How Are You Dealing with the Bias Error in Your Helical Gears?

J. Lange

Management Summary

This paper initially defines bias error—the "twisted tooth phenomenon." Using illustrations, we explain that bias error is a by-product of applying conventional, radial crowning methods to produced crowned leads on helical gears. The methods considered are gears that are finished, shaped, shaved, form and generated ground. The paper explains why bias error occurs in these methods and offers techniques used to limit/eliminate bias error. Sometimes, there may be a possibility to apply two methods to eliminate bias error. In those cases, the pros/cons of these methods will be reviewed. Profile and lead inspection charts will be used to detail bias error and the ability to eliminate it.

The paper details the simultaneous interpolation of multiple axes in the gear manufacturing machine to achieve the elimination of bias error. It also explains that the CNC machine software can be used to predict bias error. Equally important, the software can be used to create an "engineered bias correction" to increase the load-carrying capacity of an existing gear set.

Introduction

Bias error or correction (a.k.a. "the twisted tooth error" and topological correction) was understood and addressed in the mid 1970s. It was not used by designers to increase a transmission's gear load capacity and noise reduction but, rather, in a manufacturing process to finish automatic transmission gears to a quality level similar to a shaved-finished quality. The finish-rolling process required the use of dies that required bias error correction. Without bias correction, the rolling dies and the working pressure of the process would produce errors similar to bias. The bias correction process was applied to a finishing tool. However, there was little chance to apply bias correction economically to conventional gearing.

The push in almost every gearing field is to increase durability and load-carrying capacity, and to reduce noise level for a given gear set. It is common to hear of the need for higher power density, more torque capability, a quieter gear box, longer life and so on. From the aerospace industry, it might be twisted around a bit (pun intended). They want a smaller, lighter gear set, but with the same load-carrying capacity. Dealing with the loss of involute contact ratio and tooth face width bearing pattern contact—due to bias error—in turn reduces the load-carrying capacity of a given gear set. So addressing that just might make it possible to meet the demands of higher power

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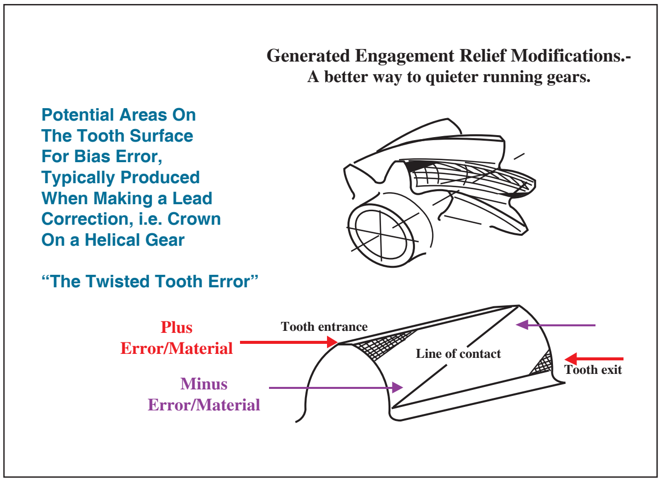

Figure 1—Line of action contact.

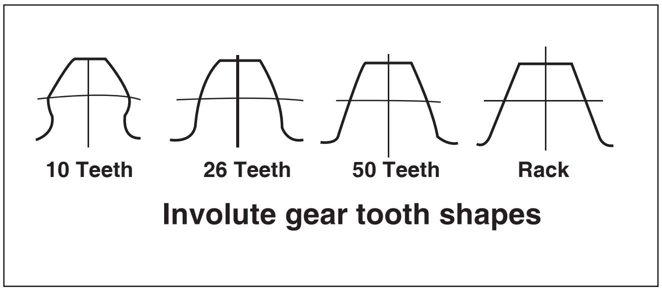

Figure 2—Curvature of the involute gear tooth shapes.

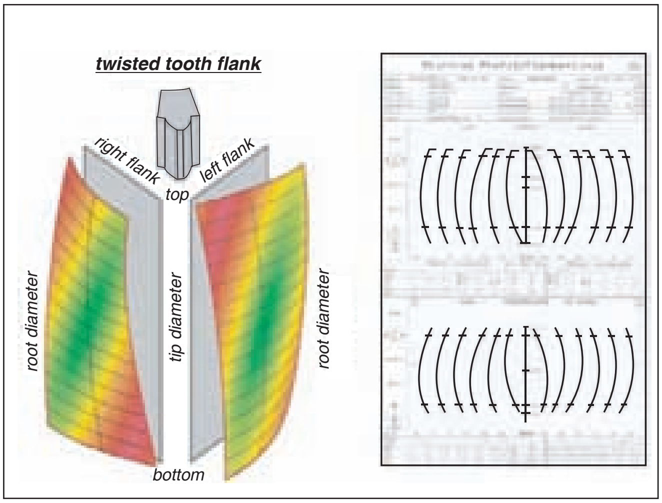

Figure 3—Amount of bias, s_α.

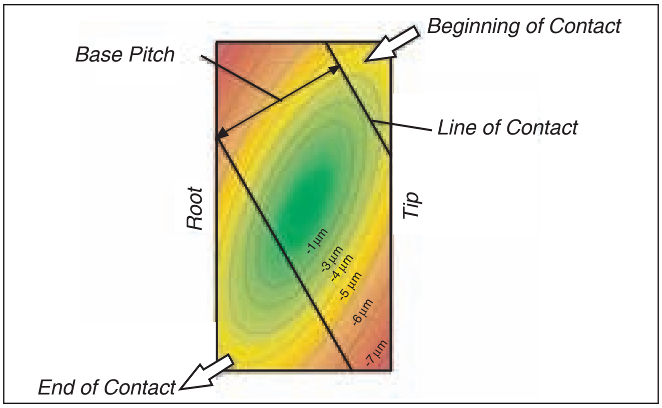

Figure 4—Flank topography.

