Precision Finish Hobbing

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Introduction

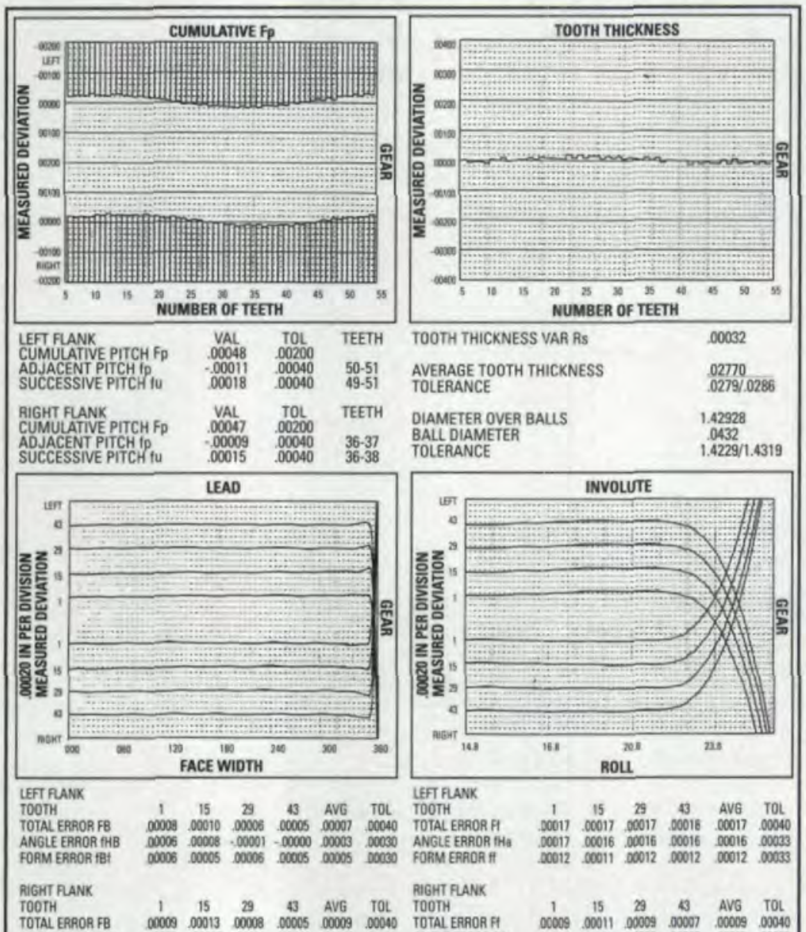
Nowadays, finish hobbing (which means that there is no post-hobbing gear finishing operation) is capable of producing higher quality gears and is growing in popularity.

This discussion addresses some of the challenges that gear makers experience when they attempt to finish hob or skive hob gears to a higher quality standard; a quality level that is higher than routinely expected in a production environment. Figure 1 shows the inspection charts of a gear with exceptional quality. One would expect such a level of quality to be the result of a secondary gear finishing operation, e.g. shaving, honing, rolling, or gear grinding. However, this gear was finished on a hobbing machine.

There are many legitimate reasons to specify a post-hobbing gear finishing operation—elimination of heat treat distortions and elevated surface finish requirements are just two. But there are also reasons that result from old paradigms, which may no longer be true.

Often, process engineers specify a post-hobbing gear finishing operation (shaving, for example) not necessarily because the gear's geometric quality and surface finish requirements are unachievable by the hobbing process, but rather because it is *difficult* to consistently achieve the desired quality. In statistical terms, the hobbing process has not been generally regarded as capable of producing AGMA quality 9 or higher (the process is considered capable when the process capability factor, Cp=Tolerance/(6Sigma), is greater than one). Another reason for specifying a post-hobbing gear finishing operation was the generative nature of the hobbing process, which creates a distinct tooth topology resulting from hob feed and enveloping marks (Fig. 2). A third reason for specifying a post-hobbing gear finishing operation was the possibility of productivity improvements during the rough hobbing. As compared to finish hobbing, the rough hobbing cycle times are usually much shorter since multi-start hobs and higher feed rates can be applied.

