Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding

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Management Summary

Modern gearboxes are characterized by high torque load demands, low running noise and compact design. In order to fulfill these demands, profile and lead modifications are being applied more often than in the past. This paper will focus on how to produce profile and lead modifications by using the two most common grinding processes—threaded wheel and profile grinding. In addition, more difficult modifications—such as defined flank twist or topological flank corrections—will also be described in this paper.

Introduction

The main reasons for gear modification are to compensate for the deformation of the teeth due to load and to ensure a proper meshing to achieve an optimized tooth contact pattern (Fig. 1). Figure 2 shows typical flank modifications that may be subdivided into profile and flank modifications (Ref. 1). Both modification types are defined separately but can be superimposed. The most common modifications—profile and lead crowning—are utilized in order to achieve a good contact pattern without having contact on both ends of the flank at either the tip or root area. Other designs are tip and root relief, and end relief. Profile or lead angle modifications are used to compensate for deformation of the teeth themselves, but also for shaft deformation within the gearbox resulting in non-parallel axes. All of these modifications can be combined and thus result in complex flank modifications (Refs. 2–3).

Beyond these "standard" modifications, it is also possible to define so-called topological modifications where each point on the tooth flank has its own amount of modification (Ref. 4). These kinds of modifications are much more difficult to produce than the standard modifications. Scores of publications deal with methods and ways of determining the optimized modification for gear sets under load considering gearbox and shaft deflection, as well as dynamic effects (Refs. 5–6). This paper does not concentrate on such an approach, but describes how to produce these kinds of modifications in the two most common fine finishing technologies, i.e.—threaded wheel and profile grinding.

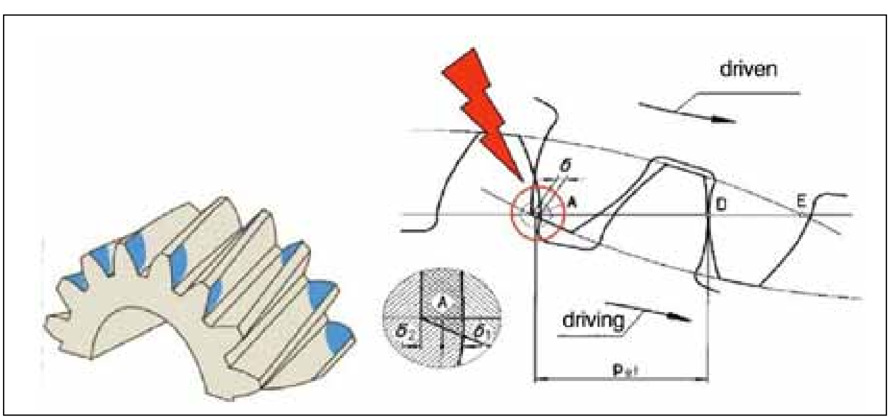

Figure 1—Reasons to modify gears.

Threaded Wheel Grinding

Threaded wheel grinding is characterized by high productivity due to the continuous process kinematic, and is used mainly for small-to-mid-size gears up to module 7–8 with a minimum diametral pitch of 3.175. As such, this technology is used mainly in automotive and light truck applications, but also for larger gears with high numbers of teeth and small modules. Examples include printing machines or industrial gearbox applications. Figure 3 shows the required kinematic for threaded wheel grinding (Ref. 1). A machine for threaded wheel grinding needs several axes to perform the required kinematic. First of all, the gear to be ground and the threaded grinding wheel have to be swiveled into a certain angle that is the sum of the gear helix angle β and the wheel lead angle γ_0. Both gear and wheel are mating together like a gear set. Hence the rotation of the wheel n_s, which results in the cutting speed v_c (red arrows in Fig. 3) and the rotation of the gear n_w, have to be synchronized. In order to remove material from the teeth, the gear or the wheel needs a radial infeed motion (blue arrow) perpendicular to the gear axis. In addition, the wheel has to perform an axial feed motion (green arrow) along the gear axis. In cases where the gear is helical, as shown in this figure, it must fulfill an additional rotational movement in order to follow the lead. Since the contact area between the wheel and the gear is smaller than the wheel width, a fourth motion is required (yellow arrow) to shift the wheel along its face width, thus using the full face width. This is the so-called shifting, which can be done continuously during the axial movement or non-continuously after a grind cycle. All of the above-described movements must be synchronized precisely in order to achieve good gear quality (Ref. 1). This synchronization is done by the machine axis following the mathematical equations presented in the bottom section of Figure 3.

When cutting the wheel and the gear along the working section, we get the normal section shown on the right-hand side of Figure 3. One can see the rack profile of the wheel characterized by the wheel pressure angle α_0 and the lead, which is module m_{n0} times π times number of threads z_0. Due to the mating movement, this rack profile is finally generating the involute shape of the gear. The shown kinematic will result in a perfect gear without any modifications.

The above-mentioned flank modifications can be achieved by using threaded wheel grinding. Thus, all profile modifications have to be generated by the dressing tool since this is defining the exact shape of the rack profile. All flank modifications are produced by the machine kinematic (Fig. 4).

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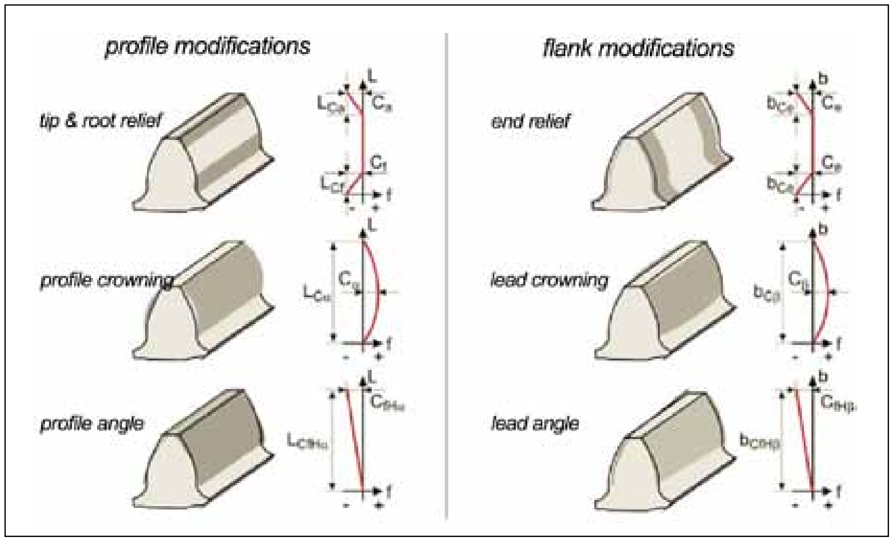

Figure 2—Typical flank modifications.

