips a preset number of slots, thus requiring several revolutions to finish all slots.

Subsequently, though, it was discovered that many acoustic phenomena were caused by skip indexing. Experience with the technique showed that the many resulting small ramps generate noise with amplitudes in the tooth mesh frequency, the gear rotational frequency, and a frequency that corresponds to the number of ramps per revolution. In some cases, there even appears to be an additional modulation.

Thus, wear compensation is the best way to reduce ramp-shaped spacing errors and other wear patterns.

The surface speed to achieve good surface finish in connection with minimal grinding wheel wear is 20–24 m/sec—a rather low value when compared with conventional grinding processes.

When finishing Formate ring gears, they should be ground using Waguri motion to make the process more stable and faster. Normally, Formate gears are ground in a plunge-cut cycle. Without Waguri motion, the grinding wheel would have simultaneous contact with both complete flank surfaces of the tooth slot. As coolant cannot reach the grinding zones, burning and fast grinding wheel contamination with metal particles may result.

The process can be stabilized, however, through an eccentric motion applied to the rotating grinding wheel spindle. This so called Waguri motion should be about e = 0.10 mm to 0.12 mm eccentric in the plane of rotation about the theoretical grinding wheel axis. The Waguri speed should be 200–500 rpm lower than the grinding wheel speed, with a typical value of 2,000 rpm and the same hand of rotation as the grinding wheel itself. This grinding technique is named for its inventor. Figure 8 shows the Waguri principle and the limited contact zone with coolant access on both sides of that zone.

Waguri grinding is extremely fast. It can achieve grinding times of one second per slot. A Waguri-ground gear with 35 teeth is ground more quickly than a conventionally ground pinion with 13 teeth.

Grinding Wheel Dressing

The function of the dressing operation is to shape and true up the grinding wheel profile, and to condition the wheel surface topography for proper material removal performance. On Phoenix grinders, truing and dressing are performed in one step.

Dressing the grinding wheel requires that modern bevel gear grinders be equipped with a diamond-plated dress roller and an appropriately accurate and powerful dressing spindle. The dress roller can rotate in the opposite direction of the grinding wheel (negative dresser speed ratio), or in the same direction (positive dresser speed ratio). The upper diagram in Figure 9 shows the dresser speed ratio, versus the

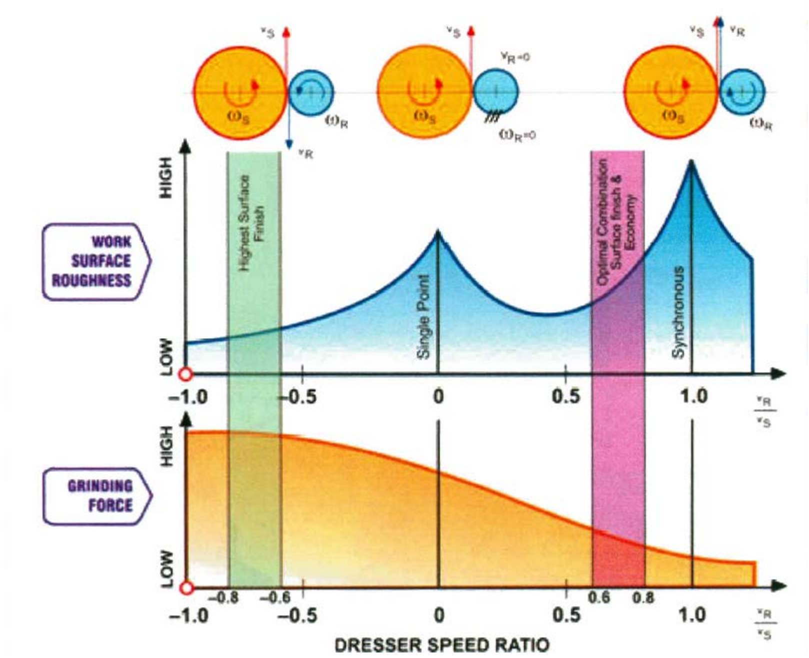


Figure 9—Dress roller ratio with preferred working sections (Ref. 2).

surface roughness, for the ground gears (Ref. 2). The lower diagram in Figure 9 shows the dresser speed ratio versus the grinding force (between grinding wheel and work), as a result of the dressing.