These paradigms can be challenged today. The continuous improvements in machine, workholding fixture, and hob quality combined with reliable QC procedures have steadily upgraded the statistical capability of the hobbing process. This, in turn, makes the finish precision hobbing process worthwhile to consider for a wider range of applications with greater precision requirements. Also, tooth surface variation due to generating marks can be minimized with the selection of an optimum hob feed rate and number of hob gashes. Tooth surface variation due to the generating marks can be so insignificant (millionths of an inch) as compared with other gear geometry errors that it may not be of concern for many gearing applications. While the visual effects of the hobbing generating marks can be dramatic, they should not be confused with the gear quality. In fact, the better the gear quality is, the more uniform the generative marks are and the greater the visual effects are. Finally, recent advancements in carbide (or comparable) cutting tool technology provide new opportunities for productivity improvements, as the increased cutting speed allowed by these tools can shorten the finish hobbing cycle time by a factor of two or three.



LEFT FLANK	VAL	TOL	TEETH
CUMULATIVE PITCH Fp	.00048	.00200	
ADJACENT PITCH fp	-.00011	.00040	50-51
SUCCESSIVE PITCH fu	.00018	.00040	49-51

RIGHT FLANK	VAL	TOL	TEETH
CUMULATIVE PITCH Fp	.00047	.00200	
ADJACENT PITCH fp	-.00009	.00040	36-37
SUCCESSIVE PITCH fu	.00015	.00040	36-38

TOOTH THICKNESS VAR Rs	.00032
AVERAGE TOOTH THICKNESS	.02770
TOLERANCE	.0279/.0286
DIAMETER OVER BALLS	1.42928
BALL DIAMETER	.0432
TOLERANCE	1.4229/1.4319

LEFT FLANK						
TOOTH	1	15	29	43	AVG	TOL
TOTAL ERROR FB	.00008	.00010	.00006	.00005	.00007	.00040
ANGLE ERROR fHB	.00006	.00008	-.00001	-.00000	.00003	.00030
FORM ERROR fBf	.00006	.00005	.00006	.00005	.00005	.00030
RIGHT FLANK						
TOOTH	1	15	29	43	AVG	TOL
TOTAL ERROR FB	.00009	.00013	.00008	.00005	.00009	.00040
ANGLE ERROR fHB	.00000	-.00007	-.00003	-.00000	-.00002	.00030
FORM ERROR fBf	.00009	.00011	.00007	.00005	.00008	.00030

LEFT FLANK						
TOOTH	1	15	29	43	AVG	TOL
TOTAL ERROR Ff	.00017	.00017	.00017	.00018	.00017	.00040
ANGLE ERROR fHa	.00017	.00016	.00016	.00016	.00016	.00033
FORM ERROR ff	.00012	.00011	.00012	.00012	.00012	.00033
RIGHT FLANK						
TOOTH	1	15	29	43	AVG	TOL
TOTAL ERROR Ff	.00009	.00011	.00009	.00007	.00009	.00040
ANGLE ERROR fHa	.00006	.00009	.00005	.00002	.00005	.00033
FORM ERROR ff	.00006	.00006	.00007	.00007	.00006	.00033

Fig. 1—Inspection charts of a gear with exceptional quality.

Effects of Hobbing Process Variables on Various Gear Characteristics

Various gear characteristics are important to overall gear quality. Some of the most common characteristics that are monitored during a gear manufacturing process are tooth lead, tooth profile, pitch variation, runout, and tooth thickness. Hobbing process quality is affected by the machine, fixture, blank, cutting tool, and cutting conditions. The hobbing machine is a very important, and certainly the most expensive, component of the hobbing process. Frequently, it is impossible to make a quality gear without a good machine. No wonder people pay the most attention to the machine. However, often the greatest contributors to gear quality are not the machine, but the fixture, the cutting tool, the blanks, the cutting conditions, or any combination thereof. These contributors affect lead, profile, pitch quality and other gear characteristics in different ways. Below is a review of some of the effects of these contributors on the quality of various gear characteristics. This review is not a comprehensive troubleshooting guide, but rather an attempt to create a checklist for gear makers who wish to consider the hobbing process for more precision gear finishing operations.