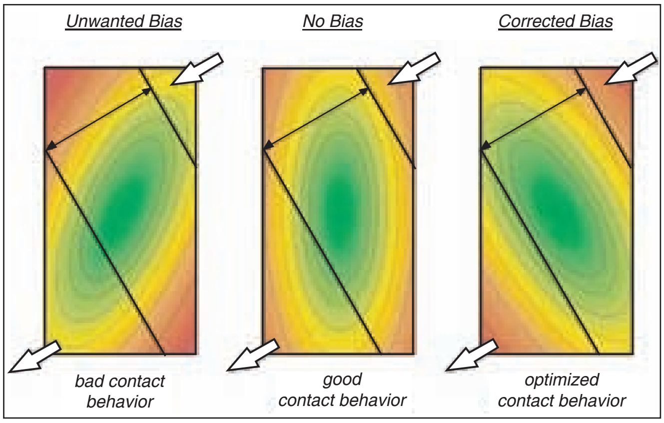

Figure 5—Impact of bias on tooth contact.

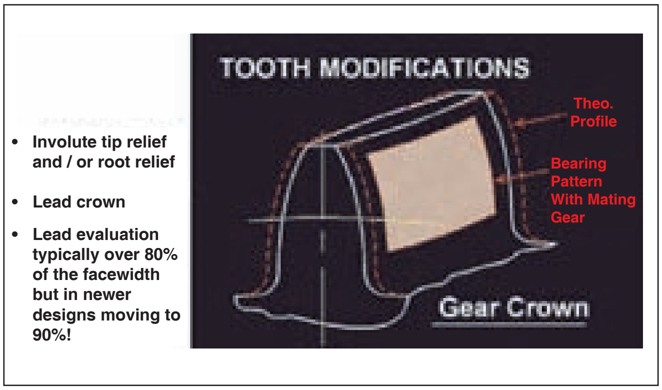

Figure 6—Load distribution: Because of varying load, tooth and gear blank/shaft bending under severe loading, there is a need to create gear tooth modifications.

density without an entire redesign of the gear set.

Discussion

Bias error is a non-uniform profile and lead geometry across the face width of a helical gear. "The twisted tooth" appears as if one end of a gear tooth was rotated clockwise and the other end counterclockwise. It is the direct result of making a lead crown correction using the conventional method of the radial displacement of the tool (cutting or otherwise) as it moves along the face width of the gear. Pinions—the lower number of teeth component in a gear set—are more prone to "inherit" this unique manufacturing error. The pinion, being the smaller gear component, is more apt to deflect under heavy loads. That deflection occurs in the lead and involute planes. It is ironic that gear designers, in an effort to maintain a reasonable face contact pattern at peak loads, specify lead crowns that in reality can have an adverse affect. There is a need to understand that a lead crown correction with bias error compensation will achieve the goals of the designers.

The contributing factors creating bias error and those increasing the amount of bias error are:

- The helical aspect relates the line of action contact pattern of two helical gears in mesh (Fig. 1);
- The pinion is the gear normally modified, and it has the highest degree of tooth curvature. The higher the tooth curvature—lower number of teeth— the greater the potential for bias error (Fig. 2);
- The coarser the module/DP, the greater the bias;
- The higher the helix angle, the greater the bias;
- The larger the face width, the greater the bias;
- The higher the amount of lead crown correction, the greater the bias.

Figures 3, 4 and 5 illustrate bias error and a corrected bias error. The red section of the plotted tooth represents unwanted plus error; yellow signifies the transition zone to the beginning of tooth contact; and green, the ideal tooth geometry along the line of contact.

What Does a Gear Designer Consider, and How Does Bias Error Affect Those Decisions?

Three significant factors figure into the load-carrying capacity rating and noise of a gear set:

1. ***Involute contact ratio***: A theoretical calculation of an average number of teeth in contact as mating gears roll in mesh—two or greater is desirable;

2. ***Load distribution***: Distributed across the face width of the gear, which at the same time, can affect the involute contact ratio negatively if the two gears in mesh are not contacting each other along the designated face width, normally 80% or more when under load (Fig. 6);

In the finished gear, plus error needs to be avoided. If not, high contact stress could lead to tooth pitting in those areas of plus error.

So to deal with it, the designer will need to define the amount of bias error being dealt with (Fig. 7). Once the designer is informed as to the amount of bias, a decision can be made to either reduce the crown to reduce the bias, or discuss with manufacturing engineering the ability to eliminate it. It may be that prototypes need to be made and inspected for bias error. See Figures 8–11 for examples of bias error evaluation methods.

Now the amount of bias error has been defined. The next step is to approach the gear designers and describe the errors that were caused when creating the specified crown correction. It may be necessary to show the following schematics illustrating how the lead crown was created. Point out the plus error issue. In addition, inquire if the crown is required on both flanks and if the root diameter changed in relation to the crown is desirable or required. The significance of these

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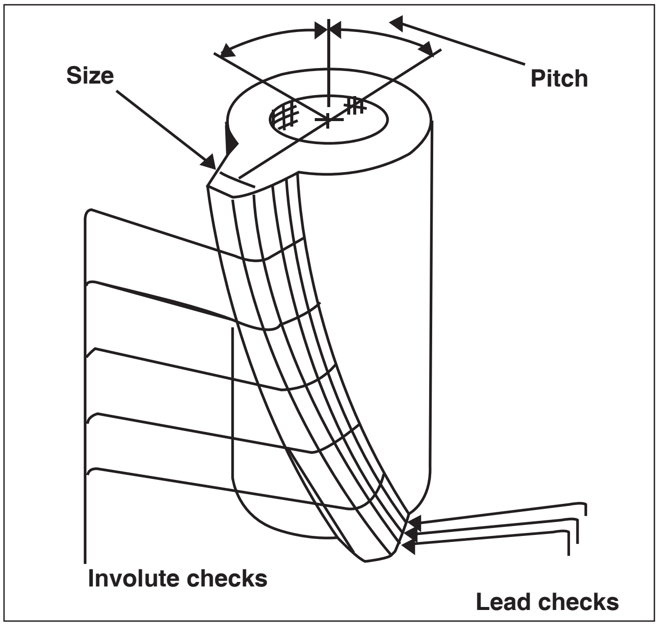

Figure 7—Inspecting for bias lead and involute measurements of a single tooth.