Dressing with negative as well as positive dresser speed ratios generates a grinding wheel-based approach path which has a trochoidal shape, excepting a dresser speed ratio of zero. Figure 10 shows the different approach paths for dresser speed ratio: –1.0 and +1.0. The right diagram in Figure 10 has a very steep slope, which makes the diamond crystals of the dress roller approach the grinding wheel grain almost perpendicular to the grinding wheel circumference (pure crushing action for dresser speed ratio +1.0). In case of dresser speed ratio –1.0 (left hand diagram in Figure 10), the diamond crystals of the dress roller approach the grinding wheel surface grains tangentially to the wheel circumference. This provides dressing with maximal abrasive action on the grinding wheel's surface grains, which in turn delivers low wheel profile roughness with high profile accuracy, as well as the fewest possible open pores for coolant and chip removal during the gear grinding.

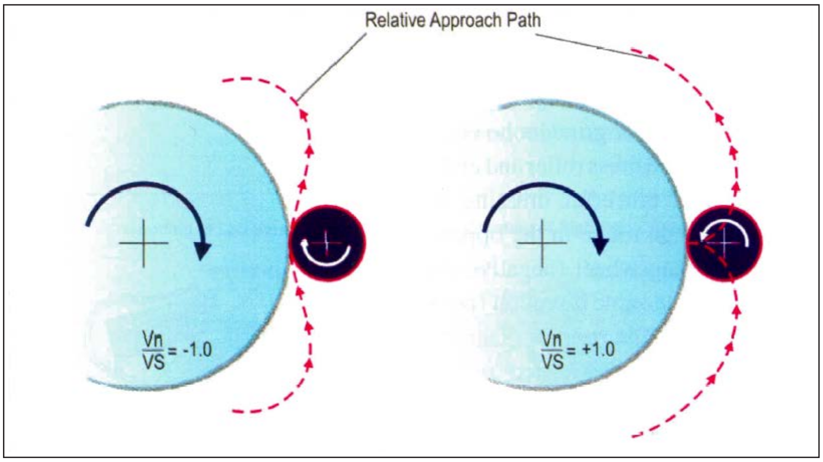


Figure 10—Cyclical relative approach path between dress roller and grinding wheel.

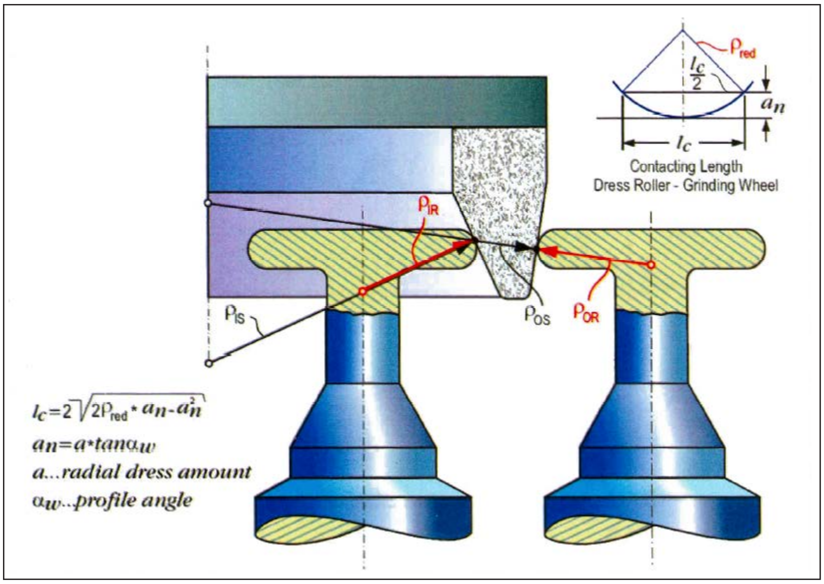


Figure 11—Unbalanced IB/OB dresser contacting length l_c.