Gear Lead (Alignment) Quality. Hobbing methods can produce lead quality up to AGMA 11, 12 or even higher in a production environment. Here are some common factors that affect the gear lead quality:

• **Machine factor.** Machine rigidity is probably the most important factor. The machine must be mechanically and electronically "solid" to be able to withstand natural variation of cutting forces, especially in the beginning and the end of the cut. Today, few people (unless they use very old machines) have to deal with the notorious "break-in" and "break-out" phenomenon caused by the winding and unwinding of the machine gear train. Another flaw sometimes found in old machines is an excessive table drive backlash that can cause an irregular lead error. Most of the machine suppliers tackled both problems by creating a shorter gear train (or even a direct drive) and some kind of anti-backlash table drive. Today, many new gear hobbing machines can hob gears with a lead quality similar to that achieved by gear grinding. To be successful in attaining lead quality that approaches that of the grinding process, one must use a workholding fixture and gear blanks with qualities similar to those used during the grinding process.

• **Workholding fixture factor.** The workholding fixture is another frequent culprit that compromises the gear lead quality. Fixture geometric errors

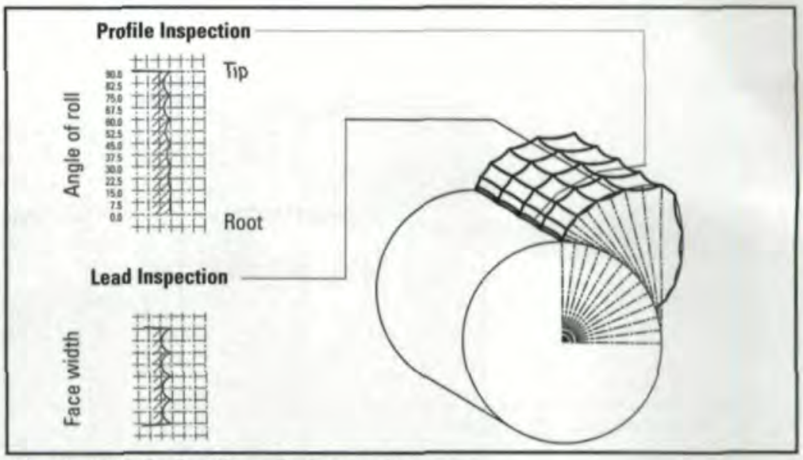


Fig. 2—Hob feed and enveloping marks.

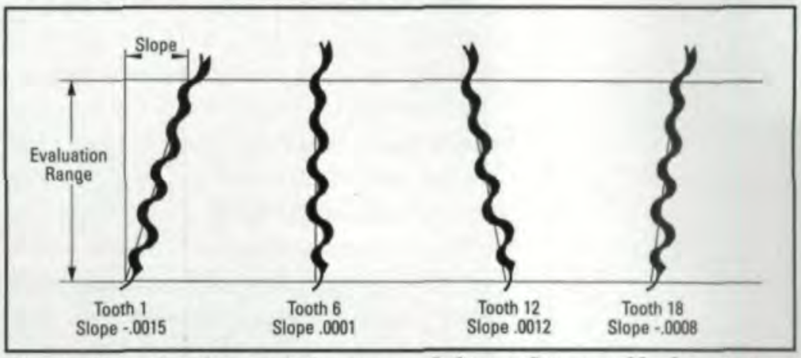


Fig. 3—Excessive slope variation can result from a fixture or blank runout.

such as misalignments with the machine centerline and an inability to center the gear blank properly can increase lead wobble or lead taper. Figure 3 shows an example of lead error affected by a part's axial runout (or radial runout for high helix angle gears). Lack of fixture rigidity is another common factor skewing the gear lead away from perfection. For example, when cutting shafts, the beam between the machine table and the tailstock should be as short as possible to improve the system rigidity. In addition, the fixture should be dynamically stable and be able to absorb the cyclical variation of cutting and clamping forces.