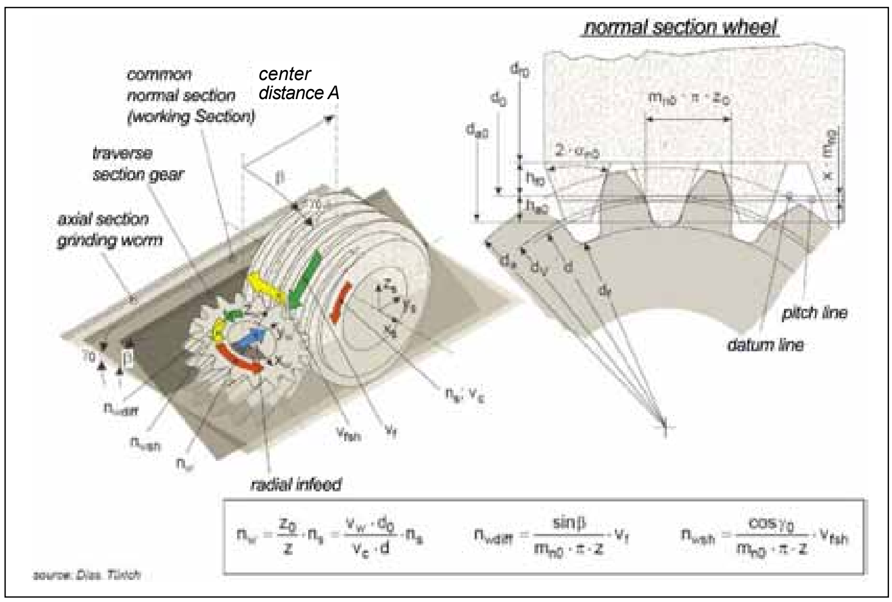

Figure 3—Kinematics in threaded wheel grinding.

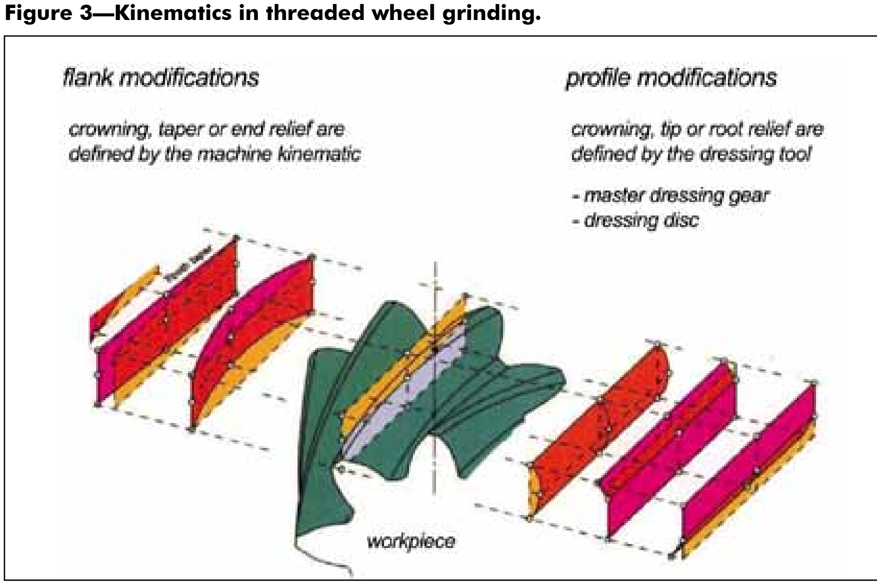

Figure 4—Modifications in threaded wheel grinding.

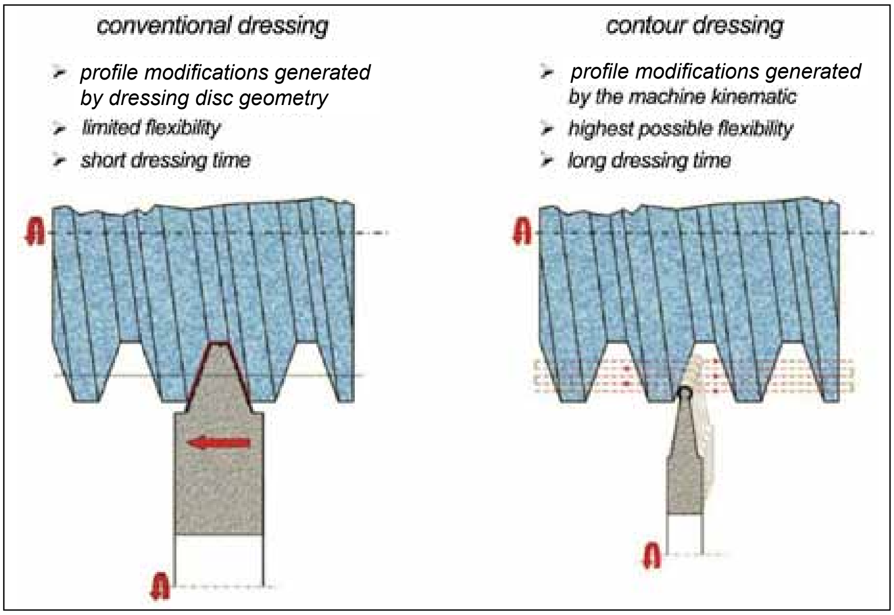

Figure 5—Dressing principles in threaded wheel grinding.

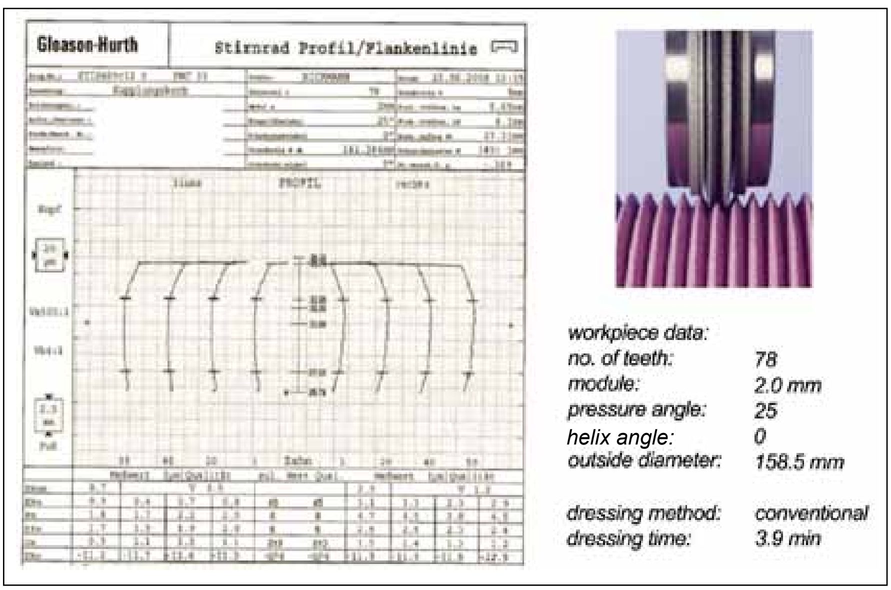

Figure 6—Profile generation by conventional dressing.