Dressing with a dress roller axis, which is collinear to the grinding wheel as shown in Figure 11, is problematic since it leads to a large, relative curvature radius ρ_{IB} at the inside profile and to a small ρ_{OB} at the outside profile. The contacting length l_c between dresser and grinding wheel depends on the relative radius ρred—or reduced radius—and the normal dressing amount a_n. A dressing method according to Figure 11 leads to a good contact length l_c at the inside profile and an insufficient short l_c at the outside profile, caused by ρ_{redIB} and ρ_{redOB}.

The axial dressing amount, used for topping the profile back without radius changes, will translate to a smaller, normal dressing amount in case of a low profile angle. This presents an additional problem on the commonly low, outside pressure angle, and results in an even smaller l_c at the outside profile. Small l_c translates into noticeable feed marks or grooves, which require a very low dresser feed rate on the outside profile (Ref. 3). Dressing according to Figure 11 requires a time-consuming reversal of the hand of rotation between dressing of the outside profile and dressing of the inside profile in order to keep the sign of the dresser speed ratio constant. A constant change of the dresser speed ratio sign would open the cavities of the diamond bond and eventually lead to a loss of diamond crystals.

Gleason has developed dress rollers and a dressing configuration in which the dress roller is positioned at an angle to the grinding wheel, thereby optimizing the relative curvature radius ρ_{red} between inside and outside profile dressing. The relationships in the diagram in Figure 12 deliver a ρ_{red} three times the common value of the method shown in Figure 11. The correct observation of curvature radii uses for the dressing method—according to Figures 11 and 12—the normal cone radii to calculate relative curvature. Modern grinding machine summary calculations compute the optimal angular position of the dress roller individually for every different bevel pinion or gear, and also propose feed rates which are optimally suited to provide—on both inside and outside wheel profiles—a favorable dressing feed mark characteristic with low peak elevations.

A dresser speed ratio of zero should be avoided; this is equivalent to single-point dressing, which occurs when the dress roller is locked. The rotating grinding wheel would cause, in addition to a bad dressing result, a flat spot in the dressing wheel. Single-point dressing is possible with the tip of a single diamond. Older mechanical machines (from the 1950s and 1960s), some of which are still used in the aircraft gear industry today, use them. Dress rollers, however, are designed to dress around their wheel circumferences.

Also, the wheel must not be dressed when the roller's surface speed is equal to the wheel's surface speed (speed ratio 1.0). At that ratio, the roller only crushes the abrasive grain out of the wheel bond. The crushing breaks complete grains out of the bond for the most open-pore wheel surface structure possible and consequently causes rough surface finish. Also, when the grinding wheel has first-grinding contact with a gear surface, additional grains that have been loosened partially during the crush-dressing will break out, which acts like an excessive, initial wear with negative influence upon the gear tooth spacing.

The combination of crushing and abrasive action creates open pores on the wheel surface and reshapes the abrasive grains. And while the abrasive action improves the wheel's ability to grind gears, it also reduces the ability to move metal particles out of the grinding zone. However, the combination of crushing and abrasive action is optimal. The abrasive action between dress roller and grinding wheel surface reduces the open space between crystals by changing the remaining crystal-shaped grains; specifically, by flattening their sharp corners towards the surface. Consequently, very small flats are generated.

This flattening is beneficial because the grains' original shape is good only for roughing. There are grinding operations that use rough grinding passes, as with very large gears. For a rough grinding, the original grain shape would be acceptable. Their crystal shape can't accurately represent the grinding wheel's dimensions and profile shape. The very small flats can, however, accurately represent the wheel's diameter and profile shape. The changed crystals mean surface roughness of ground gears will be low, but coolant will still be able to access the grinding zone, and removed material will thus be eliminated from the grinding zone.

For high-productivity grinding, a dresser speed ratio of 0.6–0.8 is recommended. For the best possible surface finish, the recommended speed ratio is between –0.6 and –0.8. In the negative ratio range, the roller only shapes the abrasive grains—it doesn't crush them—and results in a grinding wheel surface with minimum pores. Grinding wheels are dressed for this type of grinding by directing the roller speed against the grinding wheel speed and using revolutions per minute, which are calculated from the velocity ratio (between –0.6 and –0.8), leading to high relative velocities.