• **Hob factor.** When gear makers are trying to achieve the best possible quality, they usually consider a one-start hob. If this is the case, neither the hob's mounting quality, the hob's inherent quality, nor the hob's sharpening quality have any direct effect on the lead characteristic. As much as the hob's geometric quality can affect a gear's profile, the geometry errors of a one-start hob have no influence on the lead quality. This is also true for multi-start hobbing with a non-hunting ratio combination (number of gear teeth is divisible by number of starts). Thus, as long as the hob cutting edges do not dramatically deteriorate, hob geometric qualities are irrelevant for achieving good gear lead characteristics. However, when a hob becomes dull, it can create an irregular surface finish, and it can have an indirect effect on the lead geometry

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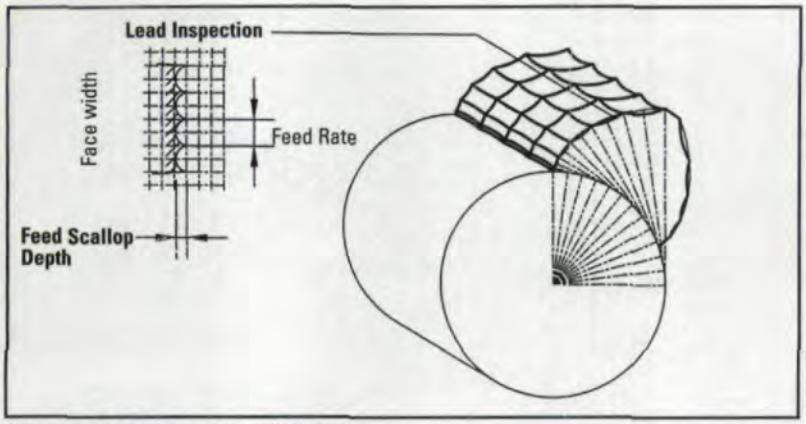

Fig. 4—Feed rate and scallop depth.

because the increased cutting forces can destabilize other factors such as fixture, blank, or machine rigidity. An irregular lead error could also be a result of a chip buildup on the hob cutting edges.

• **Gear blank factor.** Gear blank quality is another factor that can affect the lead variation. Gear mounting surfaces, i.e. bores and faces (for bore gears) or journals (for shaft gears), should be appropriately toleranced as those surfaces have a direct effect on lead quality. An inadequate blank geometry affects the slope component of the gear lead error. Figure 3 is also an example of the slope variation caused by a face-to-bore perpendicularity error. A similar error could result from excessive error in face-to-face parallelism.

• **Cutting conditions factor.** Aggressive cutting conditions can create excessive forces that may not be adequately absorbed by the fixture, thus negatively affecting lead quality. Also, as hob cutting edges wear, the cutting forces can climb considerably. In addition, oil contaminated with chips can create an irregular lead roughness. The hob feed rate also has a direct effect on tooth surface variation in the lead direction—feed scallop depth. Frequently, people who finish hob gears want the scallop depth not to exceed a certain value. The feed rate can be determined as a function of allowable feed scallop depth at the pitch circle. The effects of the feed rate on tooth surface are illustrated in Figure 4.

$$\text{Hob feed rate} = \cos(\beta) \cdot \text{sqrt}\,(\delta \cdot 4 \cdot \text{HOBOD}/\sin(\alpha))$$

Where:

Hob feed rate: Axial advance of hob per one work revolution, inch/rev.

β: Helix angle

δ: Allowable feed scallop depth at pitch dia., inch

α: Pressure angle

HOBOD: Hob outside diameter, inch

It is worth noting that the feed scallop depth is not constant within the entire tooth depth. It is greater at the tooth tip and smaller at the tooth root. Pitch circle is a convenient place to reference the limitation of feed scallop depth. If the gear lead is not inspected on the pitch circle, the amount of feed scallop depth shown could be different than what is expected.