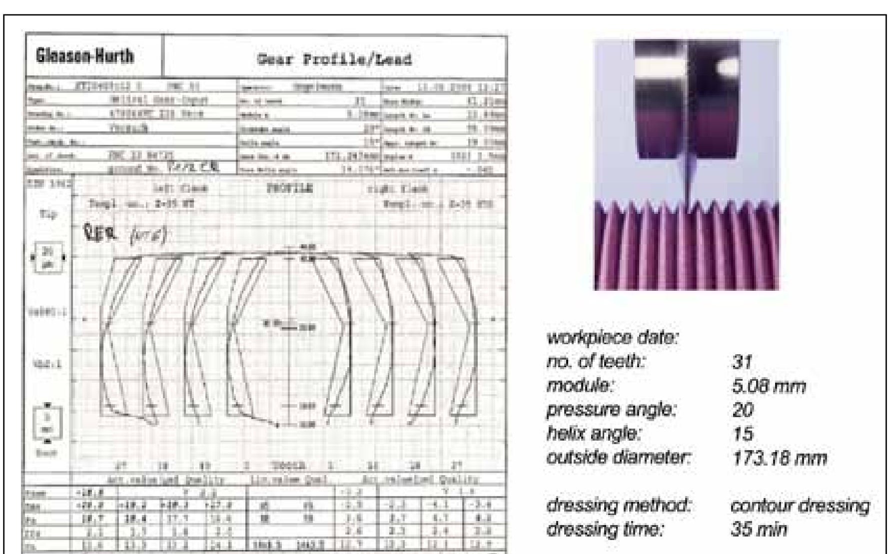

Figure 7—Profile generation by contour dressing.

Where the gear needs a certain profile modification—such as crowning—a corresponding shape has to be dressed into the rack profile in order to generate the required amount of profile crowning during the grind cycle (Ref. 7).

Figure 5 shows two different dressing principles used in threaded wheel grinding (Ref.7). The left-hand side shows the most common method, using dressing discs that are copying their shape into the rack profile. But the shape of the profile modification must be known when designing and producing such a dressing disc. A typical result using such dressing discs is shown in Figure 6. The profile on the left and right flank includes a tip relief as well as a slight profile crowning. The flexibility of such a dressing tool is very limited and, in principle, can only be used for one type of gear. But due to the line contact between the dressing tool and the grinding wheel, the dressing operation is relatively short (3.9 min, for example, shown in Figure 6).

Considering the long lead times for conventional dressing tools, it might be necessary in some cases to be more flexible. Contour dressing, shown on the right-hand side of Figure 5, can be used to achieve the highest possible flexibility. In this case, a dressing tool is used that is generating the required wheel shape by NC motions. The shape of the dressing disc itself is independent from the wheel rack profile. This opens a wide area for profile modifications, but on the other hand, the dressing operation needs much longer dressing time (Ref. 7).

A typical result using contour dressing is shown in Figure 7. The required profile was defined by so-called K–charts and was programmed using the machine interface presented in Figure 8. Such a contour dressing cycle needs about 30–40 minutes, compared to 4–5 minutes for conventional dressing in normal dressing conditions. So the advantage of contour dressing is offset by longer dressing times.

Figure 8 shows a typical interface

of modern machine software for programming profile modifications in contour dressing. Left and right flanks can be programmed separately. The user defines the target profile of the gear, and the machine automatically calculates the corresponding rack geometry and all required movements for the contour dressing cycle.

As mentioned, lead modifications are generated by the machine kinematic. Therefore, the kinematic for threaded wheel grinding described in Figure 3 has to be superimposed by additional movements to achieve the modifications. Figure 9 explains the two main principles that are used for these movements. As presented on the left-hand side, a change in the radial infeed (x-axis) results in more or less stock removal on left and right flank. So if a symmetrical lead crowning is required, as shown in Figure 10, a curved shape x–movement dependant upon the z–position (face width of the gear) is necessary, defined by a function x(z).

Changing the tangential feed (Y–movement), as shown on the right-hand side of Figure 9, without changing the rotational position of the gear results in more stock removal on one flank and less stock removal on the opposite flank.

By superimposing the two functions x(z) and y(z), any kind of lead modifications can be achieved. An example how to achieve an unsymmetrical lead crowning is shown in Figure 11.

In this case, a parabolic function has been chosen for both additional movements y(z) and x(z). The parabolic y(z) function leads in a hollow-shape crowning on the left flank and a barrel-shape crowning on the right flank, while the same parabolic function for the additional x(z) movement results in a barrel-shape crowning on both flanks. Since both functions are superimposed, the result is a straight-lead flank on the left flank and a crowned flank on the right flank. Figure 12 shows a grinding result using this method and

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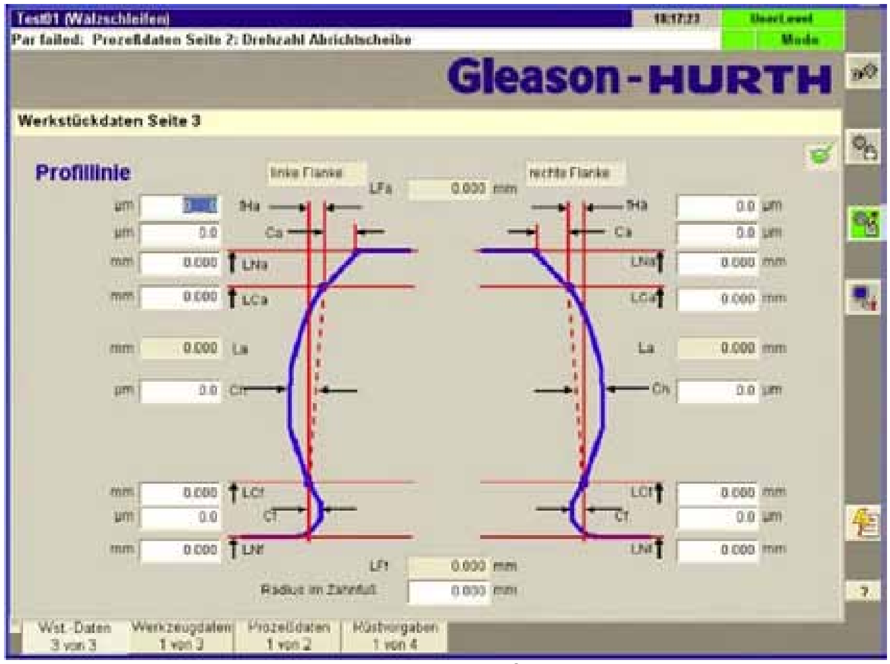

Figure 8—Contour dressing programming interface.