In addition to the aforementioned rules, the following should also be applied in order to improve the grinding result:

Grinding of non-generated gears using Waguri: Start with negative dresser speed ratio; depending on wheel type, positive dresser speed ratio may be optimal.

Grinding of generated gears without Waguri: Positive dresser speed ratio.

Pinion grinding without Waguri: Positive dresser speed ratio.

If the surface finish is too rough:

- Reduce the dress roller traversing feed rate.
- Move to the left side of the dress roller speed ratio band.
- Change to negative dress roller speed ratio, but now go to the right side of the dress roller speed ratio band and use high dress roller traversing feed rate to preserve some open-pore surface structure.
- Apply a dual rotation cycle without

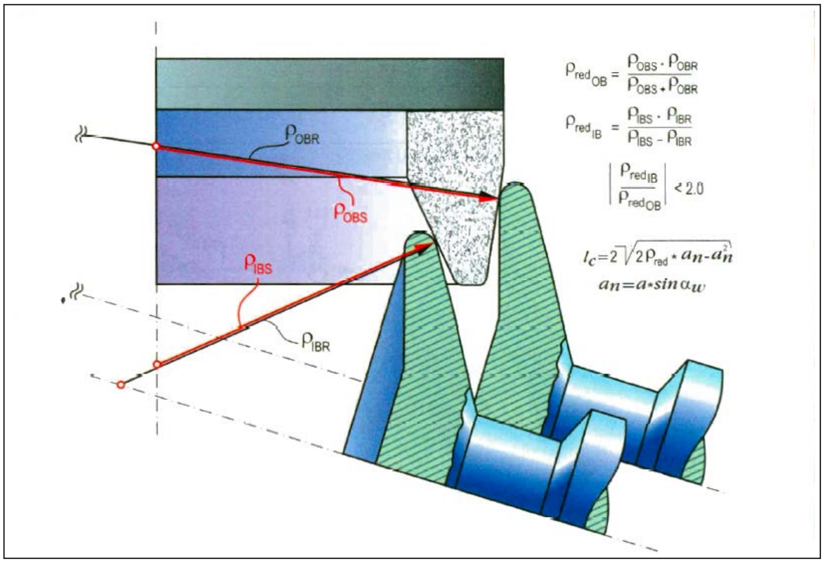


Figure 12—Dresser configuration for best balanced curvature between IB and OB.

redressing.

If spacing of first to last tooth is bad:

- Increase dress roller traversing feed rate.
- Move to the right side of the dress roller speed ratio band.
- Change to positive dress roller speed ratio, but go first to the left side of the dress roller speed ratio band and use a low dress roller traversing feed rate to preserve a high surface finish.

Burn marks on pinion surface or root:

- Increase dress roller traversing feed rate.
- Move to the right side of the dress roller speed ratio band.
- Change to positive dress roller speed ratio, but now go to the left side of the dress roller speed ratio band and use a low dress roller traversing feed rate to preserve a high surface finish.

Burn marks on Formate gear surface or root:

- Increase dress roller traversing feed rate.
- Move to the right side of the dress roller speed ratio band.
- Reduce grinding plunge feed rates.