• **Setup consistency factor.** There is no such thing as an identical setup. Every time the fixture is placed in the machine, there will be a different workpiece runout condition. Carl Eckberg, Vice President of Bourn & Koch, once paraphrased a joke about the three things important for real estate value: 1. Location, 2. Location, and 3. Location. He said that, likewise, there are three things that are important for hobbing quality: 1. Runout, 2. Runout, and 3. Runout. A tiny chip can contaminate a perfect fixture resulting in a dramatic lead variation. All mounting surfaces should be checked for proper runout. Consideration should be given to a fixture design that reduces the amount of possible mounting variations between setups. Also, a reliable, automatic system for removing chips from the fixture mounting surfaces, prior to loading the part, will facilitate a greater process capability.

Gear Profile (Involute) Quality. Improving gear lead and pitch characteristics is often easier than improving profile characteristics. In fact, it is not uncommon to see lead and pitch characteristics of hobbed gears at AGMA quality 11–12 and even better. However, when it comes to tooth profile quality, very few people can achieve quality higher than AGMA 9 on a consistent basis. Why such a discrepancy? One answer is that the gear profile quality is affected by a greater number of process variables. The profile quality depends on all contributors listed in the "Lead" section. However, the inherent hob geometry errors, i.e. lead; pressure angle; the sharpening quality of hob spacing, rake, and flute lead; and hob mounting quality are the additional and very significant contributors to gear profile quality.

• **Machine factor.** Worn bearings in the cutter spindle and outboard support, worn table drive, and dynamic instability of hob-worktable synchronization may create irregular profile errors.

• **Workholding fixture factor.** The fixture has a critical role for centering the part properly. An inadequate fixture can cause the workpiece to have a radial runout, or an axial runout, or a combination of both. Workpiece radial runout may dramatically affect the slope component of the profile error. For high helix angle gears, the workpiece axial runout can create a similar affect.

• **Hob factor.** This is probably the most frequent culprit causing profile errors. Unlike the gear lead, which is generated by the same hob cutting edge along the entire face width, the gear profile is generated by a large number of hob cutting edges. Every cutting edge, and its geometric relationship with adjacent cutting edges in the generating zone, affect the gear profile quality. Also, an inadequate hob mounting, with a radial or an axial runout, will simulate a condition of an inadequate hob index or lead quality. In the case of multi-start hobbing, there would be even greater numbers of quality contributors. That is why single-start hobbing is usually used when people are trying to achieve the best possible gear quality. The number of hob gashes is also important for precision gear manufacturing, especially for gears with a small number of teeth. The greater the number of gashes, the greater the number of profile generating cuts. Greater numbers of generating cuts reduce the inherent profile error (deviation from an ideal involute) created by the hobbing method. Figures 5 and 6 illustrate profile errors caused by a smaller and a larger number of gashes respectively. Profile deviation from the ideal involute caused by the enveloping cuts can be calculated. A greater number of hob gashes, which translates into a greater number of cutting edges, exponentially reduces the profile deviation (error) from the ideal involute.

$$\text{Profile deviation} = \pi^2 \cdot Zo \cdot \sin(\alpha) / (4 \cdot Z2 \cdot i^2 \cdot NDP)$$

Where:

Zo: Number of hob starts

α: Normal pressure angle

Z2: Number of gear teeth

i: Number of hob gashes

NDP: Normal Diametral Pitch of the gear

Profile deviation: Profile deviation from the idea involute curve, inch

• **Gear blank factor.** The gear bore quality is very important, as it can cause an inconsistent runout condition on the gear cutting vs. the gear inspection fixture. If the face of the blank is not square to the bore, a profile variation error can be observed. In the case of shafts, the journal that is used for the part clamping should be concentric with centers that might be used for locating the part during inspection. Blank errors will have a greater effect on gears with a small number of teeth, where the roll angle is very large, as well as on gears with a high helix angle.