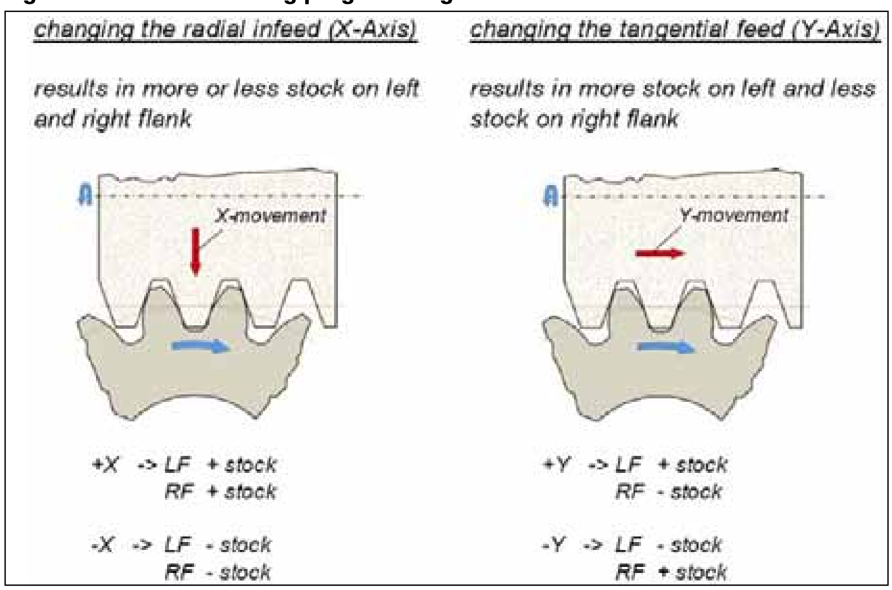

Figure 9—Generation of lead modifications.

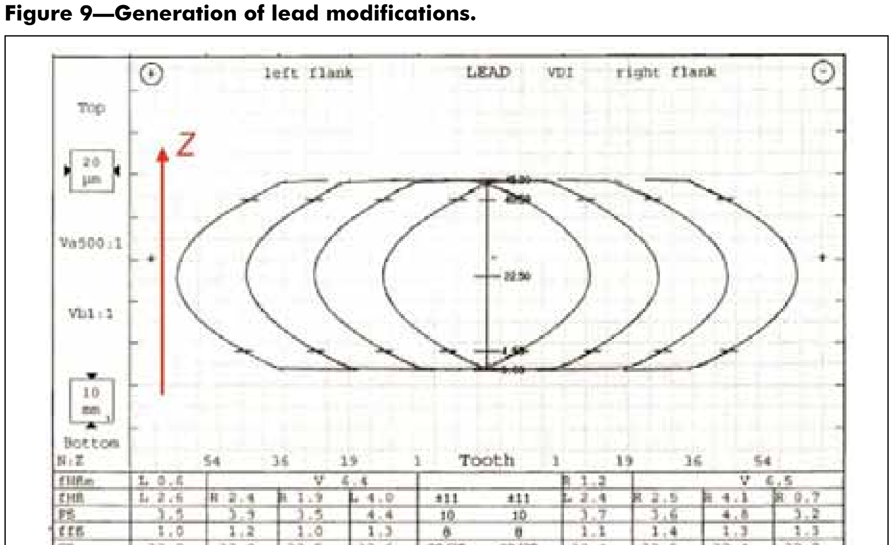

Figure 10—Example of symmetrical lead crowning generated by a parabolic function: x(z).

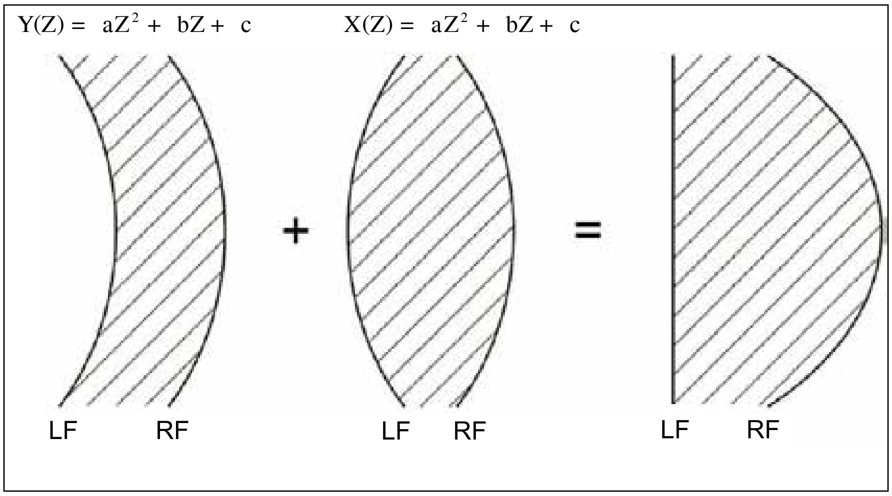

Figure 11—Principle to achieve unsymmetrical lead crowning.