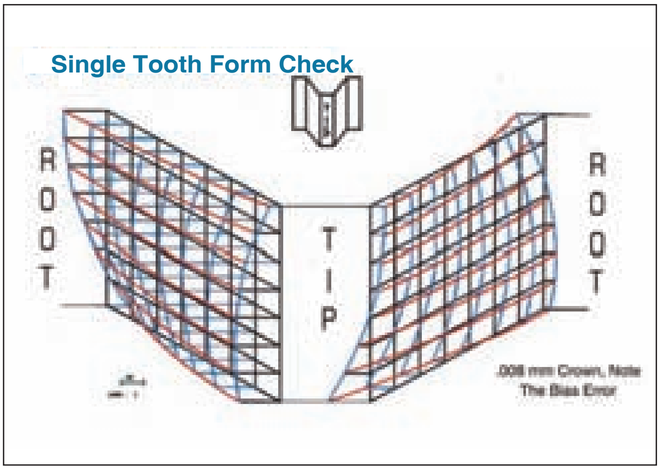

Figure 8—Single tooth with bias error.

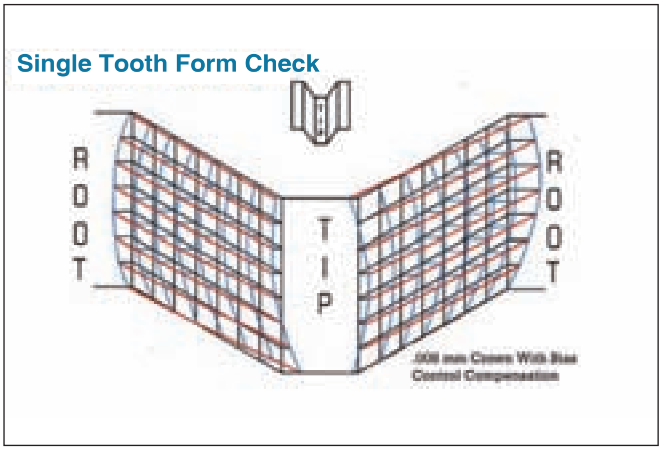

Figure 9—Single tooth without bias error.

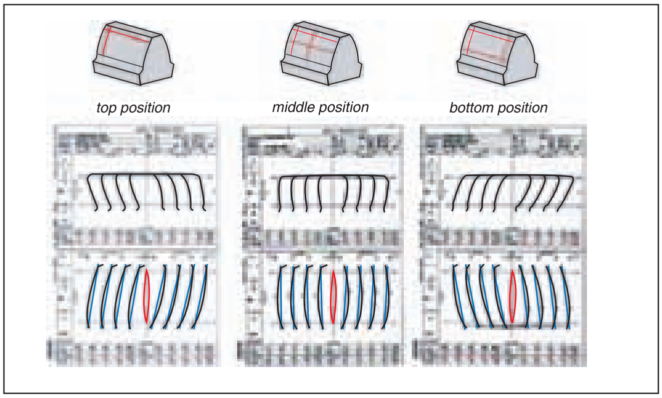

Figure 10—Typical four-teeth inspection technique with bias error.

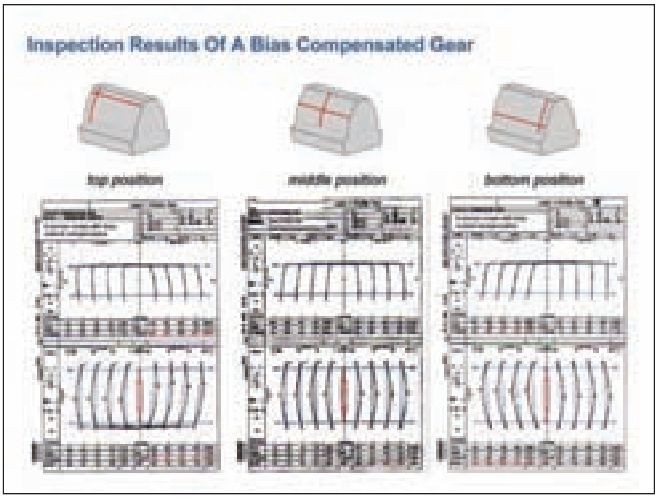

Figure 11—Typical four-teeth inspection technique with bias correction.

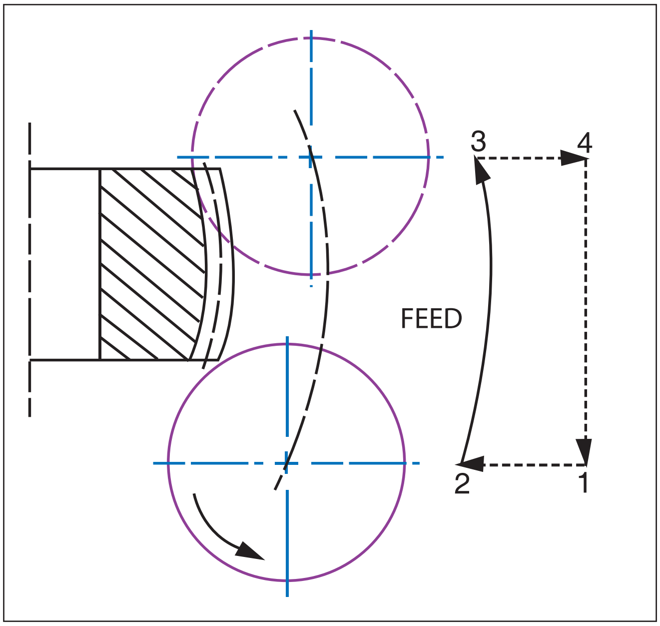

Figure 12—Traditional method for lead crown correction with a circular tool. Traditional path of hob, threaded wheel grinding and form grinding tools. This method of crowning will create bias error.

answers will become apparent a bit later in this discussion.