• **Cutting conditions factor.** In case of a spur or a small helix angle gear, the tooth profile is not affected by the feed rate (Fig. 2). But in the case of gears with high helix angle, the tooth profile quality might be affected by excessive feed marks (Fig. 7). For high helix angle gears, the feed rate has to be kept under control, as it has an effect on both lead and profile form errors.

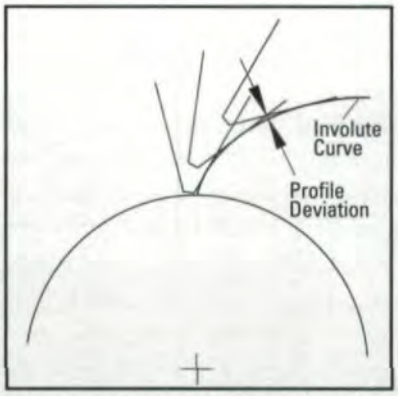

Fig. 5—Profile deviation from the ideal involute made by a hob with fewer gashes.

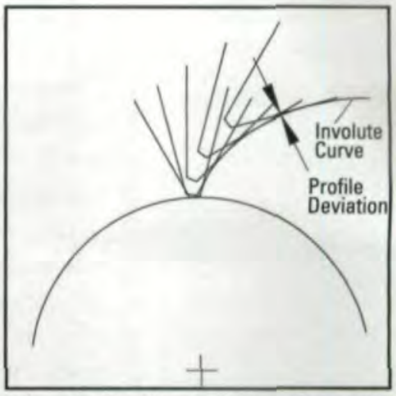

Fig. 6—Profile deviation from the ideal involute made by a hob with more gashes.

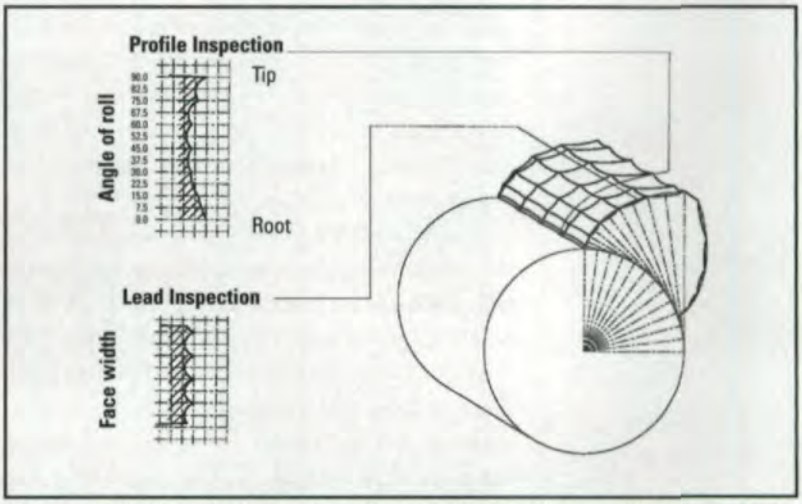

Fig. 7—Helical gear tooth topology. Excessive feed marks may affect gear profile.

• **Setup consistency factor.** A reliable hob mounting procedure, that includes a radial and axial runout inspection of proof journals on both sides of a hob, can help keep gear profile error under control. Everything listed in the relevant part of the lead section is also applicable here.

Pitch and Runout. The hobbing method can produce gears with pitch and runout quality up to AGMA 11, 12 or even higher.

• **Machine factor.** In the case of single-start hobbing, a tooth-to-tooth error is almost exclusively dependent on the hob spindle and machine table synchronization quality. Most reputable CNC hobbing machine suppliers build machines that are capable of making gears with a high degree of pitch accuracy.

• **Workholding fixture factor.** Workpiece radial runout caused by an inadequate fixture is the most frequent culprit contributing to accumulative pitch and runout errors.

• **Hob factor.** Similar to the lead characteristic, geometry errors of a one-start hob have no effect on either gear pitch quality or runout quality.

However, the thread-to-thread variation of a multi-start hob can have a dramatic effect on tooth-to-tooth errors.

• **Cutting conditions factor.** As long as the feed scallop depth is very small, which is usually the case for finish hobbing, cutting speed and feed have no effect on gear pitch and runout quality.