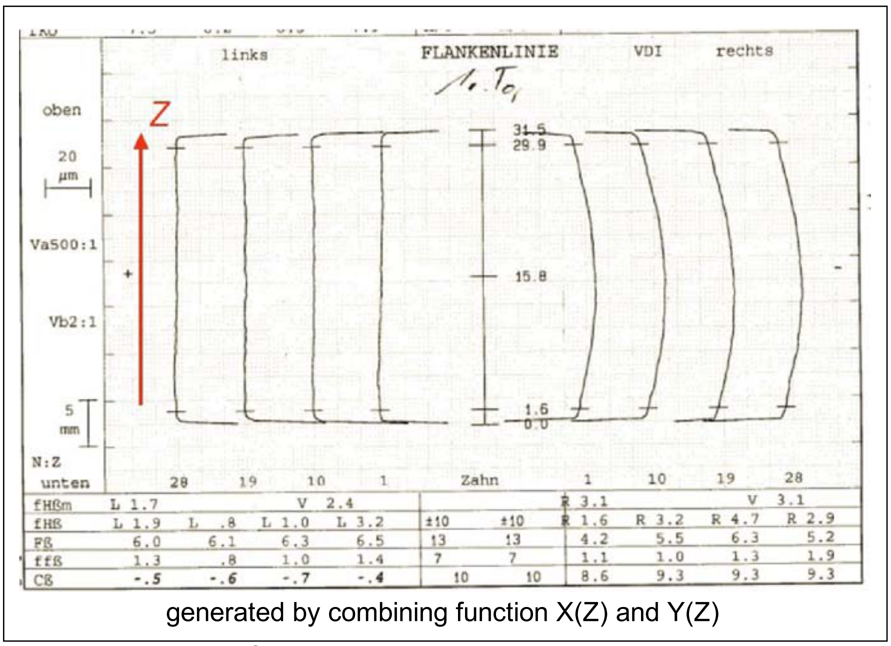

Figure 12—Example of unsymmetrical lead crowning generated by combining functions x(z) and y(z).

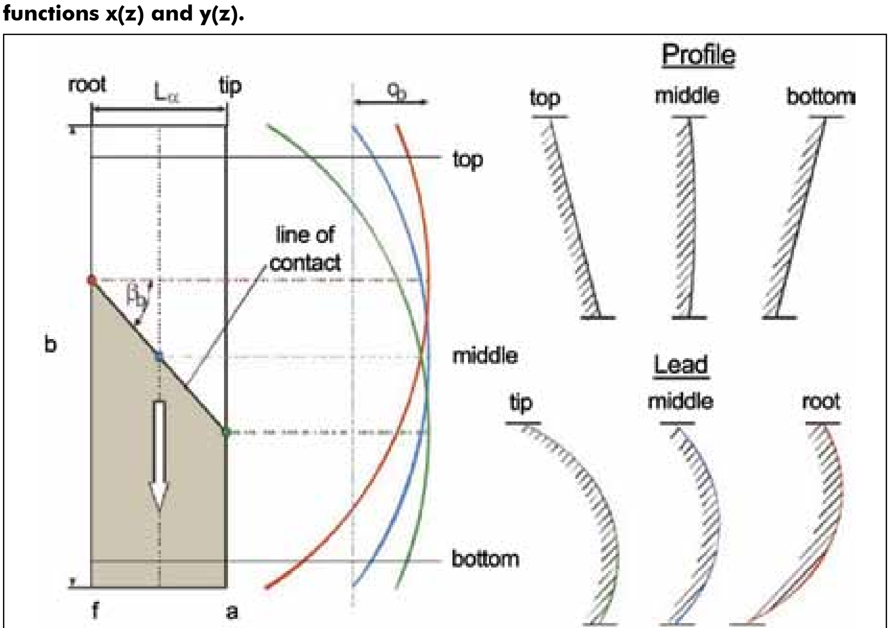

Figure 13—Contact line and twist generation in threaded wheel grinding.

proves how beautifully this method works. This principle can also be used to achieve much more complex modifications.

Up to now, profile and flank modifications were handled separately. But when grinding helical gears, lead modifications always influence the profile modification. The reason for that is the contact line between the grinding wheel and the gear tooth, which runs diagonal over the tooth as shown in Figure 13. Thus all points along this line are generated at the same time. In the case of grinding a symmetric lead crowning, a parabolic function x(z), as mentioned above, will result in a change of radial infeed over the face width "b" of the gear. Usually, the high point of a crowning is set to the middle of the teeth in terms of face width and profile height as represented by the blue point in Figure 13. Since all points along the line of contact are generated at the same time, the result is that the root area, represented by the red point, achieves its crowning high point displaced to the top of the gear. The tip area, which is represented by the green point, achieves its highpoint displaced to the bottom of the gear. The lead crowning is only symmetrical in the middle of the gear. If we measure the lead crowning in the root (red line) and tip area (green line) of the tooth, the crowning would be displaced, looking like a lead angle error. At the same time, this also affects the profile modification. The middle section has no profile error, save for a slight crowning effected by the lead crowning. The top and bottom profile lines are showing a clear profile angle error. The above-described effect is what is known as the twist phenomena, and appears when grinding helical gears with a lead crowning. Figure 14 shows a grinding result where this effect can be seen. The amount of twist error—which is defined as the absolute change in profile angle error from top to the bottom—is for this example about 25 mm, and much more than the allowed tolerance. This phenomenon is not desired.

The question now is how can this effect be compensated for and/or controlled? When looking to Figure 13 or 14, it becomes obvious that a method is required that allows grinding different profile modifications at different sections along the gear face width, which is nothing else than topological modifications. So in order to compensate or control the twist phenomena, it is necessary to at least partially compensate for the profile angle error, which changes from top to bottom on the gear. In addition, it is different in terms of its sign on the left and right flank. Gleason has a patented method to do such a compensation, which can also be used to grind topological modifications.

This method works with a modified wheel shape, along the wheel face width. As shown in Figure 15, the right-hand side of the grinding wheel is not dressed in a cylindrical shape, but rather in a hollow shape. This can easily be done during the dressing cycle by infeeding the dressing tool perpendicular to the wheel axis, again using a parabolic function across the wheel face width with no additional machine axis necessary. When looking to the detail on the left-hand side of Figure 15, one can see how such a dressed hollow-shape grinding wheel affects the grinding result. One can assume the gear being ground in this area would generate teeth with different pressure angles on the right and left flank. The right flank would be ground with a pressure angle that is the pressure angle α of the rack profile, plus an angle $\Delta\alpha$, while the left flank would be generated with a pressure angle of α minus $\Delta\alpha$. The angle $\Delta\alpha$ is the angle deviation between the perpendicular and the shortest distance between the gear center and the curved datum line (dotted line) of the rack profile.