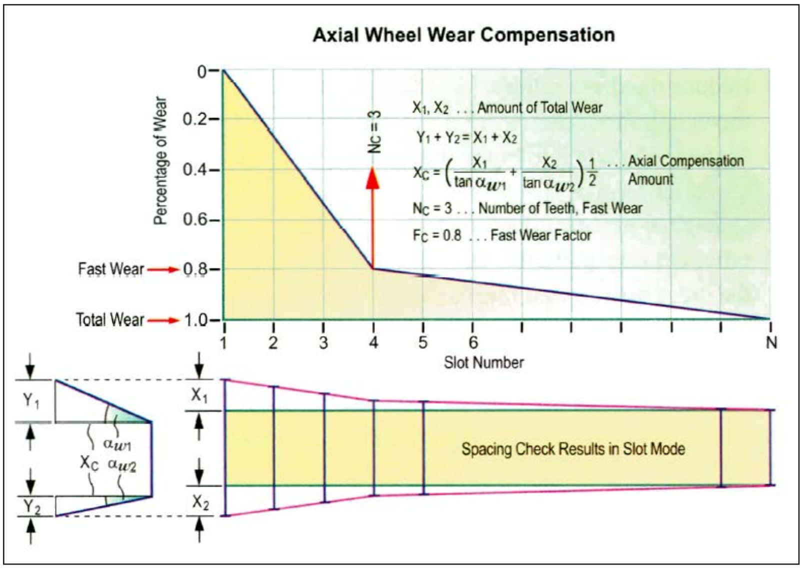


Figure 13—Grinding wheel wear compensation parameters (Ref. 2).

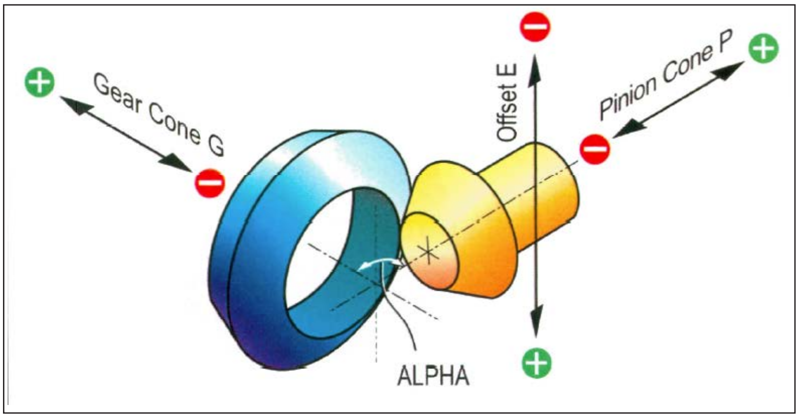


Figure 14—Testing of different pinion cone positions P, backlash compensated with G.

Wheel Wear Compensation

Gear manufacturers can also remove the grinding wheel's wear pattern from the gear finish by entering the number of teeth into the grinding machine's controller for fast wear and the percentage of this wear from the entire amount of wheel wear.

Wheel wear occurs rapidly during the first few slots and then with near-linearity for the following slots. Modern Gleason grinding machine controls have wheel wear compensation features that allow total wear compensation for the entire part and a fast wear compensation for the first slots. After total wear is compensated for, the spacing measurement will show whether the first slots require additional compensation and whether that amount should also be removed from the remaining slots.

After grinding a number of development gears, a manufacturer can obtain the numbers needed for eliminating the wheel wear pattern; specifically, the amount of total wear on the wheel (X_c), the number of teeth for the fast wear (N_c) and the percentage of fast wear (F_c). Those data are based on the spacing check, as explained in Figure 13.

Roll Testing of Ground Gear Sets

Ground bevel gears require roll testing in pairs in order to find their best operating conditions regarding tooth contact and noise. The axial pinion cone position (with the ring gear set to proper backlash) is varied in three to five positions (Fig. 14).

Pinions and gears have to be handled in pairs after the testing because the interaction of an individual pair may vary, even in case of ground bevel gear sets. Most manufacturers today use the freedom of small axial pinion position changes to improve the rolling quality in regards to motion transmission characteristics. Axial pinion shimming to individual pinion cone values generally delivers a result which would require manufacturing both members one quality level higher in order to achieve the same gearset performance in the zero build position.

Roll testing in pairs allows gear manufacturers to maintain an important advantage of grinding to gain a quality of a pair which is over the quality of the single components. Grinding lets gear manufacturers continue to deal with pinions and gears individually, until the roll testing operation, so companies can retain the less-complicated logistics and more flexible manufacturing via grinding.

After roll testing, each gear must be kept with its mated pinion and both must be labeled with the individual axial pinion shim value for them. Moreover, roll testing should be combined with a structure-borne noise evaluation in order to gain some non-subjective test results.

Strength of Ground Bevel Gear Sets

The spacing quality of ground gear sets is higher than that of lapped sets. However, the interaction of the tooth pairs in the lapping process eliminates relative spacing errors to a degree that makes them comparable to ground sets. Although the effective load sharing of gearsets increases with increased spacing accuracy, it is not possible to conclude that ground gearsets have generally better load sharing than lapped sets.