Methods to Make a Lead Crown Correction

Form grinding will be used as a means to demonstrate how the kinematics of creating a lead crown creates a bias error. See Figures 12–20.

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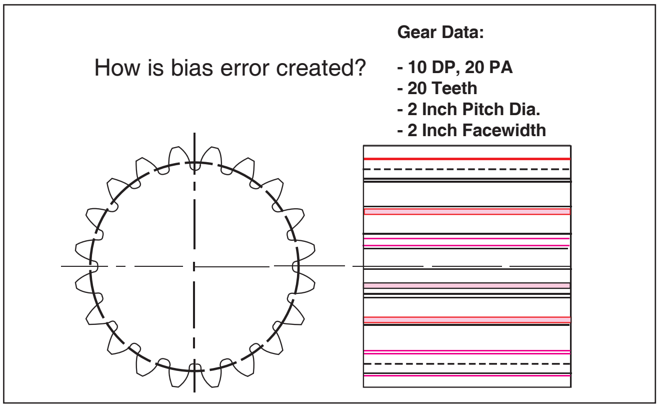

Figure 13—Form grinding example.

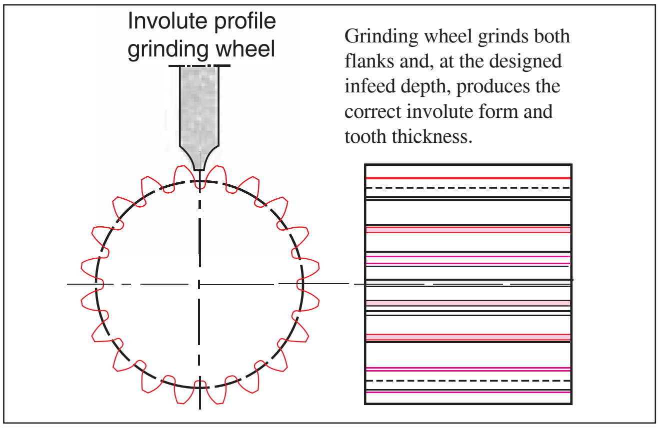

Figure 14—Form grinding method.

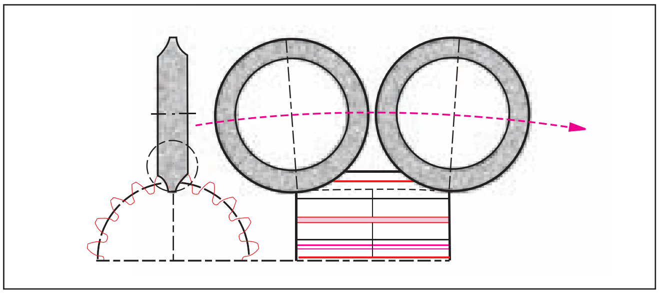

Figure 15—Form grinding wheel path for a convex crown. Form grinding wheel path required to create a symmetrical lead crown using the conventional crowning technique of radial displacement of the grinding wheel, relative to Z axis position along the gear face width.

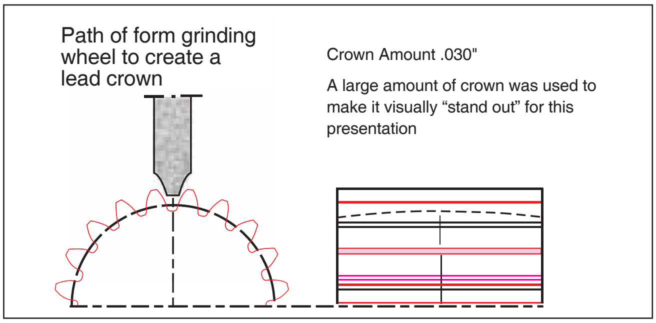

Figure 16—Tool path for a 0.030" crown per flank.

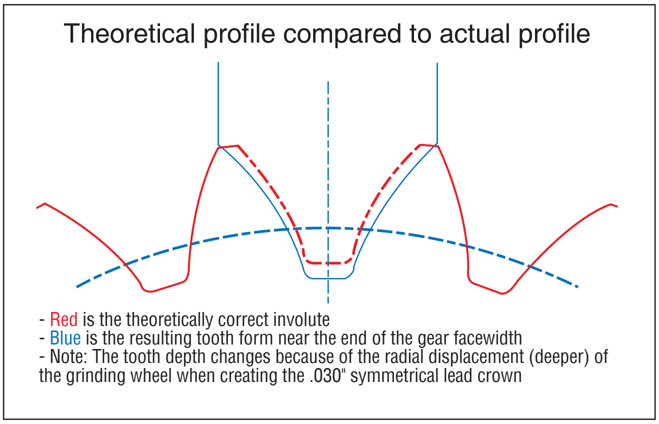

Figure 17—Involute profile "radial shift" resulting in involute errors when creating a 0.030" crown. (Note: A 0.030" crown is inordinately large, but that was done for visual effect.)