It then becomes obvious that by choosing different positions along the wheel face width, one can influence the profile pressure angle generated on the gear teeth. Since the above-described profile angle error is nothing more than a different pressure angle, it is clear how to compensate or control this effect. The gear is therefore continuously shifted along the wheel face width while performing the axial stroke as shown in Figure 16. The result is that the right side of the wheel grinds the top part of the gear, while the wheel middle portion grinds the middle

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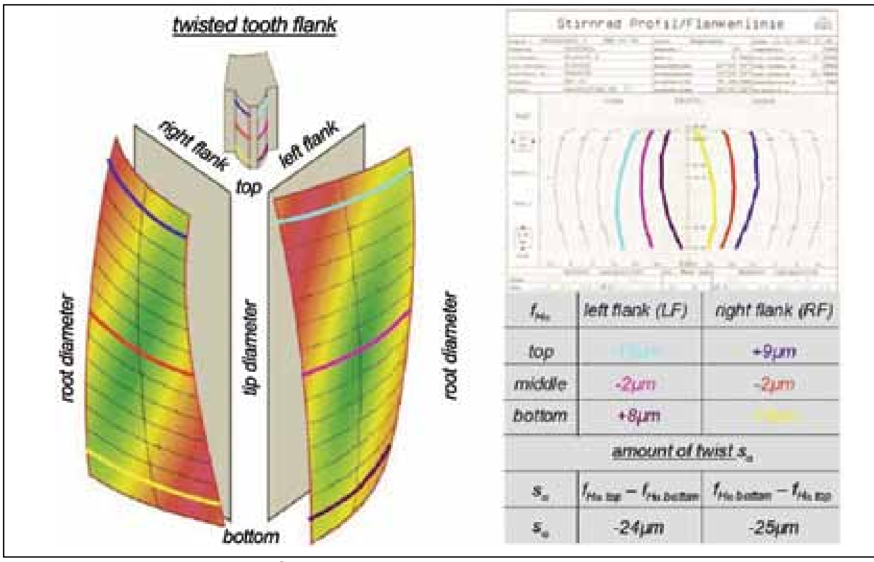

Figure 14—Twisted tooth flank.

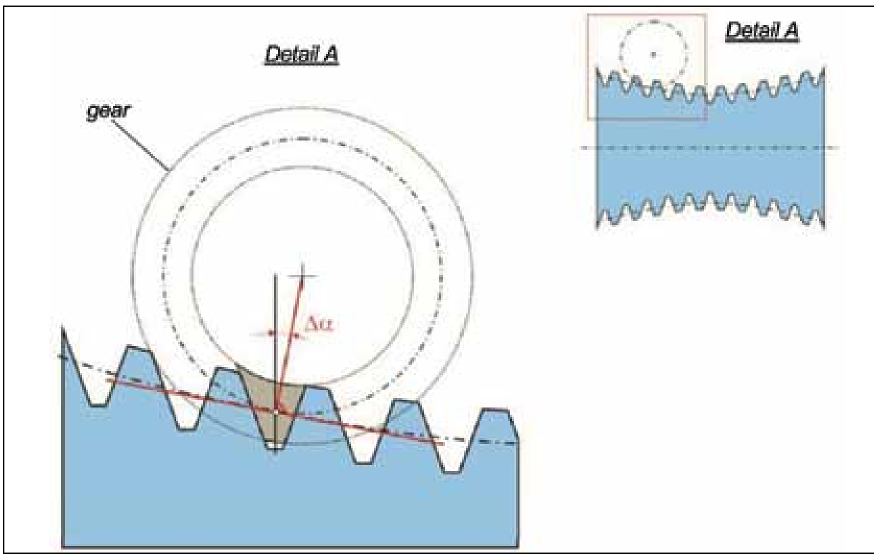

Figure 15—Principle of twist compensation.

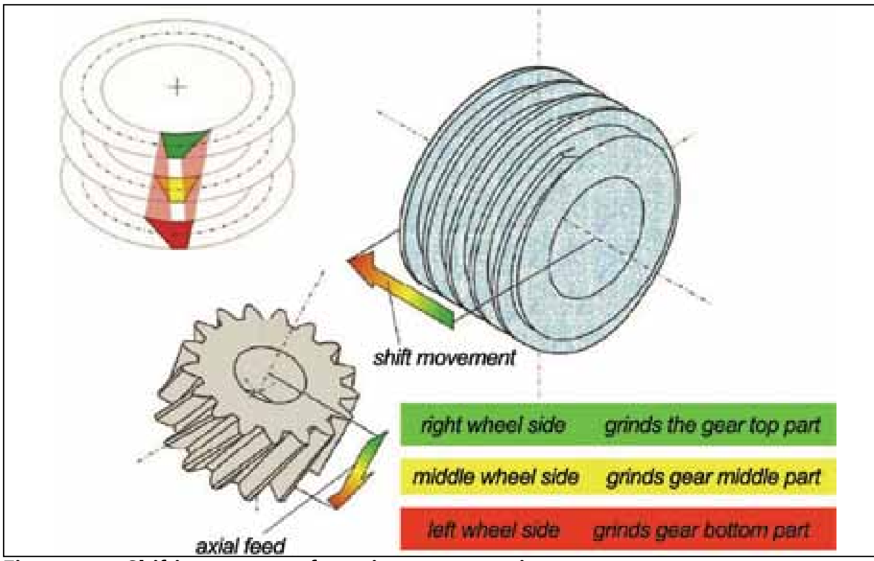

Figure 16—Shifting strategy for twist compensation.

section of the gear and the left wheel side grinds the bottom section of the gear (Ref. 8).

By considering the effect described in Figure 15, this method will result in gear teeth having different pressure angles from the top to bottom, and different signs on left and right flanks. Since this effect is superimposed with the natural amount of twist, it is obvious that by using this method one can compensate for, or control, the amount of twist. But this method can also be used to create different kinds of profile modifications along the face width of the gear that may be other than a topological modification.

Figure 17 shows two grinding results demonstrating the effect of this twist compensation method. The left-hand inspection diagram represents a gear ground without the compensation method described above. And so one can see a clear amount of twist in profile and lead. The right-hand diagram represents a result of the same gear type, but ground with this twist compensation method. It is very clear that the amount of twist has been compensated and demonstrates how well this method works.

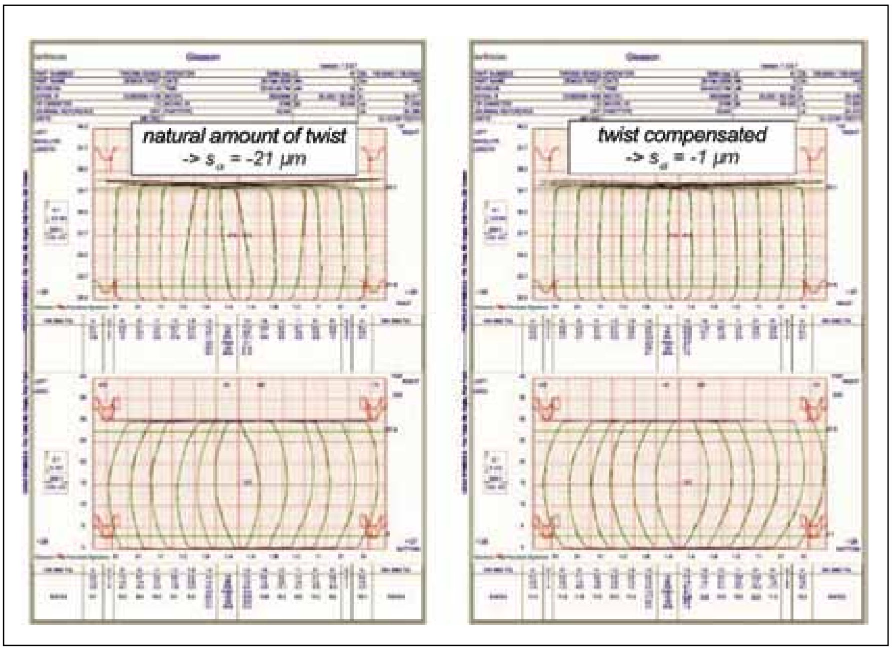

Figure 17—Result of twist compensation.