Surface durability might be negatively affected in lapped gearsets due to lapping grain incorporated in the lapped surface. Besides this, it can be stated that the lapped surface has, during the break-in process, better hydrodynamic properties than the ground surface. But after the break-in period, both surfaces have basically equal properties regarding surface durability issues such as pitting, scuffing, etc.

It can then be concluded that the gear quality differences between good lapped and ground gears have no influence on the fatigue bending strength or the pitting resistance of those gearsets.

Grinding allows the gear engineer to employ a completely different strategy when designing the ease-off in ground versus lapped gears. Figure 15 shows—at the left side a conventional ease-off, which is the result of length and profile crowning—how it is used in most of today's lapping applications. The Gleason development of blended Toprem, blended Flankrem and Universal Motions (UMC) with three flank sections results in quite different ease-off topographies, which result in the so called "selective crowning." The selective crowning uses a conjugate flank center area and crowned top, root, heel and toe sections. The selective crowning also defines in the path of contact section a flat center and progressively increased crowning on toe and heel. This results in low motion error and high effective contact ratio with optimized load sharing. Also in the contact line section, the crowning is very low in the center and increases only close to top and root. This results in low flank surface stress, yet still provides sufficient protection against top and root edge contact.

Figure 15 shows on the bottom a surface stress reduction of $\Delta\sigma_H$ of a contact line with selective crowning versus the conventional crowning. $\Delta\sigma_H$ can realistically be a reduction of 25% surface stress of the selective crowned surface pair versus a conventionally designed gearset.

The most significant influence on the root bending stress derives from the fillet radius, the root tooth thickness, the load sharing between adjacent teeth and the surface stress distribution along contact positions. Regarding the root fillet, a concrete advantage can be achieved in applying the semi-finish strategy, shown in Figures 1 and 2. The described semi-finish strategy provides, in cases of no mutilation or interference risk, a fully rounded root fillet, without steps and fins. In case of interference or mutilation risk, the wheel edge radii have to be chosen somewhat smaller, which will result in a flat root bottom, and which blends smoothly