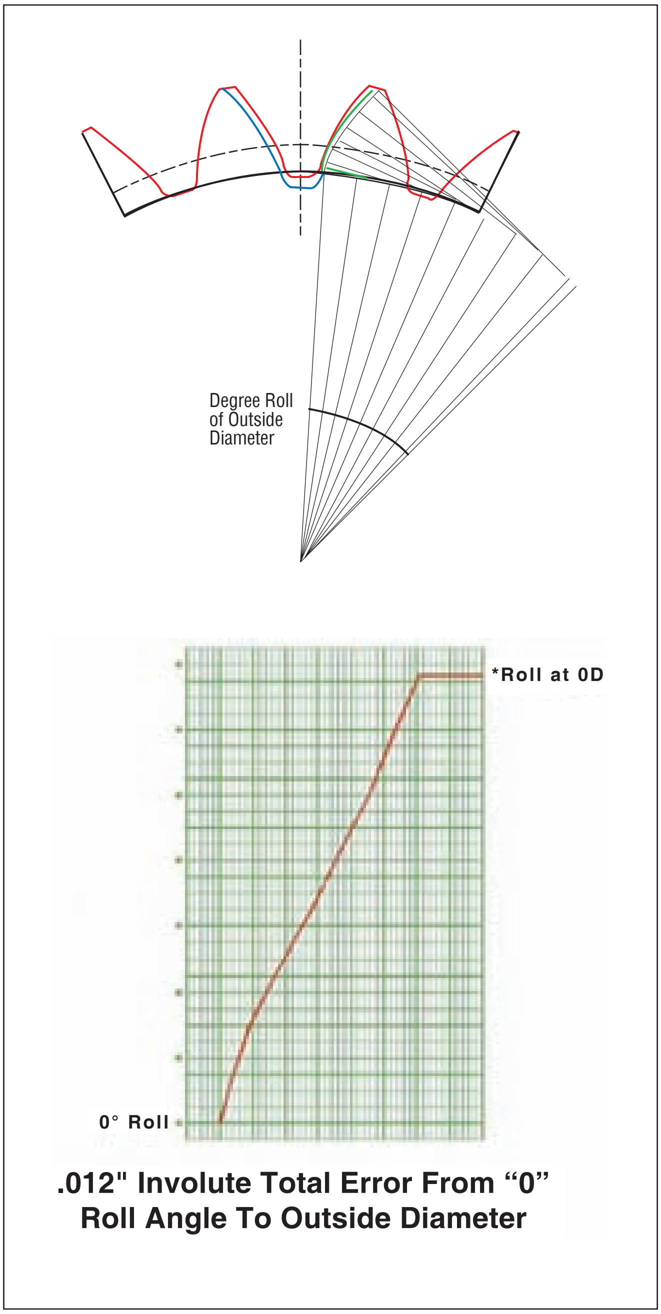

Figure 18—Lead slope error as the result of 0.030" crown.

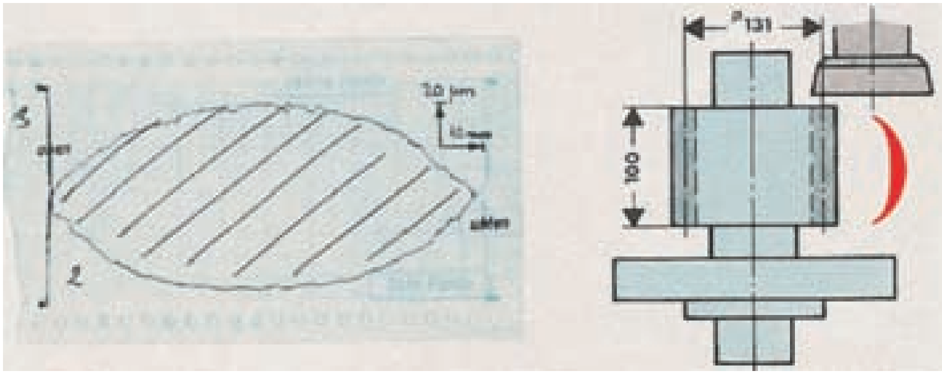

Figure 19—Shaping method for lead correction. The gear shaping process creating a lead crown with a radial position change of the path of the shaper cutter as it passes along the face width of the gear. This method of crowning will create bias error.

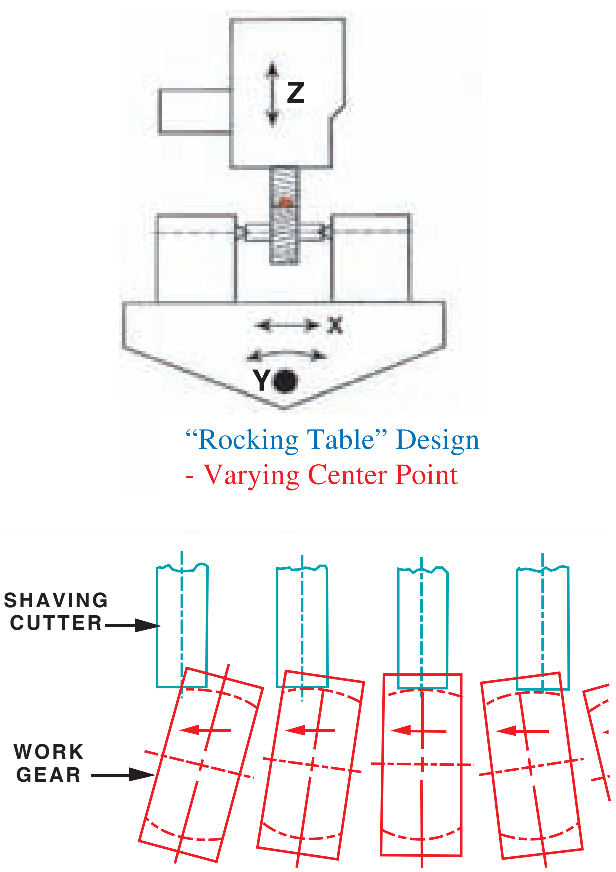

Figure 20—Shaving a lead crown correction by "rocking" the gear. In the shaving process, the crowned lead created by changing the center distance between the shave cutter and gear as the contact point moves right to left as the work side "rocks up and down." This method of creating a crowned lead will produce bias error. Note: Plunge shaving and honing having the lead crowned correction dressed into the shave cutter and hone stone, and, consequently, will not produce bias error. The Gleason Hurth Honing machine has the ability to make bias error correction using four axes of motion. It "knows" where the center point of contact is at all times and controls its position/motion to produce bias error correction.