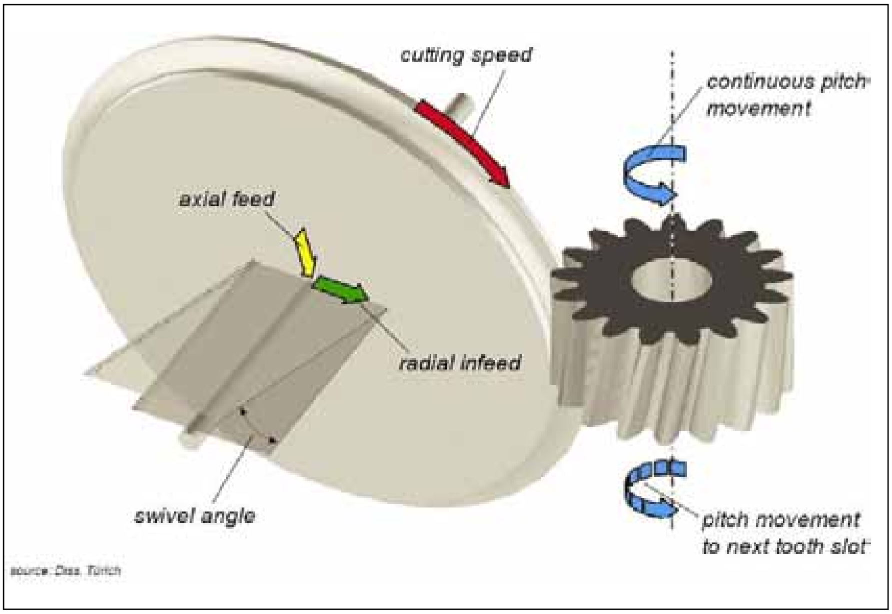

Figure 18—Kinematics in profile grinding.

Profile Grinding

Profile grinding is a process that provides great potential with respect to flexibility and quality, and can be used to grind a wide variety of gears. Thus profile grinding is used in job shop applications but also in applications that are not possible with threaded wheel grinding; e.g., large-module gears (Ref. 9). The kinematics of profile grinding presented in Figure 18 are much easier than in threaded wheel grinding since this process does not require so many synchronized movements.

A profiled grinding wheel is used, which is swiveled to the helix angle of the gear and rotates to perform the cutting speed (red arrow). In addition, the wheel must be able to be moved in a radial direction (green arrow) to remove stock from the flanks, and in an axial direction along the gear axis (yellow arrow). If the gear is helical, it requires a continuous rotational movement in order to follow the lead and a discontinuous pitch movement to grind all teeth.

Similar to threaded wheel grinding, profile modifications are generated by the grinding tool—which must be dressed in a special manner—while the lead modifications are generated by the machine axes. In profile grinding, the wheel profile shape depends on the gear data and the wheel diameter; it thus has to be recalculated for each diameter, which is no longer a problem when using modern machine software (Ref. 1). The user has to make inputs concerning the gear data and the desired modifications. Then the machine automatically calculates the required wheel profile and the corresponding movements for the dressing tool. In profile grinding, a dressing tool is used independent of the gear data; thus one dressing tool can be used to dress all kinds of wheel shapes. Such a typical dressing operation is shown in Figure 19. Beyond "standard" involute profiles, any other kind of profile can be defined and dressed, which is another advantage of profile grinding against threaded wheel grinding.

In order to achieve different flank modifications, a concept similar to threaded wheel grinding of superimposing additional movements of different axes is used. While a change in radial infeed results in more or less stock removal on the left and right flank, a change in the gear rotation position results in more stock removal on one flank and less on the opposite flank. With this concept, it is possible to achieve different flank modifications on the left and right flank. One example is presented in Figure 20, where the left flank was programmed with a 30 mm taper and the right flank with a 40 mm lead crowning. The real grinding result is shown on the right-hand side and proves how well this method works.

Threaded wheel grinding a lead modification also affects the profile, thus presenting similar problems in creating a twist error. The main reason in profile grinding is that a change in radial infeed, as it is necessary for a lead crowning, immediately results in a profile angle error (Refs. 1, 9). In addition to that phenomenon, the contact lines between the grinding wheel and gear are also running diagonal over the tooth flank.

Gleason has developed a patented method to compensate for the amount of twist in profile grinding as well. Figure 21 shows a grinding result when grinding a gear without this compensation, and one can clearly see significant change in profile and lead from the top to the bottom section of the gear. This method of compensating for or controlling a specific amount of twist uses five-axis interpolation, including a continuous swivel axis. This method allows for doing this in dual-flank grinding mode and thus saving a significant amount of time, compared to single-flank grinding, which would not require such a complex, five-axis interpolation. The result of this process can be seen in Figure 22. The amount of twist is almost eliminated. But this method not only enables compensating for twist. It can also be used to grind topological flank modifications.

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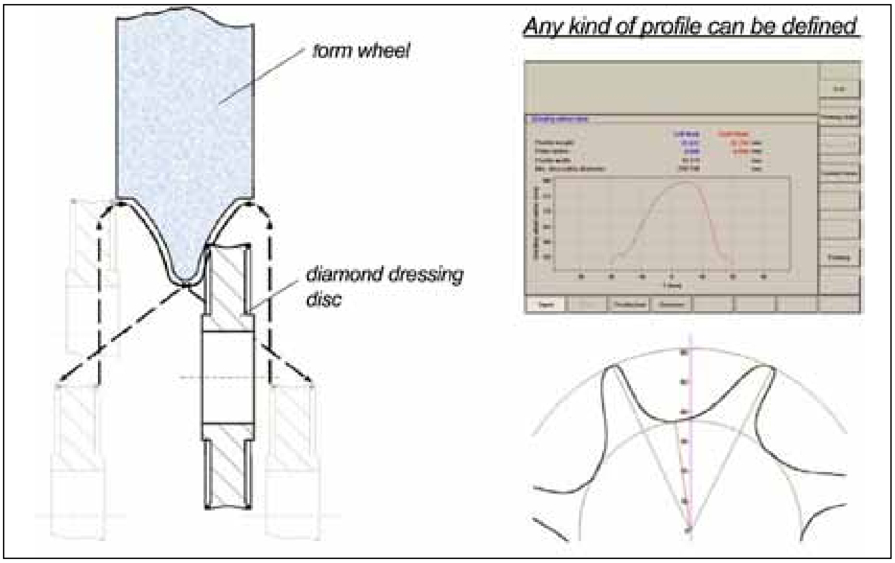

Figure 19—Dressing of form wheels.