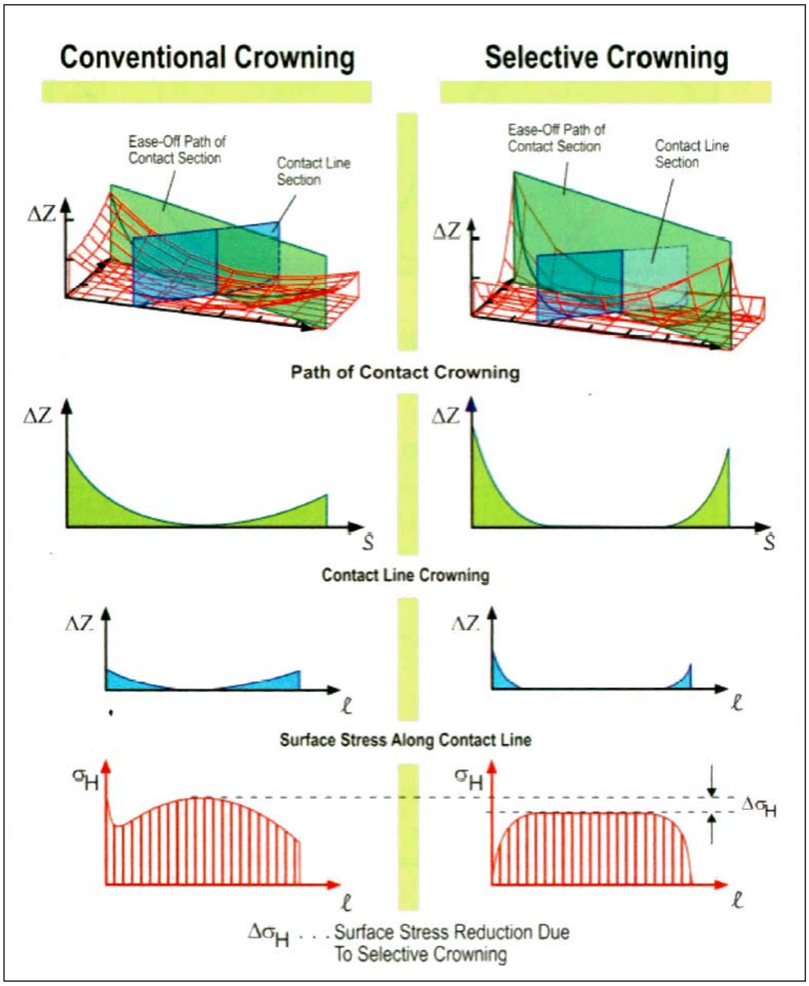


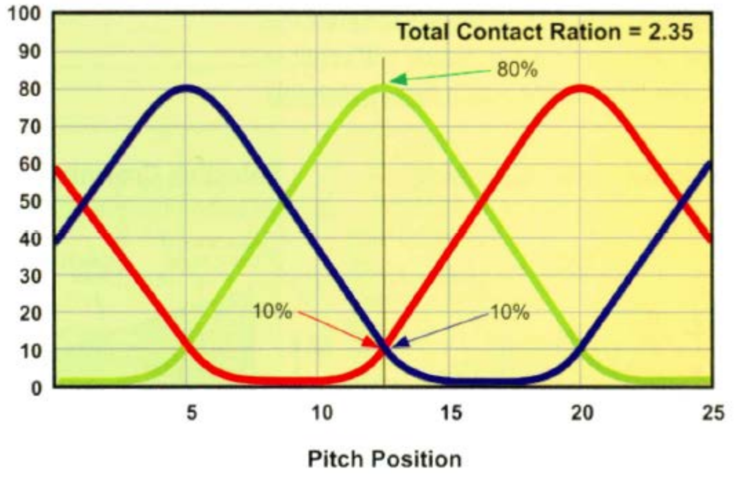
Figure 15—Stress reduction by selective crowning.

into the two fillet radii. Both cases apply the maximal possible root fillet radii and deliver the lowest possible root bending stress in the area of the stress critical 30° tangent. Face hobbed designs have a slot width taper, which has the smallest root width at the toe end of the slot. The fillet radii have to be chosen in order to fit through the small toe width of the slot, which renders them much less than optimal in the wider heel root region.

The tooth thickness along the face width of face hobbed and face milled parts might be different, but it is tapered in both cases and depends more on the spiral angle, which is not subject to change in the scope of this paper.

The load sharing, on the other hand, will change quite remarkably between the two different paths of contact crownings shown in Figure 15. The contact ratio is given on the dimension sheet and states what the maximum contact ratio, in case of full flank contact, can be. Any particular load below that will result in a lower effective contact ratio. However, even if the effective contact ratio is at a certain value (like 2.35 in Figure 16), this means that, 35% of the time, only three pairs of teeth are in contact and, 65% of the time, only two teeth are in contact. This, however, doesn't reflect how intensive this transmission contact is. Only the load sharing calculation will show how good the participation of each involved tooth pair in the load transmission really is.

Load Sharing Ratio – Conventional Crowning



Load Sharing Ratio – Selective Crowning

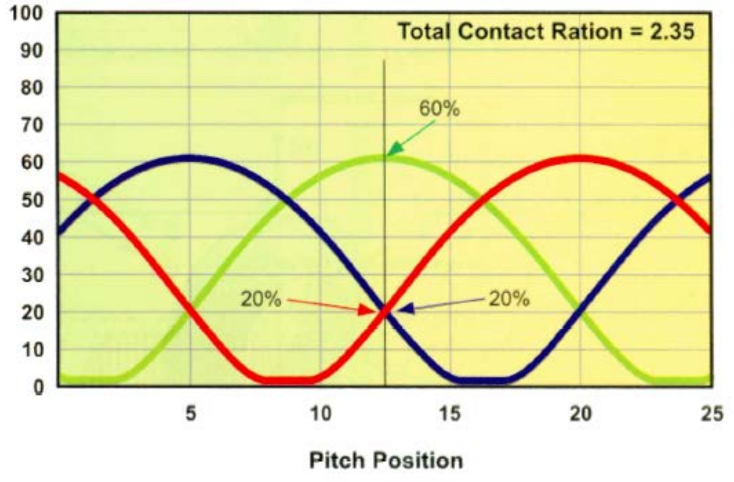


Figure 16—Load sharing improvement due to selective crowning.