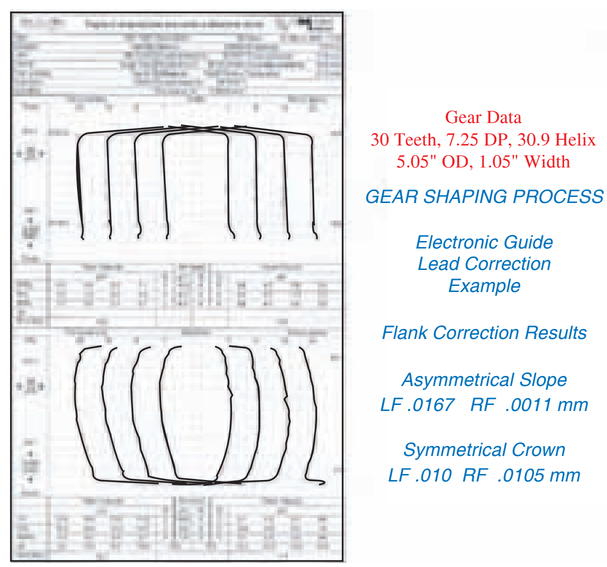

Figure 21—Lead crown correction made with a CNC guide.

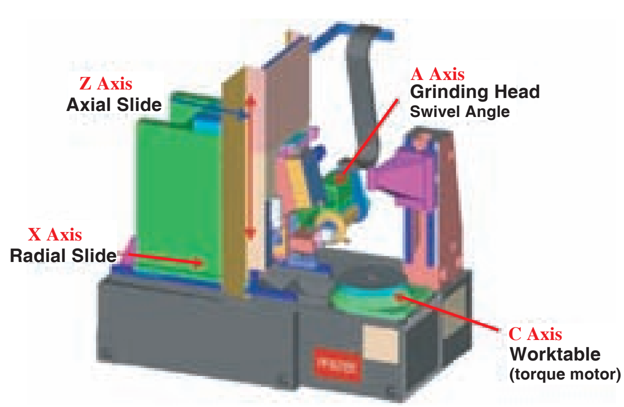

Figure 22—Axes being interpolated when making bias error correction (X, Y, A and C, depending on Z position). Multi-axes gear grinding machine interpolating 5 axes of motion to eliminate bias error when creating a lead crown grinding two flanks.

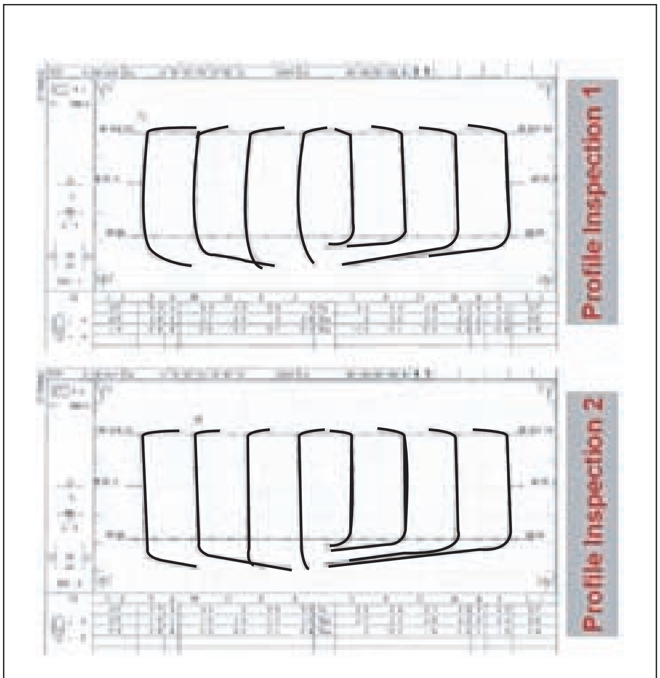

Figure 23—Dual-flank grinding without producing bias error.

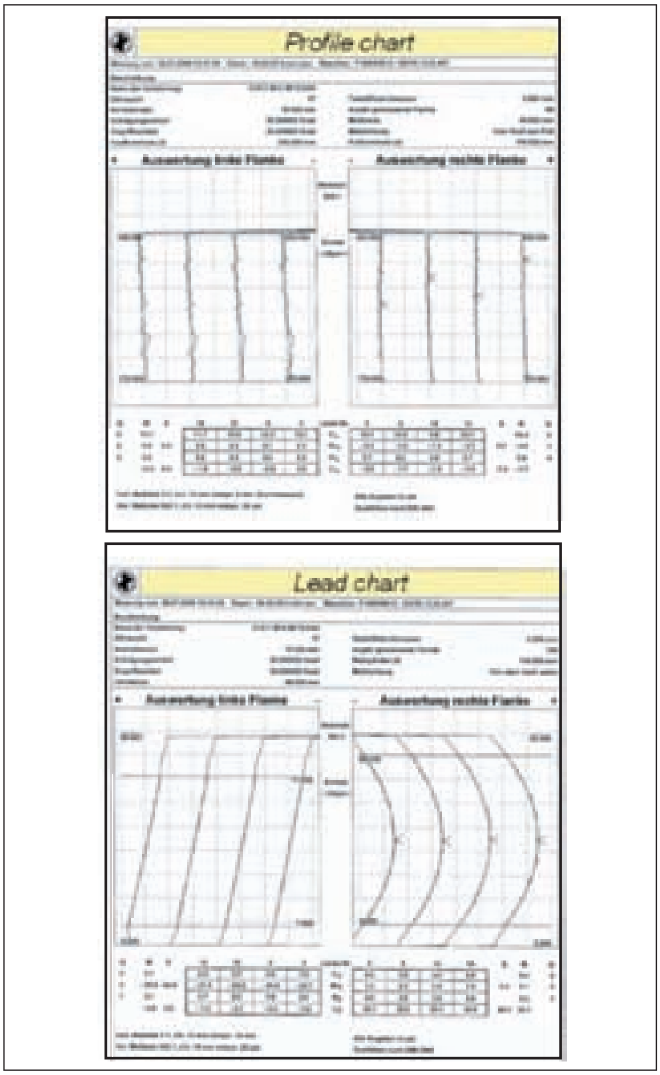

Figure 24—Dual-flank grinding without producing bias error.