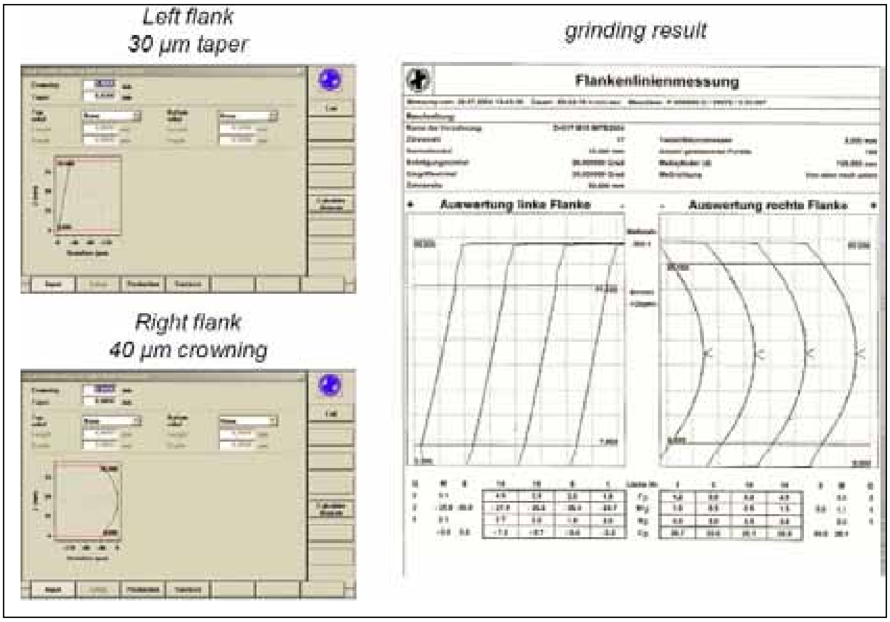

Figure 20—Grinding of different lead modifications.

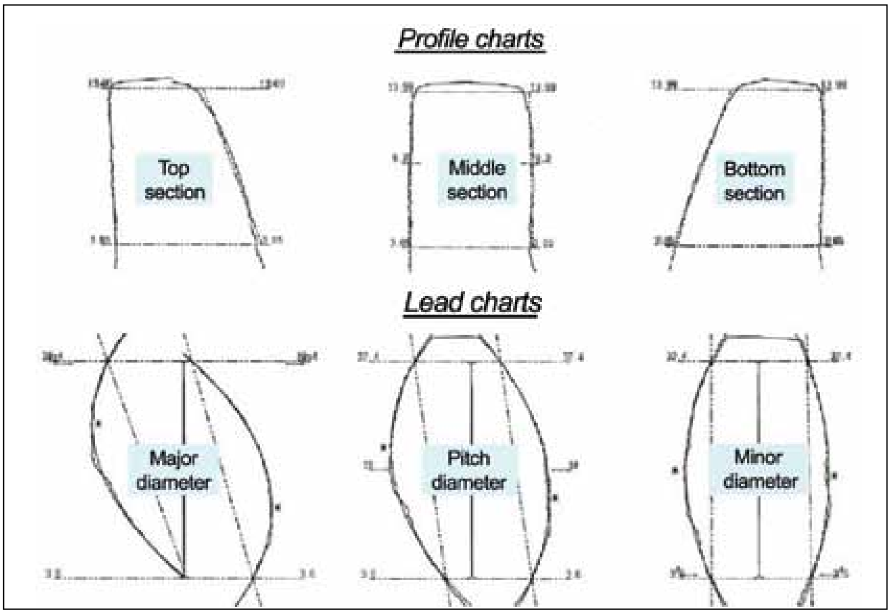

Figure 21—Natural twist in profile grinding.

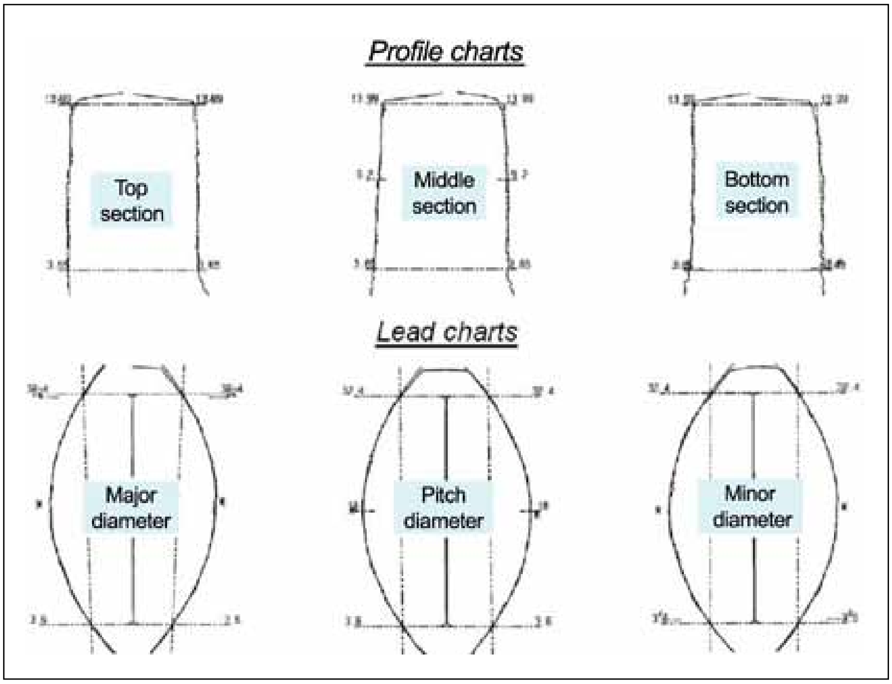

Figure 22—Compensated twist in profile grinding.

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