The load sharing is calculated by use of a true finite element approach. Three adjacent pairs of teeth are observed for flank contact, considering the elastic bending due to this contact and, in turn, the resulting flank contact if equilibrium is established. This approach duplicates with high accuracy the condition in a gearbox under a given load.

The flank surface load distribution is then used in connection with the matrix of element spring constants to calculate three dimensional stresses, which are significant for fatigue fracture in the fillet region. The load sharing diagram shows in three different colors the maximum percentage of load that each of the three adjacent pairs of teeth is subjected to. Figure 16 shows two load sharing diagrams—on top, the load sharing in case of conventional path of contact crowning; on the bottom, the result of the selective path of contact crowning. Because of the conjugate path of contact center section, the lower diagram in Figure 15 shows a 20% reduction in the maximum load of each pair of teeth (conventional crowning 80%, selective crowning 60%). In turn, the two adjacent tooth pairs of the observed pair have to transmit a higher load. In that case, as the green graph shows, a vertical line through the maximum of the green graph, the adjacent graphs (blue and red) have to each share 20% of the load. In the case of conventional crowning in Figure 16, the adjacent tooth pairs share only 10% load each. This, and the fact that conjugate contact will cause less point load concentration, results in bending stress values expected to be reduced by 25% in the case of selective crowning, versus conventional crowning.

Grinding Economics

Admittedly, grinding is slower and more expensive than lapping. For example, grinding a pair of bevel gears requires two grinding machines and two minutes for each gear. Lapping also takes two minutes for each gear, but it requires only one lapping machine. Moreover, the grinding machine cost-per-ground set is about three times the lapping machine cost-per-lapped set.

However, rejected parts and customer complaints are 1% or less for typical grinding production compared with 3–7% for lapping, depending on the requirements for certain jobs. Rejected gear sets include the cost of all previous operations plus the material. Consequently, the cost related to this difference in reject rate often makes grinding the more economical process. Figure 17 represents an estimated cost comparison between lapping and grinding (Ref. 4). Only 5 years ago, the difference between the two processes was considerably larger, in favor of lapping. The advances in that time—including machine technology, new grinding wheel abrasives, conclusive semi-finish strategy and many other accomplishments—place grinding in a completely new light, which makes it a very attractive process today.

Conclusion

These guidelines cover topics from the transition line between root and flank of pinions and gears to the grinding wheels' abrasive bond; but this list isn't all-encompassing. A major reason so many unwritten guidelines remain undocumented is because they're infinite in number and change with advances in materials, processes and equipment. Still, these guidelines should help gear engineers to skillfully grind their bevel gears sooner, rather than later.

Item	Lapping	Part Cleaning	Testing	Log of Manufac-turing Pairs	Log of Transporting from Lapping to testing in pairs	Quality
Machine Rate/Hour	$62.50		$60.00			
Operator /Hour	$17.50 (=35.00/2)		$40.00			
Door to Door time/part	0.07		0.05			
Rate per Part	$5.28	$1.50	$5.00	$2.00	$0.50	
Warranty resulting of skipped oil change						$1.25
Cost of 3.5% reject $45.00 per set						$1.58
					Total Finishing Cost	$17.11

Item	Pinion Grinding	Gear Grinding	Testing	Coordinate Measure-ment		Quality
Machine Rate/Hour	$88.50	$88.50	$62.50	$50.00		
Operator /Hour	$17.50 (=35.00/2)	$17.50	$40.00	$40.00		
Door to Door time/part	0.07	0.03	0.05	0.03 (.25/10)		
Rate per Part	$7.00	$3.50	$5.13	$2.25		
Warranty resulting of skipped oil change						
Cost of 0.5% reject $45.00 per set						$0.23
					Total Finishing Cost	$18.09

Figure 17—Comparison of finishing cost, lapping vs. grinding.

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