**How to Deal with Unwanted Bias Error—
How Not to Make Bias Error**

- Do not make a lead crown correction using the traditional, radial displacement of the tool or workpiece. This may not be practical, as the gear manufacturing equipment in use in a plant most likely has no other method of making a lead crown.
- An important point about a machine's CNC capability with special software and various CNC-controlled axes needs to be known: If the machine can cut a part cutting only one flank at a time, it may be possible to use the worktable rotation or another rotary axis to make a lead crown, and not cause bias error. This one-flank finishing process applies to form grinding and shaping. The gear designer should be asked if it is really necessary for both flanks' lead to have a lead crown correction. If yes, then two finishing passes are required to make this gear, and more cycle time is required. This single-flank crowning method does not change the root diameter. One could actually consider if making a crowned lead without a root diameter change, might you have a stronger tooth?
- If finished hobbed, there is nothing that can be done. Bias error will occur.
- If finished shaped, bias error will occur, unless the machine has a CNC guide capability and special software. Then the finish cutting method is to cut a flank at a time, making a right-hand helical until mid-face, and then a left-hand helical. It would be the opposite for the other flank. One would think that this crown cutting method would make a lead correction that would look like a chevron. This is not the case; see the example lead chart made on a Gleason/Pfauter gear shaping machine with an electronic guide and special software (Fig. 21). Note the intentional asymmetrical and symmetrical lead corrections.
- If a shaved part, use only the plunge shaving process. Plunge shaving will not create bias error. This is not practical if the part has a face width larger than 2" (50 mm), and/or if the pitch is coarser than 6 DP (4.23 module). With the parallel and diagonal shaving method, a bias error is created when making a lead crown correction.
- If grinding, you need to do the following:

1. ***Form grinding***: Use the single-flank grinding process with work spindle rotation—not "X"radial axis displacement—as the grinding wheel moves along the face width of the part. If both flanks require a crown, then an additional finishing pass is needed. Or, if the machine has a very special software and multi-axes interpolation motion capability, then a dual-flank grinding process can be done, thus saving an enormous amount of time. See

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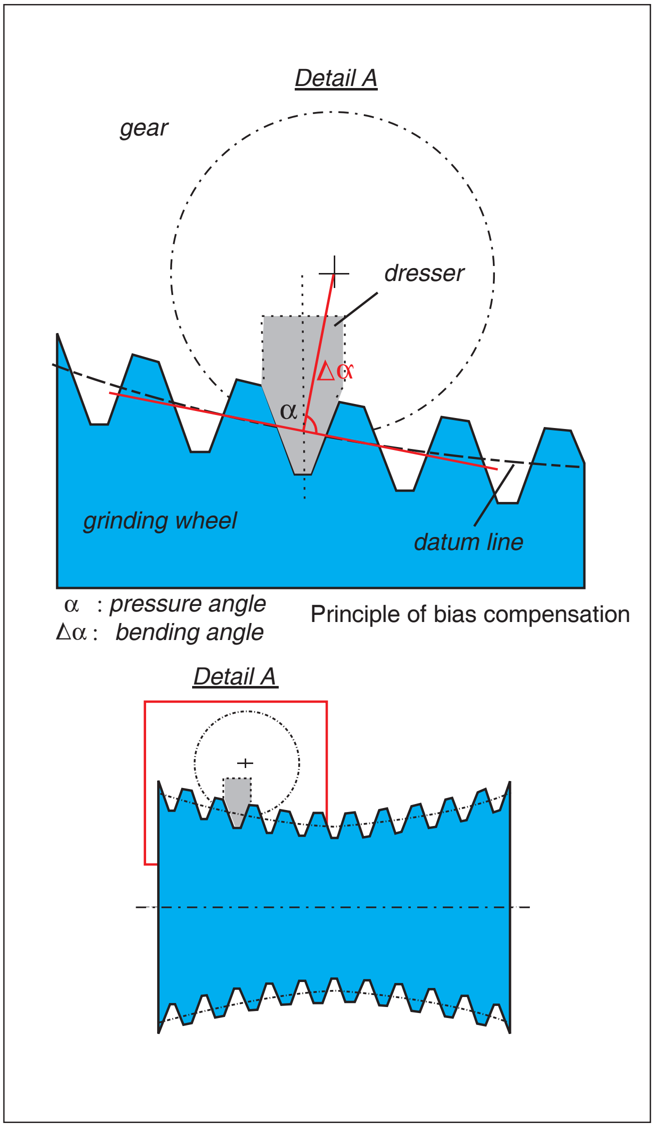

Figure 25—Special dressing technology applied to the grinding wheel to eliminate bias error when making a lead crown.

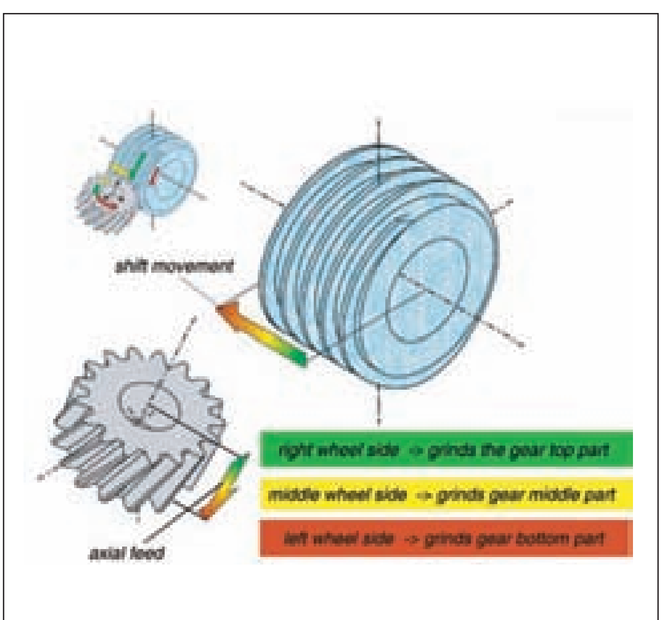

Figure 26—Special dressing technology and shifting strategy to eliminate bias error when making a lead crown.