• **Gear blank factor.** Similar to the fixture effects, the geometric quality of the gear blank has a direct effect on the gear's accumulative pitch and runout errors. The greater the number of gear teeth, the lesser the effect of blank inaccuracy on the tooth-to-tooth error.

• **Setup consistency factor.** A reliable fixture mounting procedure, combined with runout inspection of all mounting surfaces, can help keep the gear pitch and runout errors under control. Proper care should be taken to remove burrs, and/or all other surface contaminants, prior the pitch and runout inspection.

Tooth Thickness. As opposed to rough hobbing, the finish hobbing process generally has a more stringent tooth thickness tolerance. The tooth thickness consistency mostly depends on the machine's thermal stability, the accuracy of hob shifting alignment, and the hob lead quality. It is important to note that the capability of the inspection technique can be a source of confusion. Dimension Over Pins (DOP) is probably the most popular method for indirect tooth thickness measurement. Generally, it is recommended to measure DOP in at least two places, 90 degrees apart. For other methods (span, center distance device with a master gear, base pitch device, or CMM), it is important to develop a procedure that provides the measurement of an average tooth thickness. As far as tooth thickness consistency is concerned, the finish hobbing process can approach the capability of a shaving or even a grinding process, assuming that the same inspection techniques and QC procedures are used.

• **Machine factor.** A machine's thermal instability is usually the greatest contributor to tooth thickness inconsistency. That is why many people study the machine's thermal behavior when they purchase a gear hobbing machine. Another possible contributor to tooth thickness inconsistency is workpiece/hob center distance variation caused by a hob shifting mechanism. Many new machines today are capable of producing parts with only .0002–.0003" tooth thickness variation. In fact, it is not uncommon to see a tooth thickness measuring technique that is less capable than the machine itself.

• **Workholding fixture factor.** Part runout induced by an inadequate fixture will make the gear teeth of the same part unequal. However, the fixture quality has no effect on the consistency of the average tooth thickness. Excessive part runout can create an illusion of a part-to-part tooth thickness inconsistency. That is why, prior to making tooth thickness adjustment on a hobbing machine, it is generally recommended to measure the gear tooth thickness twice, 90 degrees apart.

• **Hob factor.** Hob tooth thickness consistency along the whole face width is another important factor affecting tooth thickness variation from part to part. It is of even greater importance today since many gear makers are using longer hobs. A hob lead inspection can reveal a hob taper. A taper could also be created in the hob if it were sharpened with an excessive flute error. During hob shifting, a tapered hob could contribute to tooth thickness inconsistency.

• **Gear blank factor.** Similar to the fixture, a gear's blank quality has no effect on the part-to-part average tooth thickness variation.

• **Cutting conditions factor.** As long as the feed scallop depth and enveloping cut depth are very small, which is usually the case for finish hobbing, the cutting speed and feed have no effect on the tooth thickness variation.

• **Setup consistency factor.** The tooth thickness is established during the setup. That is why the tooth thickness consistency between setups depends on the reliability of QC procedures and the capability of the measuring technique.

Conclusion

Gear hobbing, as any other process, has certain inherent quality limitations. But, during the last 20 years, those limitations have changed, opening up new opportunities for quality improvements in traditional finish hobbing applications. In addition, opportunities have been created for the hobbing process to be used as a finishing operation in many more applications where a higher degree of precision is required.

As a result, the use of hobbing machines for gear finishing operations has grown in popularity. This popularity has been reinforced by skiving/rehobbing process advancements. The skiving/rehobbing process is a secondary gear finishing operation that can be done on a hobbing machine. The skiving/rehobbing process allows the manufacturer to eliminate heat treat distortions without having to resort to grinding or another expensive machining process.

Today, finishing gears on a hobbing machine is a viable alternative for a greater variety of gear applications, opening up cost reduction opportunities for gears with quality requirements in the transition area of AGMA Q9–11. ○

The author would like to express his gratitude to John Bodine and Paul Ruff for their editing help.