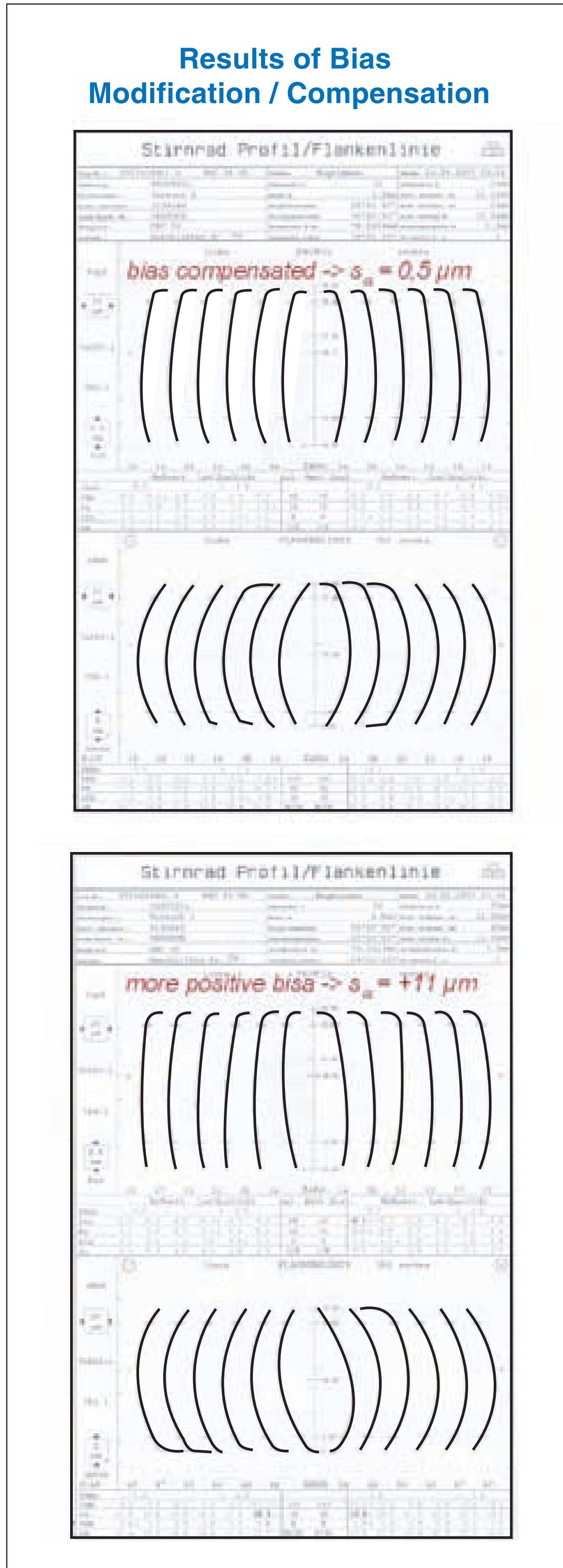

Figure 27—Threaded wheel grinding with lead crown correction and no bias error.

Figures 22–24 for an example of a Gleason/Pfauter CNC grinder using patented software producing bias error correction and, in the second example, totally different lead correction. Knowing the contact point of the grinding wheel at all times is paramount to this successful and unique lead correction technique.

2. ***Threaded wheel grinding*** Special, patented software and machine dressing capability are applied to create on the grinding wheel different geometric proportions over its length. This is an example of a Gleason software solution to eliminate bias error or to make a bias correction (Figs. 25–27).

Conclusion

Gear designers and manufacturing engineers need to know that it is now possible to make lead crown corrections without creating bias error. They need to use this knowledge along with processes to create a face load distribution over the typical 80%, which many gear designers consider for their designs. Why not even 90%, when the designer is forced to continue to use an existing gear box at higher-rated load capacity? Designers may even rethink bias error and consider using this ability to manipulate bias values into a bias correction.

References

1. *MAAG Gear Handbook*, Maag Gear Wheel, Switzerland, 1990, pp. 181–188.
2. ES 422 Topological Modifications, Maag Gear Wheel, Switzerland, June 1982.
3. Topological Modification, Maag Gear Wheel, Switzerland, June 1975.

John M. Lange *is a product manager for The Gleason Works. Active in gear manufacturing since graduating with his bachelor's degree in 1970, he is a past chairman of the AGMA Gear Manufacturing Committee and the AGMA Metrification Committee. Lange's papers have been published by Gear Technology magazine and the SME, and has authored two sections in the SAE's 1990 Gear Design, Manufacturing*

Author's Note

Just to be clear*…At the close of this presentation, the reader is left with the impression that the latest gear manufacturing machine technology for controlling bias/twist is used only to prevent bias error; or—as termed in this paper—bias* compensation.

Bias compensation serves to help in achieving a designer's original goal—to have a lead crown correction that would hopefully create a uniform load distribution across the face width of the gear at peak loads.

It was also originally stated that the future would see designers using this unique machine technology of multiple CNC axes of interpolation to make a bias correction in combination with a crown correction for the ultimate load distribution.

After the 2008 AGMA Fall Technical Meeting, conversations with several gear designers indicated that they do, in fact, have current designs with bias correction requirements.

A particular example was the need to create a bias correction of 0.003–0.004 mm for an engine balance shaft gear. The bias correction was implemented using the plunge shaving process. (You can imagine the challenge of grinding a tightly controlled bias correction into the plunge shaving cutter's lead and involute.)

Recently, we have seen four examples of part prints—from four different companies—requiring hard gear finishing with bias correction. These are automotive transmission parts that would most likely use the threaded-wheel-grinding process for three of the parts, and honing for the fourth. Honing is required because it is a pinion shaft with a 20-tooth gear next to a 37-tooth gear with a distance between the two of only 7 mm. The bias correction amounts for these four parts ranged from 0.005 mm to as much as 0.020 mm.

It would appear that an understanding by gear designers of this bias correction capability is gaining currency. One can then perhaps anticipate the next question for a future technical paper—How does a designer determine the amount of bias correction being specified?

—John Lange.

May, 2009